

Deformation in a complex crustal-scale shear zone: Errabiddy Shear Zone, Western Australia

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Abstract: Detailed mapping of four areas representing different geological units with varying formation histories within the crustal-scale Errabiddy Shear Zone shows an apparently simple temporal progression from foliation and mineral lineation development to folding and then to brittle deformation across the shear zone. However, in detail the structural evolution of the shear zone shows considerable complexity. The dominant foliation throughout the shear zone was formed in the upper greenschist to amphibolite facies during the 2000–1960 Ma Glenburgh Orogeny, which involved the accretion of the Archaean to Palaeoproterozoic Glenburgh Terrane onto the Archaean Yilgarn Craton and the subsequent formation of the Errabiddy Shear Zone. Orthorhombic kinematic indicators formed during the Glenburgh Orogeny as did the widespread mineral lineation. These fabrics were overprinted by a greenschist facies deformation and metamorphic event during the 1830–1780 Ma Capricorn Orogeny. During the Capricorn Orogeny mineral lineation development was rare, and mostly took place in high-Capricorn strain zones in areas where a pre-existing Glenburgh-aged mineral lineation was present. Such mineral lineations trend parallel to Capricorn-aged fold hinges. Regardless of the presence or absence of Capricorn-aged mineral lineations, dextral strike-slip kinematics and simple shear indicated by delta and sigma porphyroclasts, and displacement along detachment faults, are prevalent close to discrete shear zone boundaries, within the Errabiddy Shear Zone. However, between shear zone boundaries flattening and coaxial strain dominated during the Capricorn Orogeny. This difference in Capricorn Orogeny kinematics throughout the shear zone is caused by strain partitioning – although progressive deformation throughout the shear zone with dextral strike-slip faults overprinting older structures formed by pure shear also took place. These results suggest that analyses of small parts of shear zones may not give the complete history of an evolving transpressional shear zone because of the presence of strain partitioning and strain localization over time.

Crustal-scale shear zones are fundamental discontinuities that often are the sites of continental accretion, collision, extension and intraplate deformation. Such zones may accommodate deformation via simultaneous components of pure and simple shear (i.e. general shear). The distribution of strain in shear zones may vary spatially (strain localization) and also temporally and pure and simple shear deformation may be partitioned within the shear zone (Tikoff & Teyssier 1994; Jones & Tanner 1995; Dewey *et al.* 1998; Lin & Williams 1998; Reddy *et al.* 1999, 2003). Once formed, shear zones are often zones of weakness (Holdsworth *et al.* 2001a,b) and may further deform by reactivation leading to complex polyphase deformation histories (Scrimgeour & Raith 2001; Hand & Buick 2001).

Recognizing the range of complexity in shear zone evolution is difficult, as it requires quanti-

tative characterization of the spatial and temporal distribution of deformation that can only be resolved by applying careful strain and kinematic analysis together with careful dating of geological structures. Due to the spatial and temporal localization of deformation, the formation of natural shear zones can only be evaluated when as much of the shear zone as possible is studied in detail. However, studying an entire crustal-scale shear zone is often difficult due to limitations in outcrop and accessibility and most detailed studies of shear zones focus on small parts or specific sections, assuming the results can characterize the development of the entire shear zone.

In this paper we analyse four separate well-exposed areas within a crustal-scale shear zone (Errabiddy Shear Zone). The Errabiddy Shear Zone was chosen for this study for the following reasons:

- (1) it is a major crustal-scale shear zone, and site of accretion of an Archaean to Palaeoproterozoic terrane onto a stable Archaean Craton (Occhipinti *et al.* 2004);
- (2) outcrops of different geological units are easily accessible throughout the shear zone;
- (3) preliminary regional-scale work suggested that metamorphic events can be correlated throughout the shear zone and felsic magmatic events can be correlated with adjacent terranes (Occhipinti *et al.* 1998, 2004);
- (4) a detailed study to the east of the Errabiddy Shear Zone suggested shear zone development during dextral transpression and possible subsequent reactivation (Reddy & Occhipinti 2004).

Each of the four areas chosen for detailed mapping are situated in the ENE trending part of the shear zone. Each section consists of different lithological units of diverse geological age and origin. We examine in detail the geometries, kinematics and timing of structures within the four study areas by field mapping, and determining relationships between deformation fabrics, metamorphic mineral assemblages, and cross-cutting igneous rocks. The study involved detailed analysis of relative age relationships and construction of younging tables and deformation networks in each of the following areas (Potts & Reddy 2000). Different structural nomenclature for each of the four areas has been used throughout the text for ease of comparison between the areas. This nomenclature is as follows: n (for gneiss), for the Archaean basement–granitic gneiss area; g (for granite) and b (for basement) for granite and felsic gneiss, respectively in the felsic gneiss (basement) and c. 1958 Ma granite of the Erong Shear area; s (for metasedimentary) for psammitic rocks in the psammitic gneiss area; and p (for pelite) for the migmatized pelite area.

These data are used to characterize how deformation in a regional-scale shear zone developed, and to compare the results to previously completed regional-scale studies, which were accompanied by U–Pb SHRIMP dating of granites and metasedimentary rocks (Nelson 1997, 1998, 1999, 2000, 2001). By doing so we show that shear zones are the foci of the complicated formation of structures in response to both single and multiple deformation events. However, the development of structures and kinematics within a shear zone is strongly influenced by strain localization, and therefore the results of small-scale detailed studies may be scale dependent and may not be representative of the kinematics or formation of the entire shear zone.

The Errabiddy Shear Zone

The Errabiddy Shear Zone is a curved shear zone that is more than 200 km long, up to 20 km wide and forms the northwestern margin of the Archaean Yilgarn Craton. The shear zone strikes NE in its western part, ENE in its central part, and NNE in its eastern part (Fig. 1), and is exposed in the Capricorn Orogen – a Palaeoproterozoic collisional belt between the Archaean Pilbara and Yilgarn Cratons in Western Australia (Tyler & Thorne 1990; Occhipinti *et al.* 1998, 2001, 2004; Sheppard *et al.* 2002, 2004).

The Errabiddy Shear Zone formed due to the collision and accretion of the Glenburgh Terrane onto the Archaean Yilgarn Craton during the 2000–1960 Ma Glenburgh Orogeny (Occhipinti *et al.* 2001; Fig. 2). It comprises several fault-bounded lenses of rock units that differ in type and age, and are heterogeneously deformed, which have been metamorphosed at medium- to high-grade. The Errabiddy Shear Zone was subsequently reactivated in the greenschist facies at 1830–1780 Ma during the Capricorn Orogeny (Sheppard & Occhipinti 2000; Occhipinti & Sheppard, 2001; Occhipinti *et al.* 2001; Sheppard *et al.* 2004), which may record the inter-cratonic collision of the Archaean Pilbara (to the north) and Yilgarn Craton – Glenburgh Terrane (inset, Fig. 1; Tyler & Thorne 1990; Occhipinti *et al.* 1998), or intra-cratonic shortening between the already joined, and relatively stable Archaean Pilbara and Yilgarn Cratons (Occhipinti *et al.* 2004; Sheppard *et al.* 2004).

The Errabiddy Shear Zone comprises different lithological units of diverse geological age. These units include Archaean granitic gneiss basement, Palaeoproterozoic metasedimentary rocks, and Palaeoproterozoic granite, which formed in different geological environments at dissimilar crustal levels but have since been juxtaposed in the shear zone (Fig. 2). All of these rocks have been variably intruded by leucocratic pegmatites.

Archaean granitic gneiss (basement)

A well foliated to banded granitic gneiss (the Warrigal Gneiss) dominantly comprising interleaved mesocratic and leucocratic granitic gneiss, outcrops in fault-bounded lenses throughout the Errabiddy Shear Zone. Locally this granitic gneiss is pegmatite banded. The granite protoliths to the gneiss comprise medium-grained, equigranular monzogranite, and is locally porphyritic. A part of one of these

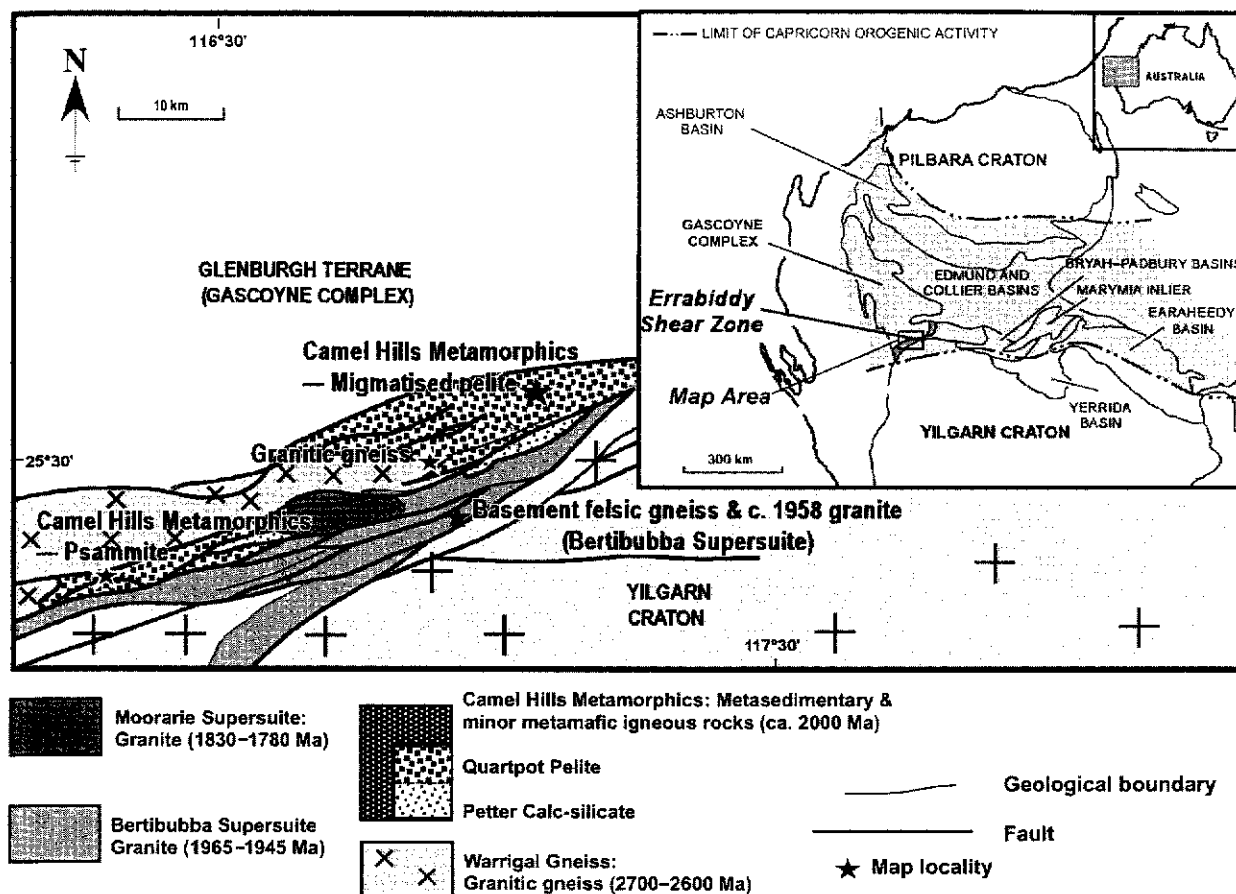


Fig. 1. Simplified geological map (modified after Occhipinti *et al.* 2004) of the Errabiddy Shear Zone and its components showing the location of the four mapped areas in this study (marked by star locations on map). Inset shows the Archaean to Palaeoproterozoic Glenburgh Terrane (to the north), the Archaean Yilgarn Craton (to the south), and the Archaean to Palaeoproterozoic Yarlwarweelor Gneiss Complex (to the east).

fault-bounded lenses located approximately 7.5 km NE of Erong Homestead at MGA 470691E 7178872N was studied (Fig. 3). The granitic gneiss consists of quartz, feldspar, and mica (variable amounts of biotite and muscovite), and locally contains garnet. SHRIMP U–Pb zircon ages on four individual granitic components of the Warrigal Gneiss from throughout the Errabiddy Shear Zone (Nelson 2000, 2001; Occhipinti *et al.* 2001), indicating that its formation was complex and not confined to one intrusive event.

Gneissic banding within the granitic gneiss is parallel to a well-developed foliation (locally mylonitic) and is broadly parallel to contacts with boundaries of supracrustal rocks. These include amphibolite schist and gneiss, calc-silicate gneiss, quartzite, and pegmatite. Amphibolite lenses within the granitic gneiss consist of both medium-grained, even-textured gneissic amphibolite (comprising plagioclase, hornblende, actinolite–tremolite) and mafic schist (comprising varying amounts of actinolite–tremolite and chlorite). The calc-silicate gneiss

comprises varying amounts of quartz, clinopyroxene, actinolite–tremolite, calcite, and feldspar. The quartzite is interleaved on a 0.3–1 m-scale with the mylonitized granitic gneiss, and both form a narrow (up to 20 m wide) mylonite zone.

Locally, amphibolite gneiss clearly cuts across layering in the granitic gneiss, indicating that the amphibolites were originally dykes. However, contacts between the amphibolite, calc-silicate and granitic gneiss are commonly either not exposed or appear to be tectonic. Massive pegmatite dykes cut the granitic gneiss, calc-silicate gneiss, amphibolite, and mylonite zone. The pegmatite edges are often broadly parallel to the well-developed foliation in the gneisses.

Deformation in Archaean granitic gneiss (basement)

The Petter Bore area of the Errabiddy Shear Zone has been polydeformed, metamorphosed, and has undergone several periods of granite

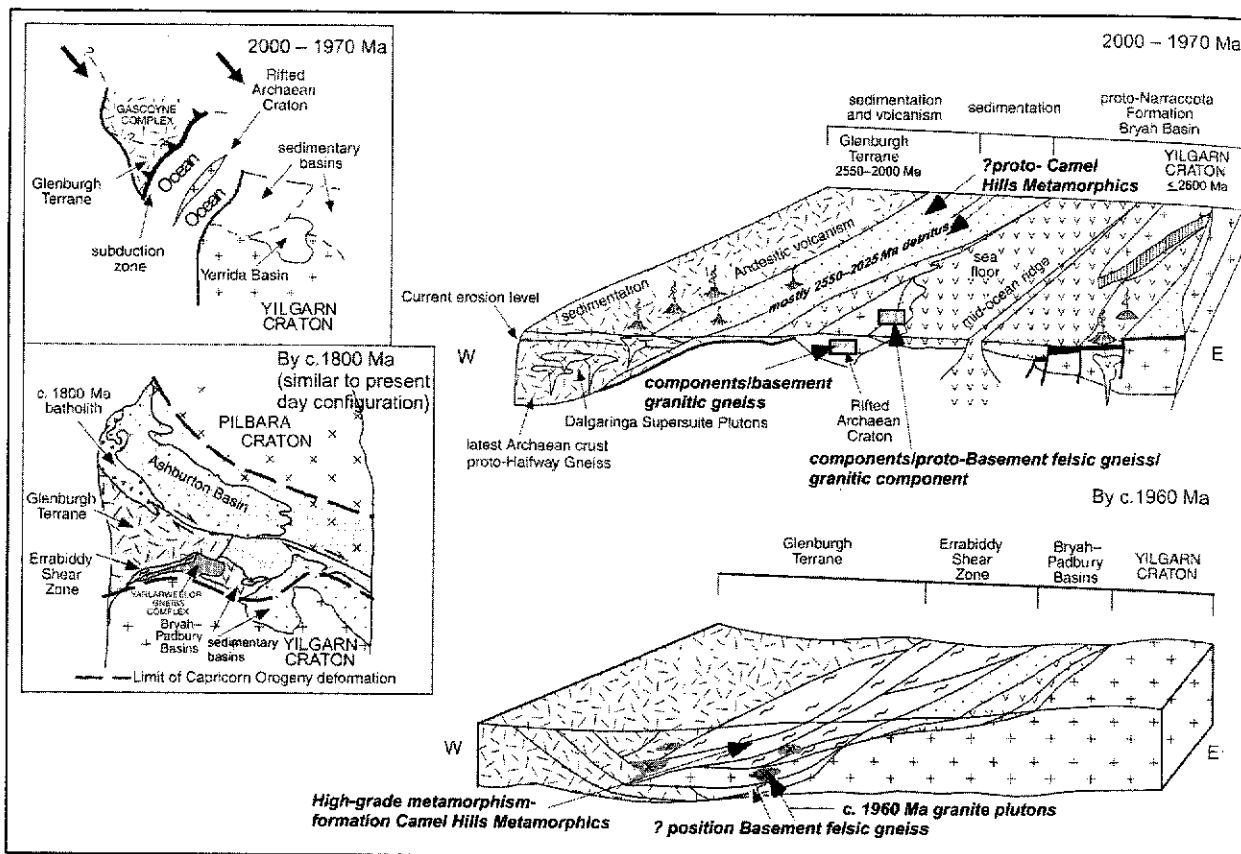


Fig. 2. Schematic diagram modified after Occhipinti *et al.* (2004) illustrating the possible tectonic evolution of the southern Capricorn Orogen, and the origin and changing position of the mapped units in this study. These units were metamorphosed and deformed during the Glenburgh Orogeny, when the Archaean to Palaeoproterozoic Glenburgh Terrane was accreted onto the Archaean Yilgarn Craton to form the Errabiddy Shear Zone. The bottom inset of the Capricorn Orogen shows the possible effects of the c. 1800 Ma Capricorn Orogeny in the region, which is largely reflected by the current-day geometry of the southern Capricorn Orogen.

intrusion (Fig. 3). The earliest recorded structure is a well-developed foliation in the granitic gneiss (S_{1n}). This was locally observed and is generally overprinted by D_{2n} to form a composite S_{1n}/S_{2n} fabric ($S_{1/2n}$, which is the most pervasive foliation in the area) (Fig. 5a). However, in low strain zones S_{1n} can be observed as having developed subparallel to the axial surface of tight to isoclinal folds deforming thin (less than 3 cm wide) pegmatite dykes.

The $S_{1/2n}$ foliation (Figs 3 & 5a) strikes east-west, subparallel to contacts between the different rock types (Fig. 3), and is steeply dipping (Fig. 5a). The $S_{1/2n}$ foliation is parallel to F_{2n} fold axial surfaces that are developed throughout the area (Fig. 5a). The F_{2n} folds are tight to isoclinal and have fold hinges parallel to L_{12n} intersection lineations, that plunge moderately to steeply towards the west to NW (Fig. 5a). Locally, F_{2n} folds and associated crenulation cleavages overprint F_{1n} isoclinal folds.

Mineral lineations, defined by quartz, mica and amphibole are present on the $S_{1/2n}$ planar surfaces (Figs 5a & 7a), plunging shallowly to

steeply towards the west or east. Locally, quartz mineral aggregate lineations plunge steeply towards the NE, and shallowly to steeply towards the west or WNW, indicating that they have been re-orientated, or there are two groups of quartz lineations (Fig. 5a).

Minor, gentle 1 m-scale folds (F_{3n}) deform the $S_{1/2n}$ foliation and F_{2n} folds (Fig. 6a). The axial planes of these folds are north to northwesterly striking and steeply dipping with subvertically plunging hinges.

Eastnortheasterly striking vertically dipping detachments and quartz veins cut the $S_{1/2n}$ foliation surface, but are locally subparallel to it (Fig. 6a). Their relationship to the F_{3n} folds is unknown. Other brittle and brittle-ductile features include dextral strike-slip, sinistral strike-slip and reverse faults. Kinematic indicators included brittle-ductile displacement of the $S_{1/2n}$ foliation, ductile displacement of $S_{1/2n}$ foliation, and S-C fabrics. Dextral strike-slip faults with no observed vertical slip trend either in an eastnortheasterly, southwesterly or northwesterly direction, whereas a measured reverse

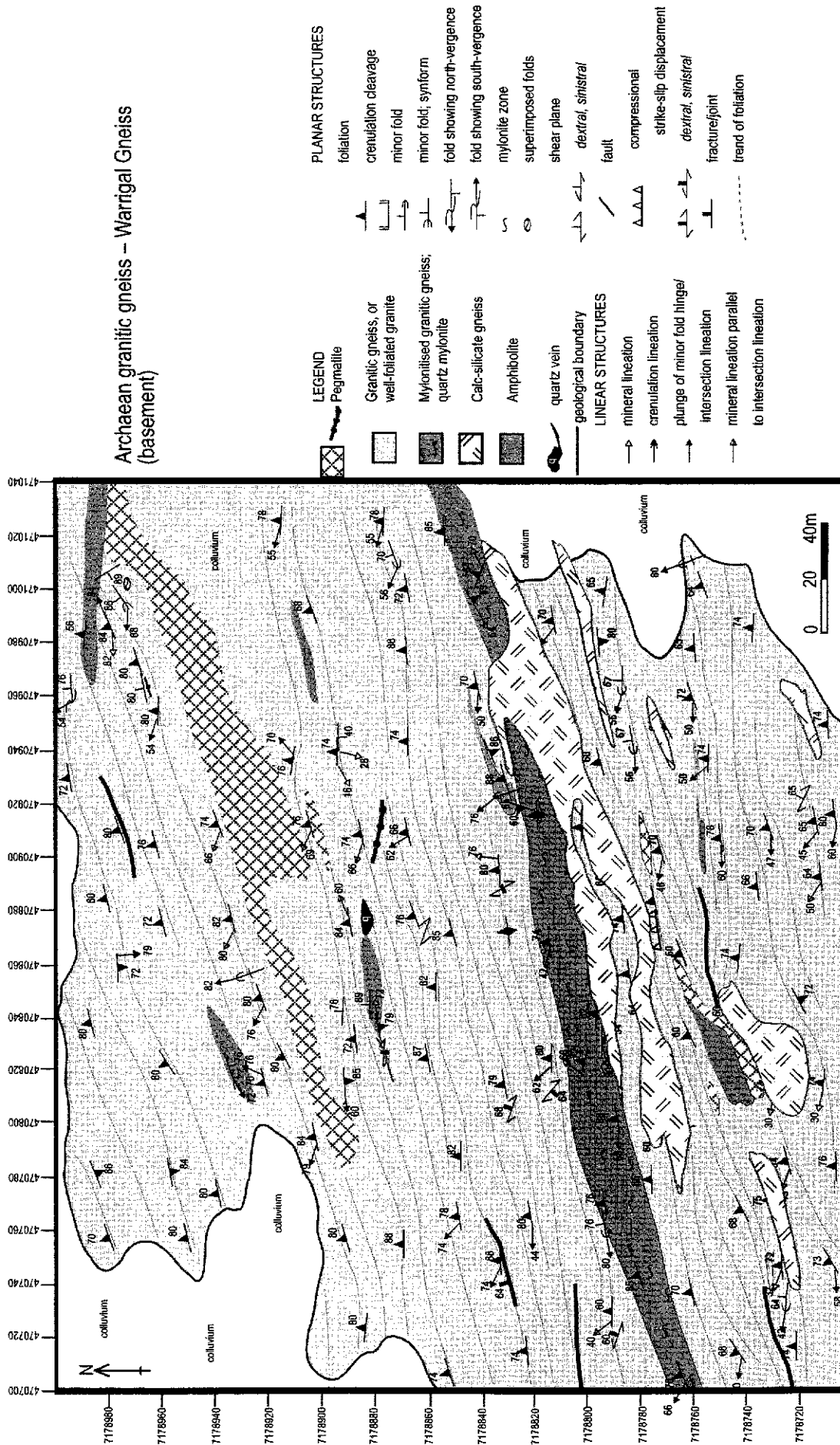


Fig. 3. Geological map of Archaean basement granitic gneiss. Coordinates are specified by Universal Transverse Mercator (UTM) coordinates using the Map Grid of Australia (MGA) and Geocentric datum of Australia 1994 (GDA94).

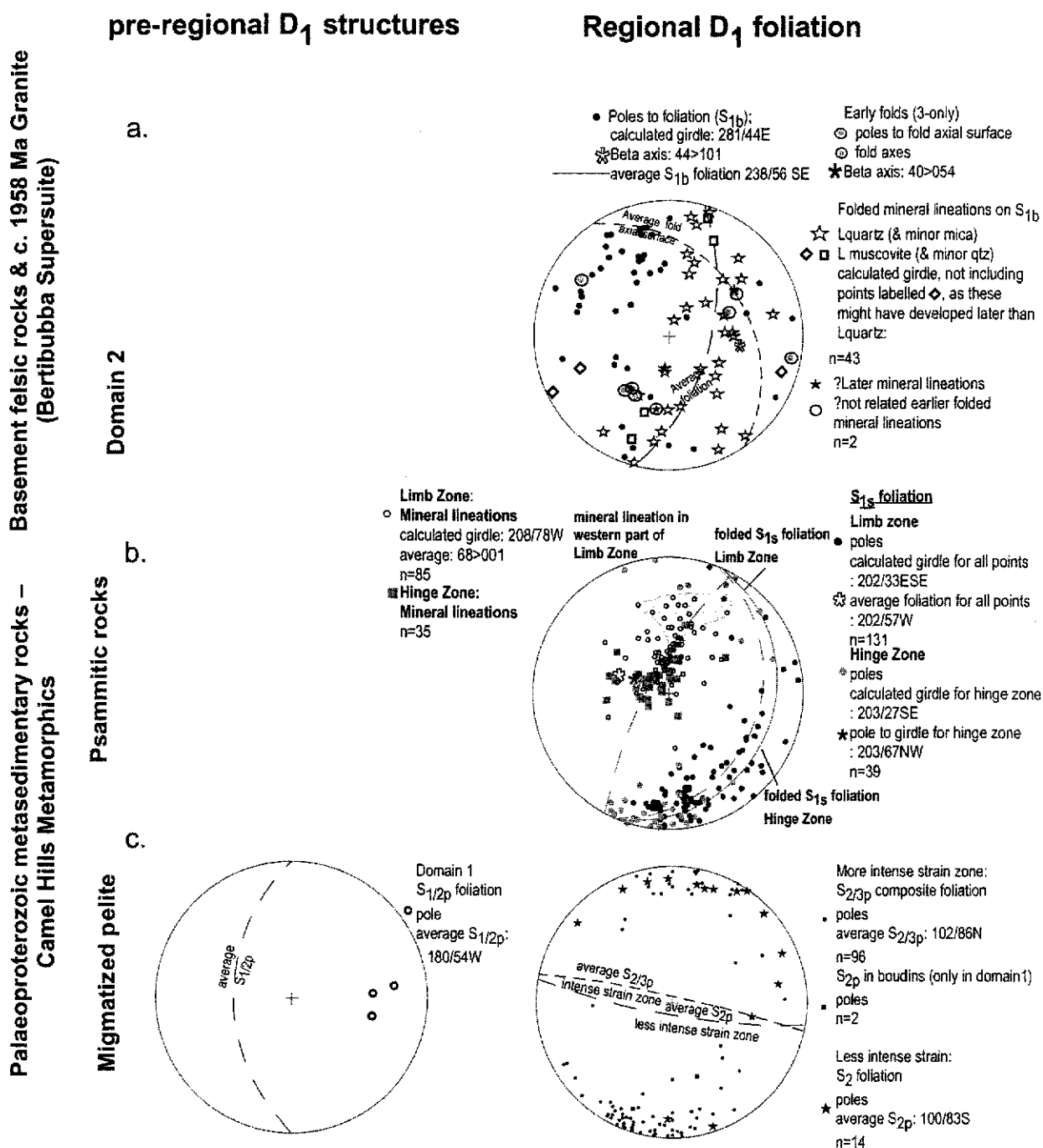


Fig. 4. Equal area stereonet of early structural fabrics (Regional D₁) observed in each of the mapped areas.

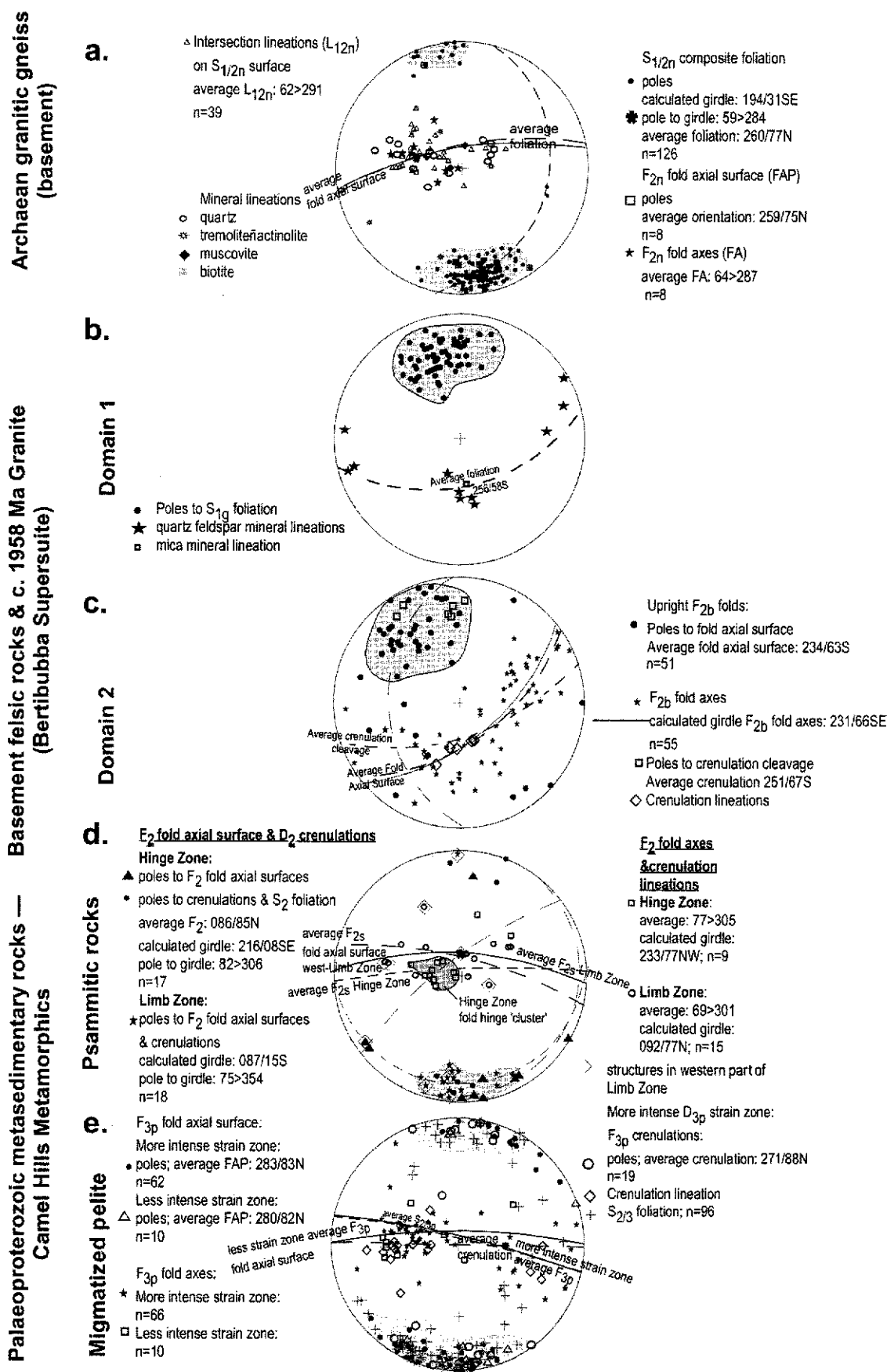
and sinistral strike-slip fault is easterly trending. The kinematics of several late fractures could not be ascertained. These are steeply dipping and northerly or westerly striking.

Felsic gneiss (basement) and c. 1958 Ma granite of the Erong Shear Area

The Erong Shear Area is located approximately 7.0 km east of Erong Homestead at MGA 474078E 7172884N (Fig. 1). The main rock types

at this locality are weakly to well-foliated granite of the Bertibubba Supersuite (Occhipinti *et al.* 2001), foliated to mylonitized granite, psammite and quartzite. The granite of the Bertibubba Supersuite was dated by U–Pb SHRIMP zircon dating as c. 1958 Ma, approximately 800 m north of the map area (Occhipinti *et al.* 2001).

The area can be divided into two structural domains (1 and 2). Domain 1 consists of weakly to well-foliated granite, which is monzogranitic in composition and ranges from porphyritic, to medium equigranular granite of 0.5–1 cm

Regional D₂ structuresFig. 5. Equal area stereonet of main structures (Regional D₂) observed in each of the mapped areas.

Regional brittle & ductile faults, and F_3 folds

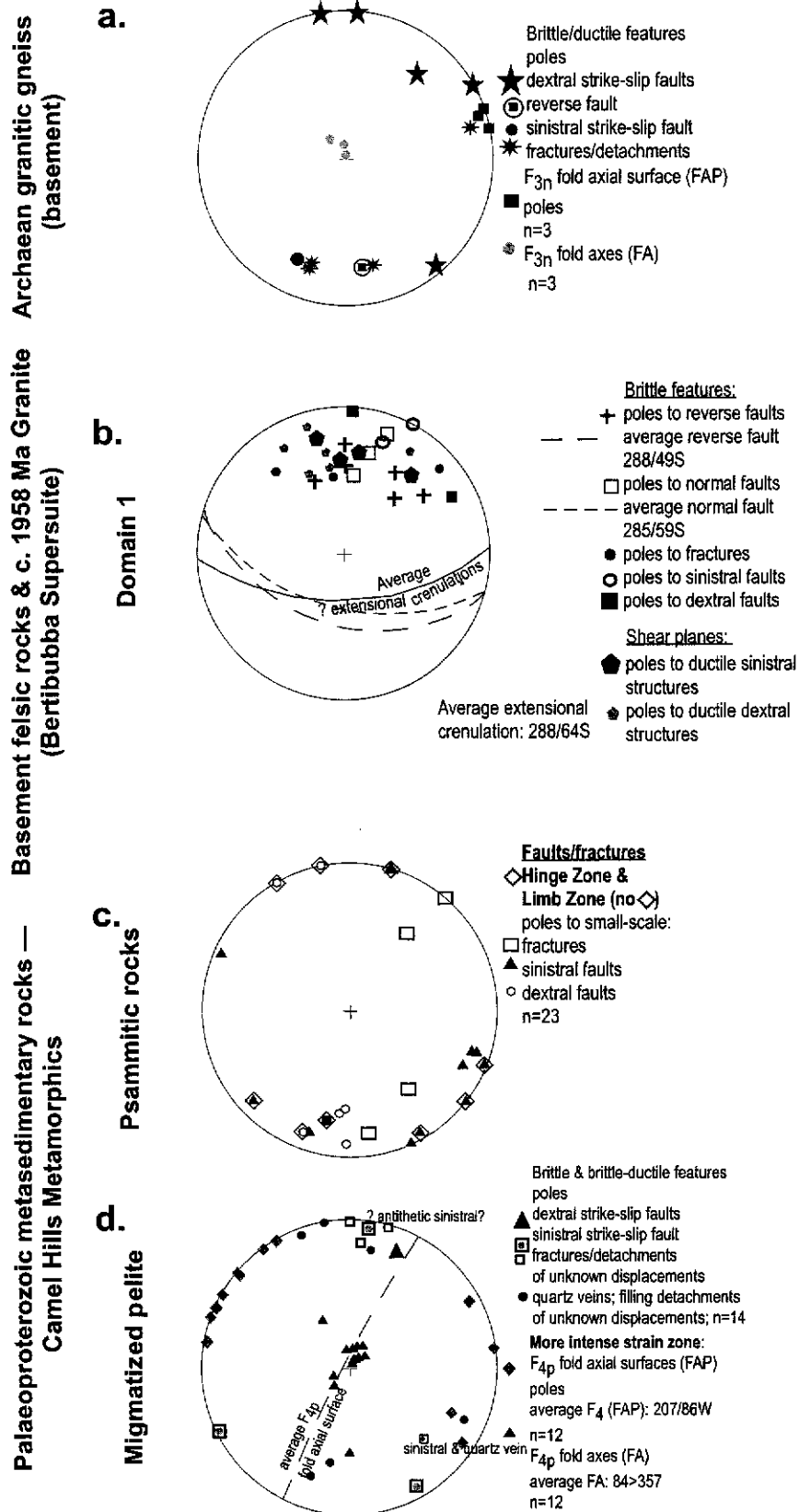


Fig. 6. Equal area stereonets of brittle and brittle-ductile structures and F_3 folds observed in the mapped areas.

grainsize, and fine-grained granite that forms 1–10 m-scale thick sheets intruded by minor pegmatite, and fine-grained granite. These rocks mainly consist of quartz, feldspar, and mica (biotite and/or muscovite). Domain 2 contains well foliated to mylonitized granite, metasedimentary rocks and quartz mylonite (henceforth Felsic gneiss), that generally comprises variable amounts of quartz, feldspar, and mica (biotite and/or muscovite). The contact between Domains 1 and 2 is a discrete high-strain zone.

Deformation in Domain 1

The earliest recorded structure in Domain 1 is a pervasive S_{1g} foliation that strikes ENE and dips moderately to steeply towards the SE or south (Figs 5b & 8). This foliation is defined by the alignment of variable amounts of deformed feldspar (variably sericitized), quartz, biotite, muscovite, and minor epidote, although epidote is often randomly orientated mainly replacing feldspar. Variably recrystallized aggregates of quartz make up domains that follow S_{1g} . Mineral lineations on the S_{1g} surface are rare (Fig. 5b). However, where present they are defined by aggregates of quartz or muscovite, and elongate feldspar porphyroclasts, now partly pseudomorphed by sericite. These mineral lineations show two preferred orientations plunging moderately to steeply to the south, or shallowly plunging to the east or west (Fig. 5b).

Pegmatite and fine-grained leucogranite dykes within the medium-grained granite commonly strike subparallel to the S_{1g} foliation. A few dykes that are oblique to S_{1g} are folded into close to tight folds with their fold-axial surface parallel to S_{1g} , although they are usually unfoliated.

Localized shear bands, which overprint S_{1g} , but are subparallel to S_{1g} may have developed soon after the formation of this foliation. These shear bands lie approximately parallel to brittle–ductile reverse and normal shears (Figs 6b & 7c). These may have developed synchronously. Delta and sigma feldspar porphyroclasts (Figs 6b & 7b) associated with the brittle–ductile shears, indicate sinistral and dextral strike-slip shearing. Locally sinistral or dextral strike-slip movements have taken place with reverse faulting, with displacement along the faults being only 1–4 cm. Reverse faults are the most abundant fault type observed in Domain 1 and strike in a southwesterly to southerly or southeasterly direction (Fig. 6b). Only four normal faults were recognized and these have similar strikes and dips as the northeasterly striking reverse faults (Fig. 6b).

Easterly to eastnortheasterly striking quartz veins cut the S_{1g} foliation in Domain 1 (Fig. 8). These are typically less than 1 m wide and discontinuous. The S_{1g} foliation in Domain 1 is locally folded about gentle, steeply plunging, upright, southeasterly striking folds. The relationship of these folds to ductile shear structures, faults, and quartz veins in the area are unknown.

Deformation in Domain 2

In Domain 2 the earliest recognizable structure is a foliation in the metasedimentary rock component of felsic gneiss, which may represent bedding or a tectonic foliation. Locally, shallow to moderately plunging isoclinal, small-scale F_{1b} folds deform this early fabric (Figs 4a & 7e).

The main regional foliation in Domain 2 (S_{1b}) is schistose to gneissic, and subparallel to observed F_{1b} fold axial surfaces (Fig. 4a). This foliation is variably defined by strongly recrystallized granoblastic quartz–feldspar domains and elongate aggregates of biotite or muscovite. Mineral lineations associated with S_{1b} are defined by elongate quartz and quartz mineral aggregates, and elongate muscovite or biotite aggregates. These mineral lineations are well developed in quartz mylonite and the felsic gneiss and have variable orientations (Figs 4a & 7f) at least in part due to later folding (F_{2b}).

F_{2b} folds are tight to isoclinal upright, with eastnortheasterly striking axial planes that typically dip steeply to the SE (Figs 5c & 7e, f). A variation in attitude of F_{2b} fold axial surface orientations to northwesterly or northeasterly striking is due to the curvilinear nature of the folding indicated by hinges with strongly variable plunges and opposing plunge directions on folds with only slightly variable axial surface orientations. Thus the spread of F_{2b} fold hinges is more likely to be due to F_{2b} folds being non-cylindrical, and strongly curvilinear.

In areas of high D_{2b} strain a well-developed crenulation to crenulation cleavage is present. In these areas feldspar is typically replaced by sericite and biotite may be partially replaced by chlorite. These crenulations dip towards the SSE and are similar to the average fold-axial surfaces of F_{2b} folds in the region. Crenulations and small-scale very tight F_{2b} folds are most common in Domain 2 along and adjacent to the contact with Domain 1, possibly indicating that this contact is a zone of later localized deformation.

Northeasterly striking, steeply dipping quartz veins cut D_{2b} structures in Domain 2. These veins are usually only a few metres long and less than 1 m wide. However, a few larger ones up to

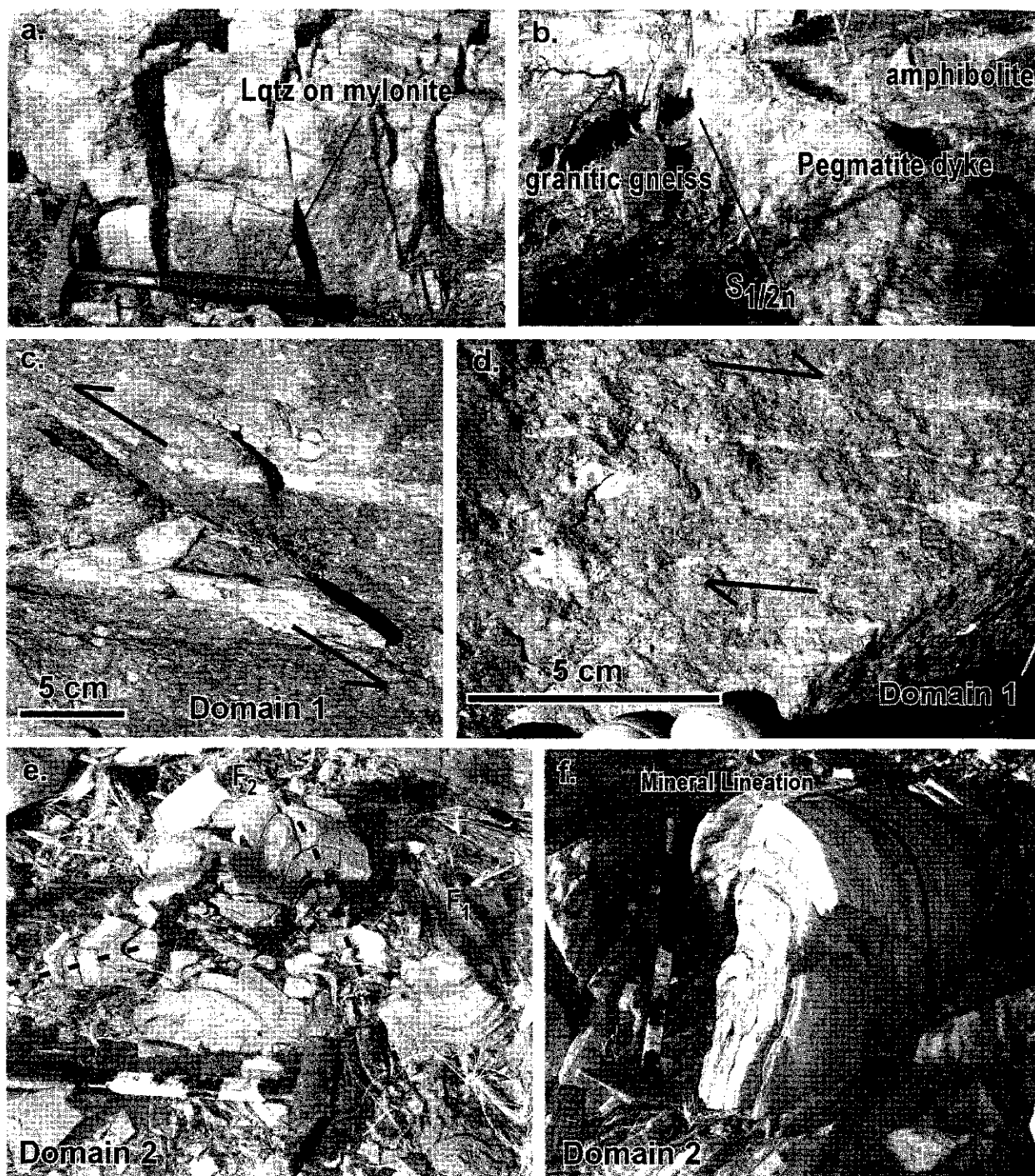


Fig. 7. (a) A strong quartz aggregate mineral lineation on the $S_{1/2n}$ foliation surface of a quartz mylonite in the Archean granitic gneiss (basement) area. (b) A pegmatite dyke (?Capricorn-aged) cutting granitic gneiss and amphibolite, but trending subparallel to the $S_{1/2n}$ foliation in the Archean granitic gneiss (basement) area. (c) Reverse fault offsetting aplitic granite vein in foliated porphyritic granite in Domain 1 of the Granitic gneiss – c. 1958 Ma granite area. The S_{1g} foliation is subparallel to the aplite vein. (d) Dextral strike-slip kinematics around deformed feldspar phenocrysts in Domain 1 of the Felsic gneiss – c. 1958 Ma granite area. (e) F_{1b} fold refolded by upright steeply plunging F_{2b} folds in quartzite in Domain 2 of the Felsic gneiss – c. 1958 Ma granite area. (f) Folded quartz aggregate mineral lineation around upright shallow plunging F_{2b} fold in Domain 2 of the Felsic gneiss – c. 1958 Ma granite area.

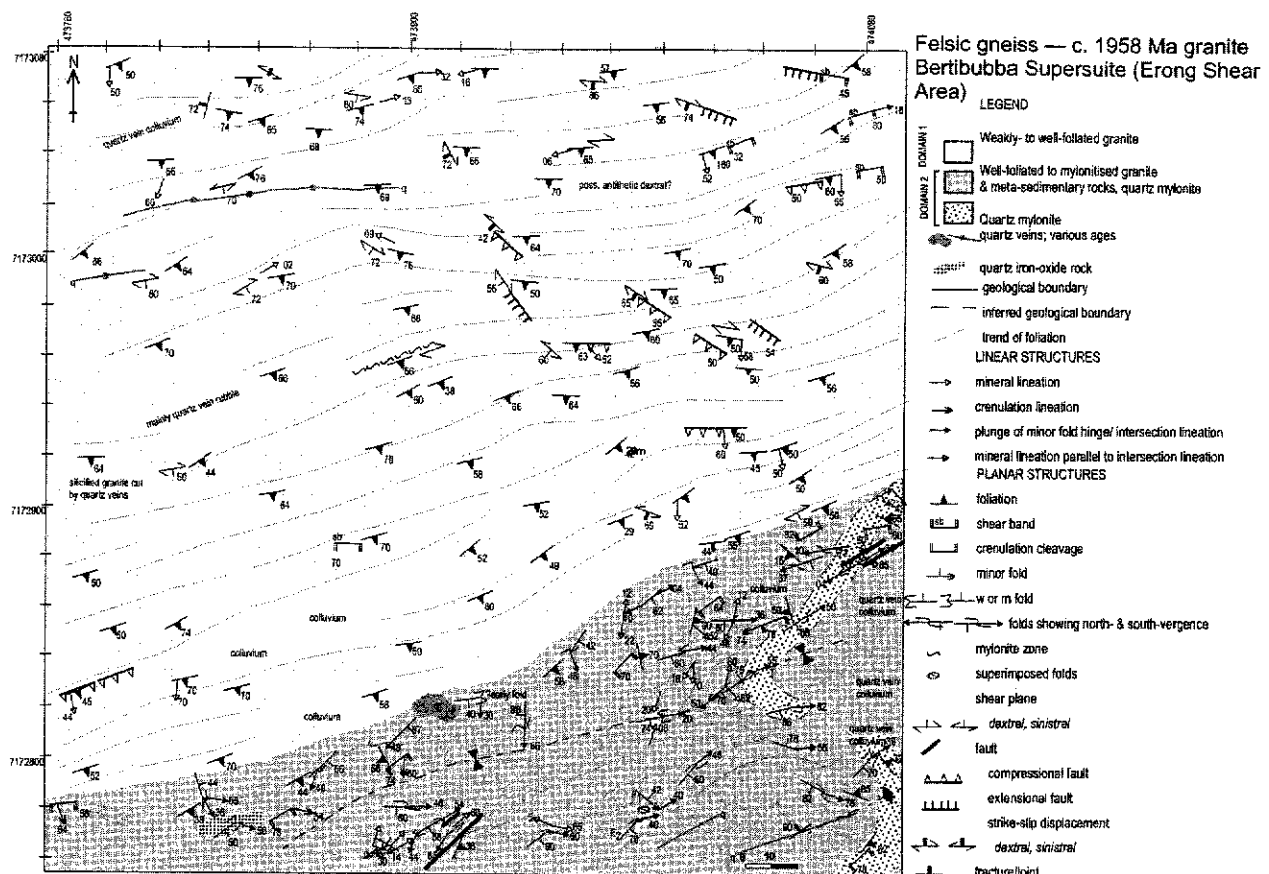


Fig. 8. Geological map of the Felsic gneiss–Bertibubba Supersuite in the Erong Shear Area. Coordinates are specified by Universal Transverse Mercator (UTM) coordinates using the Map Grid of Australia (MGA) and Geocentric datum of Australia 1994 (GDA94).

30 m long and a few metres wide are present in the area.

Palaeoproterozoic metasedimentary rocks – Camel Hills Metamorphics

In the area studied, the Camel Hills Metamorphics comprises the Quartpot Pelite (Fig. 1), an intensely deformed and poly-metamorphosed metasedimentary succession of psammitic to pelitic gneiss, intercalated with discontinuous bands or pips of minor quartzite and calc-silicate gneisses, and actinolite–tremolite schist. In the central and eastern parts of the Errabiddy Shear Zone these rocks are variably migmatized.

The Quartpot Pelite has been dated by the SHRIMP U–Pb zircon method from three localities within the Errabiddy Shear Zone (Occhipinti *et al.* 2001, 2004). These showed that the pelite was mostly derived from 2550–2025 Ma rock, and was deformed and metamorphosed at medium to high grade and locally migmatized at c. 1960 Ma (Occhipinti *et al.* 2001, 2004). Leucocratic pegmatite intrudes

metamorphosed and migmatized rocks of the Camel Hills Metamorphics, and is locally deformed with them in the greenschist facies.

Deformation in psammitic gneiss

An area of mostly psammitic gneiss of the Camel Hills Metamorphics in the central to western part of the Errabiddy Shear Zone was mapped and has been subdivided into two domains based on their location within a larger scale fold: the Limb zone and the Hinge zone (Fig. 9).

The earliest recorded structure in the Hinge and Limb Zones is a pervasive quartz–feldspar–biotite S_{1s} foliation that is easterly to northerly striking and dips moderately to steeply to the north or west (Fig. 4b). This foliation is subparallel to compositional layering in metasandstone and quartz-rich lithologies. It is also subparallel to the contacts between different metasedimentary lithologies in the area (Fig. 9). In quartzofeldspathic rocks and quartzite the foliation is gneissic, whereas in more biotite-rich lithologies a schistosity is developed. The S_{1s} foliation is defined by biotite and feldspar (in psammite)

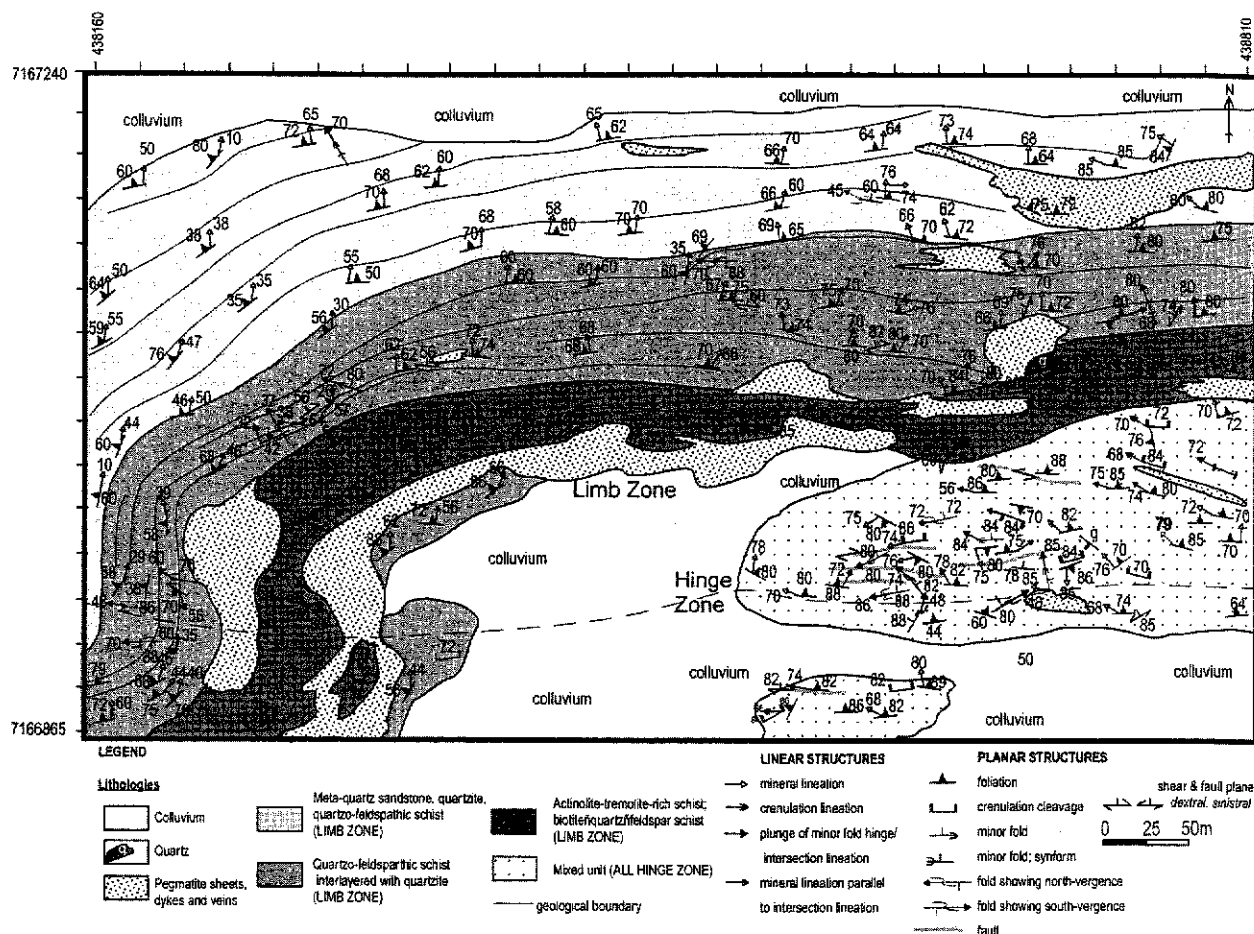


Fig. 9. Geological map of Psammitic Gneiss (Quartpot Pelite). Coordinates are specified by Universal Transverse Mercator (UTM) coordinates using the Map Grid of Australia (MGA) and Geocentric datum of Australia 1994 (GDA94).

and actinolite-tremolite (in para-amphibolite) and is much more difficult to recognize in the Hinge Zone because it has been intensely folded by F_{2s} upright tight to isoclinal easterly striking folds, and in many cases a well-developed S_{2s} crenulation cleavage is present.

A well-developed mineral elongation lineation present on the S_{1s} surface is composed of aggregates of mica and/or quartz. In the western part of the limb zone (Fig. 4b) this mineral lineation plunges moderately to the north, whereas in the remainder of the limb zone it plunges steeply to the north, oblique to the fold axis of subsequent F_{2s} folds (Fig. 5d). Elsewhere in the limb zone mineral lineations are steeply plunging trending parallel to mineral lineations observed in the hinge zone, which plunge steeply to the north or south and trend parallel to hinges of small-scale F_{2s} folds (Figs 4b & 5d).

Small-scale easterly striking F_{2s} folds that deform the S_{1s} foliation are close to tight, upright, inclined folds. These structures typically plunge steeply towards the west; although in a

few cases small-scale folds are northwesterly or southwesterly plunging, larger scale folds show south vergence.

During D_{2s} retrogression of higher-grade metamorphic assemblages that formed during D_{1s} in the greenschist facies took place. For example biotite and feldspar may be partly replaced by sericite and actinolite-tremolite (in para-amphibolite schists) is replaced by fine-grained chlorite. Retrogression is better developed in higher strain D_{2s} zones indicating a probable greenschist facies metamorphic event accompanied D_{2s} .

Brittle and brittle-ductile faults and fractures are present in both the Limb and Hinge Zones (Figs 6c, 9 & 10a). Sinistral faults are generally steeply dipping and are NE to easterly striking in the limb zone, whereas in the hinge zone they are mostly westerly to southwesterly striking. Dextral brittle and brittle-ductile faults and fractures are steeply dipping and easterly or north-easterly striking in the limb zone, and easterly to southeasterly striking in the hinge zone. These

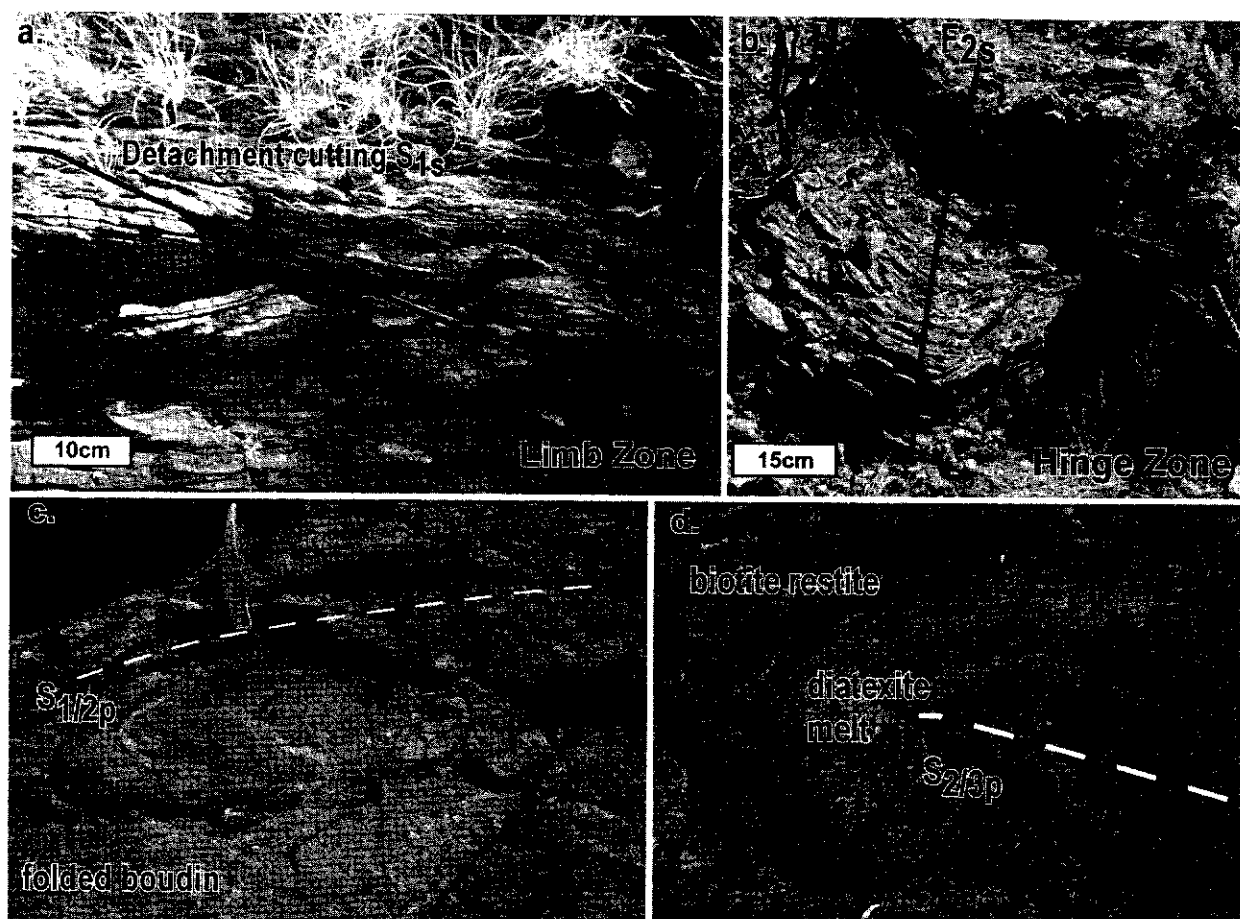


Fig. 10. Field photographs of Palaeoproterozoic metasedimentary rocks of the Camel Hills Metamorphics. (a) Detachment in the limb zone cutting the S_{1s} foliation which trends subparallel to F_{2s} fold hinges in the psammitic gneiss area. (b) F_{2s} fold that has been cut by a detachment fault in the hinge zone in the psammitic gneiss area. (c) A deformed boudin within $S_{1/2p}$ foliation in migmatized pelitic schist and gneiss. (d) Diatexite melt and biotite-rich restite folded into F_{3p} fold in migmatized pelitic schist and gneiss.

structures trend subparallel to S_{1s} in the F_{2s} fold limb, and in the western part of the limb zone and in the hinge zone they trend subparallel to the F_{2s} fold axial surfaces, even though they commonly cut F_{2s} folds further accommodating north-south shortening across the zone (Fig. 10b).

Northerly or northwesterly striking, steeply plunging gentle to open folds locally influence the orientation of both the F_{2s} fold axial surfaces, the S_{1s} foliation, and the mineral lineations in the limb zone. Late northwesterly to northeasterly striking, steep plunging kink bands or open folds cross cut F_{2s} folds and earlier structures; however, their relationship to the fractures and brittle-ductile faults in the area is unknown.

Deformation in migmatized pelitic schist and gneiss

The Pannikan Bore area of the Errabiddy Shear Zone comprises mainly pelitic to psammitic

components of the Quartpot Pelite intercalated with minor calc-silicate and quartzite. The area has been polydeformed, metamorphosed and migmatized, and has undergone distinct periods of granite intrusion and quartz vein formation. The area has been heterogeneously deformed (Fig. 11).

The earliest recorded structure is a locally developed foliation, S_1 , in quartzite and calc-silicate gneiss boudins within the more pelitic and psammitic components of the Quartpot Pelite. This foliation is folded into tight to isoclinal folds within the quartzite and calc-silicate 'pips' (Fig. 10c). The axial surfaces of these folds strike subparallel to the foliation in the surrounding pelitic and psammitic rocks, which wraps around the pips. We interpret the dominant fabric throughout Area 4 as a composite S_1/S_2 fabric, which is denoted $S_{1/2p}$ (Fig. 4c).

The $S_{1/2p}$ foliation is well developed throughout the area, and is typically a steeply dipping east to southeasterly striking fabric that ranges

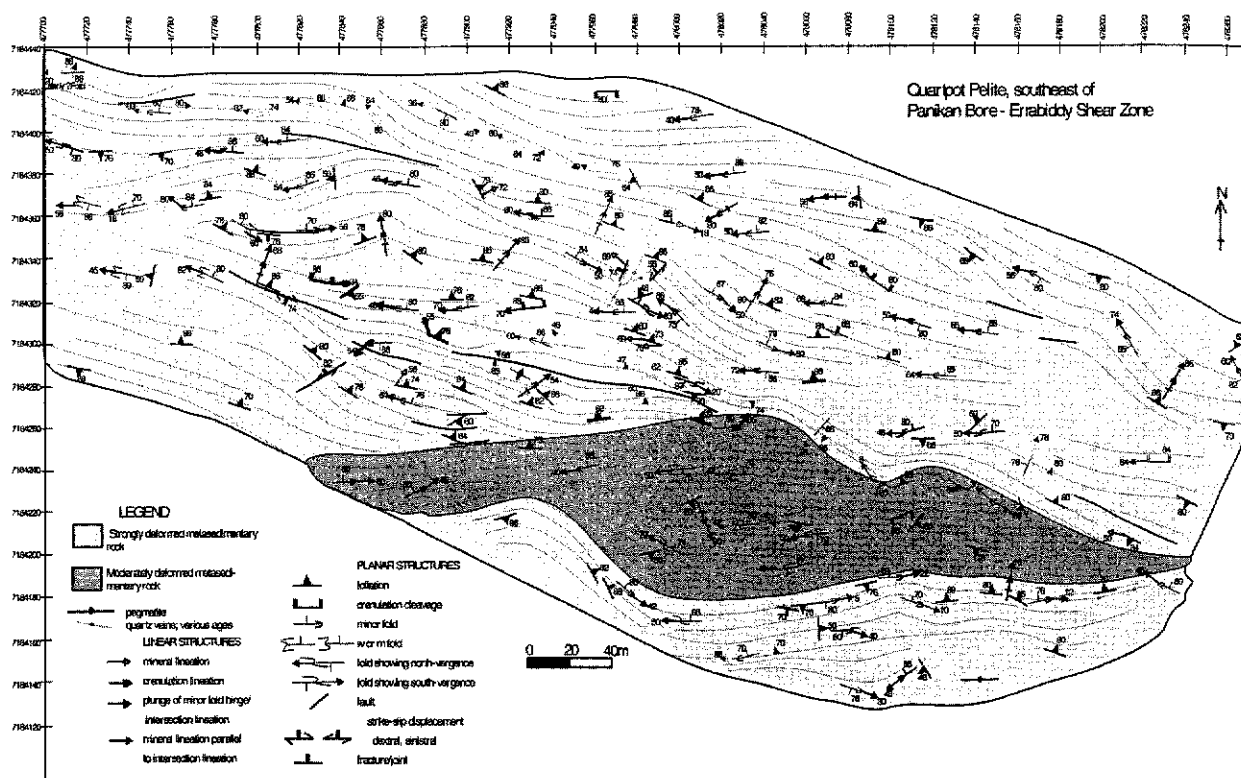


Fig. 11. Geological map of migmatized pelitic schist and gneiss—Quartpot Pelite. Coordinates are specified by Universal Transverse Mercator (UTM) coordinates using the Map Grid of Australia (MGA) and Geocentric datum of Australia 1994 (GDA94).

from schistose to gneissic (Fig. 4c). The foliation mostly consists of alternating bands of quartz, feldspar, sillimanite, and biotite. Stromatic migmatite veins which trend subparallel to $S_{1/2p}$ accentuate the foliation, although in areas of high degrees of melting $S_{1/2p}$ is often cut by melt veins. In areas where the rocks were not as intensely deformed during subsequent deformation events $S_{1/2p}$ is northerly striking and plunges moderately to the west within open fold hinge zones (Fig. 11). Rare, small (< 10 cm long), thin quartzite lenses are deformed into F_{2p} folds.

Upright to steeply inclined easterly to north-northeasterly striking F_{3p} folds and D_{3p} crenulations are present throughout the area (Fig. 5e). In areas of more intense D_{3p} strain these folds are mostly tight to isoclinal and moderately to steeply plunging structures and the development of an $S_{2/3p}$ foliation is common (Figs 5e & 10d). Contrasting this where D_{3p} strain was less intense (Fig. 11) the F_{3p} folds are open and mostly, but not exclusively moderately, westerly plunging (Fig. 5e). South of the mapped area, and elsewhere in the Quartpot Pelite, F_{3p} folds are locally commonly shallowly plunging to the east or west.

Where an S_{3p} or $S_{2/3p}$ foliation is developed, sillimanite and biotite are replaced by white mica and chlorite, garnet is replaced by chlorite,

or chloritoid and quartz has recrystallized. Fine mats of sericite also pseudomorph feldspar and sillimanite. This indicates that retrogression of the earlier higher-grade assemblages is spatially related to D_{3p} strain.

Thin, coarse-grained granite and pegmatite dykes that trend subparallel to orthogonal to F_{3p} fold axial surfaces are present in the southern part of the area. These rocks are massive to locally weakly foliated. They commonly cut F_{3p} folds and locally, they appear to be boudinaged parallel to F_{3p} fold axial surfaces, indicating that they might be a range of ages.

The $S_{1/2p}$ foliation, and F_{3p} folds and pegmatites are all boudinaged. Easterly striking detachments appear to cut the boudinaged foliations within the area; however, they may have developed in response to brittle-ductile processes operating at about the same time as the boudinage, accommodating strain in slightly higher strain domains (Fig. 6d). Northerly to northeasterly striking, steeply plunging F_{4p} kink folds deform F_{3p} folds and the $S_{1/2p}$ foliation; however their relationship to boudinage throughout the area is unknown (Fig. 6d). Possible late, northeasterly striking faults are present in the middle of Domain 1 (Fig. 6d), although it is generally difficult to tell the sense of movement around the faults.

Discussion

Structural geometry within the Errabiddy Shear Zone

Structural elements across the four map areas can be correlated based on their metamorphic grade and overprinting relationships (Figs 4–6 & 12). The oldest fabric that can be correlated across the Errabiddy Shear Zone is the main foliation in all the areas, which is denoted S_1 (Fig. 4), which is parallel to fold axial surfaces of rare F_1 folds in metasedimentary components of felsic gneiss in the region. This foliation developed in the amphibolite facies and is east to eastnortheasterly striking, and steeply dipping. However, in areas of weakest subsequent deformation it is northwesterly to northeasterly striking.

The orientation of mineral lineations on the S_1 surface is commonly highly variable both between and within the different areas. Whereas the trend of mineral lineations is significantly changeable in basement felsic gneiss and in psammitic gneiss (Quartpot Pelite), in granitic gneiss of the Warrigal Gneiss the mineral lineations are all similar, steeply plunging to the west. Mineral lineations that developed during a subsequent deformation on the ' S_{1g} ' foliation and on shear-band surfaces, slightly oblique to ' S_{1g} ' in granite of the Bertibubba Supersuite (Figs 5 & 12) also show a range in orientations and are shallow to steeply plunging. There is no evidence in the field that suggests variability of mineral lineation orientations 'between' each of the field areas is related to folding.

The variability of orientations of mineral lineations of the same age arises for several reasons. In the basement felsic gneiss, variable mineral lineation trends are the effect of re-orientation of originally shallowly plunging, possible northeasterly trending lineations by upright tight to isoclinal curvilinear folds. In psammitic gneiss of the Quartpot Pelite some variability is due to younger folding (moderately north plunging in the western part of the Limb zone to steeply north plunging elsewhere, including in the higher strain Hinge zone). However, the main change is from moderately north plunging to steeply north plunging mineral lineations. This directly corresponds to mineral lineations trending oblique to fold hinge lines in areas of lower D_2 strain, and parallel to fold hinge lines in areas of higher D_2 strain. In granite of the Bertibubba Supersuite D_2 mineral lineations range from shallow to steeply plunging.

The greenschist facies, geometrically similar regional upright tight to isoclinal folds and

crenulations denoted F_2 (Figs 5 & 12), which deform S_1 and its related mineral lineation, contain variable fold hinge orientations throughout and within most areas of the Errabiddy Shear Zone. However, in granitic gneiss of the Warrigal Gneiss the fold hinge lines and related intersection lineations are all similar, steeply plunging to the west trending sub-parallel to mineral lineations on the S_1 surface.

Variability of fold hinge orientations throughout the Errabiddy Shear Zone could be due to a number of different reasons. For example the very strong variability in the basement felsic gneiss is due to the curvilinear nature of these folds, which is probably the effect of re-folding of different parts of a large-scale sub-horizontal fold; although they could also be in part constrictional folds with a component of vertical stretch. The difference in fold hinge orientation in the hinge and limb zones of the psammitic gneiss could largely be due to heterogeneous deformation around different layers of the large-scale south verging parasitic fold. Contrasting this, the variation in fold hinge orientations in the migmatized pelitic schist and gneiss is due to refolding about upright north-northeasterly striking folds in the area. Heterogeneous regional D_2 deformation throughout the shear zone has also resulted in the development of open to close folds in areas of low D_2 strain and crenulations and crenulation cleavages in areas of high D_2 strain. The apparent parallelism of D_1 mineral lineations and F_2 fold hinges throughout the Errabiddy Shear Zone appears to correspond to areas of relatively higher D_2 strain and could be due to the strong re-orientation and recrystallization of mineral lineations during the subsequent D_2 deformation event (Figs 4, 5 & 12).

Upright easterly to eastnortheasterly striking folds did not develop in the foliated c. 1958 Ma granite of the Bertibubba Supersuite. However, the ' S_{1g} ' foliation, which is the dominant structure throughout this domain, is subparallel to the fold axial surfaces of the tight to isoclinal F_2 folds in the adjacent felsic gneiss, and also formed in the greenschist facies (Figs 5 & 12). This indicates these structures probably developed coevally. The shallow to steeply plunging D_2 mineral lineations, which have a range of orientations and are related to the formation of the ' S_{1g} ' foliation (Fig. 12) in granite of the Bertibubba Supersuite are present both on the ' S_{1g} ' surface and on shear band surfaces, slightly oblique to ' S_{1g} ' (Fig. 4). There is no evidence in the field that suggests the variable orientations of these mineral lineations is related to folding.

Detachments that cut the upright tight to isoclinal F_2 fold axial surfaces and S_2 foliation

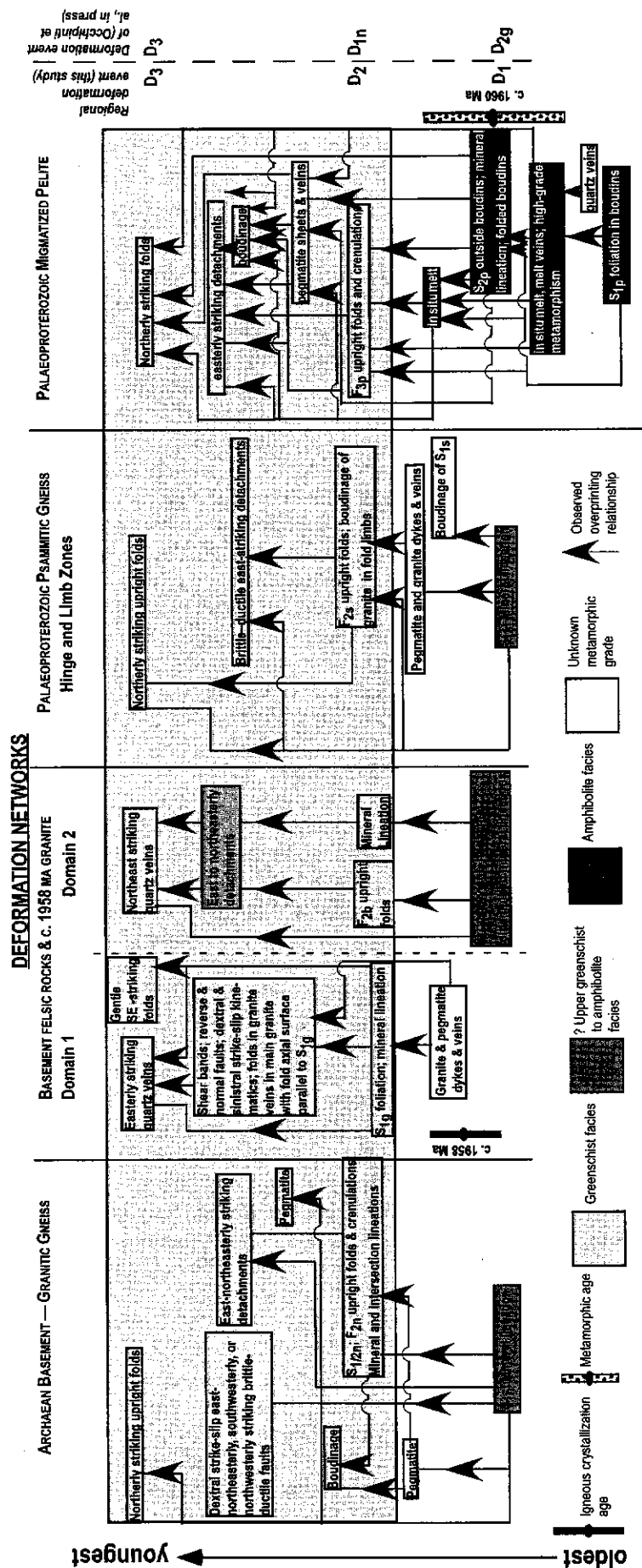


Fig. 12. Summary deformation networks from the four areas showing the general overprinting relationships observed within each of the areas and correlated between them. The relationship of observed structures to regional correlations (this paper and previous work) has also been shown. Explanations of the U-Pb SHRIMP igneous and metamorphic crystallization ages shown are in Occhipinti *et al.* (2004). Arrows indicate observed overprinting relationships. Deformation networks were constructed from four separate younging tables constructed in the field following Potts & Reddy (2000).

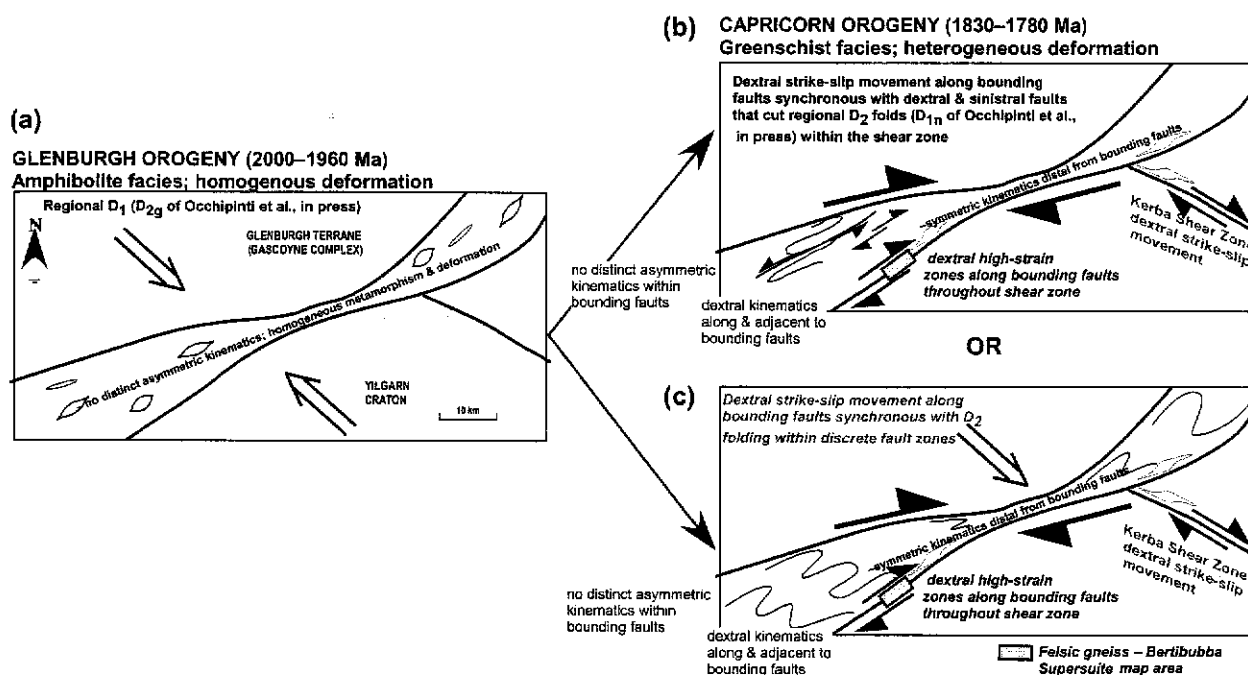


Fig. 13. Model summarizing the evolution of the Errabiddy Shear Zone. (a) shows the accretion of the Glenburgh Terrane onto the Yilgarn Craton during the Glenburgh Orogeny producing symmetrical kinematics, and homogenous deformation and metamorphism, which can be traced throughout the shear zone (regional D₁); b and c shows two possible interpretations on the effects of the Capricorn Orogeny throughout the zone. (b) Dextral strike-slip movement concentrated along main bounding faults synchronous with both dextral and sinistral faults cutting regional D₂ folds within the shear zone. (c) Dextral strike-slip faults along bounding faults synchronous with upright D₂ folding between faults within the shear zone.

within the region but strike subparallel to them probably also formed during the D₂ deformation event. The northerly striking open kinks and folds that deform the D₂ structures with variable intensity throughout the region are related to a regional D₃ deformation event.

Kinematic evolution of the Errabiddy Shear Zone

Symmetrical kinematic indicators were associated with the main foliation surfaces associated with D₁. Similarly, only symmetrical kinematic indicators were found to be associated with the upright tight to isoclinal easterly striking F₂ folds in the areas studied. However, asymmetrical kinematic indicators such as delta and sigma feldspar porphyroclasts and shear bands are present in foliated granite of the Bertibubba Supersuite. These are sometimes associated with mineral lineations on the regional 'S₂' surface, but are sometimes present where a mineral lineation is absent (Fig. 12). In the case of ductile kinematic indicators in the c. 1958 Ma granite of the Bertibubba Supersuite both dextral and sinistral ENE striking (along map strike; Fig. 8) strike-slip kinematic indicators are

present. However, dextral strike-slip movement indicators are most prevalent.

The brittle detachments that trend subparallel to fold axial surfaces of the easterly striking upright folds and the regional S₂ foliation throughout the shear zone commonly show both dextral and sinistral separations. Mineral lineations on the main foliation or shear surfaces associated with these detachments are usually absent, therefore making the kinematics difficult to interpret. Often these separations of opposing displacement sense are very near to each other (sometimes only a few metres) and suggest a bulk coaxial flow. The reverse and normal faults cut the along strike separations indicating they may have developed slightly later. However, the shear bands, deformed feldspar porphyroclasts, mineral lineations and brittle fault structures all developed in the greenschist facies and may have formed during the same progressive deformation event.

Temporal and tectonic evolution of the Errabiddy Shear Zone

The Errabiddy Shear Zone is thought to have developed as a consequence of easterly or

southeasterly directed collision and accretion of the Late Archaean to Palaeoproterozoic Glenburgh Terrane onto the Archaean Yilgarn Craton between 2000–1960 Ma ago and was probably a northnortheasterly or northerly trending shear zone (Fig. 2; Sheppard *et al.* 2004; Occhipinti *et al.* 2001, 2004). During this time one set of structures formed in the Errabiddy Shear Zone between 2000–1960 Ma (Occhipinti *et al.* 2004). Only symmetrical kinematic indicators (e.g. flattened feldspar porphyroblasts) were found to be associated with the formation of the pervasive S_1 foliation and the D_1 mineral lineation, which developed in the amphibolite or upper greenschist facies in each of the four mapped areas formed during the Glenburgh Orogeny (Fig. 13). The intrusion of the c. 1958 Ma granite of the Bertibubba Supersuite post dates this D_1 deformation event, as the granite does not contain the regional S_1 foliation.

The eastnortheasterly striking, isoclinal to tight upright F_2 folds present throughout the Errabiddy Shear Zone developed at greenschist facies conditions, suggesting that they formed during the 1830–1780 Ma Capricorn Orogeny (Sheppard & Occhipinti 2000; Occhipinti & Sheppard 2001; Occhipinti *et al.* 2001). The strike-slip, reverse and normal detachment faults that cut the F_2 folds at low angles may have developed soon after their formation and may be part of the same progressive deformation event (Fig. 12). During the Capricorn Orogeny the Errabiddy Shear Zone was probably re-orientated from a northnortheasterly, or northerly trend into its approximate current orientation. The F_2 folds, which are the dominant structure to have developed during D_2 in the Errabiddy Shear Zone are commonly associated with symmetrically flattened porphyroblasts, and where present mineral lineations around these folds mostly appear to have developed prior to their formation (Fig. 13). In addition the fold axial surfaces of F_2 folds are subparallel to the bounding faults of the Errabiddy Shear Zone, suggesting that the shortened S_1 fabric was initially highly oblique to the shear zone boundary. In contrast to areas of F_2 fold development, the S_2 foliation in the c. 1958 Ma Bertibubba Supersuite granite is dominated by dextral kinematics, also recording some sinistral deformation.

The high obliquity of the regional S_1 foliation to the shear zone boundary, prior to D_2 deformation, and the prevalence of orthorhombic kinematics, suggests that general shear with shortening perpendicular to the shear zone boundaries dominated during D_2 in much of the

Errabiddy Shear Zone. However, the prevalence of dextral strike-slip kinematics in the c. 1958 Ma granite of the Bertibubba Supersuite suggests that locally simple shear also took place during D_2 (Fig. 13). Partitioning of simple shear deformation in the foliated granite of the Bertibubba Supersuite and synchronous pure shear processes dominated deformation in the basement felsic gneiss is a similar scenario to that presented recently by (Lin & Jiang 2001) who reported that pure shear dominated in a transpressional shear zone.

No data in this study suggests that the variable orientation of F_2 fold axial surfaces that mimic the regional curvature of the Errabiddy Shear Zone (inset, Fig. 1) is due to refolding after D_2 . Northerly striking F_3 upright folds that developed after the Capricorn Orogeny only weakly deformed D_2 structures and were not responsible for the formation of this curvature. This implies that reactivation did not influence the orientation of D_2 structures around this bend in the shear zone but that a variation of the strain geometry during the regional D_2 event operated throughout the shear zone, thus supporting that transpression is likely to have taken place during D_2 .

Brittle vertical detachment faults with dextral displacement, which formed either late in D_2 , or during D_3 and cut the S_2 foliation in the foliated granite of the Bertibubba Supersuite, indicate that shear zone boundary-parallel shear took place in region. Brittle dextral separations were also common in the Archaean granitic gneiss (basement) area. The apparent rarity of dextrally displacing brittle structures in the other two areas studied might represent a sampling bias. The region of the Bertibubba Supersuite is the only area within this part of the Errabiddy Shear Zone to contain two different lithological units of probable differing geological age that have an exposed faulted boundary (Fig. 13), and the Archaean granitic gneiss area is situated only 200 m south of an inferred easterly trending boundary fault that separates it from the Quartpot Pelite (Fig. 1). Except for the case of the basement felsic gneiss–Bertibubba Supersuite area such boundaries have been inferred from aeromagnetic data and in the field usually consist of quartz veins and rubble that lie in between outcrop of different rock types (Sheppard and Occhipinti 2000). The development of dextral kinematics along and in close proximity to bounding faults within the shear zone implies that a relatively high simple shear component operated along these fault zones, whereas between these zones pure shear deformation dominated during D_2 . This is a scenario

previously reported by Tikoff and Greene (1997), and more recently by Czeck and Hudleston (2003) in the Superior Province in Canada where strain partitioning between pure and simple shear components resulted in simple shear being concentrated within discrete shear zones, whereas the areas between these shear zones underwent deformation dominated by pure shear.

To the east, the Kerba Shear Zone, which is a discrete shear zone that splays off the Errabiddy Shear Zone, contains kinematic indicators suggesting that the Archaean to Palaeoproterozoic Yarlalweelor Gneiss Complex and Palaeoproterozoic metasedimentary and metavolcanic rocks of the Bryah and Padbury basins that the shear zone separates were juxtaposed by dextral transpressional shear with only a minor dip-slip component (Reddy and Occhipinti 2004). This is further evidence that dextral transpression operated in the southern Capricorn Orogen during the greenschist facies D_2 deformation (Fig. 13).

Conclusions

This study illustrates that strain localization and kinematic partitioning within shear zones leads to differences in structural development within different parts of the shear zones. Therefore shear zone analysis requires a range of representative areas throughout the zone to be studied and correlated in order to understand the processes involved in the shear zone formation. Failure to do so could lead to misleading interpretations of shear zone development.

The four areas mapped in detail record a range of structures associated with the initial and evolving development of a reactivated shear zone. Although there are some dissimilarities between the orientations and types of structures within each of the four areas there is also an overwhelming similarity between them, and the structural elements within the different parts of the shear zone can be correlated based on their geometries, metamorphic grade, and overprinting relationships. However, despite these correlations the data presented here suggest that the evolution of the Errabiddy Shear Zone is complex, both spatially and temporally. The shear zone evolved through two main orogenic events correlated with the Glenburgh and Capricorn Orogenies, which are separated by over 100 Ma. Only orthorhombic kinematic indicators were observed in fabrics that developed during the Glenburgh Orogeny and most of the mineral lineations observed during this study developed at this time. However, it is unlikely

that deformation during the Glenburgh Orogeny was solely by pure shear processes and the apparent lack of monoclinic structures that formed during this time may reflect the subsequent pervasive re-working of structures during the Capricorn Orogeny.

Deformation during the Capricorn Orogeny was heterogeneous dextral transpression throughout the Errabiddy Shear Zone with components of both pure and simple shear operating at the same time but being partitioned throughout the area. Localization of simple shear and dextral strike-slip movements is likely to have occurred within the numerous discrete shear zones within the Errabiddy Shear Zone. These are responsible for juxtaposed different rock units of varying tectonic origin and geological age. Between these discrete shear zones pure shear processes dominated.

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