REPORT
48

GEOLOGY OF THE ARCHAEAN KALGOORLIE TERRANE — AN EXPLANATORY NOTE
(reprint of Record 1990/12)

by C. P. Swager, T. J. Griffin, W. K. Witt, S. Wyche, A. L. Ahmat, W. M. Hunter and P. J. McGoldrick

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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Cover photograph:

Chaotic breccia, clast-supported and with very little matrix, in a felsic volcaniclastic sandstone from the felsic volcanic–volcaniclastic unit in the Kalgoorlie Terrane. The sandstone is probably the product of the reworking of a crystal tuff. Exposure is 12 km north of Kalgoorlie, and a few hundred metres west of the Kalgoorlie–Leonora highway

Contents

Plates (in pocket)

Figures

Tables

Preface

This report is a reprint of GSWA Record 1990/12, which presented an explanatory note to accompany the regional interpretation map of the granite–greenstones in the Archaean Kalgoorlie Terrane, Eastern Goldfields Province. The only changes to the original text are the inclusion of Figure 3 — showing the simplified geology and major D_2 and D_3 structures of the Kalgoorlie Terrane — and minor changes to some geological boundaries on Figures 2 and 8. The reference list has also been updated. Since publication of the Record in 1990, geological mapping to the east of the Kalgoorlie Terrane has resulted in a more detailed structural–stratigraphic division of the Kurnalpi–Edjudina Terranes. That study is presented as Report 47 and should be referred to for the present nomenclature of the granite–greenstone terranes east of the Kalgoorlie Terrane. Other changes since the publication of Record 1990/12 include the renaming of the Callion Terrane as the Barlee Terrane, reflecting the recognition of the widespread distribution of that particular greenstone association.

Geology of the Archaean Kalgoorlie Terrane — an explanatory note

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Abstract

The late Archaean Kalgoorlie Terrane is defined on the basis of a distinct regional greenstone stratigraphy and deformation history.

The regional stratigraphy consists of a lower basalt unit, followed by a komatiite unit, an upper basalt unit, and a felsic volcanic and sedimentary rock unit which is unconformably overlain by locally developed, coarse clastic sequences. The regional deformation history includes D_1 thrusting, D_2 upright folding about north-northwesterly-trending axes, D_3 sinistral transcurrent faulting and continued east-northeasterly–west-southwesterly regional shortening. I-type granitoids were emplaced during deformation. Regional metamorphism at greenschist to amphibolite facies reached peak temperatures late during the D_2 to D_3 transpressional deformation.

Deposition of the mafic volcanic rocks occurred around 2.70 to 2.69 Ga, and the main regional deformation between 2.68 and 2.61 Ga. Cratonization took place before the emplacement of 2.4 Ga, east-striking Proterozoic mafic dykes.

The Kalgoorlie Terrane is subdivided into six domains separated by major faults. Regional structures such as D_1 thrust faults, F_2 folds and D_3 shears cannot be traced across the domain boundary faults. The two major central domains (Kambalda and Ora Banda) contain the complete regional stratigraphic sequence, whereas the western and eastern domains (Coolgardie and Boorara) have an upper basalt unit which is thin or absent.

The preferred tectonic setting of the greenstones in the Kalgoorlie Terrane is a marginal basin at a convergent continental plate edge.

Keywords: Yilgarn Craton, Eastern Goldfields Province, late Archaean terranes, greenstones, granitoids, regional deformation, tectonic evolution, geochronology, mineralization

The geology of the Archaean Kalgoorlie Terrane is presented at a scale of 1:250 000 on two sheets (a northern and a southern sheet) that are designed to be joined to form an integrated map. This interpretive map, compiled by C. P. Swager and T. J. Griffin, results from regional 1:100 000 mapping in the Kalgoorlie–Norseman region of the Eastern Goldfields by the Geological Survey of Western Australia (GSWA) over the past ten years. The sheets are: LAKE LEFROY* and COWAN (Griffin and Hickman, 1988; Griffin, 1988, 1990b); YILMIA and KALGOORLIE (Hunter, 1988a,b, 1993); DUNNSVILLE and MENZIES (Swager, 1989a, 1994a, 1994b; Swager and Witt, 1990); BARDOC (Witt and Swager, 1989b; Witt, 1994); KANOWNA (Ahmat, 1995a,b); DAVYHURST (Wyche et al, 1992; Wyche and Witt, 1994); NORSEMAN (McGoldrick, 1993, in prep.). The terrane map is largely based on outcrop mapping but also incorporates information from exploration and mining companies, as well as the interpretation of regional aeromagnetic maps, on areas where the Archaean rocks do not outcrop.

The Kalgoorlie Terrane contains a significant proportion of the greenstones in the southern part of the

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* Sheet names are written in capital letters to avoid confusion with similar place names.

Eastern Goldfields Province in the Yilgarn Craton of Western Australia (Fig. 1). The Kalgoorlie Terrane is separated from greenstones in adjacent terranes by either major faults or granitoid intrusions.

The greenstones of the Eastern Goldfields Province host rich deposits of nickel and gold, and comprise metamorphosed mafic volcanic and intrusive rocks and felsic volcanic and sedimentary rocks which outcrop in highly deformed, linear belts intruded by, and separated by, variably deformed and metamorphosed granitoid rocks. Distinctive features of the Eastern Goldfields Province are the large volume of komatiite concentrated in the western half of the province and the virtual absence of banded iron-formation (BIF). BIF is common outside areas (such as the Kalgoorlie Terrane) that are rich in komatiite.

I.R. Williams (1974) first interpreted this komatiite-rich greenstone sequence, which lacks BIF, as a trough or graben association. The greenstone association has subsequently been referred to as the Norseman–Wiluna belt; but its boundaries have remained poorly defined (Gee, 1979; Gee et al., 1981; Groves and Batt, 1984; Hallberg, 1986; Barley and Groves, 1988). The volcanic–sedimentary sequence has been dated at c. 2700–2690 Ma (e.g. McNaughton and Dahl, 1987; Claoué-Long et al., 1988). Archibald et al. (1978, 1981) and Gee et al. (1981) considered that the Norseman–Wiluna belt developed on sialic basement, possibly with a pre-existing greenstone

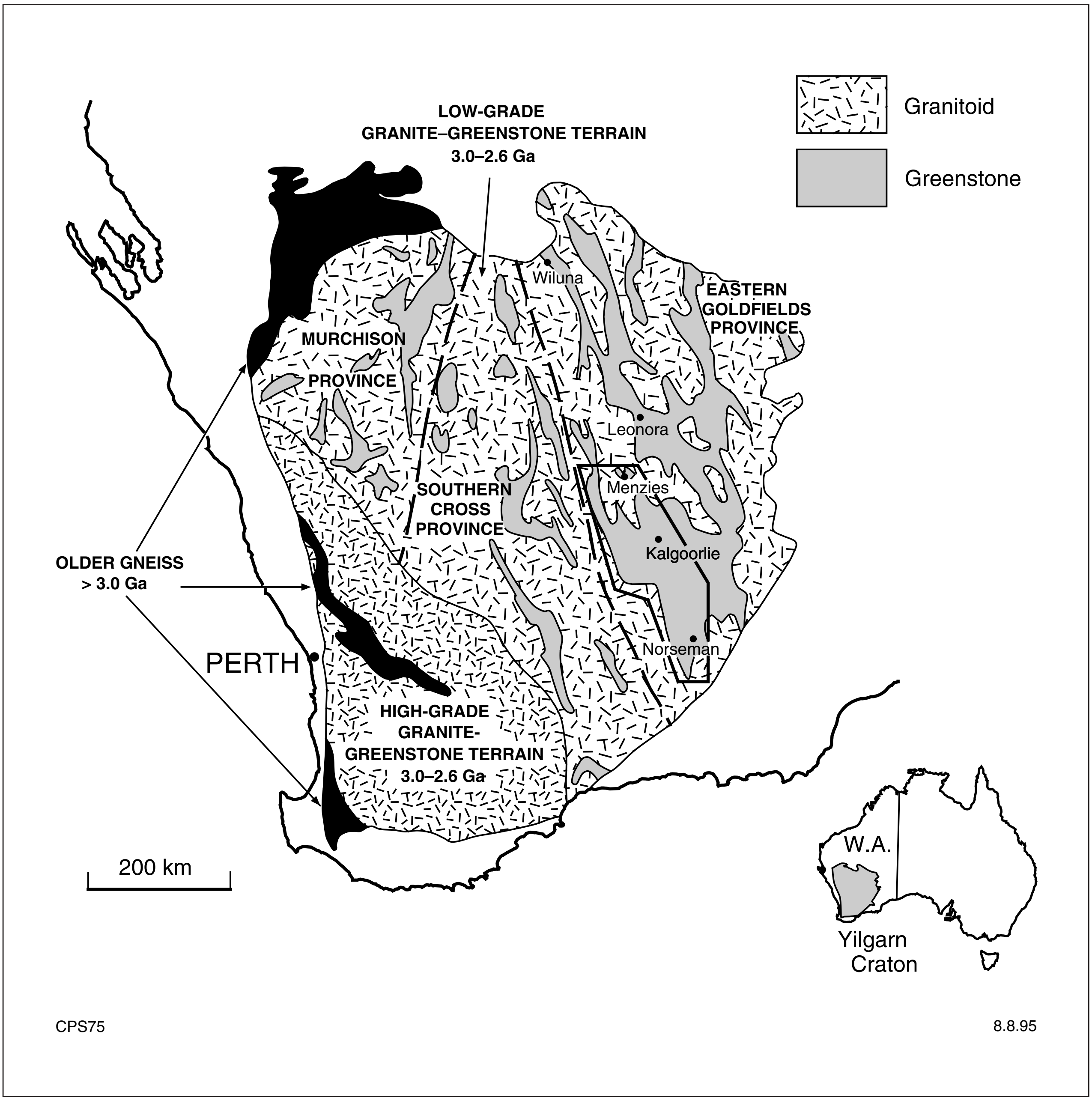

Figure 1. Geological map of the Yilgarn Craton (after Myers, 1988; province boundaries after Gee et al., 1981). The region covered by the Kalgoorlie Terrane map is shown by a bold frame

cover. The concept of an ensialic rift basin was refined by Groves and Batt (1984) who described 'rift-phase' greenstones dominated by deep-marine basalt and komatiite developed on 'platform-phase' greenstones characterized by BIF and only minor komatiite. Recently, Barley and Groves (1988) and Barley et al. (1989) have proposed a back-arc or marginal basin model for the Norseman–Wiluna belt, adjacent to an eastern arc of calc-alkaline volcanics and tholeiites.

The entire Eastern Goldfields Province is characterized by a strong north-northwest structural trend defined by major faults and shear zones, regional folds, and elongate granitoid batholiths (Gee, 1979). An anastomosing system of shear zones has resulted in elongate greenstone belts or domains with well-established stratigraphic sequences that are difficult to correlate across the major faults. Evidence of pervasive regional shortening and major strike-slip shear zones (transpression) has been interpreted in terms of large-scale Archaean plate interaction (e.g. Platt, 1980; Gee et al., 1986; Witt and Swager, 1989a). Barley and Groves (1988) inferred oblique closure of their proposed marginal basin during the transpressional deformation regime. Detailed geological documentation has not always kept pace with the proliferation of tectonic models and much more work is required to test them.

In the Kalgoorlie region, the systematic regional mapping by the GSWA has delineated a number of tectonostratigraphic domains with similar geological histories. Together these domains comprise a tectono-stratigraphic terrane — the Kalgoorlie Terrane (Myers, 1990) — which is distinguished from the adjacent Callion, Norseman, Kurnalpi, and Menzies Terranes (Fig. 2) by its distinct greenstone stratigraphy and deformation history. The main lithological–stratigraphic and structural elements of the terrane are shown on Figure 3.

Although all rocks have been metamorphosed, the prefix 'meta-' is generally omitted for ease of description.

Kalgoorlie Terrane

The Kalgoorlie Terrane is the only well-defined terrane of the Eastern Goldfields Province. Although detailed mapping of the Eastern Goldfields is incomplete, it appears that the Callion and Norseman Terranes lack significant komatiite and contain extensive BIF units that have not been found in the Kalgoorlie Terrane. The Kurnalpi Terrane is a composite unit that may be subdivided after further work. It contains komatiite but is dominated to the east by mafic and acid to intermediate volcanic rocks.

The Kalgoorlie Terrane is divided into four major domains: Coolgardie, Ora Banda, Kambalda, and Boorara Domains; and two smaller domains — Bullabulling and Parker Domains. These domains are separated by shear zones that include dismembered and attenuated elements of the stratigraphy. Despite these structural breaks, a similar regional stratigraphic succession (with some variations) and a common deformation history are recognized throughout.

Stratigraphy

Regional mapping, along with extensive mining and exploration, have resulted in a well-established regional stratigraphy for the Ora Banda Domain (Witt, 1994) and Kambalda Domain (Cowden and Archibald, in prep.) (Table 1). The characteristic sequence consists of a lower basalt unit overlain by a komatiite unit, which is in turn overlain by an upper basalt unit followed by a unit of felsic volcanic and sedimentary rocks. It includes layered and differentiated mafic sills at various stratigraphic levels. The Coolgardie and Boorara Domains have very similar successions but lack, or have only a poorly developed, upper basalt unit so that komatiite is directly overlain by felsic volcanic and sedimentary rocks. The Coolgardie Domain is characterized by a repetition of the basalt–komatiite interval of the regional succession (see geological map for this pattern around Widgiemooltha — Griffin and Hickman, 1988; Griffin, 1988; Coolgardie — Hunter, 1988a,b; Dunnsville — Swager, 1989a). This 'double' succession has been interpreted as a structural repetition on the basis of a comparison with the stratigraphic successions at Kambalda and Ora Banda (Martyn, 1987; Swager, 1989a).

Some parts of the Kalgoorlie Terrane, most notably the Parker and Bullabulling Domains, have not been placed in the widely recognized stratigraphic sequence described below. This is due to the combined effects of poor outcrop and a complex structural history which have resulted in the juxtaposition of contrasting rock types through interleaving. Generalized rock unit descriptors are used for these areas and for similar lithologies in adjacent terranes.

The mafic and ultramafic volcanic rocks have geochemical compositions which plot predominantly in the tholeiitic, high-Mg basalt, and komatiite fields (Fig. 4). A detailed discussion of the volcanology and geochemistry of these volcanics is presented by Morris (1991, 1993). The limited data on sills that intrude at various stratigraphic levels indicate they are mainly high-Mg basalt in composition but extend into the tholeiitic field (Fig. 4).

Lower basalt unit

The lower basalt unit changes upwards from high-Mg to tholeiitic in character; this compositional trend is most obvious in the Ora Banda Domain where there are two distinct basalt units (the Wongi Basalt overlain by the Missouri Basalt) separated by a thin (20–40 m) felsic volcaniclastic sedimentary unit which has been intruded by dolerite. A similar compositional trend has been noted in the Kambalda and Boorara Domains (Lunnon Basalt — Redman and Keays, 1985; Scotia Basalt — Nesbitt and Sun, 1976). Felsic volcaniclastic rocks interfinger with lower basalt (Missouri Basalt) in the Ora Banda Domain (Witt and Harrison, 1989), and a distinct felsic volcanic complex is present within the lower basalt unit in the Boorara Domain at Gordon (I. R. Williams, 1971). These felsic rocks could represent either air-fall tuffs from ash clouds produced by distant volcanoes, or fine-grained sills and dykes.

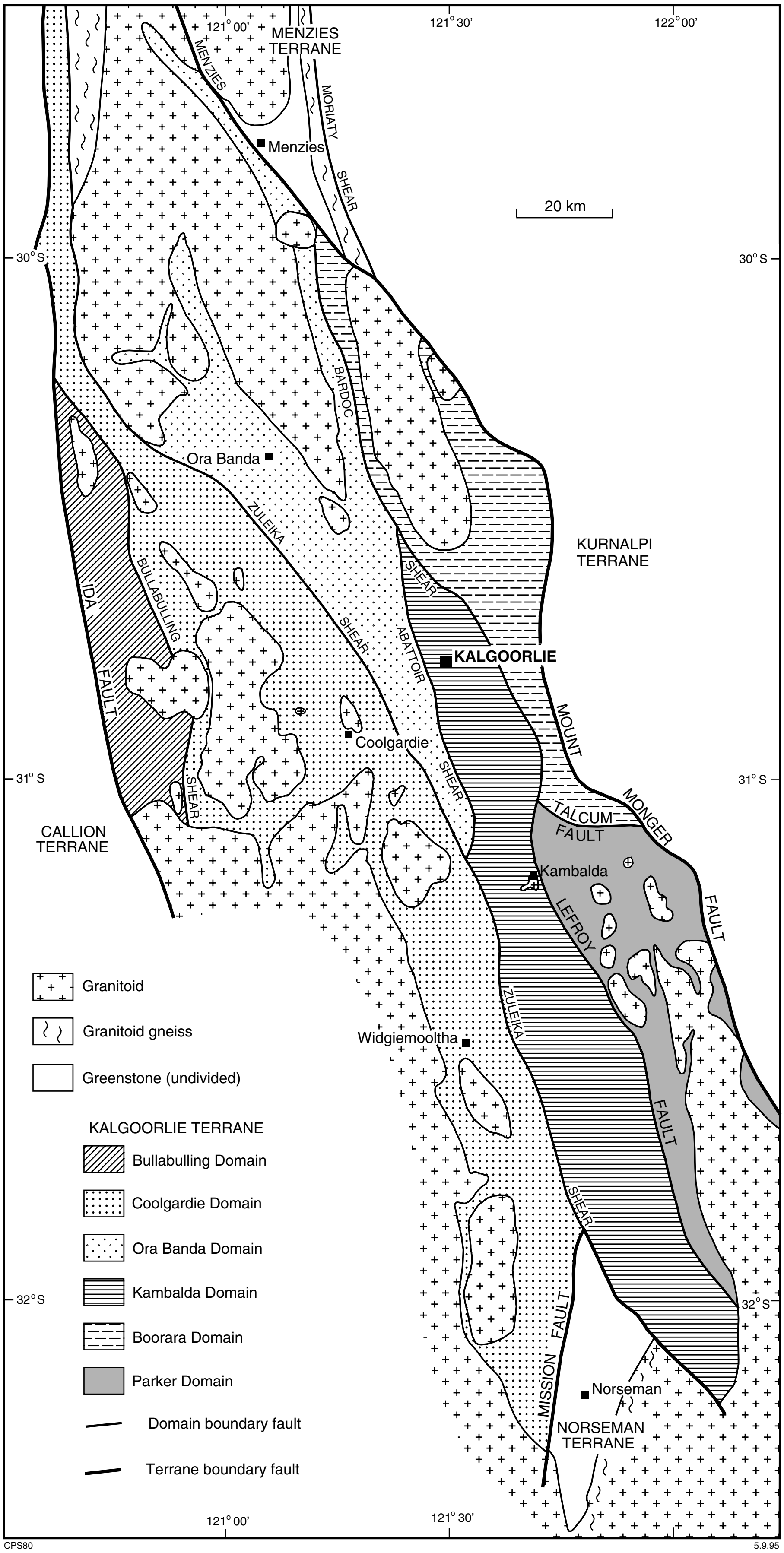

Figure 2. Terrane map of the Kalgoorlie region, highlighting the Kalgoorlie Terrane and its six constituent tectonostratigraphic domains. Note revision of boundaries

Komatiite unit

The lower basalt unit is overlain by a prominent sequence of komatiite flows — which can be used as a regional marker. The upper part of this komatiite unit consists of variolitic high-Mg basalt that forms thin, mappable units in both the Kambalda and Ora Banda Domains. Different stratigraphic names have been applied to the komatiite unit in the different domains.

The Kambalda Komatiite in the Kambalda Domain comprises flows up to 100 m thick, which may be separated by thin (<5 m) fine-grained metasedimentary beds, and includes rocks in the Kalgoorlie district that traditionally have been called the Hannan Lake Serpentinite (Keats, 1987). In the Ora Banda Domain, flows of the Siberia Komatiite are underlain by a distinctive dunite unit, the Walter Williams Formation, which has been interpreted by Hill et al. (1987) as the product of adcumulus olivine growth at the bottom of a lava flow. Stolz and Nesbitt (1981) advocated a similar origin for a more restricted pod or lens of olivine adcumulate in the Highway Ultramafics in the Boorara Domain.

There are some important differences between komatiite suites in different domains which may reflect variations in both physical and chemical environment of formation (Hill et al., 1987). Massive syngenetic Ni–Fe sulfide orebodies occur in the Kambalda area at the base of the lowermost komatiite flow, mostly in depressions at the contact with the underlying basalt. The Coolgardie and Boorara Domains also host a number of nickel mines at similar stratigraphic levels. However, nickel mineralization has not been found in the Ora Banda Domain, despite intensive exploration. Thick high-Mg basalt units with characteristic pyroxene-spinifex texture occur within komatiite of the Ora Banda and Coolgardie Domains.

Upper basalt unit

The komatiite unit is overlain by prominent tholeiitic and high-Mg basalt, the upper basalt unit, in the Ora Banda and Kambalda Domains. In the Kambalda Domain, the base of the unit is marked by the Kapai Slate, which is typically siliceous, albitic and carbonaceous, with abundant magnetite or pyrite, and is generally 1 to 3 m thick. The slate may have both chemical and clastic sedimentary components. A similar marker bed, called the Big Blow Chert, occurs at the base of the komatiite unit in the Boorara Domain. Thin sedimentary beds between lava flows are commonly sites of thin dolerite and/or felsic to intermediate porphyry intrusions. These sedimentary rocks are commonly intensely strained and, in some places, mineralized with gold.

Mafic sills

Layered mafic sills appear to have been intruded before D_1 subhorizontal deformation and some may represent subvolcanic equivalents of extrusive volcanics. Although Golding (1985) and Tomich (1986) have suggested the Golden Mile Dolerite at Kalgoorlie is extrusive, most gabbro bodies are interpreted as intrusive. The Ora Banda Sill cuts across the enclosing volcanic–sedimentary sequence and has locally melted its roof rocks (Witt, 1987).

The sills are considered to be co-magmatic with the volcanics (Williams and Hallberg, 1973; Witt et al., 1991) except for those within the Black Flag Group, which apparently have no extrusive equivalents and possibly represent the final stages of the mafic magmatism. Archaean mafic sills and dykes do not intrude the large granitoid bodies. Several epigenetic gold orebodies have been preferentially developed in fractionated high-Fe quartz dolerite zones within both tholeiitic and more magnesian sills (Groves and Barley, 1988; Witt, 1993).

Felsic volcanic and sedimentary unit

The mafic–ultramafic volcanic succession is overlain by a poorly exposed felsic volcanic–sedimentary unit, the Black Flag Group. It does not host much of the known mineralization and therefore has not been studied in great detail. The felsic extrusive rocks range in composition from rhyolite to andesite but are predominantly dacite, and include lava flows, tuff and agglomerate. They are intimately interbedded with quartzofeldspathic siltstone and sandstone (e.g. Spargoville area — Fehlberg and Giles, 1984; Kanowna area — Taylor, 1984; Ahmat, 1995a, b). Clastic sedimentary rocks dominate this unit, particularly the upper part, and comprise thin-bedded, graded sandstone and siltstone which were largely derived by erosion of the felsic volcanics. Oligomictic conglomerates, dominated by feldspar–quartz porphyry pebbles, are abundant throughout the sequence, but there are also locally polymictic conglomerates with mafic and ultramafic rock pebbles in a chloritic matrix. Mafic and felsic igneous activities appear to have overlapped. Thin komatiite and basalt lava flows and gabbro sills occur within the Black Flag Group, although some may result from tectonic interleaving.

Coarse olistostromes of felsic volcaniclastic rocks, stromatolitic chert blocks, and komatiite pebbles occur within komatiite near Kanowna (Taylor, 1984; Ahmat, 1995b). At Mount Shea in the Kambalda Domain, the upper basalt unit is thin and both basalt and komatiite interfinger with felsic volcaniclastic rock (Keats, 1987).

Kurrawang Formation and Merougil Conglomerate

The youngest stratigraphic units are the Kurrawang Formation and Merougil Conglomerate, which lie within locally fault-bounded synclines parallel to the regional tectonic trend. They contain alluvial, fluviatile, and possibly shallow-marine coarse clastic sandstone and polymictic conglomerate. The Kurrawang Formation includes BIF pebbles which suggest a provenance outside the Coolgardie Domain, possibly from the Callion Terrane (Fig. 2). Sedimentation is interpreted to have been structurally controlled, perhaps with predominantly longitudinal sediment transport (Glikson, 1971), and developed syntectonically (early during

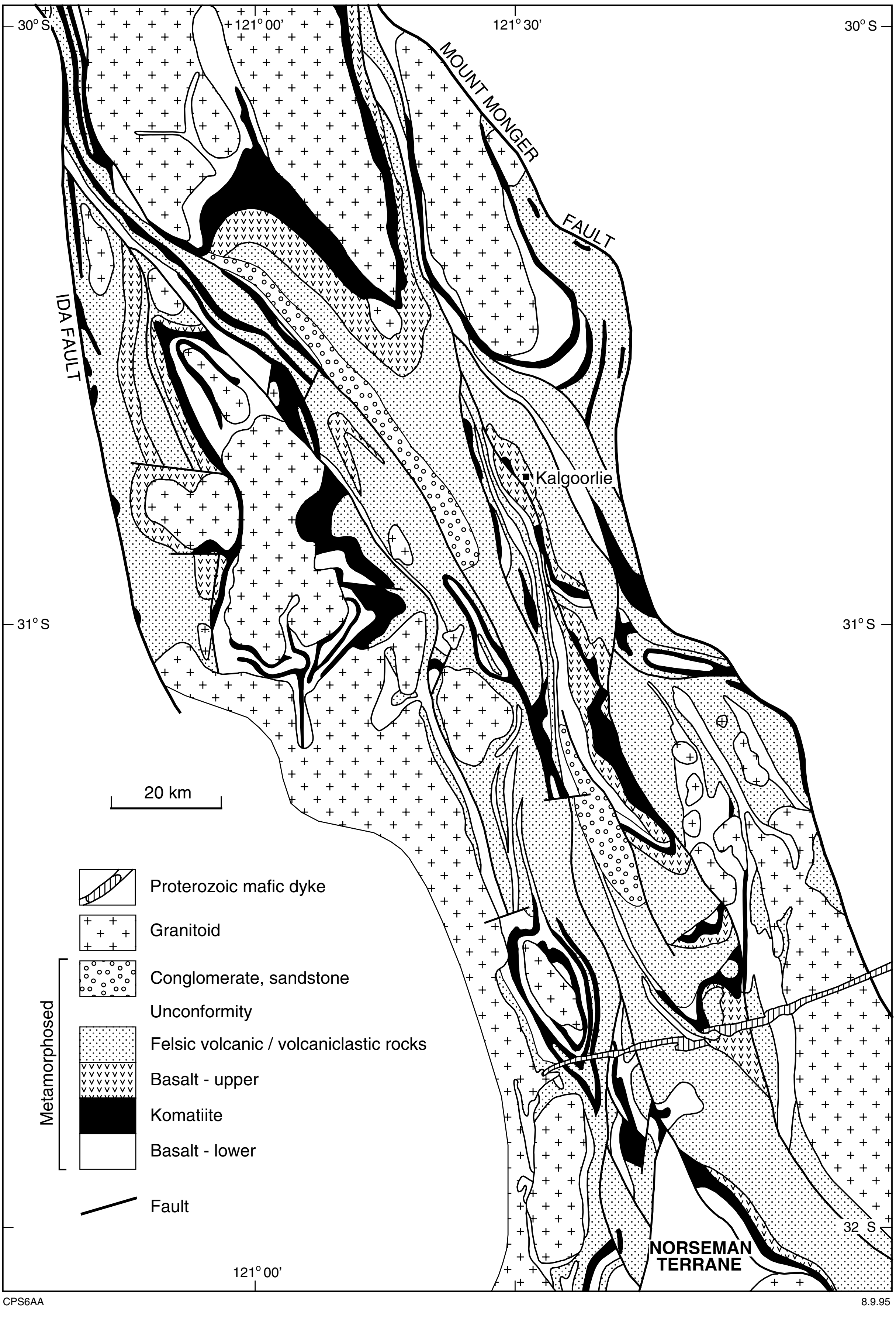

Figure 3A. Simplified geology of the Kalgoorlie Terrane

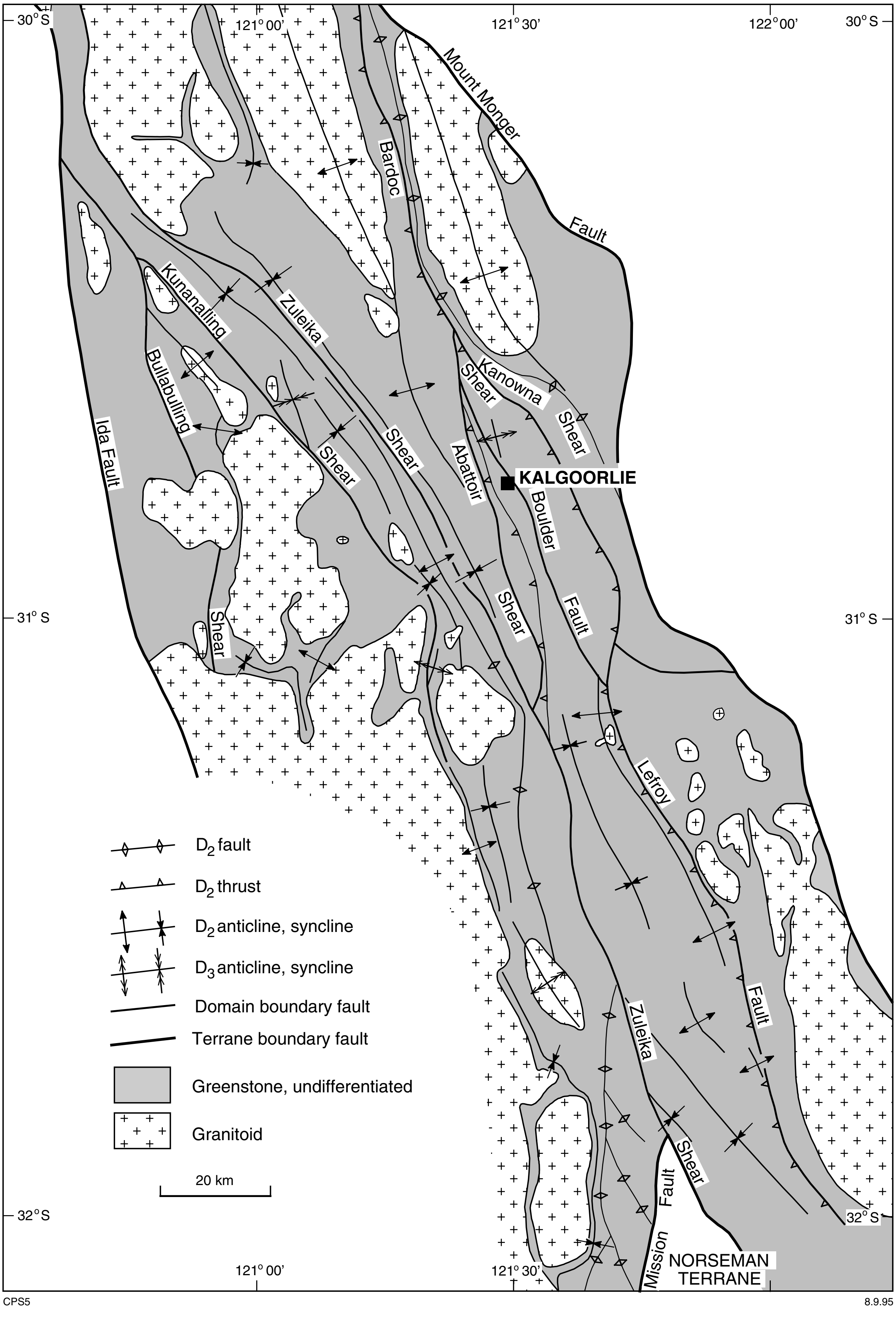

Figure 3B. Major D_2 and D_3 structures in the Kalgoorlie Terrane

Table 1. Stratigraphic correlations for the Ora Banda, Kambalda, Coolgardie, and Boorara Domains of the Kalgoorlie Terrane

STRATIGRAPHIC SUCCESSION	CHARACTERISTIC LITHOLOGIES	ORA BANDA DOMAIN	KAMBALDA DOMAIN	COOLGARDIE DOMAIN	BOORARA DOMAIN
Polymictic conglomerate unit	Polymictic conglomerate Immature sandstone; coarse trough cross beds, graded beds	Kurrawang Formation	Merougil Conglomerate	Absent	Absent
Felsic volcanic and sedimentary unit	Felsic volcaniclastic-sedimentary rocks, ranging from coarse clastic sandstone to interbedded sand/siltstone Rhyolite to dacite, locally andesite; lava, tuff, agglomerate	BLACK FLAG GROUP: Pipeline Andesite Orinda Sill Ora Banda Sill	BLACK FLAG GROUP: Junction Dolerite Condenser Dolerite Golden Mile Dolerite Triumph Gabbro	BLACK FLAG GROUP: White Flag Formation Powder Sill Spargoville Formation	Felsic unit, volcanic and sedimentary rocks
Upper basalt unit	High-Mg and tholeiitic basalt; massive, pillowed and vesicular lavas	GRANTS PATCH GROUP: Victorious Basalt Bent Tree Basalt Mt Pleasant Sill Mt Ellis Sill	KALGOORLIE GROUP: Paringa Basalt Defiance Dolerite Williamstown Dolerite Kapai Slate	COOLGARDIE GROUP: Absent or thin and discontinuous	Absent or thin and discontinuous
Komatiite unit	High-Mg basalt at top; thin komatiite flows with minor interflow sedimentary beds, overlying thicker komatiite flows and/or massive olivine adcumulate	LINGER AND DIE GROUP: Big Dick Basalt Siberia Komatiite Walter Williams Formation	KALGOORLIE GROUP: Devon Consols Basalt Kambalda Komatiite	COOLGARDIE GROUP: Hampton Formation	Highway Ultramafics
Lower basalt unit	Tholeiitic and high-Mg basalt flows, subaqueous	POLE GROUP: Missouri Basalt Wongi Basalt	KALGOORLIE GROUP: Lunnon Basalt	COOLGARDIE GROUP: Golden Bar Sill Burbanks Formation Three Mile Sill	Big Blow Chert Scotia Basalt
References		Witt (1987, 1994)	Roberts (1988) Woodall (1965) Langsford (1989) Cowden and Archibald (in prep.)	Hunter (1993)	Christie (1975) Witt (1994)

GSWA 25667

D_2–D_3) as a result of movements along major faults (Witt and Swager, 1989a; Griffin, 1990b).

Deformation

The regional deformation history involves early D_1 recumbent folding and thrusting followed by a transpressional regime with large-scale, upright D_2 folding, then a period of transcurrent D_3 faulting with associated en echelon folds followed by continued regional D_4 shortening (Table 2). This deformation sequence, established in the northern part of the Kambalda Domain by Swager (1989b) and Swager and Griffin (1990a), is similar to that previously described by Archibald et al. (1978, 1981) and Clark et al. (1986) from the southern parts of the Kambalda and Coolgardie Domains. Archibald (1987) distinguished two stages of subhorizontal deformation: the first resulting in stratigraphic stacking, the second in isolated recumbent to inclined folding. On a regional scale, only one subhorizontal deformation event (D_1) is recognized.

The D_1 deformation event, noted in all major domains except Ora Banda, resulted in large-scale stratigraphic repetition (Figs 5, 6). Swager and Griffin (1990a) described a regional-scale thrust duplex structure which extends from Kambalda to Kalgoorlie duplicating the stratigraphy within the Kambalda Domain (Fig. 5). In the Boorara Domain at least two stacked recumbent anticlines are well-preserved in the low-strain area around Carnilya (Perriam, 1985; Griffin and Hickman, 1988) (Fig. 6A). Northward from Carnilya the sequence becomes strongly attenuated and D_1 structures are difficult to recognize. Other D_1 structures include sheared-through recumbent F_1 folds which have been rotated during D_2 into vertical attitudes (e.g. Kalgoorlie–Boulder mining area), and small-scale thrusts in sedimentary rocks between lava flows (Fig. 6B).

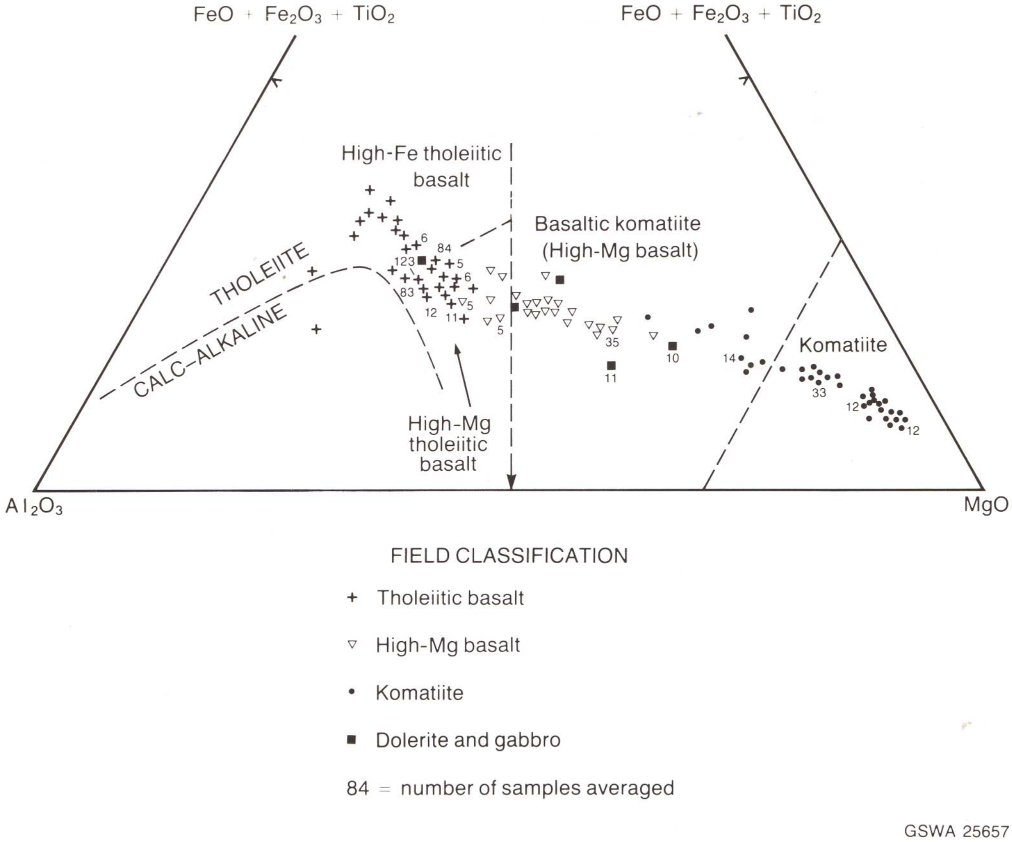

Figure 4. Cation percentage plot of mafic and ultramafic volcanic and intrusive rocks from the Kalgoorlie Terrane (data from Williams and Hallberg, 1973; Gresham and Loftus-Hills, 1981; Redman and Keays, 1985)

Stratigraphic repetition on a regional scale is inferred for the Coolgardie Domain from the 'double' mafic–ultramafic sequence referred to above (Martyn, 1987; Swager, 1989a). This succession can be traced from south of Widgiemooltha to Dunnsville in the north. Although the double sequence can be interpreted as an original stratigraphic feature, intense shearing in the lower, thin komatiite unit is interpreted to indicate a thrust fault across which the lower basalt–komatiite units were repeated. The overlying felsic volcanic–sedimentary unit does not appear to be involved in this large-scale repetition because the proposed major thrust fault lies stratigraphically below it.

Regional-scale D_1 thrust slices are inferred in the area between Coolgardie and Widgiemooltha where narrow, highly deformed and attenuated mafic–ultramafic rock packages wedge out along strike and appear to be stacked and subsequently folded into steep attitudes. On a smaller scale, repetitions of gabbro sills and large-scale, rootless intrafolial folds are interpreted as D_1 structures. Early recumbent folds have been observed within the sedimentary pile and are clearly refolded by upright F_2 folds (Archibald et al., 1981; Archibald, 1987; Griffin and Hickman, 1988; Griffin, 1988). Two stages of subhorizontal deformation, distinguished by Archibald and co-workers on the basis of large-scale stratigraphic repetition and recumbent folds, may represent different scales (and/or geometries) of D_1 structures.

Subsequent D_2 folding and D_3 transcurrent faulting have affected all domains. Regional north-northwest trending upright F_2 folds can be traced over long distances and have gently plunging to horizontal fold axes, as shown, for example, by well-preserved, granitoid-cored anticlines such as the Goongarrie–Mount Pleasant and Scotia–Kanowna Anticlines (Witt, 1987; Witt, 1994). The subvertical regional foliation is interpreted in most cases as a composite $S_2 + S_3$ fabric, particularly outside the main shear zones. Initial foliation development occurred during D_2 folding and intensified during continued regional shortening (D_3).

The Boulder Fault (Fig. 7) and Kunanalling Shear in the Kambalda and Coolgardie Domains respectively are well-defined D_3 transcurrent faults. These faults vary in width from 100 m to 1 km and comprise anastomosing zones of intensely foliated rock which surround pods of less deformed rock. They are associated with F_3 en echelon folds which indicate sinistral displacement. Matching stratigraphies across both faults indicate displacements of approximately 12 km (Langsford, 1989; Swager, 1989b) (Fig. 7). The F_3 en echelon folds may show very steep plunges because they formed in already steeply tilted sequences.

Syntectonic granitoid intrusions are associated with 'accommodation' folds and faults, which are of only local

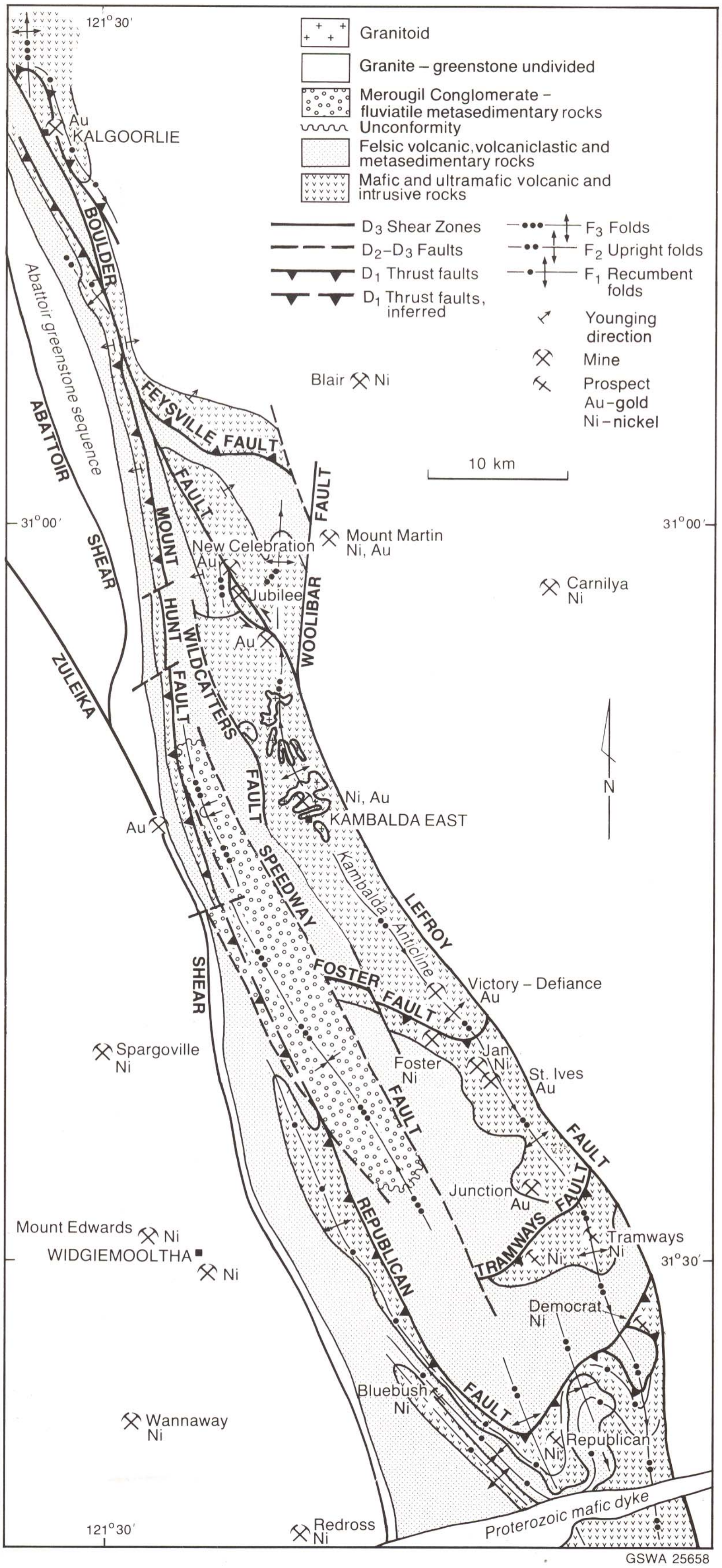

Figure 5. Regional-scale D_1 thrust duplex in the Kambalda Domain

A. Regional map between Kalgoorlie and the Republican–Democrat area

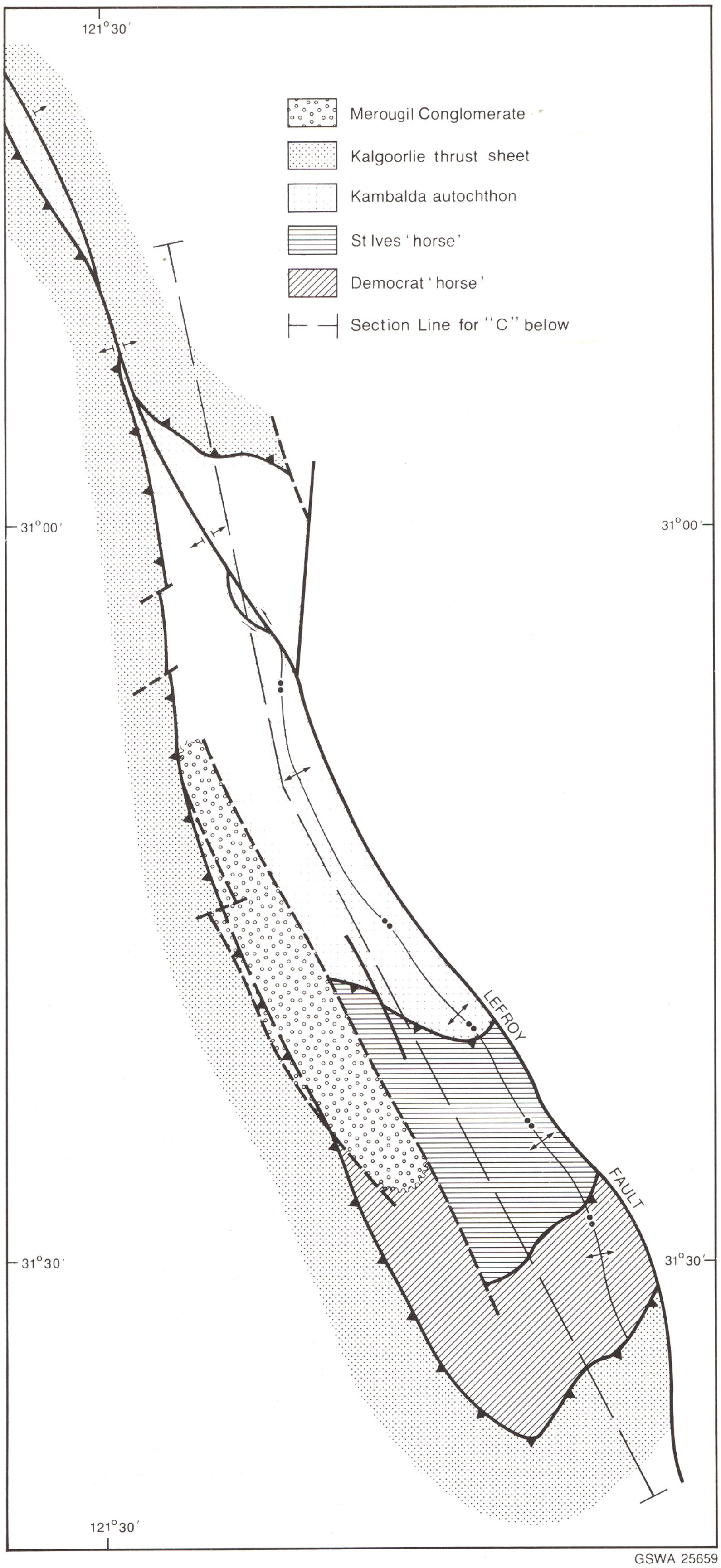

Figure 5B. Simplified interpretation of the thrust duplex, highlighting the Kalgoorlie thrust sheet above a roof thrust, D_1 fault-bounded blocks or horses, and possible Kambalda autochthon

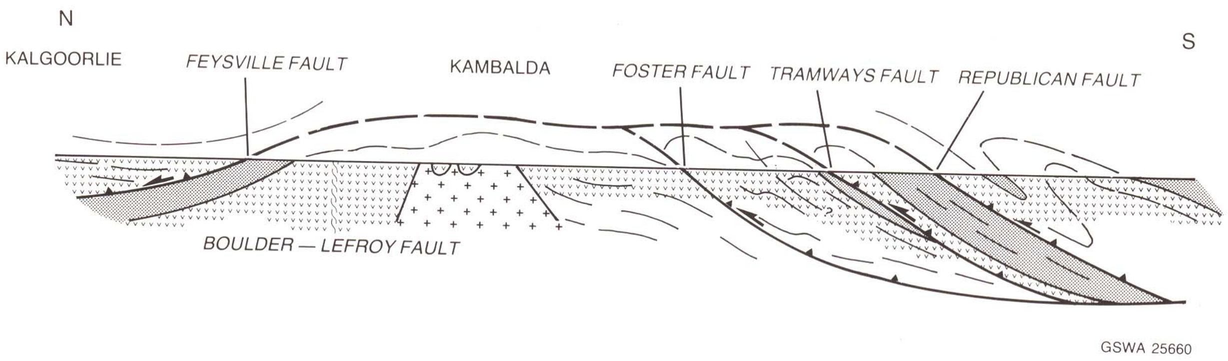

Figure 5C. Schematic longitudinal section parallel to the F_2 Kambalda anticline axis showing one of several possible interpretations of D_1 movement direction, with horses developed at frontal ramp (after Swager and Griffin, 1990a)

extent, have various orientations, and commonly postdate the regional F_2 folds (e.g. around Coolgardie).

Continued regional shortening (D_4) is particularly evident in the major mining centres. At Kalgoorlie, Swager (1989b) described late-stage foliations (developed in sericite–carbonate–quartz schist of the gold lode system) and sets of reverse strike faults, all compatible with continued shortening after D_3 sinistral shearing. Prominent 'oblique' faults, which crosscut and offset these late-stage structures, have been described as a separate D_4 event (Mueller et al., 1988), but can be explained by a small rotation in the main shortening direction. At gold-mining localities near Kambalda, there is evidence for late-stage reverse strike faults and steep movements on the Lefroy Fault (Clark et al., 1986).

The Boorara and Coolgardie Domains are generally more strongly deformed than the Ora Banda and Kambalda Domains, which contain large areas in which original textures have been preserved. The Coolgardie Domain has attained higher metamorphic grades, and reaches middle to upper amphibolite facies along its western margin; and the Boorara Domain is highly sheared and attenuated, particularly east of Kalgoorlie along the Bardoc and Boorara Shears.

None of the major D_1 thrust faults, F_2 fold traces, or D_3 shear zones can be traced from one domain into another. However, the overall deformation history in each domain is directly comparable.

Domain boundary faults

Fault structures bounding the different domains are characterized by wide zones of shearing which result in the attenuation and disruption of the greenstone succession and are associated with widespread carbonate alteration.

The Zuleika Shear separates the Coolgardie Domain from the Ora Banda Domain in the north and the Kambalda Domain in the south (Fig. 2) and forms the northeastern boundary of the Norseman Terrane. It can be traced to the southeast from Callion for at least 250 km. The shear zone is defined by a complex zone of attenuation and stratigraphic mismatch, in places over 1 km wide. No unequivocal marker units have been recognized across it. Evidence for both horizontal and vertical movements can be found at specific localities but these are late-stage and possibly reflect only minor displacements.

Earlier movements (i.e. pre-D_2) are suggested by the different D_1 geometries across the shear. The Zuleika Shear may thus have acted as a major D_1 tear fault, juxtaposing a greenstone sequence with possible major stratigraphic repetition (Coolgardie Domain) against a sequence without any apparent repetition (Ora Banda Domain).

Two major elongate areas, delineated by outcropping coarse clastic sedimentary rocks (the Kurrawang Formation and the Merougil Conglomerate) east of the Zuleika Shear, were possibly synclinal basins formed during D_2 folding. Movements along precursors to the Zuleika Shear and Lefroy Fault may have played an important, but as yet little understood, role in the development of these basins. Conglomerates in the Kurrawang Formation contain internally folded BIF pebbles, which were possibly derived from the nearest BIF outcrop in the Callion Terrane to the northwest.

The Bardoc and Boorara Shears form the boundary between the Boorara Domain and the Kambalda and Ora Banda Domains. North-northeast of Kambalda, the Woolibar Fault connects the Boorara Shear with the Lefroy Fault (Fig. 5). The Bardoc–Boorara Shear zone is up to 3 km wide in the north and includes many interleaved and attenuated slices of various greenstone lithologies. In the far north, the Menzies Shear separates the Ora Banda Domain from the Menzies Terrane. Witt (1994), Swager (1994b), and Swager and Witt (1990) recorded several late-stage (horizontal, oblique and vertical) displacements along the Bardoc–Menzies Shear systems.

The Abattoir Shear, which separates the Kambalda Domain from the Ora Banda Domain, lies west of a narrow sheared sequence of mafic and ultramafic rocks (Fig. 5). These greenstones overlie, and are similar to, the sequence

Table 2. Regional deformation history, granitoid intrusion history, and selected radiometric ages

REGIONAL DEFORMATION HISTORY (a)	GRANITOID INTRUSION (b)	KAMBALDA DOMAIN	ORA BANDA DOMAIN	COOLGARDIE DOMAIN	NORSEMAN TERRANE
D_4 regional shortening, oblique N-striking faults; dextral (Kalgoorlie)	late-tectonic granitoid	metasomatic biotite 3 2601 ± 3 Ma ($^{40}Ar/^{39}Ar$) retrograde carbonation 2627 ± 7 Ma (rutile U-Pb)	Liberty Granodiorite 8 2645 ± 17 Ma 2675 ± 23 Ma	Mungari Monzogranite 6 ~ 2610 Ma	
D_3 continued, regional ENE–WSW shortening; transcurrent faults NNW-trend; sinistral en-echelon folds Formation of syntectonic, clastic basins	post-D_2 to syn-D_3 granitoid	9 ? Granodiorite in Red Hill Granitoid Complex 2 2662 ± 6 Ma Merougil Conglomerate	Kurrawang Formation		
D_2 regional, upright folds NNW-strike	pre- to syn-D_2 granitoid	Early quartz–albite dyke 3 2680^{+21}_{-12} Ma Early lamprophyre dyke 7 2684 ± 6 Ma			Buldania Granitoid Complex 2689 ± 22 Ma 6
D_1 thrust stacking recumbent folding	?				
greenstone volcanism		Kapai Slate 1 2692 ± 4 Ma (euhedral zircon in air-fall tuff) Interflow sediment, near base of Kambalda Komatiite 2702 ± 4 (pyroclastic zircon)	Black Flag Group 4 2704 ± 8 Ma (Pipeline Andesite) bulk U–Pb zircon Ora Banda Sill 5 2762 ± 32 Ma (Sm–Nd, mineral separates)	Felsic volcanic porphyry in mafic volcanics 2686 ± 6 Ma (Pb ^{207}/Pb^{206}) 4 2689 ± 7 Ma 6	Noganyer Fm 6 2706 ± 5 Ma Penneshaw Fm? c. 2900 Ma

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NOTES: Radiometric ages are ion-microprobe single zircon U–Pb dates, unless specified otherwise

(a) Swager, 1989b; Swager and Griffin, 1990a
(b) Witt and Swager, 1989a

Geochronological references:
1. Claoué-Long et al., 1988
2. Hill and Compston, 1986
3. Clark et al., 1986
4. Pidgeon, 1986
5. Chauvel et al., 1985
6. Campbell and Hill, 1988
7. Perring et al., 1989
8. McNaughton and Cassidy, 1990

in the Kambalda Domain, and possibly represent a further structural repetition.

The inferred Bullabulling Shear separates the Coolgardie Domain from the poorly exposed Bullabulling Domain, which comprises interleaved high-grade felsic schist, metasedimentary rock, amphibolite, and minor metakomatiite.

The Lefroy Fault and Talcum Fault separate the little-understood Parker Domain from the Kambalda Domain to the west and the Boorara Domain to the north (Fig. 2). The approximate position of the Talcum Fault is indicated by the change in regional structural trend from east–west in the southern part of the Boorara Domain to north–south in the Parker Domain. The Parker Domain includes tholeiitic basalt, and minor high-Mg basalt and felsic volcaniclastic rocks that are intruded by several granitoid plutons. The greenstones appear to correlate with the upper basalt unit and felsic volcanic–sedimentary unit of the Kambalda Domain (Table 1). However, in the east, felsic volcaniclastic–sedimentary rocks contain magnetite-rich BIF horizons, which indicate that these rocks may be more closely associated with the adjacent BIF-bearing sedimentary rocks in the Kurnalpi Terrane.

All major shear zones are probably long-lived structures, in which a possible extensional regime during deposition has been repeatedly reactivated by subsequent complex compressional and transcurrent movements during regional deformation. The total amount of displacement is impossible to determine. However, the similarity of greenstone geology on either side of, for example, the Zuleika Shear precludes craton-scale displacements juxtaposing entirely different tectonic units.

Terrane boundary faults

The Kalgoorlie Terrane is separated from adjacent terranes by the Ida Fault to the west, and by the Moriaty Shear–

Mount Monger Fault system and Menzies Shear to the east (Fig. 2). The Ida Fault is delineated by pronounced aeromagnetic 'highs' that are correlated with variably sheared ultramafic rocks. In the north, this regional structure forms the eastern boundary with the Callion Terrane. The total displacement along the interterrane faults cannot be determined, but may be very large. They are interpreted to represent suture zones along which major tectonic units were juxtaposed.

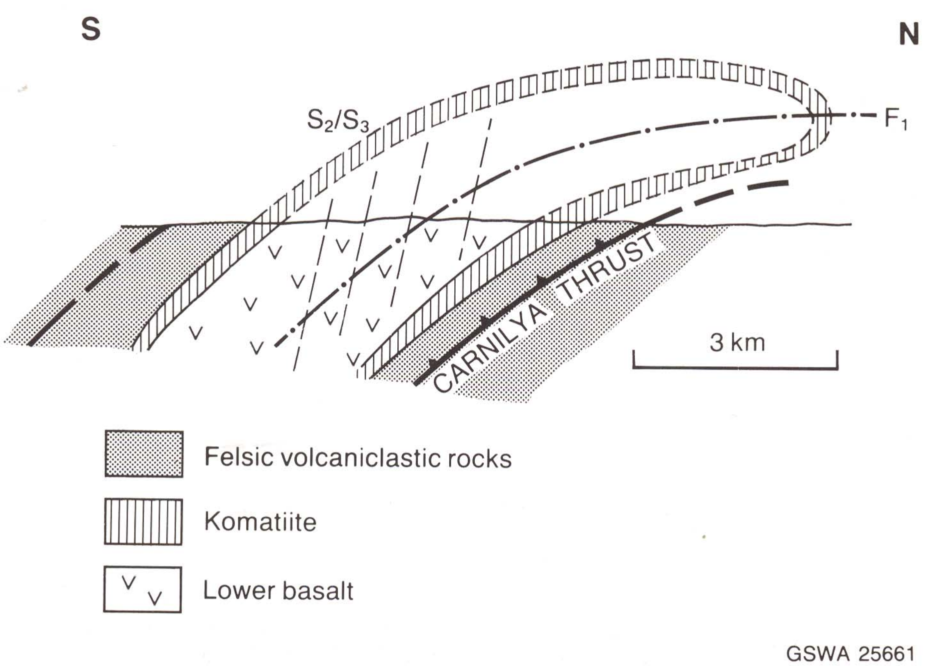
Granitoids

Most granitoids in the southeastern Yilgarn Craton consist predominantly of patchily recrystallized biotite monzogranite with intervening screens or enclaves (mainly inferred) of granitoid gneiss (Bettenay, 1977, 1988). In the northern Kalgoorlie Terrane, Witt and Swager (1989a) distinguished two groups of intrusive granitoids on petrographic criteria: relatively leucocratic biotite monzogranite accompanied by hornblende-bearing granodiorite, and monzogranite with abundant mafic xenoliths. Limited geochemical evidence indicates that both groups have I-type characteristics, similar to those in other areas of the eastern Yilgarn Craton (Lawlers — Foden et al., 1984; Leonora–Laverton — Hallberg, 1985). Some late-stage monzogranites are described by Bettenay (1977) as K-rich 'fractionated leucoadamellites'. Studies by Hallberg (1985) and Hallberg and Giles (1986) in the northeastern Yilgarn Craton indicate that the felsic volcanic complexes and at least some of the early granitoids may be cogenetic.

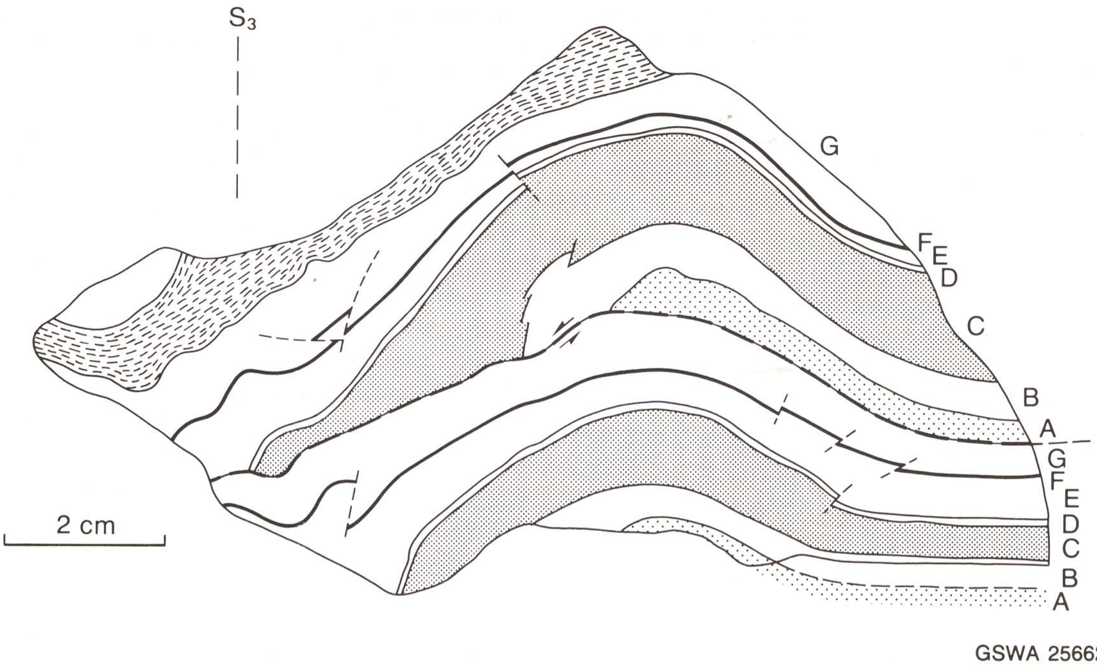
Archibald et al. (1978, 1981) related granitoids to a single tectonothermal event between 2700 and 2600 Ma. They distinguished 'prekinematic banded gneiss' as well as 'synkinematic' and 'postkinematic' intrusions. Recently, Witt and Swager (1989a) proposed a more detailed subdivision with respect to the D_1–D_3 deformation events in the northern Kalgoorlie Terrane.

Subdivision of granitoids for this map follows Witt and Swager (1989a) and is based on the development of tectonic fabrics and relationships with regional structures in the greenstones (Table 2). Foliated monzogranite, granodiorite, and gneissic granitoid — which are interpreted as pre-D_2 to syn-D_2 granitoids — contain a widely spaced S_2 foliation and form large ellipsoidal complexes that occupy the cores of regional F_2 anticlines. Monzogranites with well-foliated margins are regarded as post-D_2 to syn-D_3 granitoids, which are ovoid to circular in outcrop and displace or cut across regional F_2 folds (e.g. Siberia Monzogranite). The more elongate plutons are subparallel to the regional foliation, and contain S_3 foliations that clearly postdate the upright F_2 folding (Widgiemooltha Monzogranite — Griffin and Hickman, 1988; Griffin, 1988, 1990b). Undeformed monzogranite and granodiorite, which are interpreted as late-D_3 to post-D_3 granitoids, generally form small plutons transgressive to F_2 folds. These granitoids may be affected by late fracture systems. Emplacement mechanisms include both passive stoping and forceful intrusion, accommodated by local folds and faults that postdate F_2 folds.

Granitoid gneiss, such as the Fifty Mile Tank Gneiss east of the Pioneer Granitoid Complex in the Coolgardie Domain (Griffin, 1988), possibly represents old sialic crust on which the greenstones were deposited (Archibald and Bettenay, 1977). However, as there are no isotopic constraints for the age of this rock unit, it could equally well represent a slice of early, highly deformed, intrusive granitoid that was subsequently tectonically emplaced at higher levels in the greenstones.



A.



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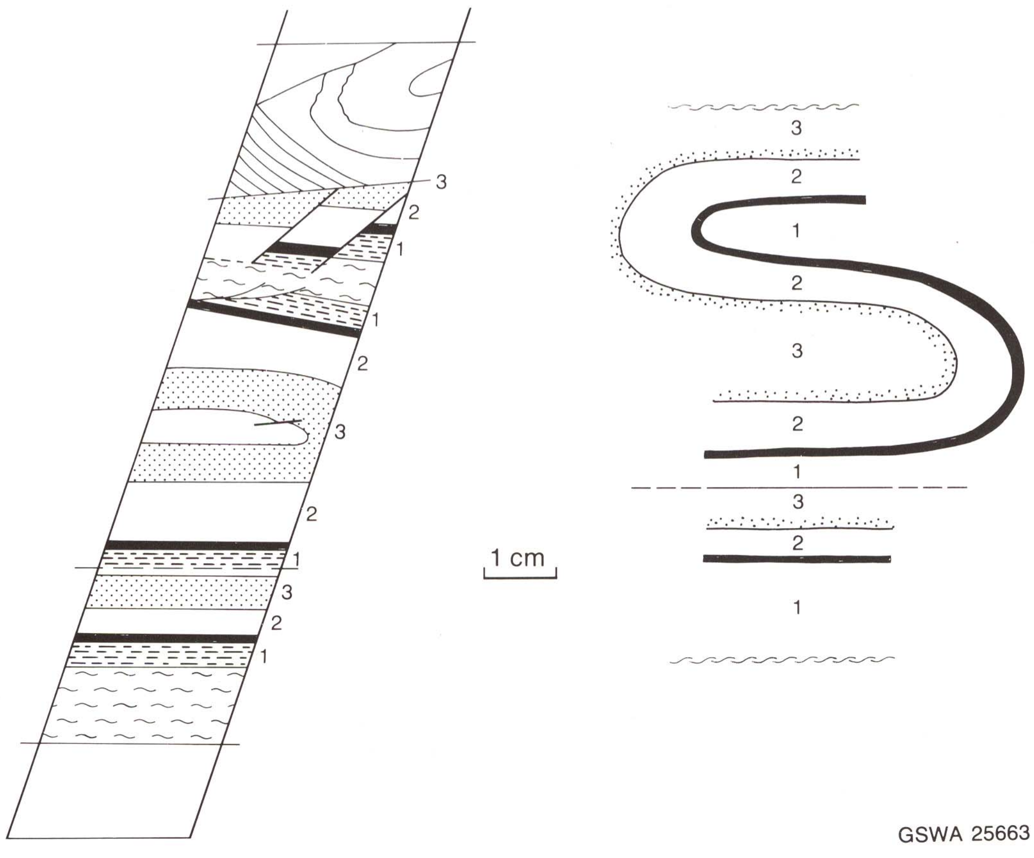

C.

Figure 6. Schematic diagrams of large- and small-scale D_1 structures

A. Recumbent F_1 anticline above the D_1 Carnilya thrust in the southern Boorara Domain (after Perriam, 1985)

B. Small-scale thrust and recumbent fold-and-thrust structures in slates within the upper basalt unit, Croesus opencut, Kalgoorlie

C. Small-scale thrust and recumbent fold-and-thrust structures in slates of the Lower Black Flag Group (shown in drillcore from North Kalgurli mine (after Swager, 1989b))

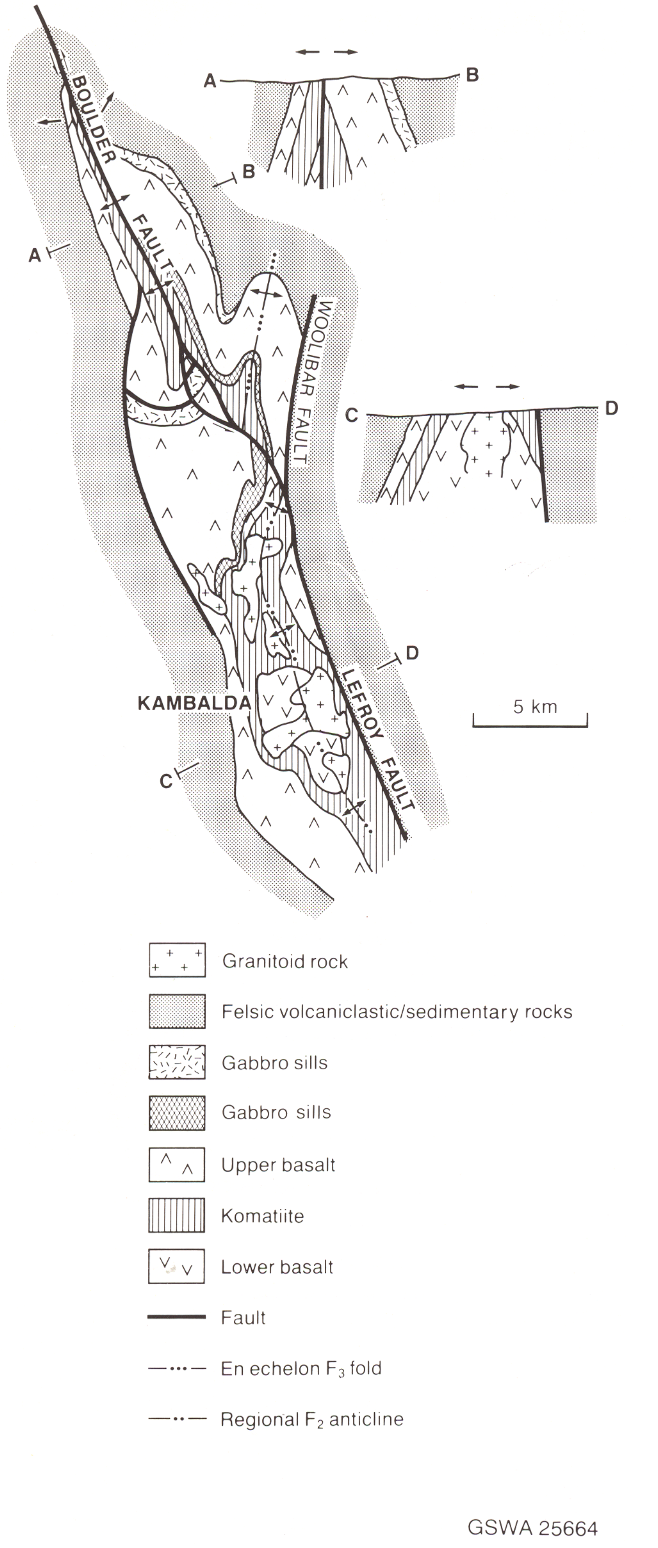

Figure 7. Relationship between regional F_2 anticline and D_3 sinistral Boulder Fault, north of Kambalda. From south to north the D_3 fault cuts across the east limb of an F_2 anticline, until it occupies the F_2 axial planar position (after Griffin and Hickman, 1988; Langsford, 1989)

Metamorphism

Hydrothermal metamorphism

Barley and Groves (1987, 1988) recognized seafloor hydrothermal metamorphism of the mafic–ultramafic volcanic succession in the Kambalda Domain. The metamorphic grade increases rapidly down through the stratigraphy from greenschist to amphibolite facies, much like the shortened metamorphic profiles in ophiolite complexes that result from high heat flow below the seafloor. Alteration associated with the hydrothermal metamorphism increases towards the top of the succession, and is commonly most intense beneath regionally extensive sedimentary horizons. Mafic lavas are patchily altered to albite–chlorite–actinolite–epidote or to chlorite- and carbonate-rich assemblages. Altered komatiites contain serpentine-dominated or talc–carbonate-dominated assemblages. Carbon and oxygen isotope data suggest interaction with Archaean seawater during this serpentinization (Golding et al., 1987). At Kambalda, the lower basalt unit (Lunnon Basalt) is little altered, except for a thin spilitized zone at the top, and contains amphibolite-facies assemblages with relict igneous plagioclase locally preserved. Later regional metamorphism does not appear to have destroyed these early hydrothermal mineral assemblages.

Regional metamorphism

Regional metamorphism is characterized by low to intermediate pressures, less than 4.5 kb, as indicated by widespread andalusite stability (Binns et al., 1976), and reached peak temperatures late during D_2–D_3 transpressional deformation, contemporaneous with syn-D_3 granitoid emplacement.

Binns et al. (1976) distinguished ‘static style’ and ‘dynamic style’ regional metamorphism. Static-style areas generally occupy the central, low-strain part of the greenstone regions away from the granitoids and typically have lower metamorphic grades (prehnite–pumpellyite to upper greenschist facies). Strain is concentrated in narrow zones so that textures are well-preserved in more massive and competent rocks. Dynamic-style areas of greenstone have higher metamorphic grades (upper greenschist to upper amphibolite facies) and are characterized by more pervasive foliation, particularly along the contacts with large granitoid terrains. Figure 8 shows the regional distribution of metamorphic facies in the Kalgoorlie Terrane (adapted from Binns et al., 1976; Griffin, 1990a; Witt, 1993).

Intrusion of post-D_2 to syn-D_3 granitoids, both in high-grade dynamic-style areas (e.g. Widgiemooltha) and lower grade static-style areas (e.g. Siberia, Menzies), has resulted in thermal aureoles of various widths. Detailed studies (Bickle and Archibald, 1984; Wong, 1986) suggested that the thermal aureoles were superimposed isobarically on already elevated regional metamorphic temperatures.

McQueen (1981) documented metamorphic assemblages in various lithologies (mafic, ultramafic and sedimentary rocks) in a wide area around the Widgiemooltha Monzogranite. These assemblages indicate middle to upper amphibolite facies (500–600°C and 3–5 kb). At Lake Zot, some 20 km south of Widgiemooltha (Fig. 8), Bickle and Archibald (1984) inferred peak P–T conditions of 530–560°C at 4.2 kb in a transitional 'static-to-dynamic' domain on the basis of several assemblages in greywackes and conglomerates: quartz–chloritoid–cordierite–staurolite–garnet–biotite; quartz–staurolite–andalusite and quartz–cordierite–andalusite–biotite. At Pioneer, a higher strain ('dynamic style') locality further south (Fig. 8), Bickle and Archibald (1984) described complex prograde assemblages in pelites that indicate peak temperature between 600 and 650°C at 4.2 kb.

Wong (1986) inferred low amphibolite facies (520 ± 20°C) for the rocks in the Kambalda area from detailed mineral chemistry data on co-existing amphibole and plagioclase. Higher, middle amphibolite, temperature conditions (575 ± 20°C) prevailed in a 400 m-wide zone around the syntectonic Red Hill Granitoid Complex. Bavington (1981) estimated pressure at 2.5 ± 1 kb at Kambalda.

Assemblages of quartz–aluminosilicate–fuchsite–rutile – chromian spinel along contacts between ultramafic schist (derived from komatiite) and felsic volcaniclastic schist have been used to estimate metamorphic conditions at two localities. Near Jowett Well, 3 km east of Menzies township, Ashley and Martyn (1987) estimated peak metamorphism at a temperature range of 440–510°C and pressure less than 4 kb, based on co-existing assemblages in quartz–andalusite–fuchsite rocks and tremolite–chlorite schist. Near Mount Martin, 45 km southeast of Kalgoorlie, a detailed mineralogical study found all three aluminosilicate polymorphs in apparent equilibrium, indicating that regional metamorphism took place under conditions close to those of the aluminosilicate triple point. Independent geothermometry and geobarometry results are in reasonable agreement with this triple point at about 500°C and 4 kb (Purvis, 1984).

Microstructural observations indicate late-stage recrystallization (e.g. random amphibole sheaf textures within S_3 foliation in sheared basalt) and crystallization (e.g. andalusite and garnet porphyroblasts growing across and enclosing regional S_2–S_3 trails in various metapelites) without any or only minor deformation. This suggests probable late-stage attainment of peak metamorphic temperatures (Binns et al., 1976).

Extensive carbonation and hydration occurred along and adjacent to major fault systems. Carbonation may have commenced shortly after volcanism in long-lived structures, but continued during regional deformation and metamorphism. Although mineral assemblages are similar to those produced during hydrothermal metamorphism, carbon isotope data indicate contributions from both mantle and crust (Golding et al., 1987). The carbonation assemblages also show late-stage recrystallization textures. High CO_2 contents in the hydrothermal fluids maintained relatively low-grade metamorphic assemblages in shear zones and fractures (Clark et al., 1986).

Mineralization

The Kalgoorlie Terrane is a major producer of gold and nickel, with world-class deposits such as the Golden Mile gold-lode system in the Kalgoorlie–Boulder region (Clout et al., 1990) and the Kambalda nickel deposits (e.g. Gresham and Loftus-Hills, 1981).

Syngenetic nickel sulfide deposits are hosted by ultramafic volcanic rocks (Gresham and Loftus-Hills, 1981; Donaldson et al., 1986). They are best developed at or close to the base of komatiite lava flows, generally concentrated in depressions that were probably scoured by the lava flows through thermal erosion (Groves et al., 1986). The greatest concentration of nickel deposits occurs at Kambalda around a granite-cored culmination on the Kambalda Anticline (Fig. 5). Other deposits occur in the Widgiemooltha area (Wannaway, Redross), and at Spargoville, Nepean, Mount Martin, Carnilya Hill and Scotia. The existence of substantial nickel mineralization in all major domains, except Ora Banda, lends further support to the interpretation that they are part of a single terrane.

Epigenetic gold mineralization occurs in all domains in a variety of structural and metamorphic settings. The structures can, in virtually all cases, be related to D_3–D_4 deformation (e.g. Groves and Barley, 1988; Witt, 1993). Faults related to granitoid emplacement are mineralized in places, e.g. at Comet Vale. Mineralization is broadly contemporaneous with peak regional metamorphism, and associated alteration assemblages correlate broadly with regional metamorphic grade. Alteration assemblages are controlled locally by increasing CO_2 content of the auriferous hydrothermal fluids towards the centre of the mineralized structure (Clark et al., 1986). As with carbonation assemblages in regional shear zones, metasomatic assemblages are overprinted by late amphibole, garnet, andalusite, and chloritoid porphyroblasts in high-grade domains adjacent to syn-D_3 granitoids (Witt, 1993).

Geochronology

Compilations of isotopic data (McNaughton and Dahl, 1987; Browning et al., 1987; Barley and McNaughton, 1988) indicate that the greenstones in the Kalgoorlie Terrane were deposited around 2.7 Ga with the main period of deformation, granitoid intrusion, metamorphism, and epigenetic gold mineralization between 2.66 and 2.64 Ga. The Kalgoorlie Terrane probably contains one of the youngest greenstone sequences in the Yilgarn Craton, although reliable geochronological data from throughout the craton are scarce. Browning et al. (1987) inferred 3.0 Ga greenstone volcanism in the Murchison and Southern Cross Provinces on the basis of lead model ages derived from syngenetic massive sulfide deposits. The only published (conventional) U–Pb depositional age for the Southern Cross Province is 2722 ± 13 Ma (Pidgeon, 1986), which predates all available U–Pb zircon deposition ages for the Kalgoorlie Terrane.

Recent publication of ion-microprobe single zircon U–Pb ages (Hill and Compston, 1986; Claoué-Long et al.,

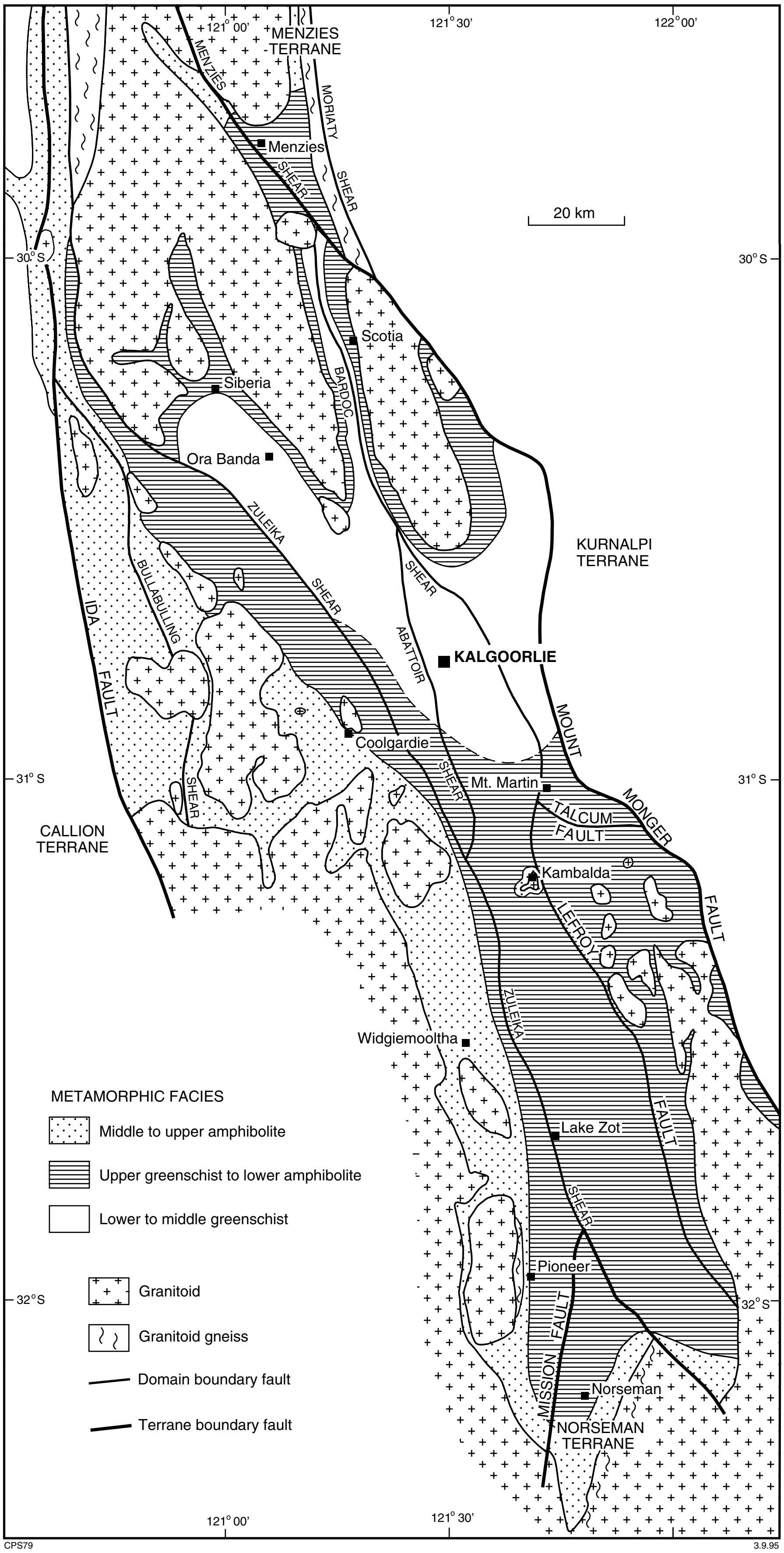

Figure 8. Regional distribution of metamorphic facies in the Kalgoorlie greenstones. Based on data from Binns et al. (1976), Griffin (1990a) and Witt (1993)

1988; Campbell and Hill, 1988) from the Kalgoorlie Terrane appear to introduce a new level of accuracy in radiometric dating. Available U–Pb zircon dates and other selected recent age determinations are included in Table 2. Some of the data indicate a relatively short history of greenstone deposition and deformation: e.g. mafic volcanism directly before and after 2692 ± 4 Ma (Kapai Slate); syntectonic granitoid intrusion at 2662 ± 6 Ma (Red Hill Granitoid Complex–Kambalda Granodiorite); and late-stage (D_3–D_4) epigenetic gold deposition at c. 2673 Ma (Golden Mile gold lodes; Clout, J. M. F., 1989, pers. comm.; Claoué-Long, J. C. 1990, pers. comm.). However, several late-stage events are considerably younger, suggesting a much longer history (e.g. the Mungari Monzogranite c. 2610 Ma and late-stage gold mineralization south of Kambalda at 2627 ± 7 Ma and 2601 ± 3 Ma; Clark et al., 1986).

The complex considerations in deriving a reliable age from a large data set are well documented by Claoué-Long et al. (1988). However, calculation of 'preferred ages' involves 'often subjective selection of the available data' (Hill et al., 1989, p. 1261). Examples of different interpretations of the same data set are those given by Hill and Campbell (1989) and McNaughton and Cassidy (1990). Hill and Campbell (1989) interpreted an emplacement age of 2593 ± 10 Ma for the Liberty Granodiorite, a late tectonic intrusion in the Ora Banda Domain. McNaughton and Cassidy (1990) argued that this age can only be considered a conservative minimum age, and reinterpreted the data to indicate a minimum emplacement age of 2645 ± 17 Ma. To confirm this considerably older age, they carried out Pb–Pb analyses, and concluded that the combined age of 2675 ± 23 Ma is the most reliable estimate for the emplacement age of the Liberty Granodiorite.

U–Pb ion-microprobe studies have shown the widespread occurrence of xenocrystic zircons (and zircon cores) with age populations at 3100–3300 Ma and 3400 Ma (Compston et al., 1986; Claoué-Long et al., 1988; Campbell and Hill, 1988; Hill et al., 1989) (Fig. 9). These zircons, which were found in both granitoids and greenstones, imply that the greenstones were underlain by considerably older sialic crust that could have provided the source for the intrusive granitoids. The ages of xenocrystic zircons correlate well with those of major crustal events in Oversby's (1975) model based on lead-isotope systematics in intrusive granitoids between Kalgoorlie and Norseman. Oversby (1975) proposed initial formation of continental crust at before 3300 Ma and later reactivation around 3100 Ma, before widespread partial melting at 2700–2600 Ma.

Post-cratonization dyke swarm

Unmetamorphosed, undeformed and mainly east-northeast trending Proterozoic dykes postdate cratonization of the Yilgarn Craton (Hallberg, 1987). A prominent lopolith in the Jimberlana Dyke at Norseman was emplaced at 2411 ± 38 Ma (Turek, 1966; Fletcher et al., 1987).

Adjacent terranes

Norseman Terrane

The Norseman Terrane (Fig. 2) contains a greenstone succession with an apparently well-defined, west-younging stratigraphy established by Hall and Bekker (1965) and Doepel (1973). However, bedding-parallel, high-strain zones suggest stratigraphic discontinuities, including possible structural repetition (e.g. Doepel, 1973; Spray, 1985). This implies a number of tectonostratigraphic units rather than a simple stratigraphy (McGoldrick, in prep.).

Doepel (1973) mapped a basal, mainly mafic unit, the Penneshaw Formation, which contains a wide zone of interleaved amphibolite, schistose to mylonitic granitoid, banded granitoid gneiss, and, locally, BIF and sedimentary rocks along its eastern contact with the intrusive Buldania Granitoid Complex. This interleaving may be tectonic, intrusive, or both. Spray (1985) identified pre-D_1 fabrics in the southern exposures of the granitoid gneiss and suggested that the high-grade zone between amphibolite and gneiss represents an originally subhorizontal D_1 tectonic contact which was subsequently rotated into a steep attitude and retrogressed to greenschist-facies conditions. He thus concluded that the granitoid gneiss is possibly part of the sialic basement juxtaposed with the greenstones during D_1. The Penneshaw Formation also contains feldspar-phyric felsic schists with amphibolite intervals (?dykes) near its western contact with the Noganyer Formation (McGoldrick, in prep.).

The Penneshaw Formation is overlain by the Noganyer Formation which is characterized by persistent BIF layers within clastic, partly felsic, sedimentary rocks, and is intruded by gabbro sills. Small-scale structural repetition of BIF layers by folding (Keele, 1984) and faulting (McGoldrick, in prep.) has been recognized. The Penneshaw and Noganyer formations are strongly deformed throughout and reached amphibolite-facies conditions, as indicated by garnet-, andalusite- and cordierite-bearing assemblages in the metasedimentary rocks.

The Woolyeenyer Formation, which overlies the Noganyer Formation, is a monotonous sequence of massive basalt flows with a minor ultramafic component. A detailed local stratigraphy for the lower part of the sequence has been proposed by Hall and Bekker (1965). Although the sequence has an apparent thickness of approximately 10 km, shear zones within the formation can be interpreted as thrust faults that have repeated parts of the stratigraphy (McGoldrick, in prep.).

The Mission Fault is a major structural discontinuity (Fig. 2) which separates the Woolyeenyer Formation from the Mount Kirk Formation — a tightly folded sequence of sedimentary rocks containing major gabbro sills (Doepel, 1973), and here interpreted as part of the Coolgardie Domain. Campbell and Hill (1988) published a preliminary date of 2689 ± 7 Ma for felsic volcanic rocks in the Mount Kirk Formation immediately west of the Mission Fault.

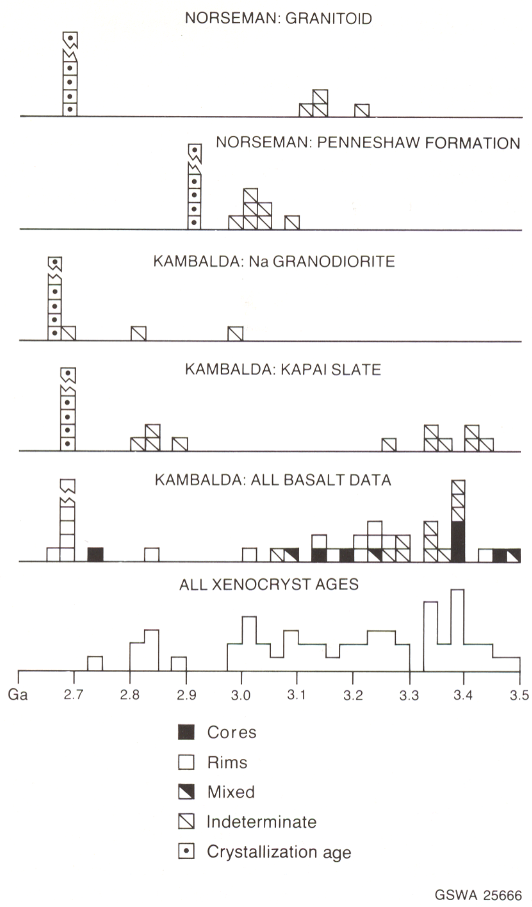

Figure 9. Range of minimum zircon xenocryst ages (from Campbell and Hill, 1988; includes data from Compston et al., 1986; Claoué-Long et al., 1988)

The Norseman Terrane has generally been considered to contain the oldest greenstones in the south-eastern Goldfields (Gemuts and Theron, 1975). The prominent BIFs and minor volumes of komatiite indicate a depositional environment similar to that of the Callion Terrane, which may also predate the greenstones in the Kalgoorlie Terrane. Campbell and Hill (1988) interpreted U–Pb ion-microprobe zircon data to indicate an approximate 2900 Ma age for felsic volcanic components in the Penneshaw Formation, and dated chert in the Noganyer Formation at 2706 ± 5 Ma.

The presence of BIF and pre-2700 Ma greenstones, and the overall structural and stratigraphic setting, distinguish the Norseman Terrane from the Kalgoorlie Terrane.

Callion Terrane

The western boundary of the Kalgoorlie Terrane is partly masked by extensive late tectonic granitoids. In the northwest, the Ida Fault separates the Kalgoorlie Terrane from the Callion Terrane (Fig. 2). This terrane comprises basalt and dolerite with prominent BIF, and may be related to the platform-phase greenstone successions of Groves and Batt (1984). The Ida Fault can be traced south as an aeromagnetic lineament, which is marked in places by isolated ultramafic schist and dunite bodies. Greenstone outliers near Queen Victoria Rocks contain BIF (Gole and Klein, 1981; Hunter, 1988c) and are therefore assigned to the Callion Terrane.

Menzies Terrane

The Menzies Terrane occupies a highly deformed wedge between the Moriaty and Menzies Shears north of the Comet Vale Monzogranite. A highly deformed sequence of ultramafic schist and minor amphibolite is overlain by a narrow marker unit of felsic volcaniclastic rocks that are in tectonic contact with various basalt units. It is not yet known whether this terrane can be correlated with rock sequences to the south in the Kurnalpi Terrane.

Kurnalpi Terrane

Several rather diverse tectonostratigraphic domains to the east of the Moriaty Shear–Mount Monger Fault system are combined provisionally in the Kurnalpi Terrane (Fig. 2). Their geology is not well understood, mainly because few or no detailed studies have been done and because systematic regional mapping is still under way.

Tectonic evolution

Stratigraphic, structural, and geochronological data indicate that the Coolgardie, Ora Banda, Kambalda, and Boorara Domains have very similar deposition, deformation, and early granitoid intrusion histories. These observations suggest a single tectonic terrane divided into several domains in which the same geological processes resulted in directly comparable volcanic and sedimentary sequences.

Earlier regional geological interpretations in the Menzies to Norseman region have invoked cyclic depositional models (Williams, 1969, 1974, 1976; Gemuts and Theron, 1975). Williams (1976) distinguished three repetitions or cycles of a sequence in which mafic–ultramafic volcanic rocks are followed by felsic volcanic–volcaniclastic rocks, which are in turn overlain by clastic sedimentary rocks. Gemuts and Theron (1975) recognized eight sequences between Coolgardie and Norseman, making up two cycles which overlie the supposedly oldest sequences at Norseman (i.e. Penneshaw and Noganyer Formations). Other authors, when describing the local stratigraphy, indicated similar cyclic sequences (McCall, 1969; Glikson, 1971). Although the structural complexity of the Kalgoorlie greenstones was acknowledged, it was not until the early 1980s that structural repetition of a single sequence was proposed (Griffin et al., 1983).

The nature of the basement to the greenstones of the Kalgoorlie region has been debated for more than 30 years (see review in Hallberg and Glikson, 1981). In the early 1970s, an ensimatic (ophiolitic) origin for the greenstones was proposed, based on geochemical arguments and a perceived analogy with Alpine-type geosynclinal belts (Glikson, 1970, 1979; McCall and Leishman, 1971; Hallberg, 1972a).

Subsequently, Oversby (1975), Bettenay (1977), and Archibald and Bettenay (1977) suggested that the greenstone basins developed on sialic basement. Oversby's (1975) proposal was based on initial lead-isotope signatures in various intrusive granitoids. Bettenay (1977) argued that the overwhelming predominance of potassic granitoids in the southeastern Yilgarn Craton implied anatexis of underlying sialic crust. Archibald and Bettenay (1977) suggested that gneissic components in intrusive granitoids could represent relics of a sialic basement. However, gneissic margins along granitoid plutons can be explained by emplacement-related deformation or inclusion of slightly older, already deformed, intrusive phases.

More recently, several other lines of indirect evidence for sialic crust prior to the formation of the 2700–2600 Ma greenstones have been presented, including geochemical evidence for contamination of basalt by felsic rocks (Barley, 1986; Arndt and Jenner, 1986), and the occurrence of zircon xenocrysts older than 3100 Ma in basalt (Compston et al., 1986), interflow slate (Claoué-Long et al., 1988), and felsic volcanic rocks (Hill et al., 1989); see also Figure 9. Oversby (1975) suggested that this early crust formed initially at c. 3400 Ma (see also Browning et al., 1987). Campbell and Hill (1988) supported Oversby's conclusions on the basis of zircon xenocryst ages dating back to 3400 Ma. Hill et al. (1989) inferred a broadly andesitic composition for this primitive crust which, after initial formation, evolved largely by thermal reworking. Whether this sialic basement existed as a continuous sheet or as small isolated crustal blocks remains to be resolved.

The proposed ensialic setting of the greenstone succession led to the development of a cratonic rift or basin model (Archibald et al., 1978; Gee et al., 1981; Groves and Batt, 1984; Hallberg, 1986). Groves and Batt (1984) favoured 'fast' rifting to explain the absence of clastic material at the base of the rift sequence, and the 'deep' marine basalt and komatiite in the lower part of the sequence. They argued that this rift association is now represented by the Norseman–Wiluna belt, and is distinguished from a platform association characterized by BIF and considerably less komatiite. The platform greenstones were thought to predate the rift greenstones, and to flank and underlie the rift. In this model, the Callion Terrane and the Penneshaw and Noganyer Formations in the Norseman Terrane are interpreted as part of this older platform sequence, whereas the greenstones in the Kalgoorlie Terrane are assigned to the rift sequence.

The ensialic rift model is essentially a 'vertical tectonics' model driven by thermal upwellings in the mantle (Archibald et al., 1981; Campbell and Hill, 1988). This is supposed to have caused initial komatiite and basalt extrusion followed by granitoid intrusion (solid-state diapirism) which was responsible for deformation of the greenstones it intruded (Gee et al., 1981). The granite diapirism model does not explain the structural evolution of the Kalgoorlie Terrane and other areas in the Eastern Goldfields Province because it neglects the evidence for the pervasive regional shortening and strike-slip shear zones (Archibald et al., 1978; Platt et al., 1978; Martyn, 1987; Eisenlohr et al., 1989; Swager, 1989b; Williams et al., 1989). These features rather suggest large-scale Archaean plate interaction (Platt, 1980; Gee et al., 1986; Witt and Swager, 1989a).

Barley and Groves (1988) and Barley et al. (1989) have proposed a tectonic model in terms of present-day plate tectonic principles. They have argued that rather than a symmetrical rift system, the Eastern Goldfields Province contained an asymmetrical distribution of lithologic associations, including a western association with komatiite and tholeiite (largely corresponding to the 'rift-phase' greenstones) and an eastern association with subaerial calc-alkaline volcanic rocks and tholeiite. Giles (1981) concluded that these calc-alkaline volcanic rocks (Giles and Hallberg, 1982), which occur as isolated centres rather than continuous arcs, have geochemical characteristics analogous to those in modern subduction environments. Barley et al. (1989) proposed that the western and eastern associations represented a back-arc or marginal-basin complex and a volcanic arc respectively. The marginal basin was subsequently closed by an oblique collision, inferred from the D_2–D_3 transpressional deformation regime. In this model, the Kalgoorlie Terrane lies within the back arc, whereas rocks of the Kurnalpi Terrane would form part of the volcanic arc. A similar model has been proposed for the late Archaean Abitibi Belt in Canada, where a 'southern volcanic zone' developed as rift basins which dissect an earlier volcanic arc, the 'northern volcanic zone' (Ludden et al., 1986).

Witt et al. (1989) described apparently diachronous structural and metamorphic histories between greenstones in the Kalgoorlie Terrane and the Leonora region (Fig. 1) — which they attributed to accretion of microplates. Myers (1990) applied a model of crustal aggregation by continental collision and accretion to the entire Yilgarn Craton.

Drummond (1988) argued that seismic-reflection results show a uniform crust in the southern part of the Yilgarn Craton and so do not support an accretionary model. However, the major partial melting event responsible for the widespread granitoid emplacement would have homogenized the lower crust and thus produced an essentially uniform and thick crust that has remained stable since the late Archaean. Consequently, early stages of the tectonic history are unlikely to be evident in the seismic reflection profiles.

An accretionary model appeals as a working hypothesis to explain the variety in stratigraphic and structural histories of the terranes. The transpressional deformation recorded throughout the Eastern Goldfields Province suggests that translation of crustal blocks or fragments was likely before, during, and possibly even after, accretion, even though some terranes may have developed proximally. A tectonic model for the evolution of the Kalgoorlie Terrane that involved a marginal basin within and along a continental plate edge accounts for the following:

(a) the regional stratigraphic evolution from mafic–ultramafic volcanic rocks through felsic volcanic to sedimentary rocks, with evidence of local early (?distal) felsic volcanism contemporaneous with basalt or komatiite;

(b) mafic–ultramafic geochemical processes that are unique to the Archaean;

(c) large volumes of felsic volcanics, which are characteristic of continental margin accretionary environments;

(d) the presence of sialic basement during greenstone volcanism;

(e) the regional subhorizontal deformation regime (early thrusting), which was followed by upright folding and transcurrent shear zones implying externally imposed stress fields;

(f) I-type granitoids, which were emplaced throughout the deformation history; and

(g) peak regional metamorphism late in the deformation history.

Summary

The late Archaean Kalgoorlie Terrane is distinguished from the adjacent Norseman, Kurnalpi, Callion, and Menzies Terranes by its distinct greenstone stratigraphy and deformation history. The stratigraphy consists of the following units in upward succession: lower basalt, komatiite, upper basalt, and felsic volcanic and sedimentary units, locally overlain by coarse clastic rock. These units have been metamorphosed at greenschist- or amphibolite-facies conditions. The mafic volcanic rocks were deposited at 2.70–2.69 Ga. Inherited zircon xenocrysts and contamination of mafic volcanic rocks by felsic material suggest that the greenstones were deposited on sialic crust.

The regional deformation sequence comprises D_1 thrusting, upright D_2 folding about north-northwest axes, sinistral transcurrent D_3 faulting, and prolonged east-northeast to west-southwest regional D_4 shortening. The D_2–D_3 deformation occurred at 2.68–2.61 Ga. I-type granitoids were emplaced throughout the deformation history. Regional metamorphism reached peak temperatures late during the D_2–D_3 transpressional deformation.

The Kalgoorlie Terrane is subdivided into six domains separated by major faults. Regional structures such as D_1 thrust faults, D_2 folds, and D_3 shears cannot be traced across the domain boundary faults. The two major central domains (Kambalda and Ora Banda) contain the complete regional stratigraphy, whereas in the western and eastern domains (Coolgardie and Boorara), the upper basalt unit is very thin or absent.

The primary tectonic setting of the Kalgoorlie Terrane can be interpreted as a marginal basin at a convergent accretionary continental plate edge. The Kalgoorlie Terrane was integrated into the stable Yilgarn Craton before the emplacement of 2.4 Ga, east-trending mafic dykes.

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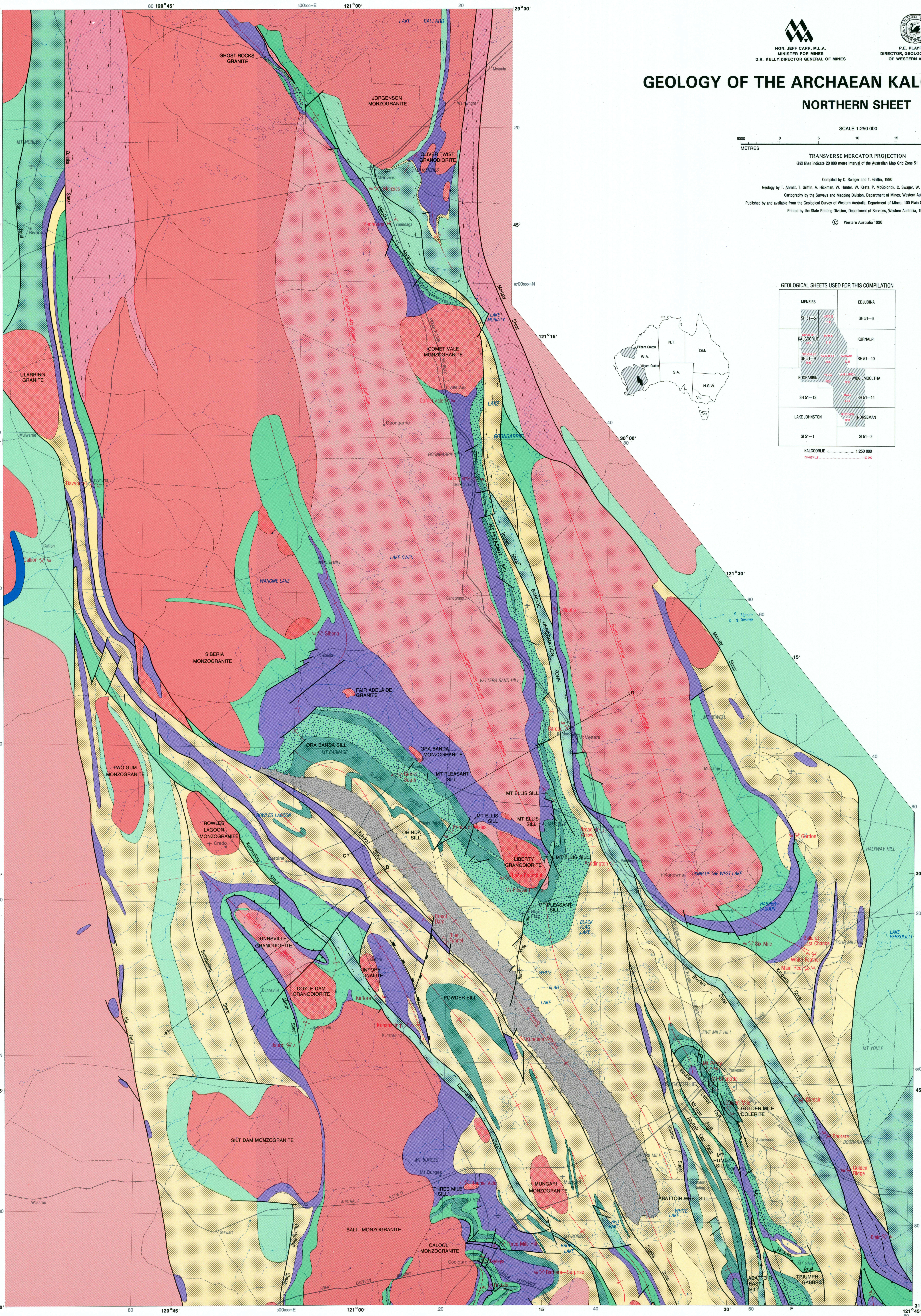

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GEOLOGY OF THE ARCHAEAN KALGOORLIE TERRANE

NORTHERN SHEET

SCALE 1:250 000

5000 METRES 0 5 10 15 20 25 KILOMETRES

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

Compiled by C. Swager and T. Griffin, 1990
Geology by T. Ahmat, T. Griffin, A. Hickman, W. Hunter, W. Keats, P. McGoldrick, C. Swager, W. Witt, and S. Wyche
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GEOLOGICAL SHEETS USED FOR THIS COMPILATION

MENZIES SH 51—5 (MENZIES 3138)	EDJUDINA SH 51—6
KALGOORLIE (DAVYHURST 3037, BARDOC 3137)	KURNALPI
SH 51—9 (DUNNSVILLE 3036, KALGOORLIE 3136, KANOWNA 3236)	SH 51—10
BOORABBIN (YILMIA 3135, LAKE LEFROY 3235)	WIDGIEMOOLTHA
SH 51—13 (COWAN 3234)	SH 51—14
LAKE JOHNSTON (NORSEMAN 3233)	NORSEMAN
SI 51—1	SI 51—2

KALGOORLIE 1:250 000
DUNNSVILLE 1:100 000

REFERENCE

PROTEROZOIC

- Mafic dyke — positive magnetic anomaly; negative magnetic anomaly

ARCHAEAN

- Granitoid, undivided; including porphyry
- Monzogranite and granodiorite; undeformed stocks (late-D_2)
- Monzogranite; foliated, particularly along margins (post-D_1 to syn-D_2)
- Foliated monzogranite, granodiorite, and gneissic granitoid (pre-D_1 to syn-D_2)
- Granitoid gneiss

Greenstones: volcanic and sedimentary rocks and intrusive sills; metamorphosed to greenschist or amphibolite grade

- Polymictic conglomerate and pebbly sandstone
- Gabbro and dolerite; layered mafic and ultramafic intrusions
- Sedimentary rock; predominantly felsic volcaniclastic siltstone, sandstone and conglomerate; minor shale, chert, and felsic volcanics
- Felsic volcanic rock; includes subvolcanic porphyry, and minor sedimentary rock
- Banded iron-formation
- Basalt, dolerite and gabbro; minor ultramafic rock, sedimentary rock, and felsic schist
- Basalt and komatiite; minor mafic sills

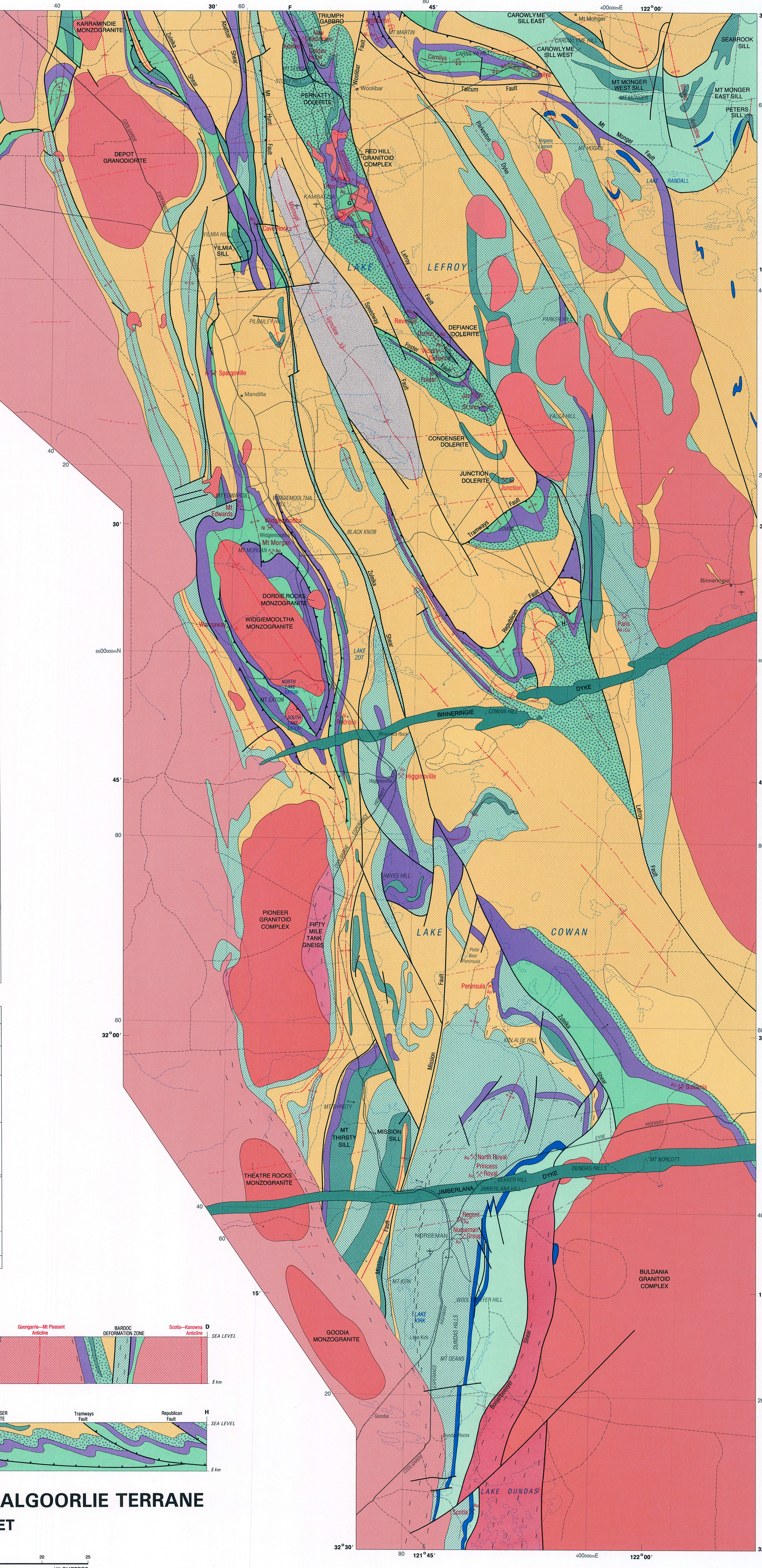
Widely recognized stratigraphic sequence

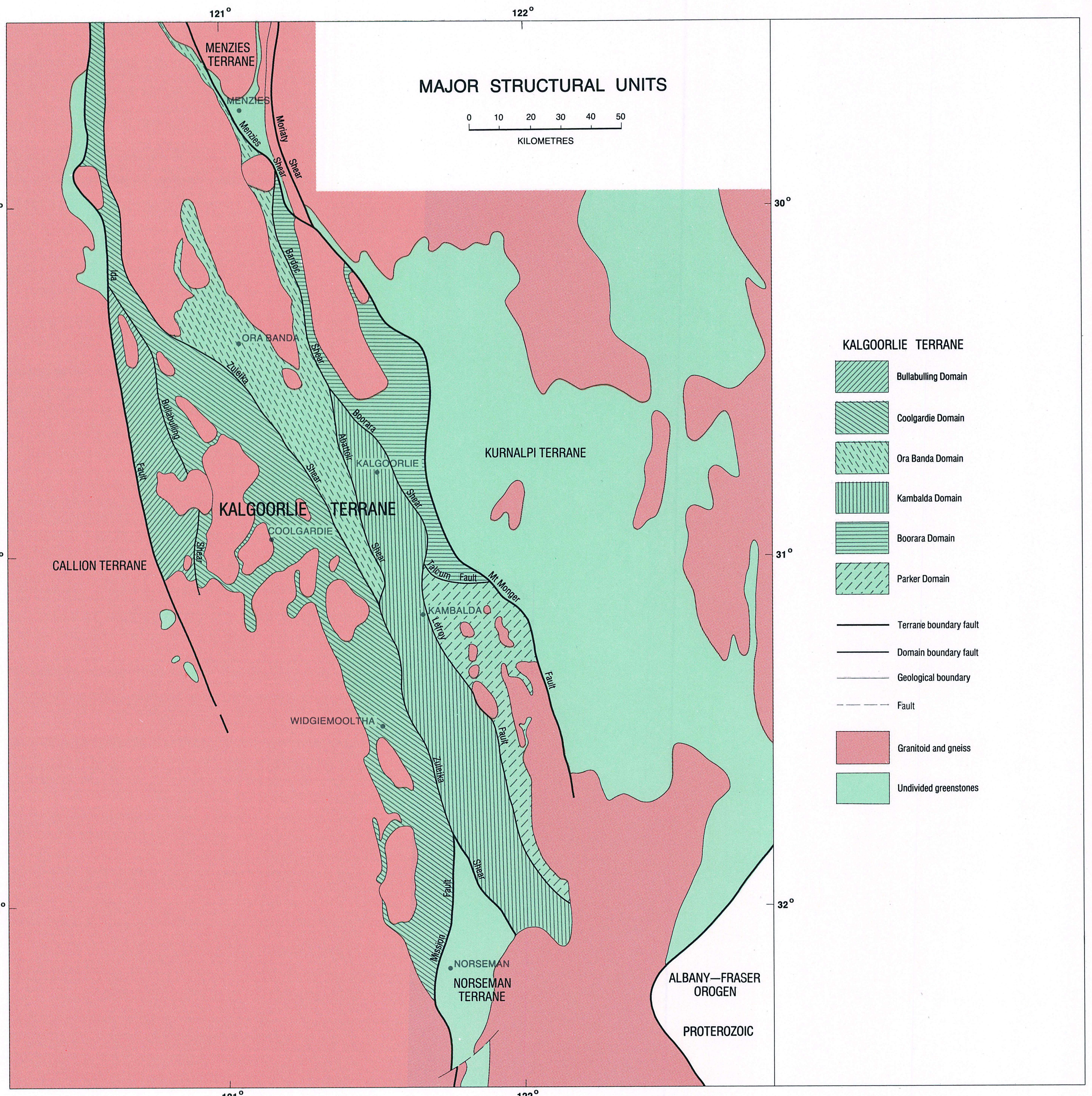
- Basalt, high-Mg (variolitic-textured) and tholeiitic; minor komatiite, dolerite, and sedimentary rock
- Komatiite; minor basalt, dolerite, and sedimentary rock
- Basalt, tholeiitic and high-Mg; minor komatiite, dolerite, and sedimentary rock

SYMBOLS

- geological boundary
- geological boundary, interpreted from aeromagnetics
- fault or shear
- reverse fault
- D_1 thrust fault
- sheared rock
- fold trace, generation unknown
- D_1 fold trace
- D_1 fold and fault structures
- D_2 fold trace
- sheared D_2 fold trace
- D_3 fold trace
- D_3 en-echelon fold trace
- anticline, showing plunge; overturned
- syncline, showing plunge; overturned
- unconformity
- younging direction
- mine, abandoned mine; Au—gold, Ni—nickel, Cu—copper
- highway
- road
- track
- railway, with siding (Myamin)
- homestead (Carbine)
- airfield, landing ground
- lake, permanent, ephemeral
- watercourse, intermittent

METAMORPHIC FACIES



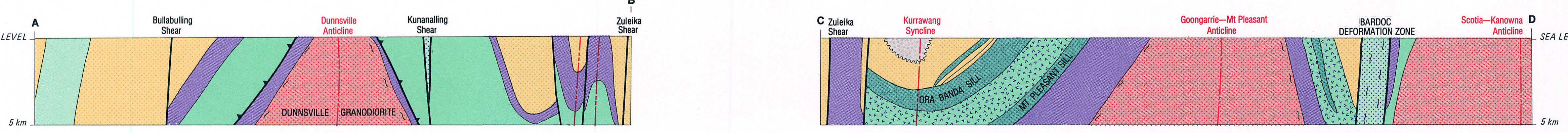


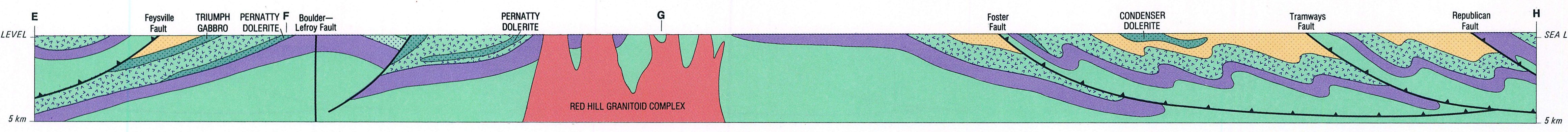
STRATIGRAPHIC CORRELATIONS

STRATIGRAPHIC SUCCESSION	CHARACTERISTIC LITHOLOGIES	ORA BANDA DOMAIN		KAMBALDA DOMAIN		COOLGARDIE DOMAIN		BOORARA DOMAIN
Polymictic conglomerate unit	Polymictic conglomerate, immature sandstone; coarse trough cross beds, graded beds		Kurrawang Formation		Merougil Conglomerate		absent	absent
Felsic volcanic and sedimentary unit	Felsic volcaniclastic-sedimentary rocks, ranging from coarse clastic sandstone to interbedded sand/siltstone ; rhyolite to dacite, locally andesite; lava, tuff, agglomerate	BLACK FLAG GROUP	Pipeline Andesite Orinda Sill Ora Banda Sill	BLACK FLAG GROUP	Junction Dolerite Condenser Dolerite Triumph Gabbro Golden Mile Dolerite	BLACK FLAG GROUP	White Flag Formation Spargoville Formation Powder Sill	felsic unit, volcanic and sedimentary rocks
Upper basalt unit	High-Mg and tholeiitic basalt; massive, pillowed and vesicular lavas	GRANTS PATCH GROUP	Victorious Basalt Bent Tree Basalt Mt Pleasant Sill Mt Ellis Sill	KALGOORLIE GROUP	Paringa Basalt Defiance Dolerite Pernatty Dolerite Williamstown Dolerite Kapai Slate	COOLGARDIE GROUP	absent or thin and discontinuous	absent or thin and discontinuous Big Blow Chert
Komatiite unit	Thin variolitic-textured, high-Mg basalt at top. Thin komatiitic flows with minor interflow sedimentary beds, overlying thicker komatiitic flows and/or massive olivine adcumulate	LINGER AND DIE GROUP	Big Dick Basalt Siberia Komatiite Walter Williams Formation		Devon Consols Basalt Kambalda Komatiite		Hampton Formation	Highway Utramafics
Lower basalt unit	Tholeiitic and high-Mg basalt flows, subaqueous	POLE GROUP	Missouri Basalt Wongi Basalt		Lunnon Basalt		Burbanks Formation Three Mile Sill	Scotia Basalt
References		Witt (1987, in press)		Woodall (1965), Roberts (1988), Langsford (1989)		Hunter (in press)		Christie (1975), Witt (in press)

DIAGRAMMATIC SECTIONS

NATURAL SCALE





GEOLOGY OF THE ARCHAEAN KALGOORLIE TERRANE

SOUTHERN SHEET

SCALE 1: 250 000

5000 0 5 10 15 20 25
METRES KILOMETRES

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