A metamorphic investigation of the Palaeoproterozoic metasediments of the Willyama Inliers, southern Curnamona Province, South Australia

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Results from literature review, fieldwork, petrography, and the spatial distribution of metamorphic minerals

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Geological Survey Branch

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Panoramic view of Cathedral Rock (Photo 049081)

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ABSTRACT

The deformed metasediments of the South Australian Willyama Inliers (southern Curnamona geological province) preserve petrologic evidence of a complex and protracted metamorphic history. There are numerous sources of petrographic and petrologic data compiled from the South Australian Willyama Inliers (SAWI). These sources include thin sections, petrographic reports, annotated air photos, academic theses, research articles, and petrographic databases. Some of these data have important metamorphic implications for evolution of the terrane.

This study synthesises and evaluates a wide range of the existing metamorphic data from this part of the province. A database was constructed that contains spatially located mineralogical information from metamorphic rock samples. GIS analysis was then used to spatially interrogate the data, and was combined with detailed petrographic observations to enable mapping of metamorphic mineral isograds. The results of the GIS analysis were then compared to existing mineral isograd data. This approach yielded several significant conclusions.

Firstly, the M_1 event is responsible for the majority of the primary metamorphic mineral assemblages seen in the pelites of the SAWI. This includes the growth of chiastolite, andalusite, biotite, sillimanite (both fibrolitic and prismatic), and the early garnet.

Secondly, an M_2 event, responsible for the growth of staurolite and chloritoid-bearing assemblages, is generally late stage and mainly post-kinematic. These minerals overgrow the early M_1 metamorphic event. Both staurolite and chloritoid are observed overgrowing late, low-grade, retrograde, sericite-bearing assemblages. Furthermore, staurolite often post-dates chloritoid growth. These data suggest that much of the terrane experienced two metamorphic cycles (M_1 and M_2), separated by a low-grade retrogression event.

Previous studies had recognised one, anticlockwise metamorphic cycle to explain the observed sequence of mineral paragenesis (e.g. Clarke et al., 1987).

Thirdly, there is microstructural evidence of two stages of garnet growth at several localities in the SAWI. The localities that contain evidence of two stages of garnet growth correspond to the areas where both staurolite and chloritoid occur together in rocks of an appropriate bulk composition. This implies a metamorphic link between staurolite, chloritoid and secondary garnet growth (during the M_2 event).

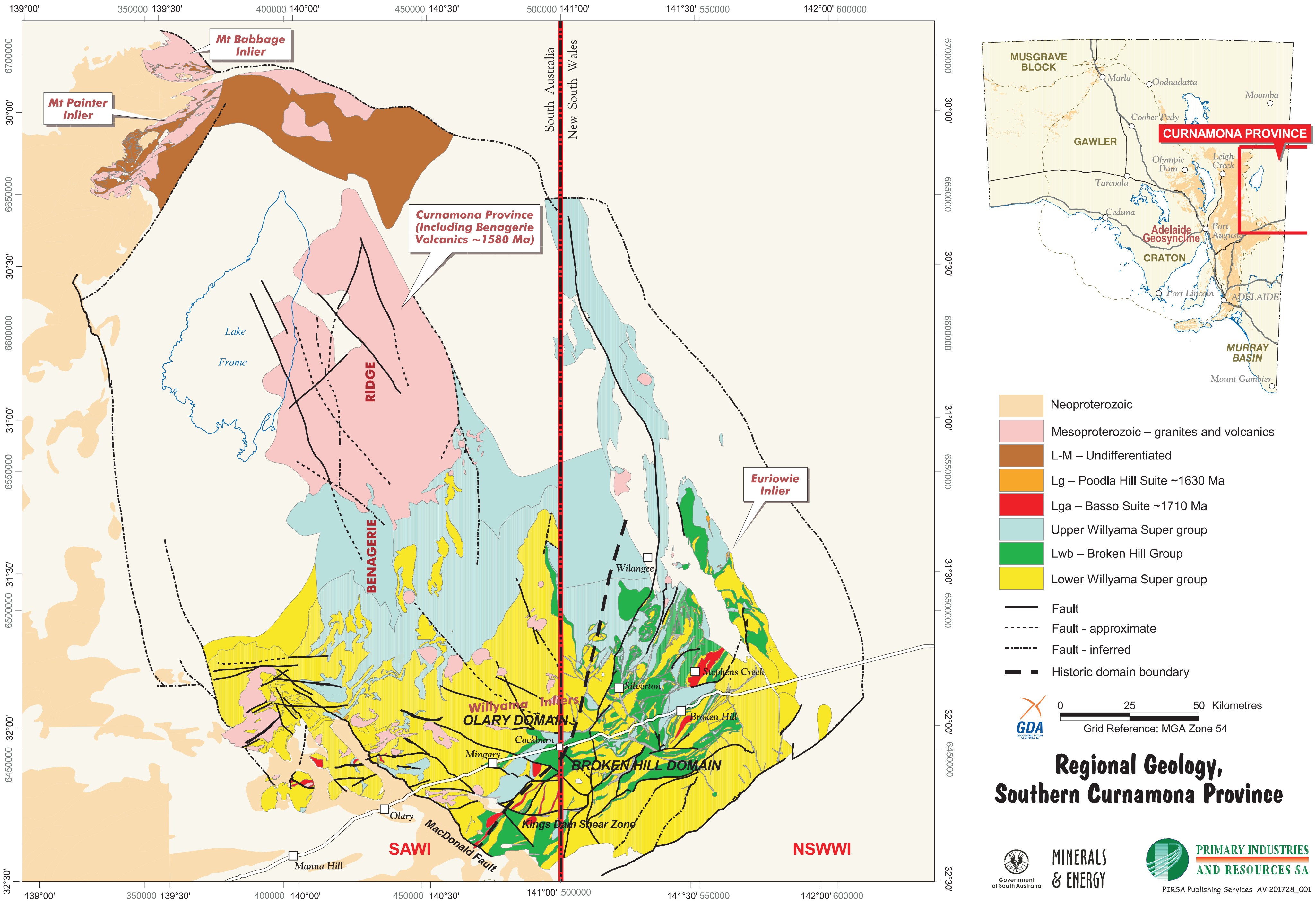
Fourthly, the rocks in the southeastern SAWI (around Mutooroo Mine) attained granulite grade and subsequently retrogressed to middle to upper amphibolite grade. This area was previously described as reaching sillimanite–muscovite grade (i.e. middle amphibolite grade; Clarke et al., 1987, 1995). Metamorphic isograds in the SAWI appear to link up with corresponding isograds in the New South Wales Willyama Inliers (NSWWI). This new conclusion allows the southeastern SAWI (around Mutooroo Mine) to be correlated at least in terms of metamorphic grade with the high-grade rocks of the adjacent Broken Hill Domain in the NSWWI. The alliance of the southeastern SAWI with the southern Broken Hill Domain reinforces the apparent lithostratigraphic correlations and suggests that a broader area is more prospective for 'Broken Hill style' mineralisation than previously recognised.

PREFACE — DOMAIN BOUNDARY NOMENCLATURE

The question of how to subdivide the Willyama Inliers in a geologically significant manner has been the subject of much debate, with many of the points of view covered in Crooks (2001). The northeast–southwest-trending magnetic and gravity feature (located to the west of the historic Mutooroo Mine, Mingary 1:100 000 map area; e.g. Flint and Parker, 1993) and, arbitrarily, the state border between New South Wales and South Australia (e.g. Clarke et al., 1987) have been used in the past as the domain boundary (Fig. 1). This report subdivides the Willyama Inliers in two ways. Firstly, they are subdivided on purely geographic grounds, with the state border as the boundary between the South Australian Willyama Inliers (SAWI) and the New South Wales Willyama Inliers (NSWWI). The name SAWI refers to the full extent of Willyama Supergroup rocks exposed on the South Australian side of the border that are the subject of this study. Secondly, the apparent metamorphic-grade isograds, documented here, suggest that metamorphic grade cannot be used to define a satisfactory domain boundary. It is the opinion of the authors that a satisfactory basis for a subdivision boundary is yet to be defined, therefore, the geophysical lineament previously used as a domain boundary (described above) can still be considered, perhaps arbitrarily, as the basis of a geophysically defined domain boundary. All SAWI rocks to the northwest of this boundary, irrespective of metamorphic grade, are therefore referred to herein as the Olary Domain, while the high-grade SAWI rocks to the southeast of this lineation are referred to as the Broken Hill Domain.

1 INTRODUCTION — AIMS AND OBJECTIVES OF THIS STUDY

Understanding regional and local variations in metamorphic grade is an important part of reconstructing the tectonic and thermal history of the Curnamona Province. The Palaeoproterozoic rocks of the Willyama Inliers (southern Curnamona Province) preserve metamorphic and structural evidence of the complex tectonic history. Despite numerous studies focusing on the tectonic evolution of this important terrane there is still a lot of ambiguity about the timing relationships between individual deformation episodes and metamorphic events (e.g. Flint and Parker, 1993). One reason for this is the high degree of pervasive retrograde overprinting of peak metamorphic assemblages seen in many of the rocks (Clarke et al., 1987; Flint and Parker, 1993). This has had the effect of erasing petrologic information relating to earlier metamorphic deformation events. Hence, detailed and comprehensive metamorphic analysis is required to interpret the full metamorphic history of this terrane.



Mt Babbage Inlier
Mt Painter Inlier
Curnamona Province (Including Benagerie Volcanics ~1580 Ma)
Euriowie Inlier
South Australia
New South Wales
Lake Frome
RIDGE
BENAGERIE
Willyama Inliers
OLARY DOMAIN
BROKEN HILL DOMAIN
Kings Dam Shear Zone
MacDonald Fault
SAWI
NSWWI
Wilangee
Stephens Creek
Silverton
Broken Hill
Cockburn
Mingary
Olary
Manna Hill
MUSGRAVE BLOCK
GAWLER
CRATON
Adelaide Geosyncline
MURRAY BASIN
CURNAMONA PROVINCE
Marla
Oodnadatta
Moomba
Coober Pedy
Olympic Dam
Leigh Creek
Tarcoola
Ceduna
Port Augusta
Port Lincoln
ADELAIDE
Mount Gambier
Neoproterozoic
Mesoproterozoic – granites and volcanics
L-M – Undifferentiated
Lg – Poodla Hill Suite ~1630 Ma
Lga – Basso Suite ~1710 Ma
Upper Willyama Super group
Lwb – Broken Hill Group
Lower Willyama Super group
Fault
Fault - approximate
Fault - inferred
Historic domain boundary
0 25 50 Kilometres
Grid Reference: MGA Zone 54
GDA
Regional Geology, Southern Curnamona Province
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Figure 1

This study was initiated to examine some of these issues in detail. The study forms part of a research collaboration between the Curnamona Program of the Geological Survey Branch of the PIRSA Division of Minerals and Energy, and Dr Martin Hand and Mr Lachlan Rutherford from the University of Adelaide. This research collaboration was set up to investigate the structural, metamorphic, and magmatic history of the Olary Domain, southern Curnamona Province. The aims include:

- compilation of a metamorphic mineral database for use in this study and future metamorphic and tectonic studies
- delineation of temporal links between sequential mineral growth and sequential generations of penetrative fabric development
- determination of mineral isograd boundaries within the SAWI with respect to different metamorphic events
- spatial correlation of metamorphic rocks with similar character between the Olary and Broken Hill Domains of the Willyama Inliers.

This approach aims to assist in addressing some of the outstanding fundamental questions about the metamorphic history of the SAWI.

2 REGIONAL GEOLOGY

The Curnamona Province is a roughly circular feature comprising outcropping to deeply buried Palaeoproterozoic to Mesoproterozoic basement rocks extending from the northeastern Flinders Ranges into northwestern New South Wales. Significant outcrops of these multiply deformed rocks occur along the southern margin of the province where they form the basement to the Adelaidean succession and younger sedimentary packages (Fig. 1). The Willyama Inliers have been deformed by at least five distinct deformation events (Flint and Parker, 1993). The first three events (D_1–D_3) occurred during the Mesoproterozoic Olarian Orogeny (~1600–1500 Ma). The last two deformation events (D_4 and D_5) are thought to have occurred during the Delamerian Orogeny (~500 Ma). The first two (Olarian) deformations are correlated with the earliest metamorphic associations found in the Willyama Inliers (Clarke et al., 1987). This early metamorphic event (M_1) is characterised by high temperature – low pressure metamorphic facies. There is a general decrease in (M_1) metamorphic grade from granulite facies in the southeast to lower amphibolite facies in the north and northwest of the inliers. Drill core from Benagerie Ridge (Fig. 1) contains Willyama Supergroup-age rocks that are very low grade to unmetamorphosed and contain little evidence of deformation (Preiss, 1998). Minerals associated with the M_1 event (in pelites) include chiastolite, andalusite, sillimanite, garnet, biotite and K-feldspar.

Subsequent metamorphism of the Willyama Inliers (primarily involving retrogression, and staurolite and chloritoid growth) is historically attributed to the retrograde segment of the M_1 event (Phillips and Wall, 1981; Corbett and Phillips, 1981; Clarke et al., 1987; Stuwe and Elhers, 1997). This suggests that the metamorphic history can be essentially described as a relatively simple anticlockwise pressure–temperature–time (P–T–t) loop during the Olarian Orogeny (Clarke et al., 1987). Laing (1996) appears to concur with this general tectonic model, while subdividing the observed changes in metamorphic mineral assemblages into three metamorphic zones (M_1 to M_3) coinciding with the three Olarian deformations (D_1 to D_3).

However, there are several lines of evidence suggesting that this subsequent ‘retrograde’ metamorphism records more than one metamorphic cycle (Spry and Henley, 1975; Flint, 1981; this study). Therefore, it is useful to describe both the pervasive sericite retrogression, and the growth of staurolite and chloritoid, as two separate events that may be temporally distinct from the prograde M_1 event. These are termed ‘M_1-retro’ and M_2, respectively. The Olary Domain contains retrograde shear zones that post-date the Olarian Orogeny and the latest granitoids, but which pre-date deposition of the Neoproterozoic Adelaidean sediments (Clarke et al., 1995; Ethridge and Cooper, 1981; Paul et al., 2000). These shear zones often contain coarse garnet–chlorite ($\pm$staurolite) schist. Recent geochronology from these shear zones indicates that they were reactivated during the Delamerian Orogeny (L. Rutherford and M. Hand, University of Adelaide, unpublished data, 2002; Bottrill, 1998; Hartley et al., 1998).

3 PREVIOUS WORK

3.1 Published research

There are few published papers relating to the metamorphic history of the SAWI. This is surprising considering the extensive body of research concerning metamorphism of the NSWWI.

Aluminosilicate deposits found in the SAWI were evaluated by several authors (Ridgway and Johns, 1950; Olliver and Farrand, 1986; Olliver and Barnes, 1988). However, these records contain very coarse metamorphic descriptions and generally proved to be not very useful in the current context.

The metamorphic isograds for the Olary Domain (including the Mutooroo Mine area) were first described by Clarke et al.(1987; Fig. 2). This work followed on from pioneering isograd mapping in the NSWWI by Binns (1964), Katz (1976) and Phillips (1978). The first metamorphic event was allied with the S_1 fabric of Clarke et al. (1986, 1987). Metamorphic mineral assemblages associated with this event were used to divide the terrane into three M_1 metamorphic zones (Fig. 2). A further subdivision was made on the basis of chloritoid and staurolite (M_2) distribution associated with a later fabric (S_2 of Clarke et al., 1986, 1987). However, in later work (Clarke et al., 1995), the same mineral assemblages were associated with an S_3 and an S_4 fabric, respectively. Inclusion trail and porphyroblast–matrix criteria were cited as evidence for the existence of at least two fabrics prior to the development of what they had formerly identified as the S_1 fabric. This revision was based on microstructural analysis of pelitic metasediments in the northern Walparuta Inlier of Preiss and Conor (2001). Flint and Parker (1993) emphasised the microstructural complexity of most pelitic rocks from the SAWI. They suggested that correlation of metamorphic and structural events is hindered by the pervasive retrograde sericitisation of metapelitic rocks, such that most of the earlier metamorphic history is obliterated. They noted that the metamorphism in many sub-areas is related to the thermal aureoles of syntectonic granites (e.g. the development of migmatite around granodiorite–tonalite bodies in the Billeroo – Crockers Well and Wiperaminga Hill areas). Similarly, several authors have noted the occurrence of all three aluminosilicate polymorphs (andalusite, sillimanite and kyanite) in close proximity to syntectonic granitoids (e.g. Clarke et al., 1987; Flint and Parker, 1993). Flint and Parker also suggested that the Delamerian deformation was accompanied by greenschist-facies metamorphism.

In the Mutooroo Mine area, Spry et al. (1977) recognised the presence of amphibolite-grade mineral assemblages that probably represented former two-pyroxene granulites. Preserved two-pyroxene granulites were described from diamond drillcore from the Mutooroo Mine by Flint (1979).

3.2 Honours and PhD theses

Honours and PhD theses contain scattered metamorphic information. The validity of information extracted from honours theses is questionable as there is little consistency to the petrographic–petrologic methodology or degree of documentation used by different students and researchers. However, data from honours theses was useful for filling in the significant gaps in the coverage of petrologic data available from other sources in several parts of the SAWI.

PhD theses were given more credence but they generally contained very little detailed metamorphic information. An exception to this was the work of Clarke, with most of the metamorphic data published in Clarke et al. (1987).

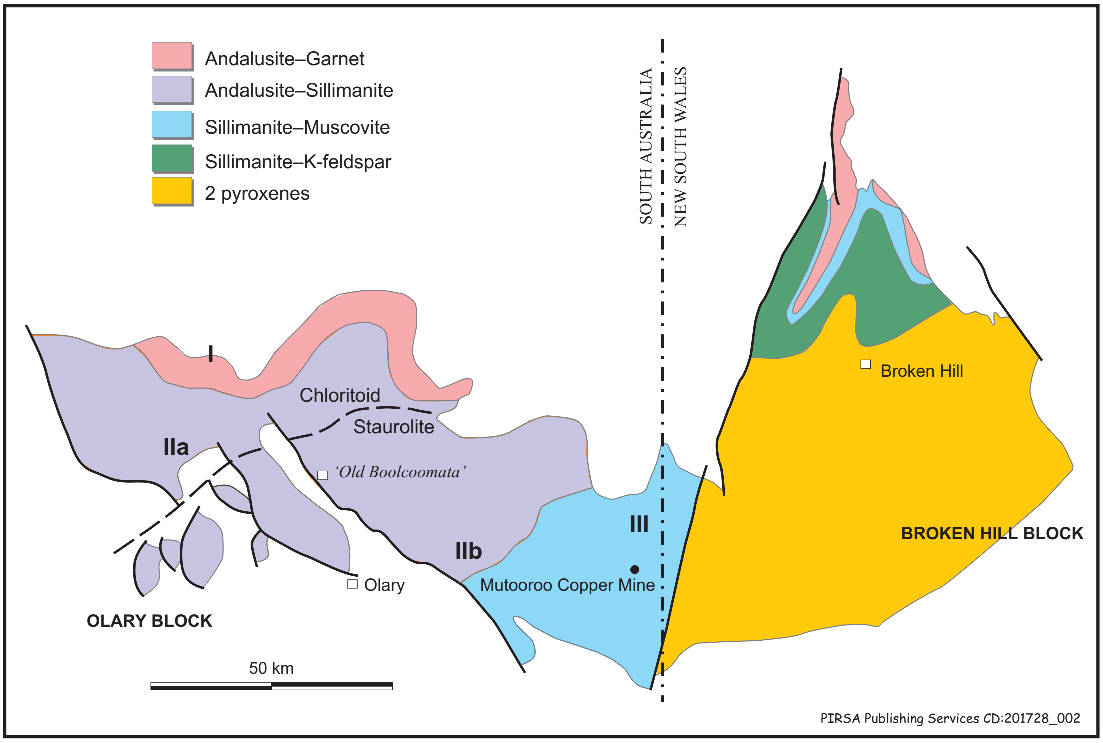


Figure 2 Metamorphic isograd map (from Clarke et al., 1987)

For simplicity, data from research theses is integrated directly into the petrographic descriptions in this report.

3.3 SA_Geodata

The rock sample section of SA_Geodata, PIRSA's geoscientific database, is the main source of information on the origin, characteristics, and location of rock samples and thin sections held by the Geological Survey in South Australia.

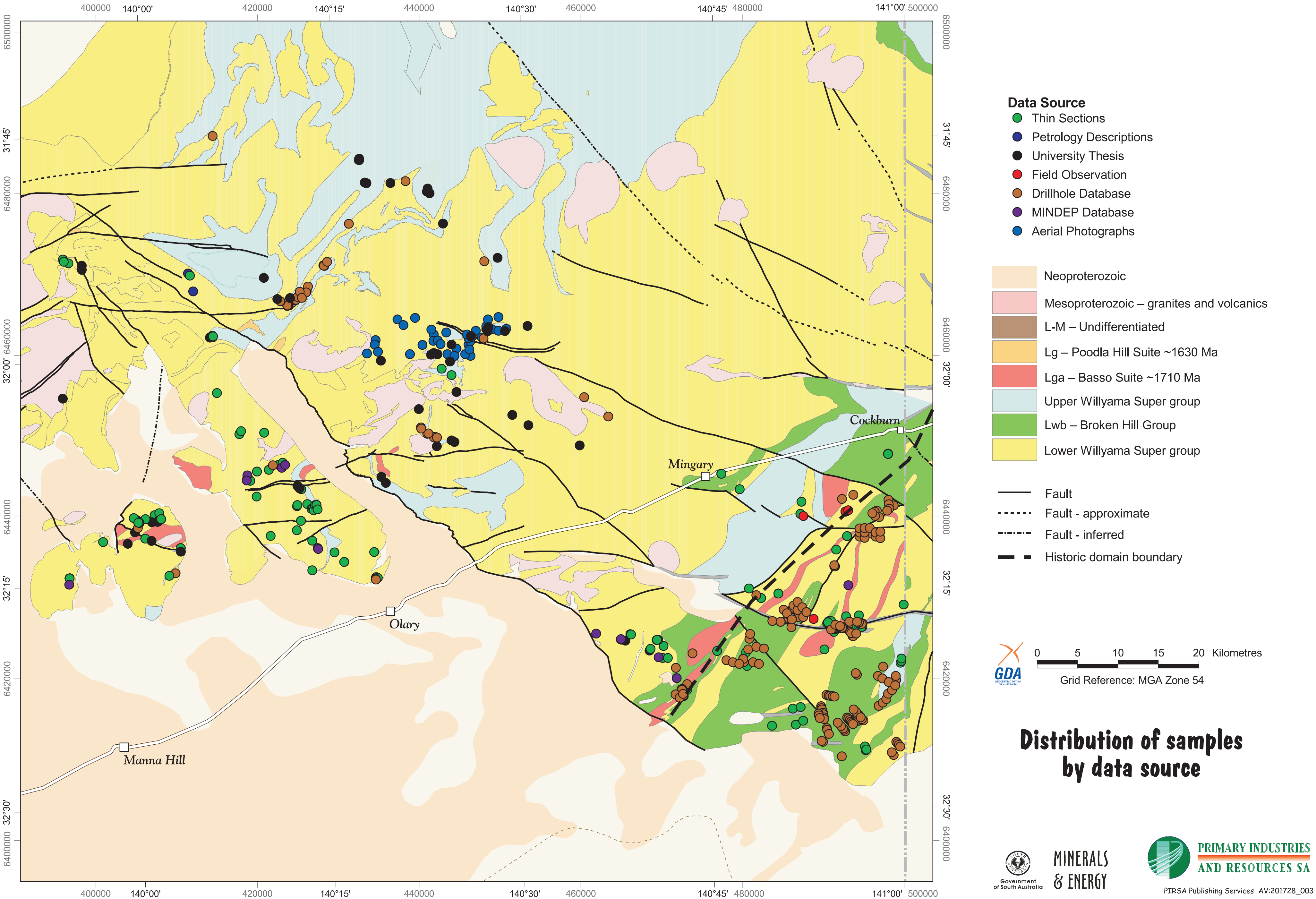
4 CURRENT WORK

4.1 Metamorphic mineral database

Geographically located mineralogical and petrological data were combined into a petrographic database. Where possible, individual database entries are based on the mineralogy of a single rock sample. This means that individual mineral species can be related to each other in terms of paragenetic groupings rather than just independent occurrences. Mineralogical and petrologic data were derived from many sources for input into the database (Fig. 3). These sources included:

1. Thin sections

Thin sections of useful metamorphic rock samples provided the majority of reliable mineralogical data points for the database. Thin section data were sourced from samples from the PIRSA Division of Minerals and Energy thin-section library (referenced in SA_Geodata), from samples acquired during this study (including field sampling and diamond-drillcore sampling), and from thin sections referenced in honours and PhD theses. Some difficulties were experienced determining the validity of both the interpretations of petrological data and the geo-location of the sampling sites of the thin sections referenced in external theses. Samples held by PIRSA were less problematic because they were generally located via GPS measurements in the field. Recently collected samples, including those collected during the course of this study, were usually located via averaged GPS measurements. This reduced the potential horizontal error significantly, and should make future re-sampling easier. Unfortunately, there is not enough ground coverage of thin



400000
140°00'
420000
140°15'
440000
140°30'
460000
140°45'
480000
141°00'
500000
6500000
31°45'
6480000
6460000
32°00'
6440000
32°15'
6420000
32°30'
6400000
Cockburn
Mingary
Olary
Manna Hill
Data Source
Thin Sections
Petrology Descriptions
University Thesis
Field Observation
Drillhole Database
MINDEP Database
Aerial Photographs
Neoproterozoic
Mesoproterozoic – granites and volcanics
L-M – Undifferentiated
Lg – Poodla Hill Suite ~1630 Ma
Lga – Basso Suite ~1710 Ma
Upper Willyama Super group
Lwb – Broken Hill Group
Lower Willyama Super group
Fault
Fault - approximate
Fault - inferred
Historic domain boundary
0 5 10 15 20 Kilometres
GDA
Grid Reference: MGA Zone 54
Distribution of samples by data source
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Figure 3

sections (and thin-section references) to determine changes in metamorphic grade across the whole of the SAWI. Less-accurate data sources, such as annotated air photographs, were included in the metamorphic mineral database to fill in major gaps.

2. *Mineral deposit locality database*

This forms part of the Olary GIS package. The database was used to locate aluminosilicate deposits such as andalusite, sillimanite and kyanite. While these deposits are generally mono-mineralic, they may contain appreciable amounts of muscovite and minor amounts of staurolite, chloritoid and tourmaline (e.g. sample R36172). The data source references only the major mineral of economic importance and, therefore, has no consistent detailed information on the total mineral assemblages that make up each deposit. However, the only data extracted from this database for this study were the spatial distribution of the aluminosilicate polymorphs of andalusite, sillimanite and kyanite. Since the stability of these polymorphs (with relation to each other) is only dependent on the pressure and temperature conditions and is effectively independent of the bulk composition of the rock, this database does contain useful information on the distribution of the aluminosilicate polymorphs in relation to metamorphism.

3. *Drillhole locality database*

This database is also part of the Olary GIS data package. A field was included in the database for inputting brief lithological and mineralogical information on lithologies found within the hole. This information proved useful in several areas where there was a poor coverage from other data sources (e.g. thin sections). The mineralogical information from this source is representative of all minerals found in the drillhole. Therefore, these data are not related to an individual lithology but, rather, to all lithologies found in the hole. However, this data source proved useful for delineating the distribution of minerals that are bulk composition independent in relation to each other (e.g. the aluminosilicate polymorphs andalusite, sillimanite and kyanite).

4. *Annotated aerial photos*

Pioneering field work was done in the Olary region by B. Campana (~1950–60) and annotated aerial photographs believed to have been used by him contain useful references to field localities delineating the distribution of aluminosilicate mineral occurrences (particularly of kyanite, sillimanite and andalusite) in several key localities. Due to the inherent uncertainty in interpreting mineralogical data from antiquated aerial photos, referenced aluminosilicate occurrences were visited to ground truth some photo data points. Due to the regional nature of this study, the uncertainty involved in geo-location of some point sources from aerial photos does not have a significant effect on the validity of the mineral data set or the metamorphic information drawn from it.

5. *Field references*

Some field mineral occurrences described in internal report books, honours and PhD theses were also included in the metamorphic mineral database. However, these data proved to be the most difficult to validate.

The spatial distribution of the data reference by the different data sources is shown in Figure 3. The metamorphic mineral database has been created in both Excel and ArcView-ready formats for easy updating and data manipulation. The complete Excel spreadsheet of the metamorphic mineral database is contained in Appendix A.

4.2 SA_Geodata update

As part of this project, brief descriptions of the metamorphic minerals, contained in pelite samples, were added to the SA_Geodata database to make it more useful for future research. The additional descriptive data were added to the rock sample database fields: ‘sample geology’, ‘rock modifier’ and ‘comments’. A total of 149 SA_Geodata records were updated in this fashion as part of this study.

5 PETROGRAPHY OF PELITIC ROCKS FROM FIELD AREAS IN THE SOUTH AUSTRALIAN WILLYAMA INLIERS

The following petrographic descriptions and metamorphic petrological interpretations are generally focused on mineral paragenesis found in pelitic rocks. This is because these rocks contain the best record of mineral paragenesis and reaction in response to changing P–T conditions. The mineral abbreviations used in the text and diagrams are described in Table 1.

Table 1 Mineral abbreviations used in text and diagrams, and generalised formulae

Mineral	Abbreviation	General Formula
Garnet	g	$(Fe,Mg,Mn)_3Al_2Si_3O_{12}$
Chloritoid	ctd	$(Fe,Mg,Mn)Al_2SiO_5(OH)_2$
Chlorite	chl	$(Fe,Mg,Mn)_4(Fe,Mg,Mn,Al)_2Si_2(Si,Al)_2O_{10}(OH)_8$
Muscovite (sericite)	Mu (ser)	$K(Al,Fe,Mg)_2Si_2(Al,Si)_2O_{10}(OH)_2$
Biotite	bi	$K(Fe,Mg,Mn)(Al,Fe,Mg)_2Si_2(Al,Si)_2O_{10}(OH)_2$
Cordierite	cd	$(Fe,Mg,Mn)_2Al_4Si_5O_{18}$
Staurolite	st	$(Fe,Mg,Mn,Zn)_4Al_{18}Si_{7.5}O_{48}H_4$
Kyanite	ky	Al_2SiO_5
Sillimanite (fibrolite)	Sill (fib)	Al_2SiO_5
Andalusite (chiastolite)	and (chiast)	Al_2SiO_5
Graphite	gra	C
Plagioclase	plag	$(Ca,Na)AlSi_2(Al,Si)O_8$
Quartz	q	SiO_2
Water	H_2O	H_2O

Fieldwork was carried out with three agendas in mind:

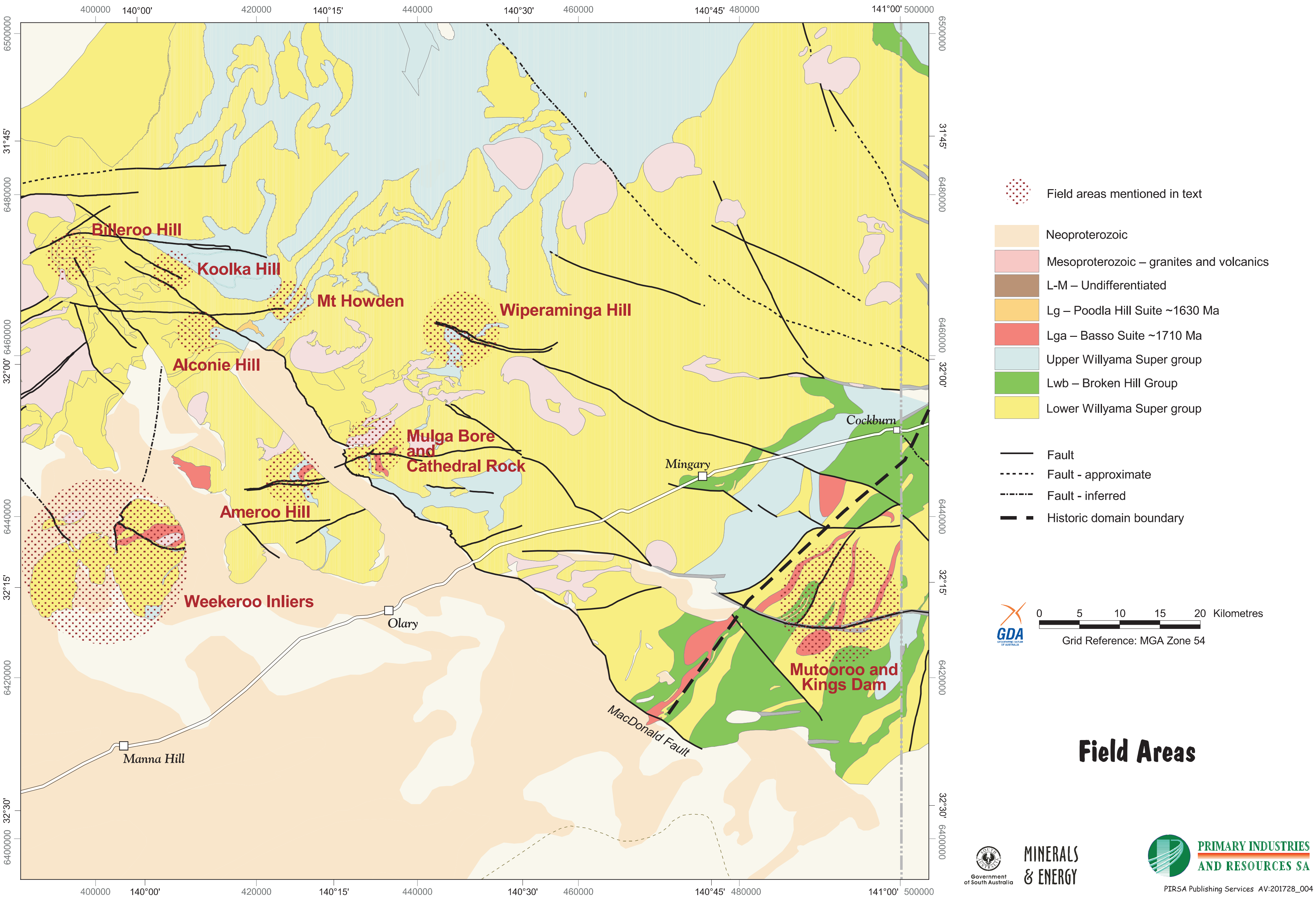
- Areas representative of each of the metamorphic zones of Clarke et al. (1987; Fig. 2) were visited. These included Alconnie Hill and Koolka Hill (zone I), Billeroo Hill (zone IIa), northern Walparuta Inlier (zone IIb), and the Mutooroo Mine area (zone III).
- The nature of the isograd boundaries in relation to macroscopic structures were delineated. Areas visited included south of the Mingary siding (zone III), Wiperaminga Hill (zone IIa/b), and the Walparuta Inlier (zone IIb).
- Field sites were visited where pelitic metasediments are believed to have experienced contact metamorphism related to adjacent granite intrusions. These sites included Wiperaminga Hill (zone IIa/b) and the northern Walparuta Inlier (zone IIb).

All field areas visited (Fig. 4) are discussed below. In addition, samples collected by University of Adelaide researchers Martin Hand and Lachlan Rutherford from the Ameroo Hill, Cathedral Rock and Mulga Creek Bore areas (all within zone IIb) are described.

Thin sections held by the Division of Minerals and Energy are referred to by an ‘R number’ (e.g. R000001). All such thin sections are incorporated into the metamorphic mineral database in Appendix A.

5.1 Alconnie Hill (Clarke et al. (1987) — zone I)

Alconnie Hill consists of folded pelitic (andalusite-bearing) and psammopelitic schists, with minor calcsilicate lithologies and intrusive pegmatite bodies. Based on the stratigraphy of Conor (2000), the pelitic schists appear to overlie calcsilicates that probably represent the Bimba Formation. This suggests that the pelitic schists are units of the Strathearn Group (Saltbush Subgroup and possibly lower Mount Howden Subgroup), and that the units are right way up.



Billeroo Hill
Koolka Hill
Mt Howden
Wiperaminga Hill
Alconie Hill
Mulga Bore and Cathedral Rock
Ameroo Hill
Weekeroo Inliers
Mutooroo and Kings Dam
Cockburn
Mingary
Olary
Manna Hill
MacDonald Fault
Field areas mentioned in text
Neoproterozoic
Mesoproterozoic – granites and volcanics
L-M – Undifferentiated
Lg – Poodla Hill Suite ~1630 Ma
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Upper Willyama Super group
Lwb – Broken Hill Group
Lower Willyama Super group
Fault
Fault - approximate
Fault - inferred
Historic domain boundary
0 5 10 15 20 Kilometres
Grid Reference: MGA Zone 54
Field Areas
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Figure 4

The pelitic lithologies can be divided into two conformable units based on two dominant mineral associations. The first, 'lower' assemblage contains abundant large (30–100 mm long) chiastolite porphyroblasts and rare small garnets (0.5–1 mm). Chiastolite porphyroblasts define a mineral elongation lineation that plunges moderately to the east. However, end sections to chiastolite porphyroblasts preserve pressure shadow geometries that can be interpreted as forming 'sigma'(σ)-object, kinematic indicators (Plate 1; Passchier and Trouw, 1996). This suggests that the sequence was sheared in an orientation orthogonal to the long axes of the chiastolite porphyroblasts. The porphyroblasts are partly retrogressed by intergrown chloritoid, muscovite and graphite (Plate 2). Graphite laths define weak foliation within the retrogressed chiastolites that is at an angle to the external foliation. A reaction rim of coarse porphyroblastic muscovite surrounds the retrogressed chiastolite porphyroblasts. This rim completely separates the internal composite assemblage from the matrix assemblage. The matrix assemblage is dominated by muscovite and quartz. The matrix has a strong shear fabric that anastomoses around porphyroblastic minerals. These porphyroblastic minerals include the retrogressed chiastolite chloritoid and relict garnet. Chloritoid that occurs in the matrix contains curved inclusion trails indicating syn-kinematic growth. Garnet occurs as anhedral fractured remnant clasts that do not appear to be in equilibrium with the shear fabric. Fractures within garnet are filled with late biotite that is partly isomorphically replaced by chlorite. Fibrolitic sillimanite occurs in the matrix in association with coarse muscovite. The implied paragenesis and reaction sequence for this rock is:

- local S_1 assemblage: g–chiast–mu–q–sill

which is replaced by:

- local S_2 assemblage: mu–q–ctd–sill.

The replacement of chiastolite by ctd–mu–gra is believed to be late and post-kinematic because chloritoid and muscovite are unorientated. Biotite replacing garnet is also probably late since the biotite is also unorientated.

The other 'upper' pelite unit contains completely retrogressed andalusite porphyroblasts and abundant larger garnets (up to 5 mm). The matrix is composed of muscovite, quartz and biotite (with minor amounts of fibrolitic sillimanite). Muscovite also occurs as large pseudomorphous porphyroblasts (presumably replacing andalusite). The rock fabric has a 'micro-S-C' character in several sub-domains. This supports the notion that these rocks have experienced significant shearing. Garnet is generally euhedral with weak inclusion trails that are at a high angle to the rock fabric. The pre-existing fabric implied by these orientated inclusions is designated local S_1, while the main shear fabric is local S_2. Biotite (with crystallographic rutile inclusions) is common in the S_2 pressure shadows of garnet (Plate 3). Garnet may be consumed by fibrolite and muscovite where Fe-oxide staining preserves the original outline of the garnet porphyroblast (Plate 3). Fibrolite is best preserved within the pressure shadows of euhedral garnet. Where an 'S-C fabric' is developed, fibrolite parallels the schistosity (the 'S' plane) and is truncated by the cissallement (the 'C' plane). Therefore, fibrolite pre-dates (at least in part) development of the 'S-C' shear fabric. Chloritoid occurs as highly oxidised porphyroblasts within the S_2 fabric and as post-kinematic porphyroblasts growing across S_2. Similarly, plagioclase is intergrown with S_2 quartz, but also overgrows S_2 muscovite and biotite (Plate 4). The interpreted paragenesis and reaction sequence is as follows:

- S_1 assemblage: g–and–q–mu
- S_2 assemblage: mu–sill–ctd–bi.

This is followed by post-kinematic growth of mu, ctd and plag.

5.2 Koolka Hill (Clarke et al. (1987) — zone I/II?)

Koolka Hill contains many of the lithologies that characterise the Willyama Supergroup stratigraphy. These include calcsilicate, metasomatised amphibolite, migmatite, pegmatite, quartzite, psammite, psammopelite, and retrogressed pelite. Cross-bedding in quartzite

Plate 1 ‘σ’ objects (chiastolites) from Alconnie Hill. View southwesterly. (Photo 049437)

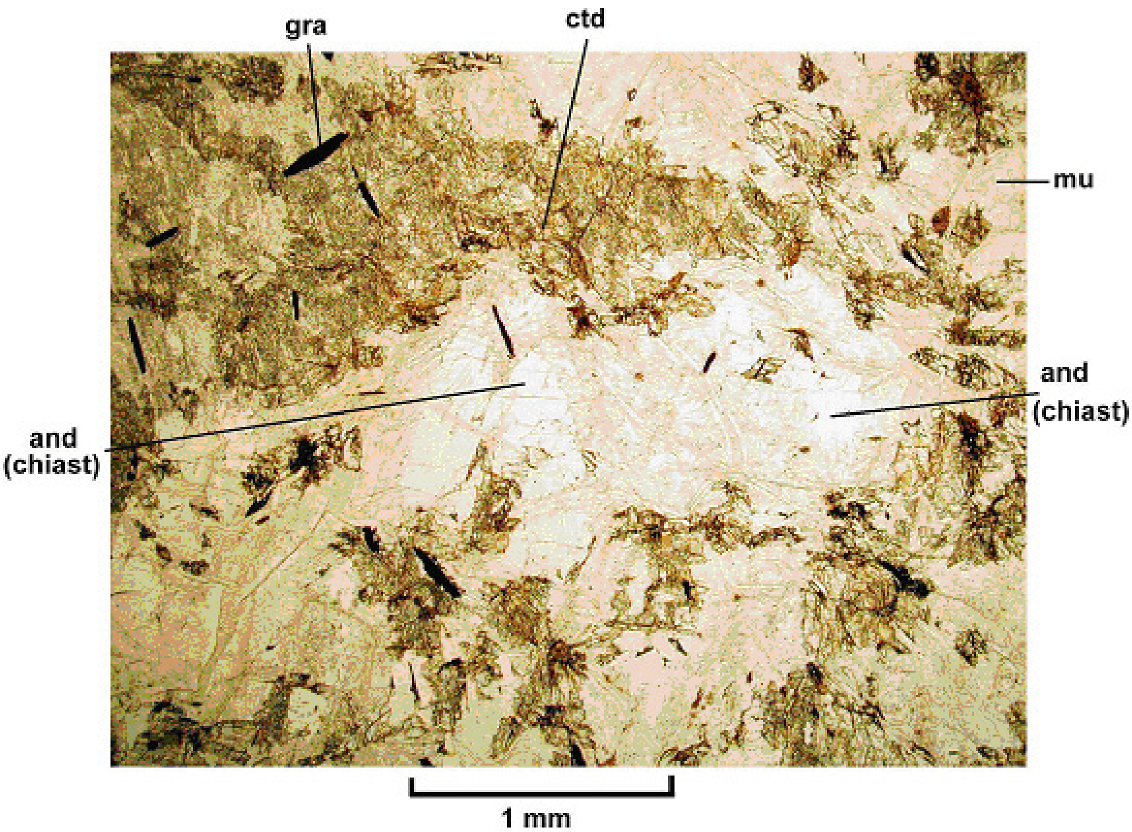

Plate 2 Chiastolite (partly) retrogressed by chloritoid, muscovite and graphite, ‘lower pelite’ unit, Alconnie Hill. (Photo 049438)

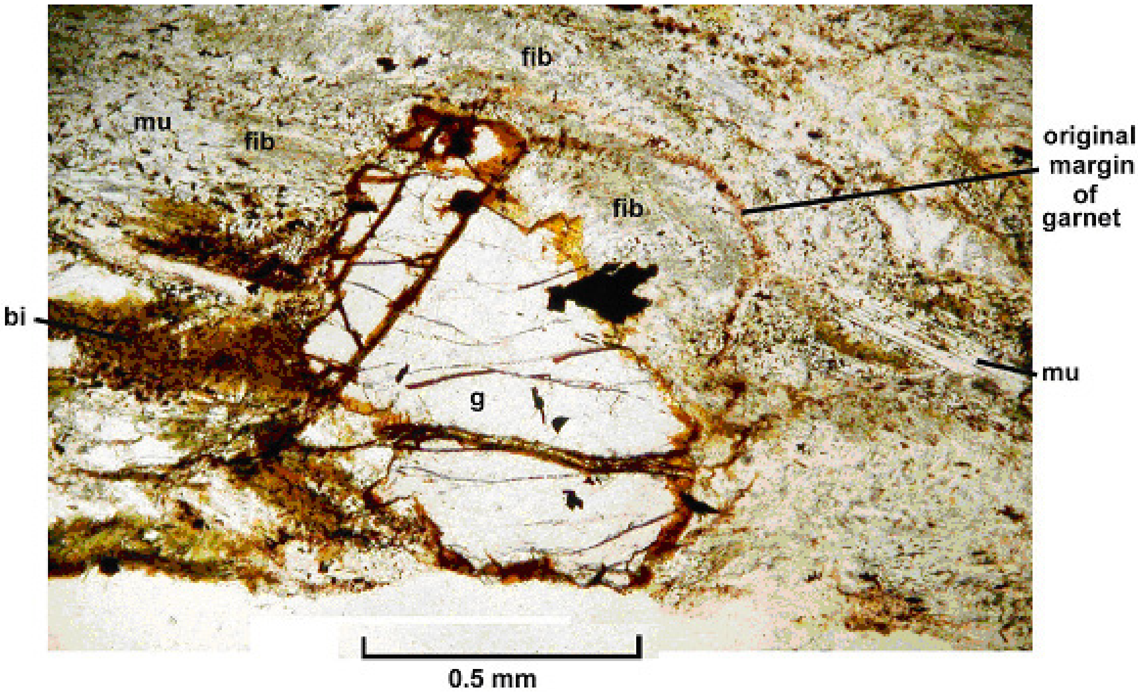

Plate 3 Garnet retrogressed by fibrolitic sillimanite (with biotite in pressure shadow), 'upper pelite' unit, Alconnie Hill. (Photo 049439)

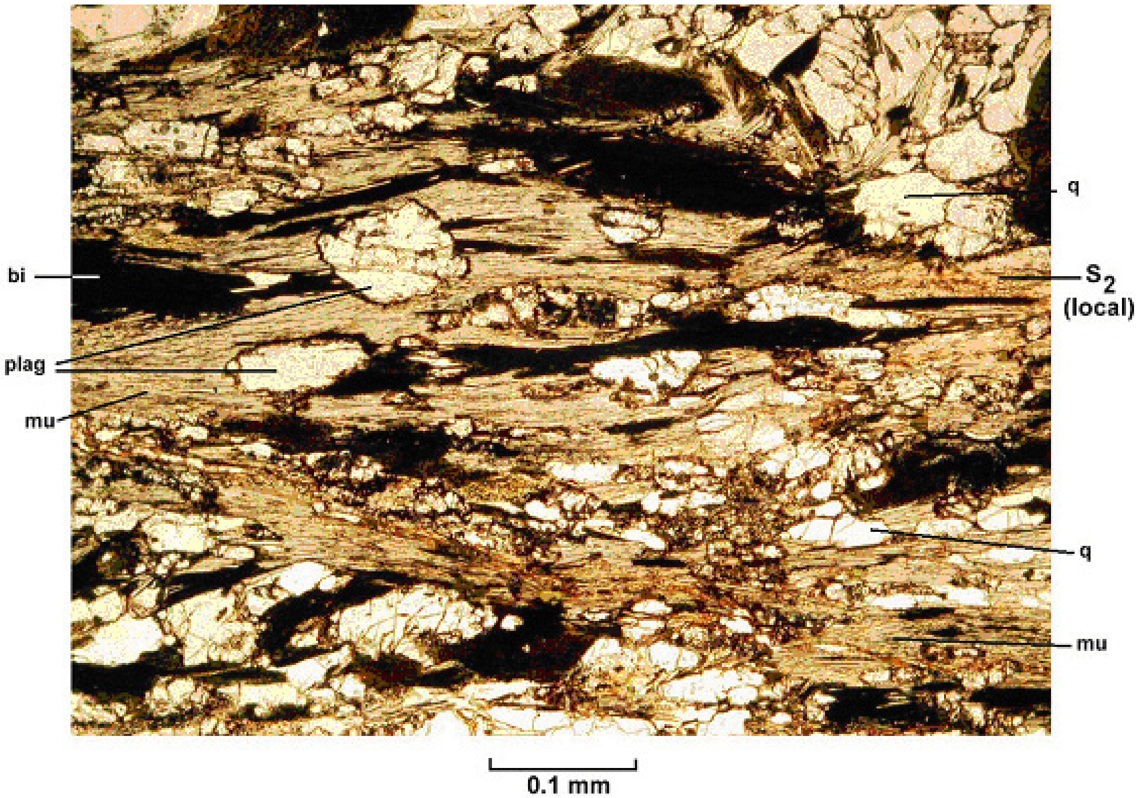

Plate 4 Plagioclase overgrowing S_2 muscovite, 'upper pelite' unit, Alconnie Hill. (Photo 049440)

layers that crop out on the southern flanks of the hill (Plate 5) indicate that the package is right way up.

The hill is dominated by strongly retrogressed and Fe-oxide-stained pelite. Garnet, quartz, and rare fibrolitic sillimanite are the only primary minerals remaining due to the intensity of retrogression. Pseudomorphs of chloritoid (replaced by fine-grained clay minerals) can be seen in pelite hand specimens (Plate 6). The 'silky' texture of the fabric indicates that sillimanite was a major rock constituent prior to retrogression. The rare preserved garnet is highly FeO stained. Large, square pseudomorphs (with internal inclined layering) wrapped by the rock fabric can be seen in hand specimen (Plate 7). This is similar to the pattern formed by chiastolite porphyroblast end sections at Alconnie Hill (Plate 1) and by andalusite porphyroblasts in the northern Walparuta Inlier (see section 5.4.1). Furthermore, the general character of rock is similar to samples collected from Alconnie Hill.

Large retrogressed andalusite porphyroblasts occur in psammopelites in several localities around Koolka Hill. However, andalusite is the only porphyroblastic mineral in the psammopelitic rocks. This limits the petrological usefulness of these rocks.

Migmatitic rocks on the northern side of Koolka Hill are multiply refolded (Plate 8). There appears to be an early isoclinal folding event that has produced the dominant layering in the migmatite. The layering is folded by at least two further generations of folding (Plate 8). These later folds have consistent fold axial orientations, suggesting that they are systematic cylindrical folds rather than disordered migmatitic folds.

Drilling by Delta Gold Ltd intersected coarse prismatic sillimanite northeast of Koolka Hill (A. Brewer, Delta Gold, pers. comm., 2002).

The MacDonald Fault separates Koolka and Alconie Hills (Fig. 4). The Delamerian reactivation of this fault juxtaposes Willyama Supergroup rocks against Adelaidean sequences further to the southeast. The potential for significant offset on this fault must therefore be considered in any metamorphic interpretation of the area.

5.3 Billeroo Hill (Clarke et al. (1987) — zone IIa)

The dominant lithology of Billeroo Hill (Fig. 4) is Fe-rich pelite. The intensity of deformation in these rocks makes it difficult to identify original layering with confidence and hence younging direction is equally hard to determine. Some outcrops contain a strong parallel shear fabric defined by very fine-grained quartz, and muscovite and coarser sillimanite. Adjacent outcrops containing a much coarser mineral texture comprised of sillimanite, quartz, muscovite and plagioclase show less deformation. This heterogeneous deformation strongly suggests the development of compositionally controlled strain partitioning into discrete shear zones during metamorphism.

The strongly sheared pelites (e.g. sample R504852) contain chloritoid porphyroblasts with sygmoidally curved inclusion trails defined by coarse prismatic sillimanite (Plate 9). The same chloritoid is wrapped by coarse sillimanite within the anastomosing shear fabric. Relict anhedral garnets occur in association with quartz within augen structures. Rare post-kinematic chlorite grows in the pressure shadows of chloritoid. The inferred paragenesis and reaction sequence includes:

- early S_1 assemblage: g–bi–q–mu–sill

which is replaced by:

- late S_1 to S_2 (shear fabric) assemblage: ctd–sill–q–mu
- and post-kinematic growth of chl.

The less-deformed rocks (e.g. sample R504854) have a similar mineralogy to the intensely sheared rocks, however, they contain coarse quartz and plagioclase. These rocks contain coarse gneissic layering defined by the alternating quartz-rich and plagioclase-rich domains.

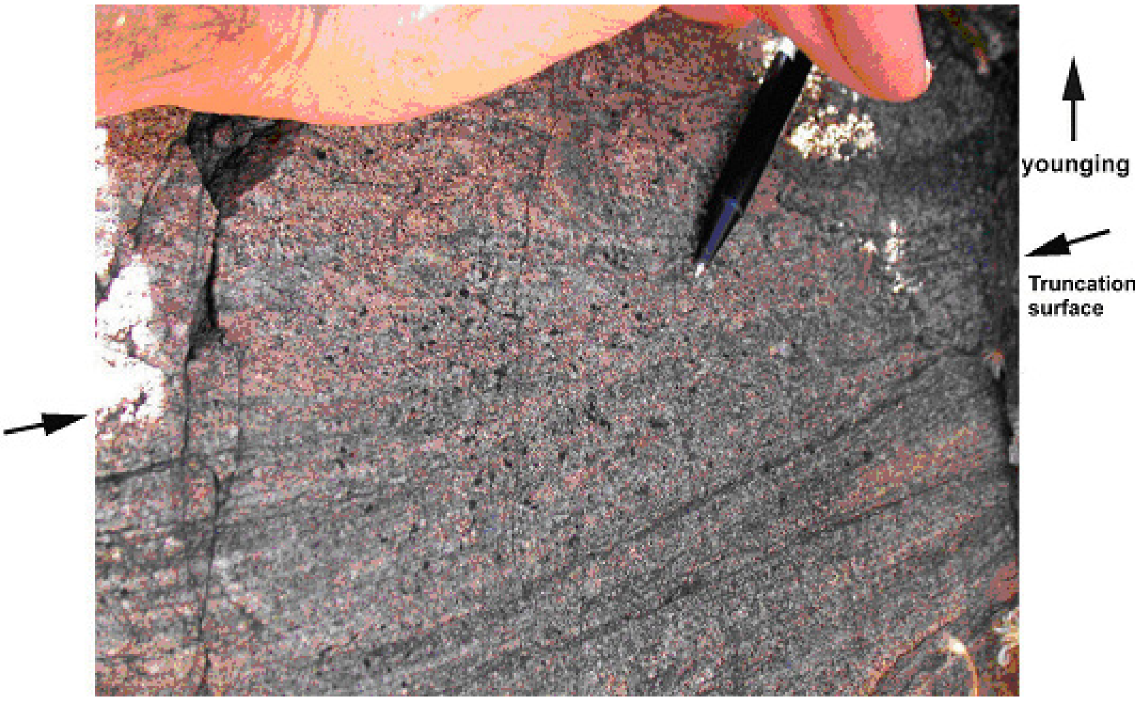

Plate 5 Cross-bedding at Koolka Hill. (Photo 049441)

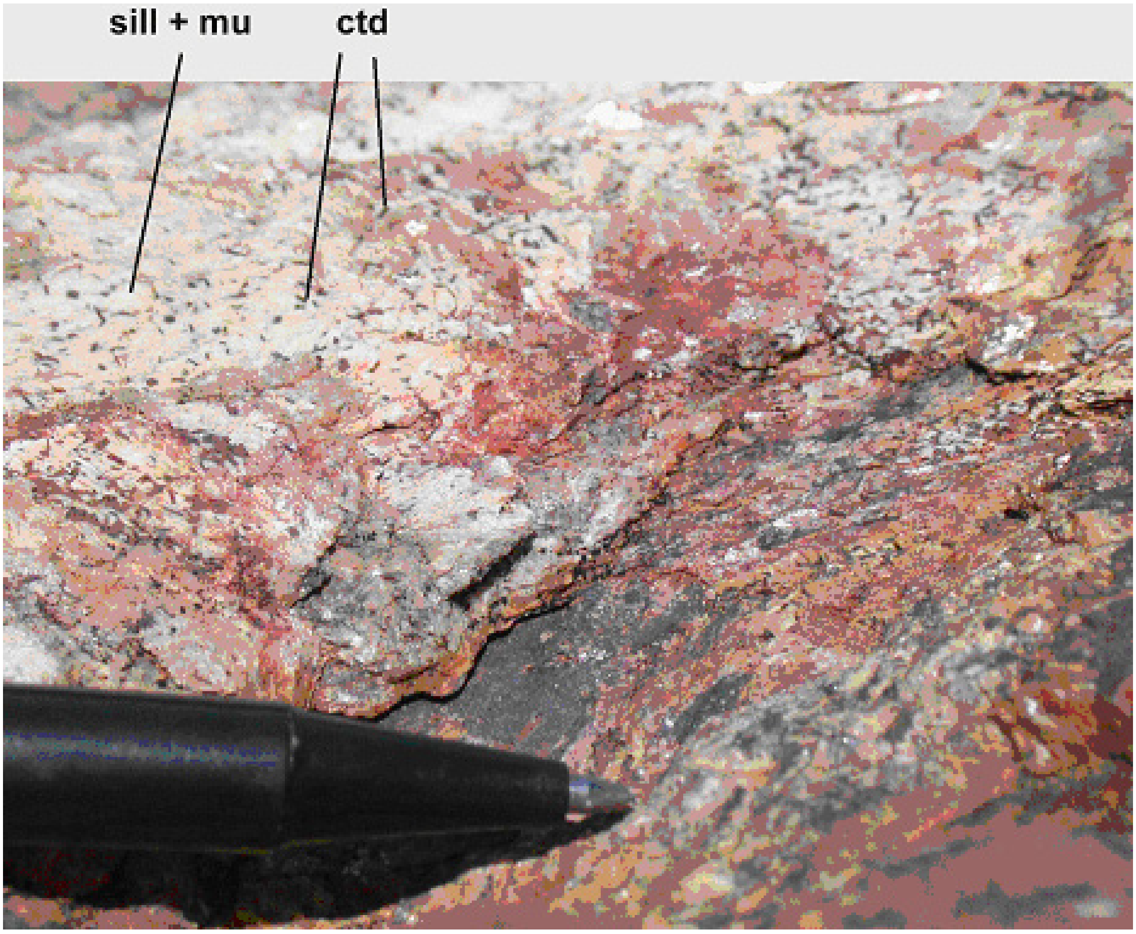

Plate 6 Chloritoid in sillimanite rich pelite, Koolka Hill. (Photo 049442)

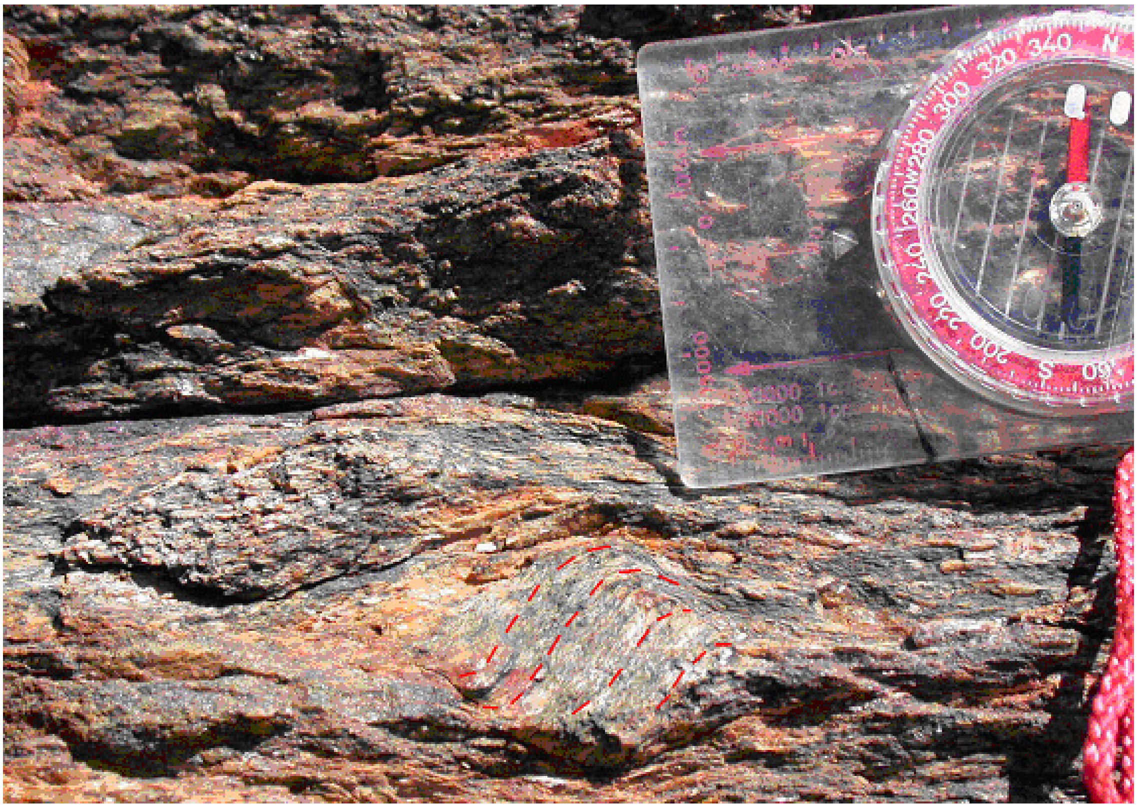

Plate 7 Retrogressed andalusite forming ‘σ’ object in pelite, Koolka Hill. (Photo 049443)

Plate 8 Multiply folded migmatite, Koolka Hill. (Photo 049444)

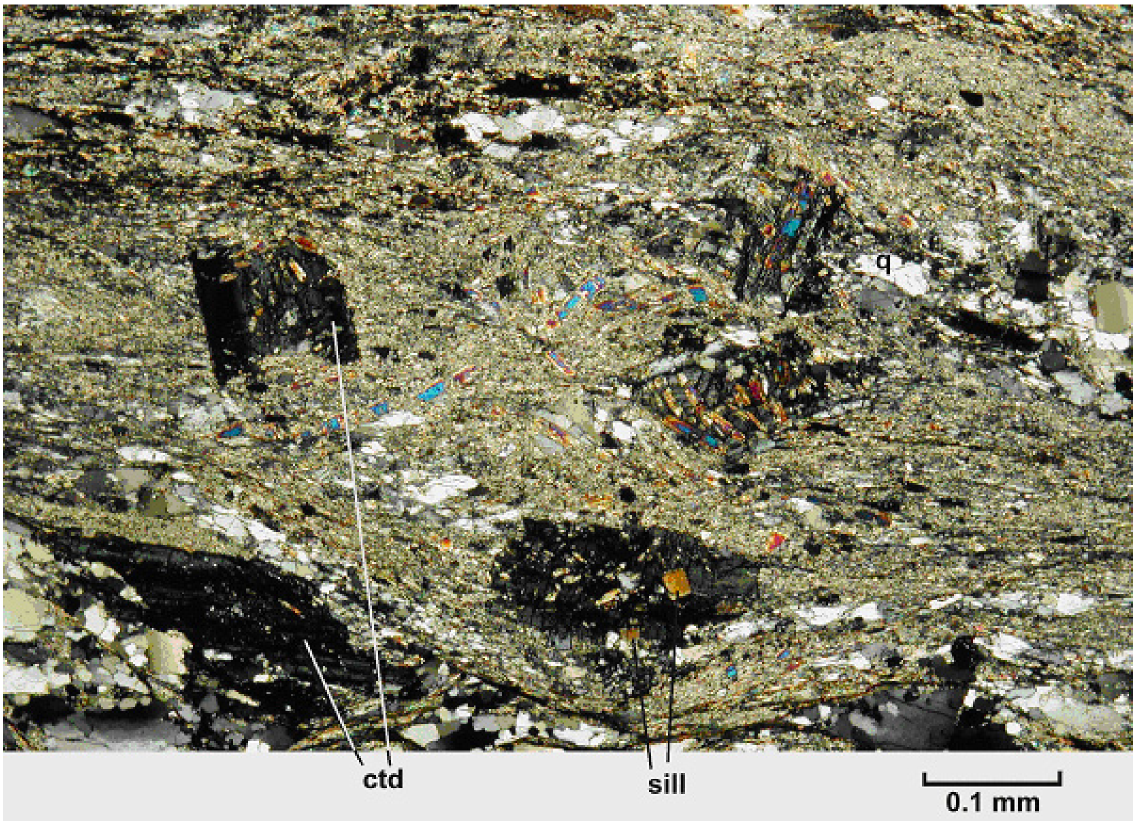

Plate 9 Prismatic sillimanite in porphyroblastic, syn-kinematic chloritoid. Billeroo Hill. (R504852; crossed polars) (Photo 049445)

The main fabric is defined by coarse sillimanite and muscovite that overgrows this gneissic layering. Chloritoid porphyroblasts occur within the sillimanite–muscovite fabric. They contain crenulated inclusions of prismatic and fibrolitic sillimanite that are continuous with the external fabric (Plate 10). Sillimanite has also been observed wrapping inclusion-rich chloritoid porphyroblasts. The inferred paragenesis and reaction sequence includes:

- gneissic S_1 assemblage: plag–bi–q–mu

which is replaced by:

- early S_2 assemblage: sill–ctd–mu–q

and the:

- late S_2 assemblage: sill–mu–q.

Chiastolite-bearing schists have been recorded at Billeroo Hill and Billeroo North (Menzies, 1992).

5.4 Weekeroo Inliers (Clarke et al. (1987) — zone IIb)

5.4.1 WALPARUTA (EASTERN) INLIER (FIG. 5)

Pelite schist and gneiss from the northern Walparuta Inlier (Preiss and Conor, 2001) contain the most texturally complex and variable mineral assemblages of the field areas visited in the Olary Domain. The porphyroblast–porphyroblast and porphyroblast–matrix relationships recorded in these rocks provide a detailed record of metamorphism of this area. Porphyroblastic minerals found (or implied to have existed) in these rocks include garnet, andalusite, kyanite, cordierite, staurolite and chloritoid. Relevant matrix minerals include quartz, chlorite, muscovite, biotite and sillimanite. The following petrographic descriptions focus on the relationship of each porphyroblastic mineral to the surrounding mineral textures and deformation record.

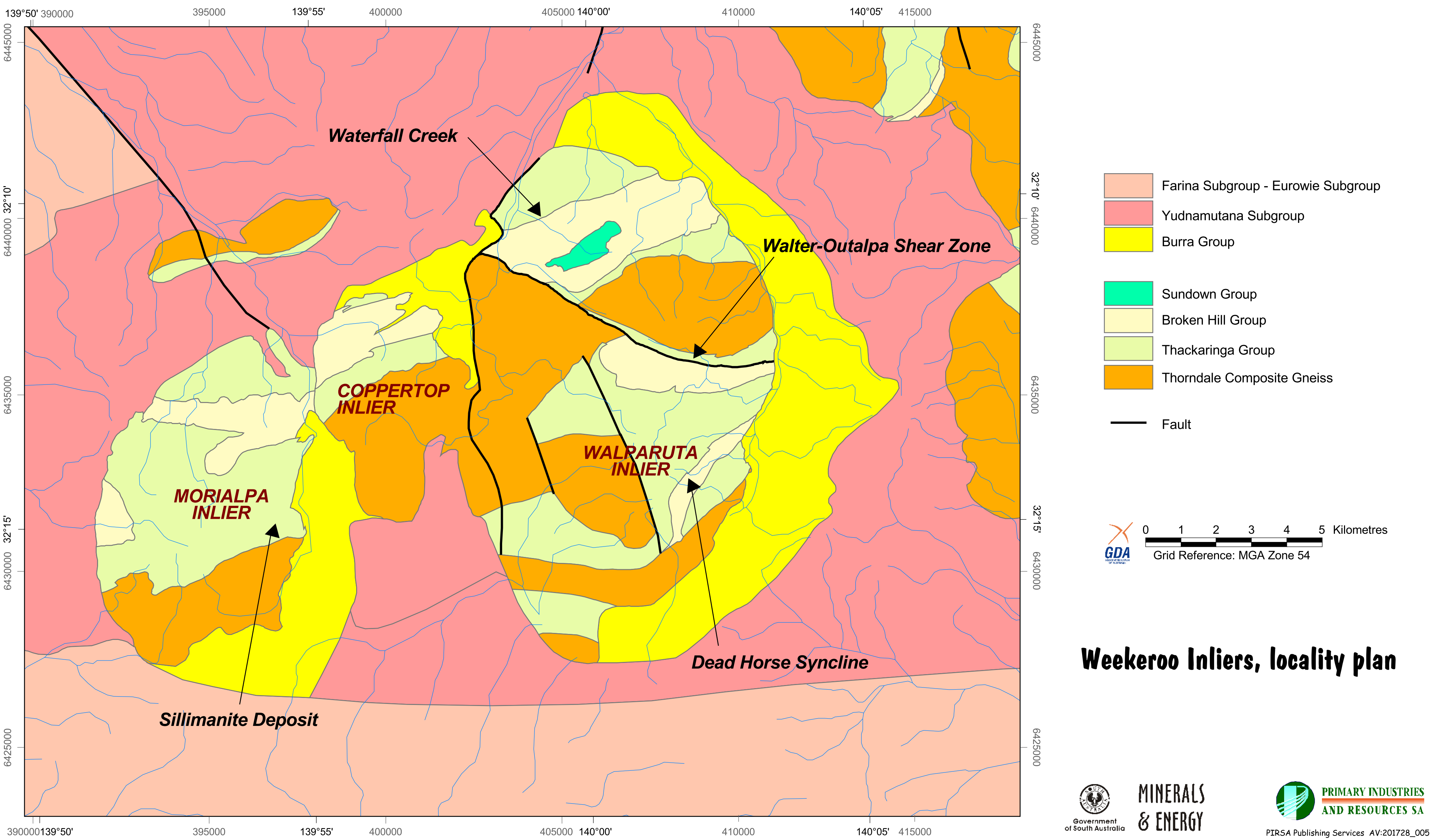
Waterfall Creek
Walter-Outalpa Shear Zone
COPPERTOP INLIER
WALPARUTA INLIER
MORIALPA INLIER
Dead Horse Syncline
Sillimanite Deposit
Farina Subgroup - Eurowie Subgroup
Yudnamutana Subgroup
Burra Group
Sundown Group
Broken Hill Group
Thackaringa Group
Thorndale Composite Gneiss
Fault
0 1 2 3 4 5 Kilometres
Grid Reference: MGA Zone 54
Weekeroo Inliers, locality plan
MINERALS & ENERGY
PRIMARY INDUSTRIES AND RESOURCES SA
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Figure 5

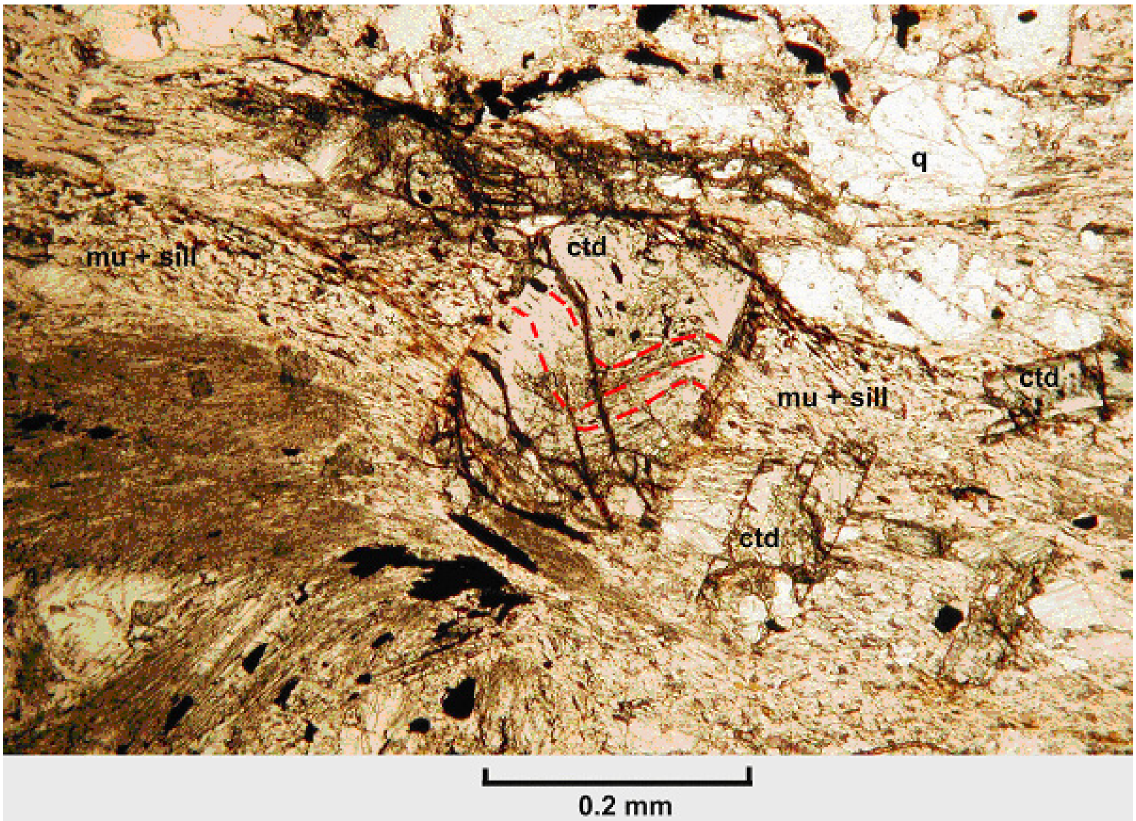


Plate 10 Chloritoid with crenulated inclusion trails of sillimanite, Billeroo Hill. (R504854) (Photo 049446)

Andalusite schist forms a distinct stratigraphic unit in the upper section of Waterfall Creek (Fig. 5). Very large andalusites, up to 0.2 m across, occur in the foliation surfaces of prominent pelite outcrops that trend roughly east–west across the creek (Plate 11). The andalusite crystals contain an internal layering that can be seen in hand specimen (Plate 11), defined by variable layers of elongate quartz inclusions within the porphyroblasts. This layering is often at a high angle to the main rock fabric.

Garnet occurs as inclusions in the andalusite and staurolite porphyroblasts and also in the matrix. Crystallographically flattened euhedral garnets define a weak foliation within the layered andalusites. This flattening orientation is at a high angle to the internal foliation within the andalusites (Plate 12). This suggests that the growth of the orientated garnets (the flattening orientation, or local S_1) predates development of the foliation defined by the elongate quartz inclusions overgrown by the andalusite (local S_2). Euhedral to subhedral garnet porphyroblasts often contain foliated quartz inclusions. These inclusions define a crenulation in a number of samples (e.g. R504842; plate 13).

Another conspicuous feature of garnet porphyroblasts from this area is the development of a secondary growth rim (Plate 13). This feature is well developed in garnets within the main fabric (local S_3) and those found within retrogressed porphyroblast domains. Garnets do not appear to develop this secondary rim if they are preserved within pristine andalusite or staurolite porphyroblasts. The secondary garnet rim often incorporates inclusions that are undisturbed and continuous with the main rock fabric (Plate 13). This implies that the secondary garnet growth overgrows the rock fabric post-tectonically in most cases.

Muscovite in the fabric, however, is sometimes deflected around the secondary garnet rims in a few samples (e.g. R504843). Furthermore, sample R504841 (northwestern Walparuta Inlier) contains a muscovite foliation (local S_4) that wraps the secondary garnet rims and overprints the folded, main rock foliation (local S_3, defined by chlorite; plate 14). This suggests that deformation occurred after the secondary garnet growth. Secondary growth of garnet has not been recorded from metamorphic rocks of the Willyama Inliers prior to this

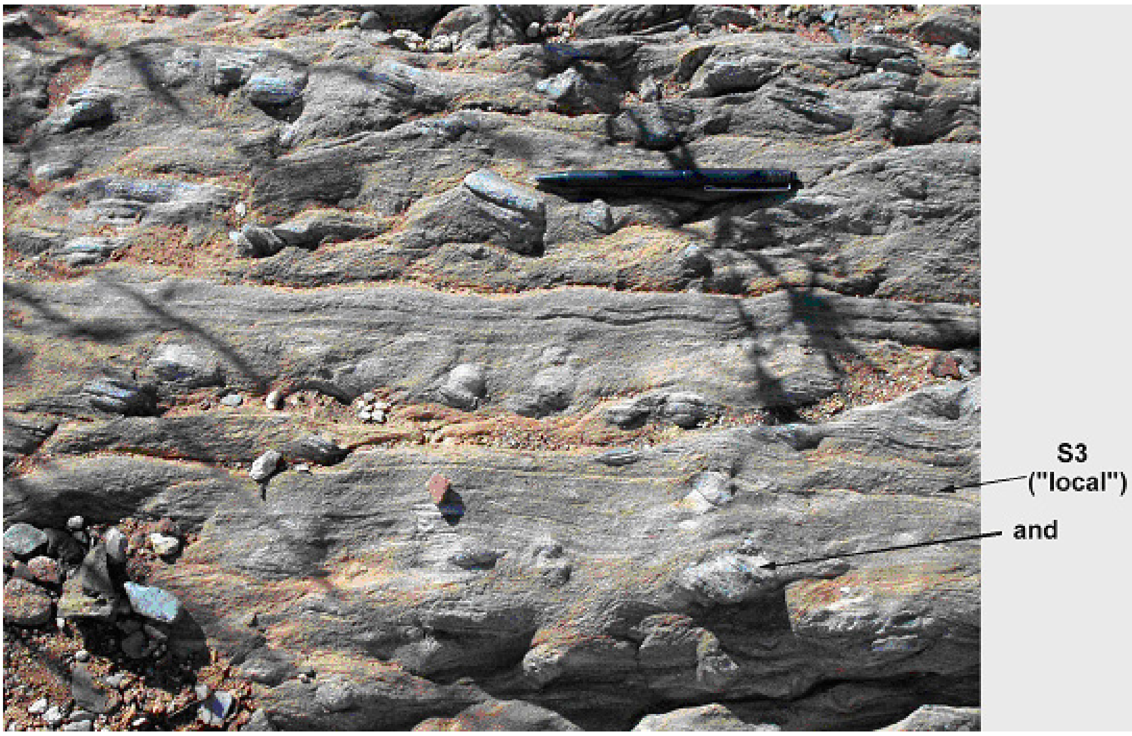


Plate 11 Andalusite schist, Waterfall Creek, Walparuta Inlier. (Photo 049447)

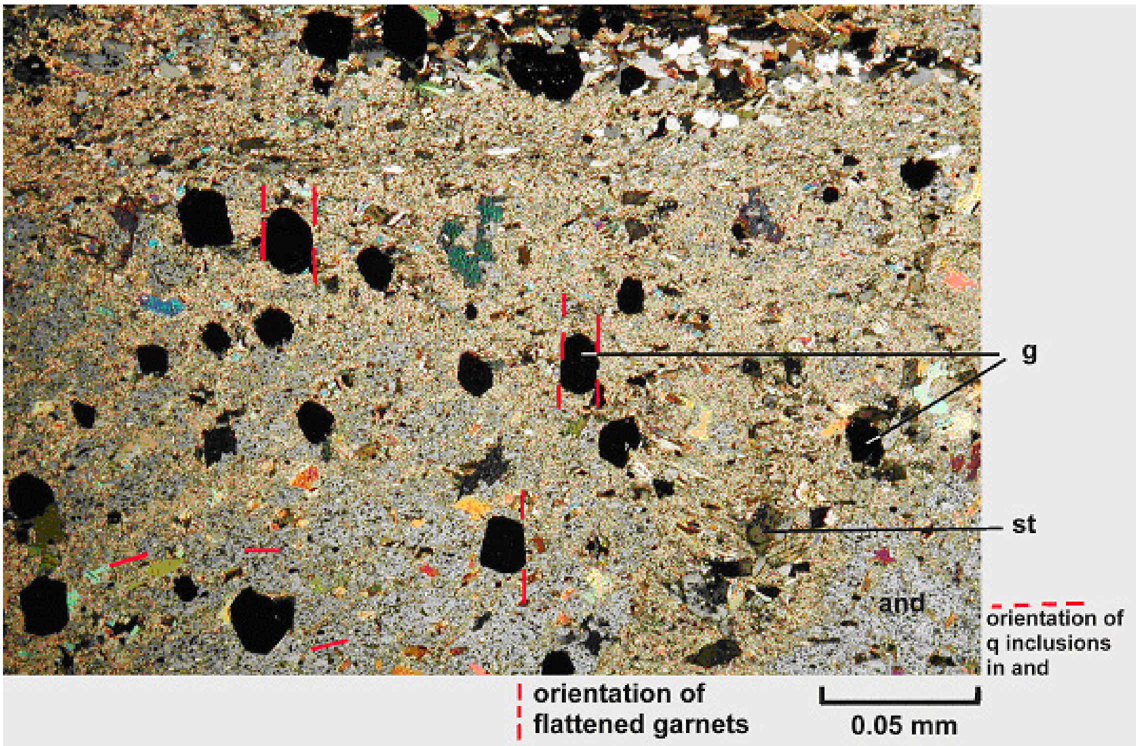


Plate 12 Flattened garnet in andalusite porphyroblasts, Waterfall Creek, Walparuta Inlier. (crossed polars) (Photo 049448)

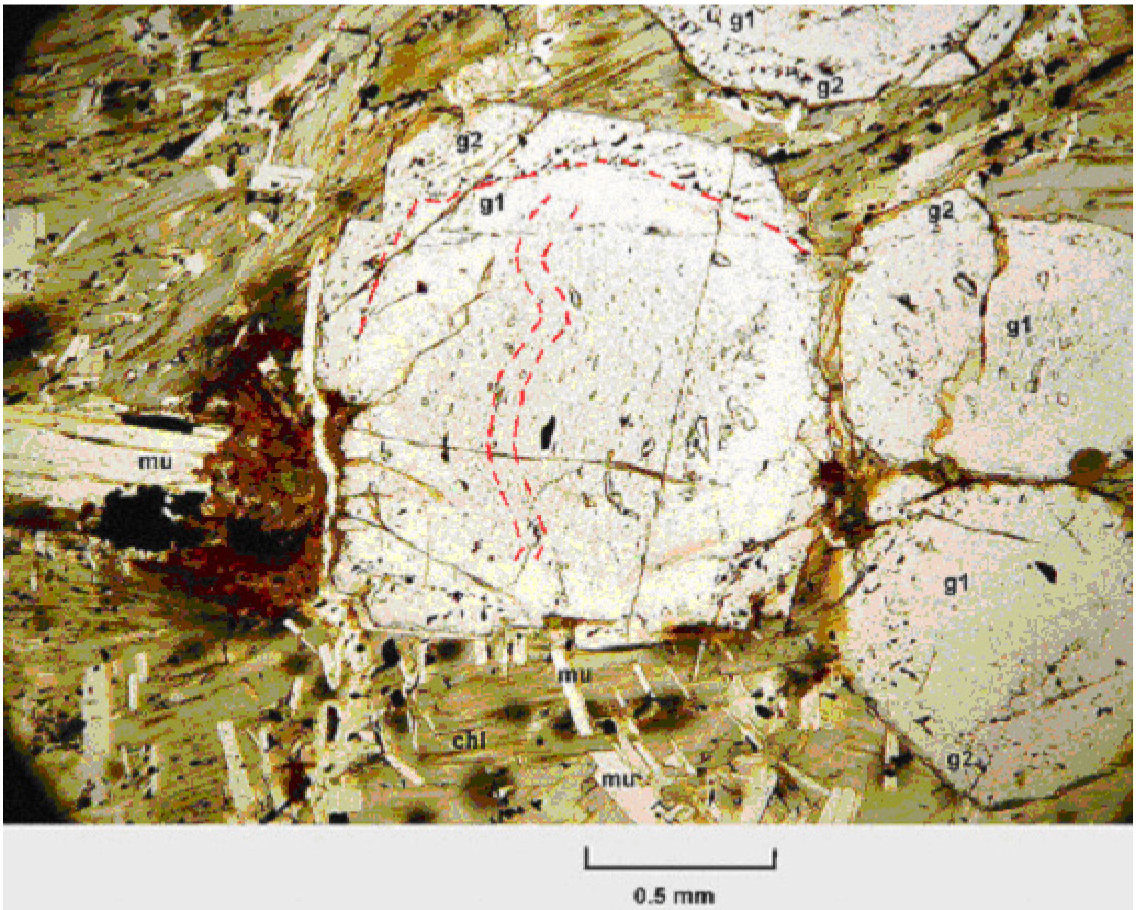


Plate 13 Crenulated inclusions in garnet. Note inclusions in g2 are continuous with the foliation of the matrix, northern Walparuta Inlier (R504842) (Photo 049449)

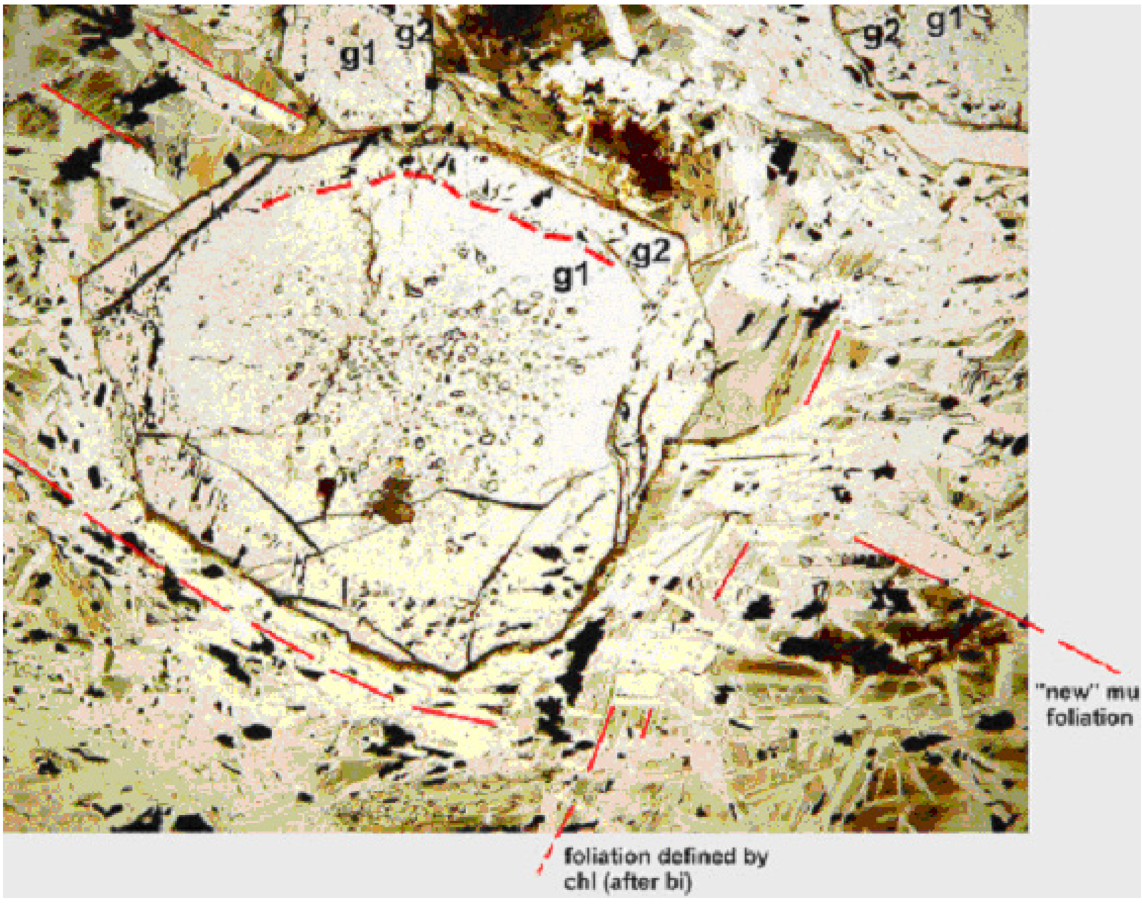


Plate 14 Chlorite and muscovite foliations, northern Walparuta Inlier. (Photo 049450)

study. This characteristic, secondary garnet growth is now known to occur across zone II of Clarke et al. (1987), including the Dead Horse Gap syncline, Ameroo Hill, Mulga Bore area and Cathedral Rock (see section 6.3).

Staurolite occurs within the andalusite schist in two common geometries. Firstly, staurolite occurs as highly poikiloblastic porphyroblasts that are wrapped by the main muscovite–quartz fabric (local S_3–S_4; plate 15). The poikiloblastic staurolite contains euhedral garnet porphyroblasts with crenulated inclusion trails (Plate 15). The staurolite porphyroblasts also contain elongate quartz inclusions. These have variable abundance throughout the porphyroblasts suggesting that these quartz inclusions may represent original compositional variation in the S_0 layering (Plate 15).

The second form of staurolite found is as weakly to randomly orientated porphyroblasts that always overgrow the main fabric in the rock. This essentially post-kinematic generation of staurolite often grows adjacent to partly retrogressed early andalusite (Plate 16). It is also commonly observed growing within retrogressed pseudomorphs after andalusite (e.g. R504842 and R504845; plate 17). Staurolite overgrows, and incorporates elongate quartz inclusions from, both the main foliation (local S_3) and the inclined early foliation preserved in an andalusite pseudomorph in sample R504842 (local S_2). These relationships suggest that post-kinematic staurolite growth also post-dates the pervasive retrogression of the andalusite schist. However, pseudomorphs filled with fine-grained sericite and abutting completely retrogressed andalusite pseudomorphs (Plate 18) have geometries indicative of euhedral staurolite. These sericite pseudomorphs after staurolite completely crosscut the main fabric indicating that they are post-tectonic. This suggests that some sericite retrogression occurred after the post-kinematic staurolite growth.

An unusual mineral association (informally referred to as a ‘choc-mint’ texture) occurs in pelite at the northwestern end of Waterfall Creek. Flattened ellipsoidal bodies (20–100 mm long) are distributed within a pelitic unit with a matrix of chlorite, muscovite, biotite and quartz (Plate 19). The matrix fabric can be resolved into two elements: a partly developed differential foliation and a fully developed differential foliation where no evidence of the previous foliation is preserved. These two fabric elements occur in adjacent sub-domains that are continuous with each other. These two elements are interpreted to represent different stages in the differentiation of the main fabric. The ellipsoidal pseudomorphs, contained in this matrix, are divided into two mineralogical domains. The core is composed of highly weathered, fine-grained, green, phengite clay and a very fine-grained clear mineral, probably quartz (Plate 20). The rim is composed of coarser grained quartz and muscovite with garnet occurring at the interface with the core (Plate 21). The core domain has a foliation, defined by the phengite clay, that parallels the external rock foliation and the long axis of the pseudomorph. Quartz and garnet in the rim, however, preserve elongate inclusions that are orientated at a high angle to the external fabric and the long axis of the pseudomorph (Plate 21). The external domain of these composite pseudomorphs is folded around mesoscopic crenulations that are believed to be associated with development of the differential foliation in the matrix (Plate 20, which is an inset of plate 19). This suggests that the formation of the composite pseudomorphs, from a porphyroblastic precursor (probably cordierite), occurred prior to development of the differential cleavage in the matrix.

Retrogressed andalusite schist from the northeastern corner of Walparuta Inlier is in close proximity to a syntectonic granite body (Plate 19) and contains layer parallel aluminosilicate-rich pods that are composed of all three polymorphs (andalusite, kyanite and sillimanite; G. Clarke, Sydney University, pers. comm., 2002).

The presence of chloritoid has been reported in honours theses from the Walparuta Inlier (e.g. Pointon, 1980; Tilley, 1990) but was not found in this area during field work carried out for this study.

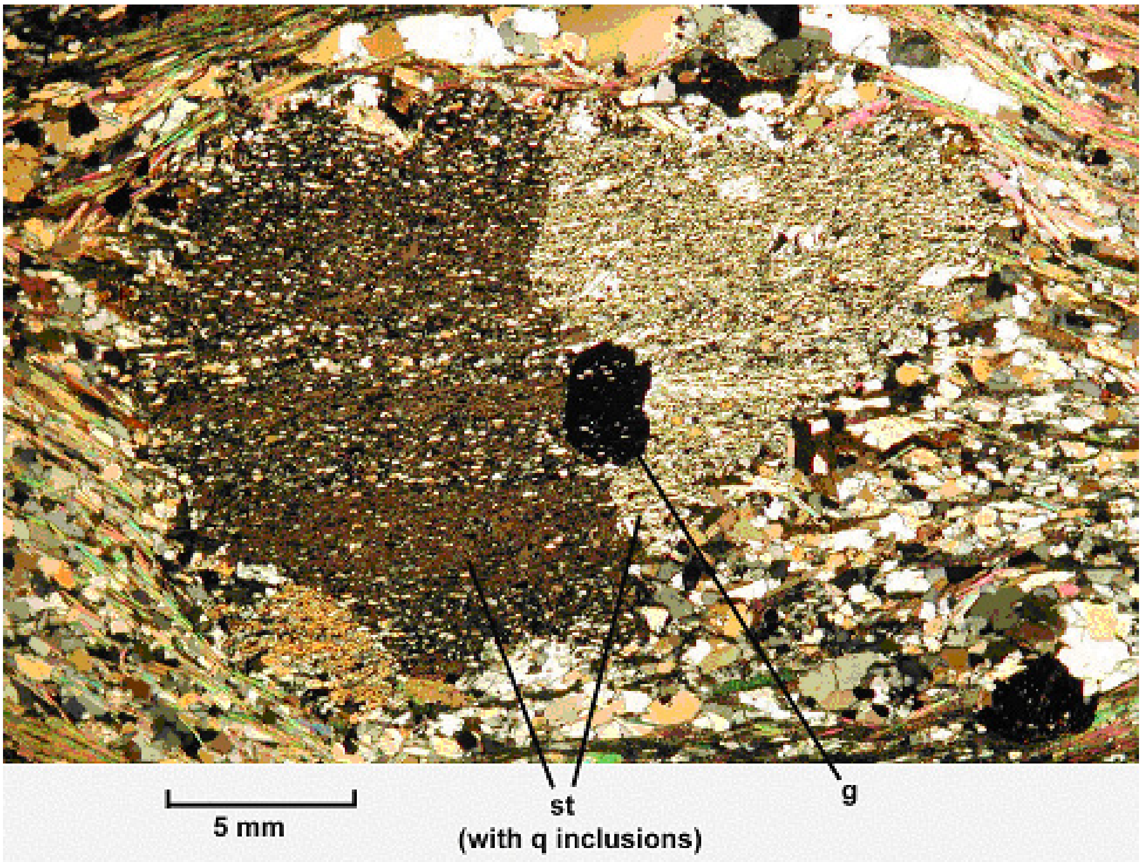


Plate 15 Early staurolite with garnet inclusions, Waterfall Creek, northern Walparuta Inlier. (crossed polars) (Photo 049451)

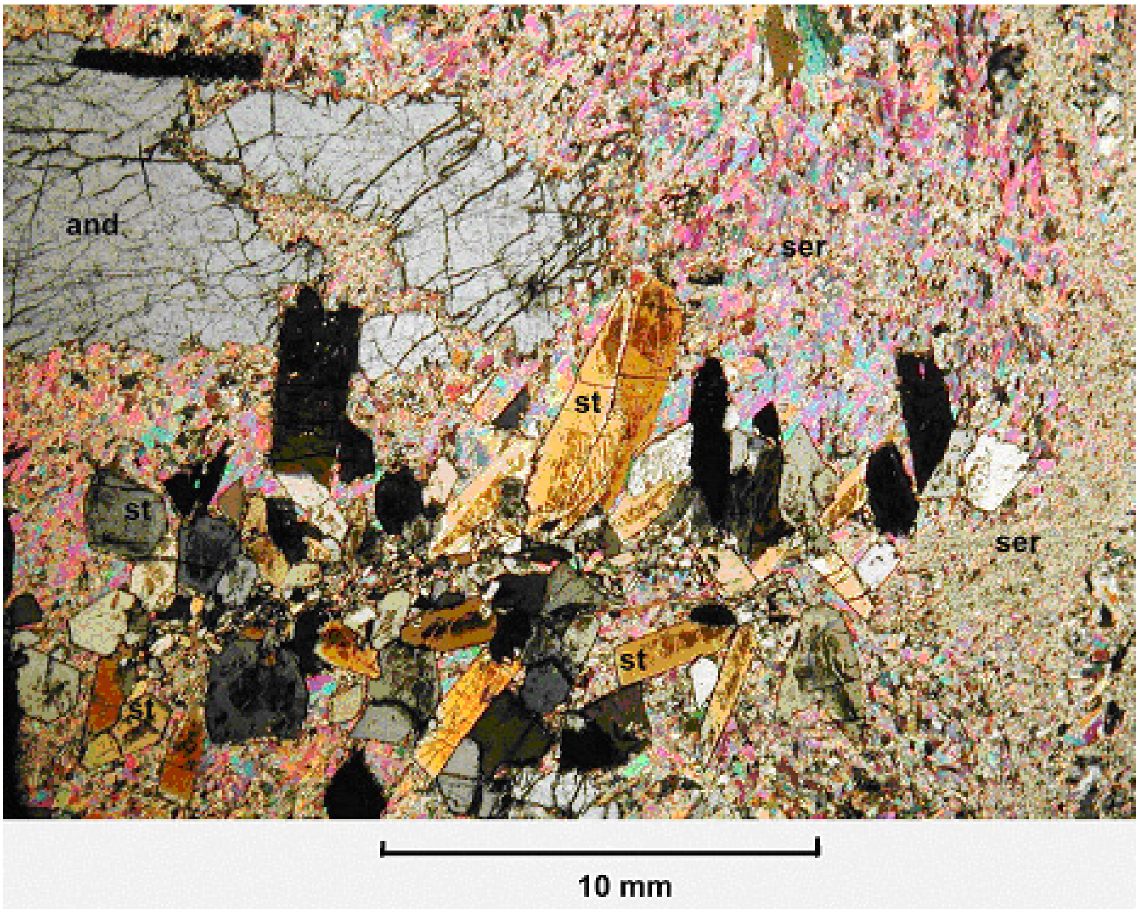


Plate 16 Late staurolite growing in retrogressed andalusite, Waterfall Creek, northern Walparuta Inlier. (crossed polars) (Photo 049452)

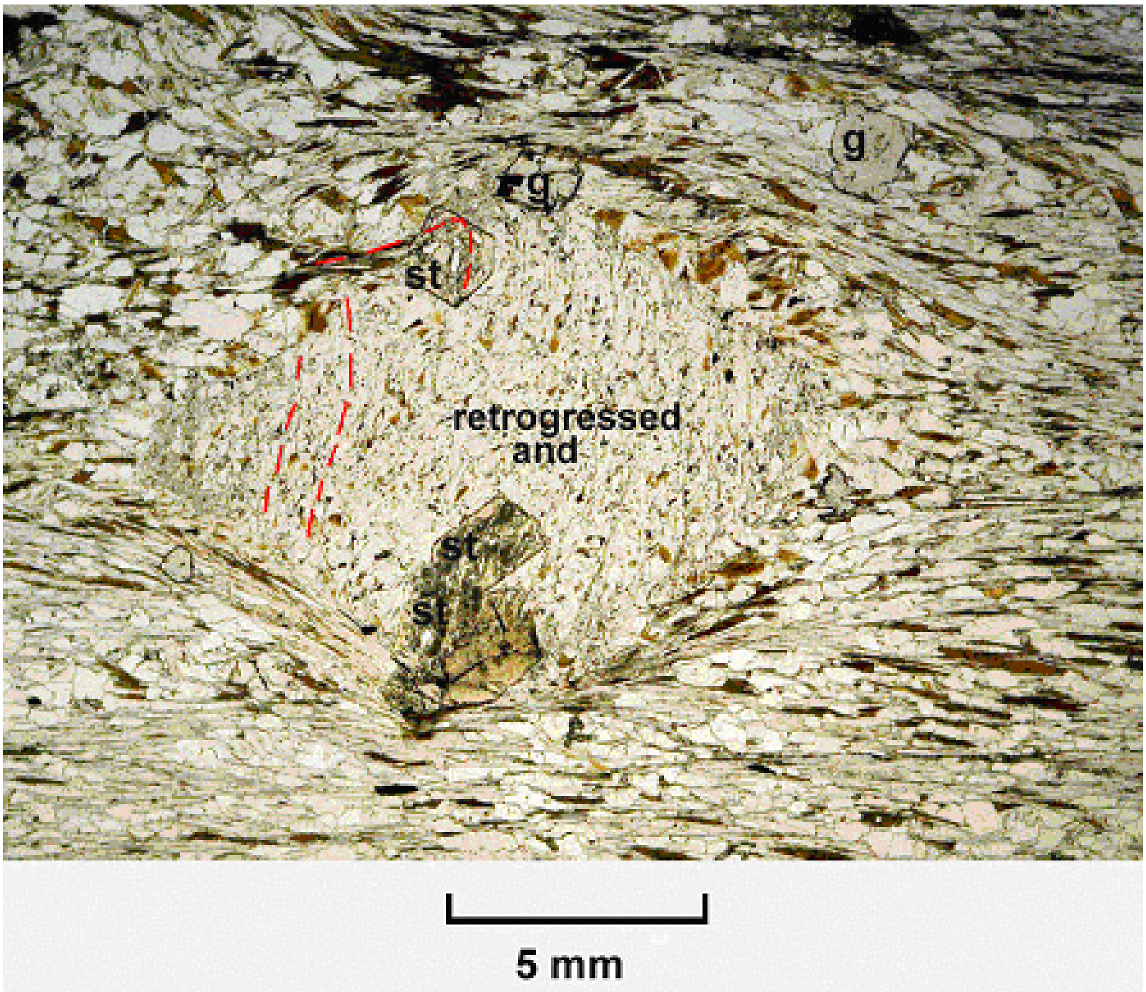


Plate 17 Staurolite in retrogressed andalusite, Waterfall Creek. (Photo 049453)

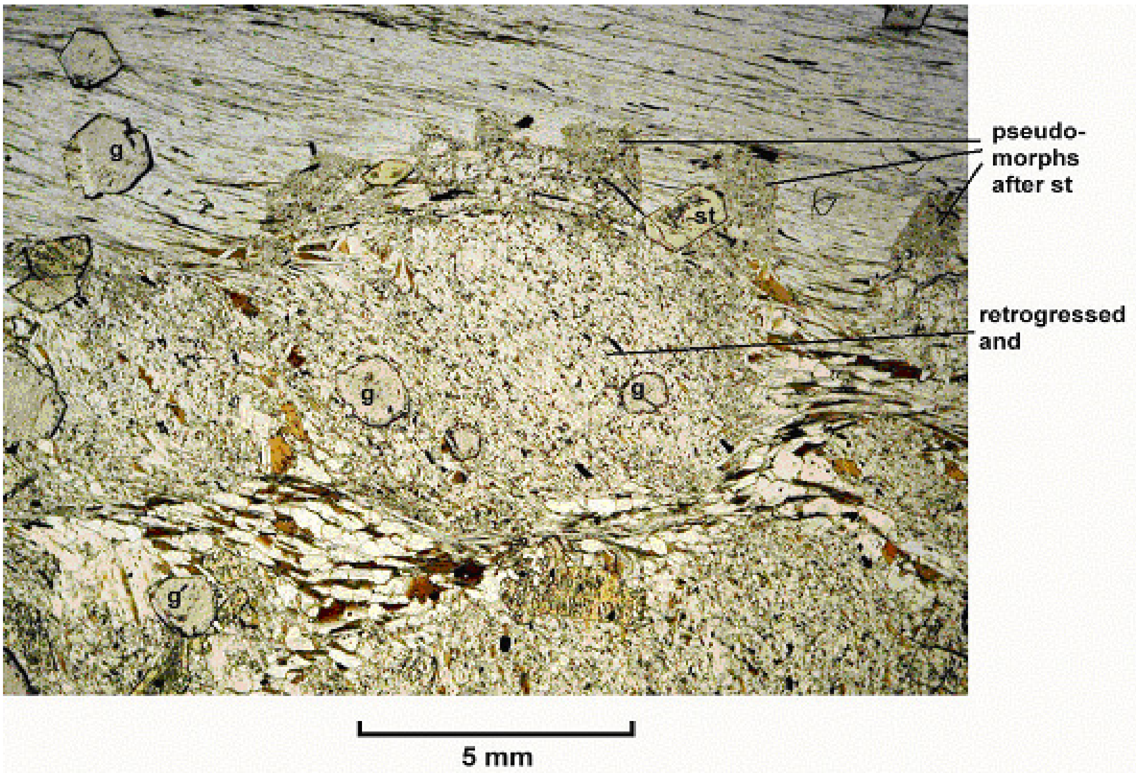


Plate 18 Staurolite pseudomorphs abutting retrogressed andalusite, Waterfall Creek, Walparuta Inlier. (Photo 049454)

Plate 19 'Choc-mint' texture in outcrop, Waterfall Creek, Walparuta Inlier. Outlined area shown enlarged in plate 20. (Photo 049455)

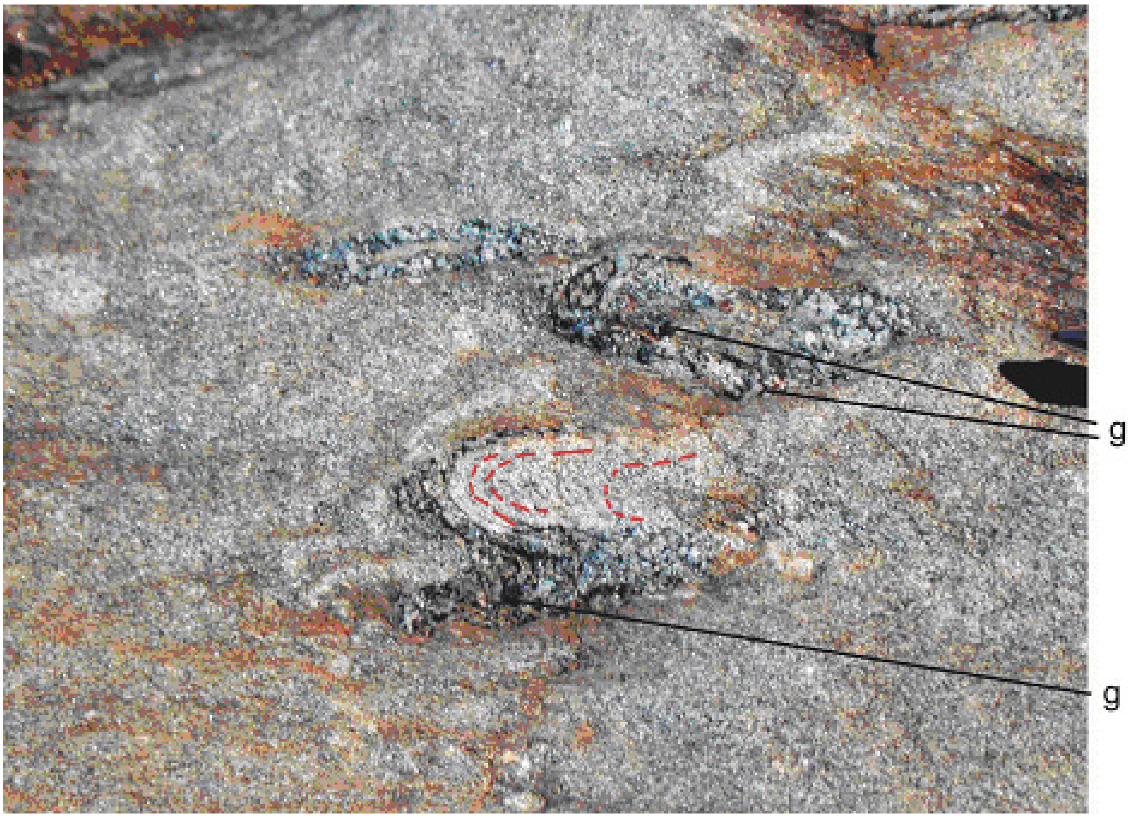


Plate 20 Enlargement of 'choc-mint' texture from plate 19 showing internal foliations. Waterfall Creek, Walparura Inlier. (Photo 049456)

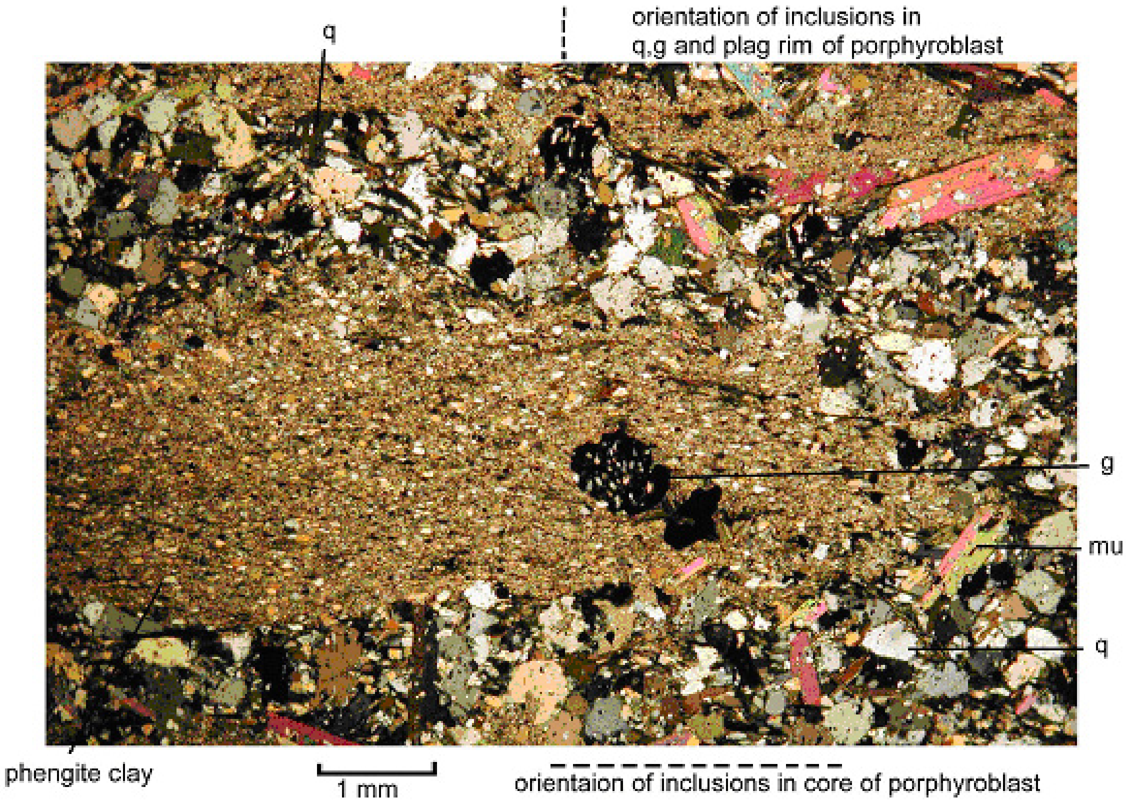


Plate 21 'Choc-mint' texture, Waterfall Creek, Walaruta Inlier. (crossed polars) (Photo 049457)

Plate 22 Fold envelope for en echelon, retrogressed andalusite in schist, northern Walparuta Inlier. (Photo 049458)

The petrography of andalusite schist samples from Waterfall Creek is discussed in detail in Clarke et al. (1995), and is in general agreement with the petrographic interpretation described in this study. The interpreted sequence of mineral growth and deformation is summarised in Figure 6.

Chlorite–garnet schist near Whey Whey Creek is thought to represent late-stage retrograde shear zones that bisect the Walparuta Inlier and connect with the Walter–Outalpa shear zone (Fig. 5). Current research by Lachlan Rutherford and Martin Hand at the University of Adelaide suggests garnet growth within this shear zone may be related to reactivation and deformation of the shear zone during the Delamerian Orogeny. Similar retrograde shear zones near Mutooroo Mine are also thought to have grown metamorphic garnet during the late Cambrian (L. Rutherford, University of Adelaide, pers. comm., 2002; see section 5.8.3).

5.4.2 METAMORPHOSED PELITIC ROCKS FROM OTHER PARTS OF THE WEEKEROO INLIERS

Thin sections collected by L.C. Barnes (~1985) from the Coppertop Inlier (Fig. 5) record late staurolite and chloritoid in this area. Highly retrogressed andalusite schist in the northern part of the Coppertop Inlier is identical to andalusite schist found in the Waterfall Creek section of the Walparuta Inlier (e.g. sample R504845).

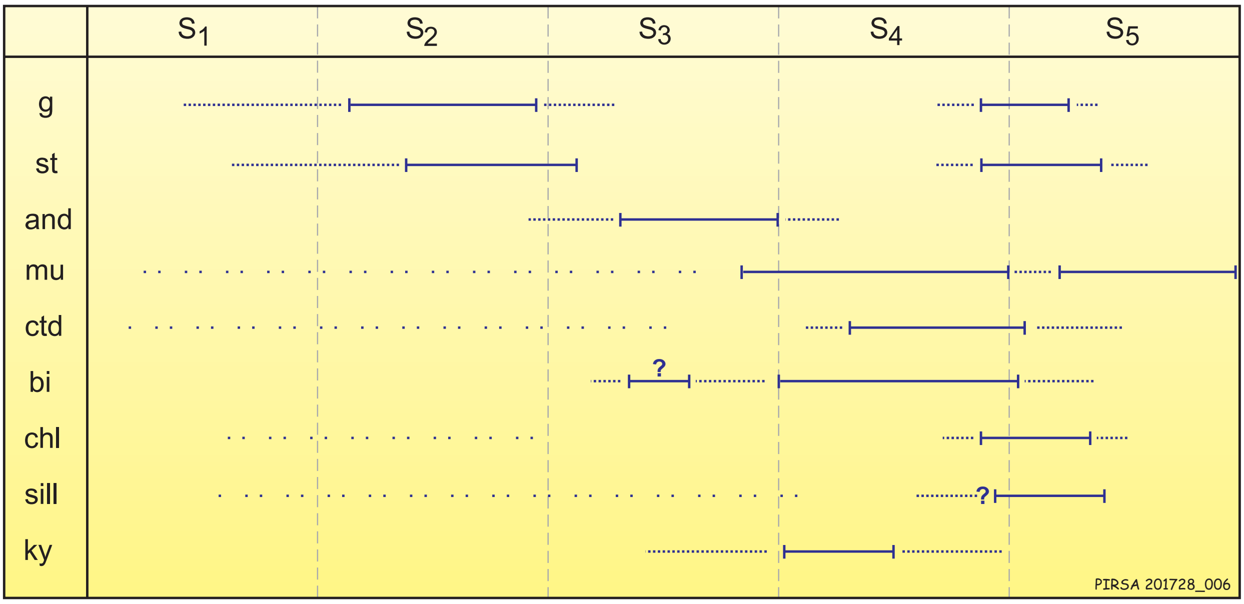
To the west, the Morialpa Inlier (Fig. 5) hosts large sillimanite bodies, first described by Ridgway and Johns (1950). These are composed of massive fibrolitic sillimanite. Thin sections (R36165–R36177) from one of these sillimanite pods show chloritoid intergrown with the sillimanite, however, the timing relationship of these two minerals is ambiguous. The massive sillimanite contains brittle fractures filled with sericite. The sericitised fractures are overgrown by randomly orientated staurolite porphyroblasts (Plate 23). This relationship provides further evidence that sericite retrogression of the Weekeroo Inliers occurred prior to the growth of the post-kinematic staurolite.

5.5 Ameroo Hill (Clarke et al. (1987) — zone IIb)

Ameroo Hill (Fig. 4) was not visited during this study. However, Lachlan Rutherford and Martin Hand (University of Adelaide) kindly provided several samples for petrographic analysis. Field relationships suggest local metamorphic grade inversion, with high-grade metamorphic rocks apparently thrusted over lower grade rocks (Gibson et al., 2002). Pelitic samples commonly contain garnet, staurolite, chloritoid, fibrolitic sillimanite, andalusite, biotite, muscovite, and quartz. To the north of Ameroo Hill, pelitic schist contains retrogressed andalusite and chiastolite whereas pelite on top of Ameroo Hill contains prismatic sillimanite overprinting andalusite (Gibson et al., 2002). Gibson (Geoscience Australia, pers. comm., 2002.) suggested that this prismatic sillimanite may be syn-S_2, whereas the andalusite and chiastolite is syn-S_1. Fibrolitic sillimanite is commonly preserved in porphyroblastic muscovite.

Garnet is abundant in pelite samples that are not aluminous enough to contain appreciable staurolite or chloritoid. Garnet often contains inclusion patterns indicative of at least two stages of growth (e.g. R505765). This pattern of two-stage garnet growth is similar to that found in the northern Walparuta Inlier, described above, and also seen in the Mulga Bore – Cathedral Rock area. Garnet overgrowths containing opaque inclusions, probably ilmenite, mimetically replace biotite (Plate 24).

Chloritoid may occur within the main ('local' S_2) rock fabric (Plate 25) or may overgrow the fabric post-kinematically (e.g. R505764). Post-kinematic staurolite overgrows fabric-parallel chloritoid (Plate 25). This correlates with the regional trend for the late staurolite growth to post-date chloritoid growth (where the two mineral occur together) in the Olary Domain.



S_1 to S_4 are based on the scheme of Clarke et al. (1995)

Figure 6 Interpreted sequence of mineral growth for northern Walparuta Inlier

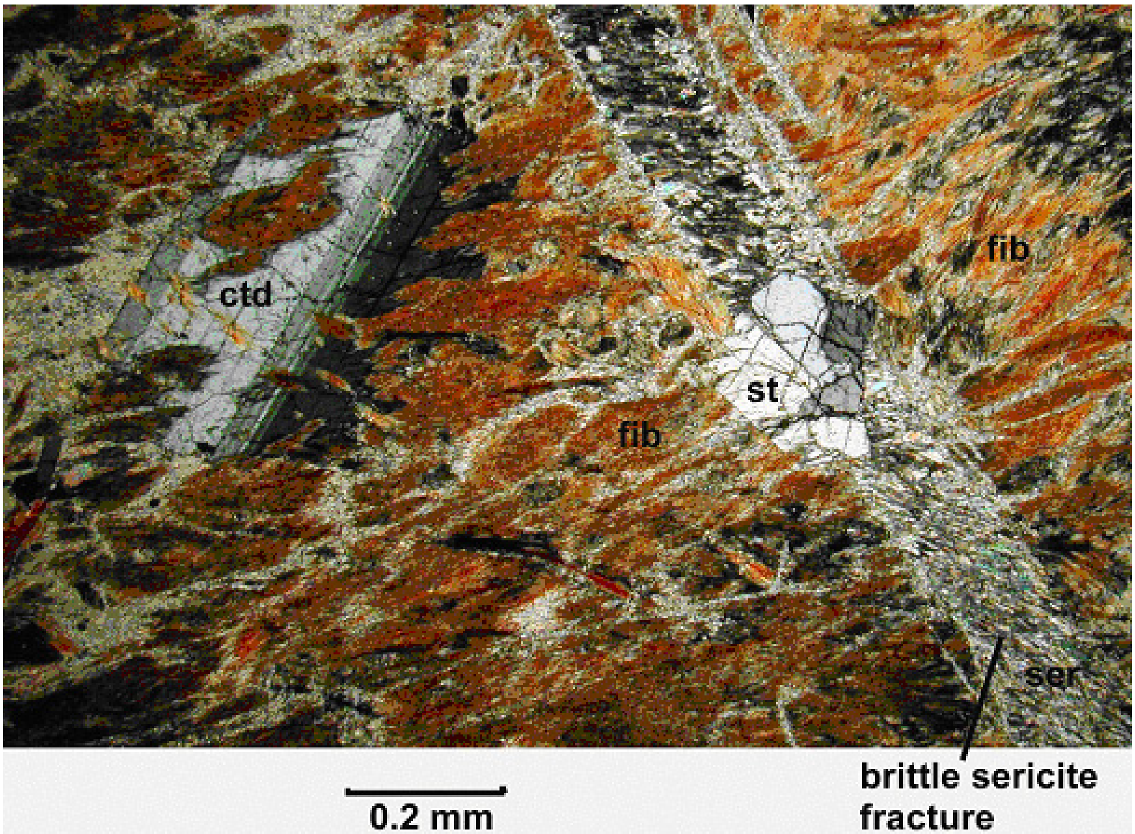


Plate 23 Staurolite overgrowing sericite-filled brittle fracture, Morialpa Inlier (crossed polars).
(Photo 049459)

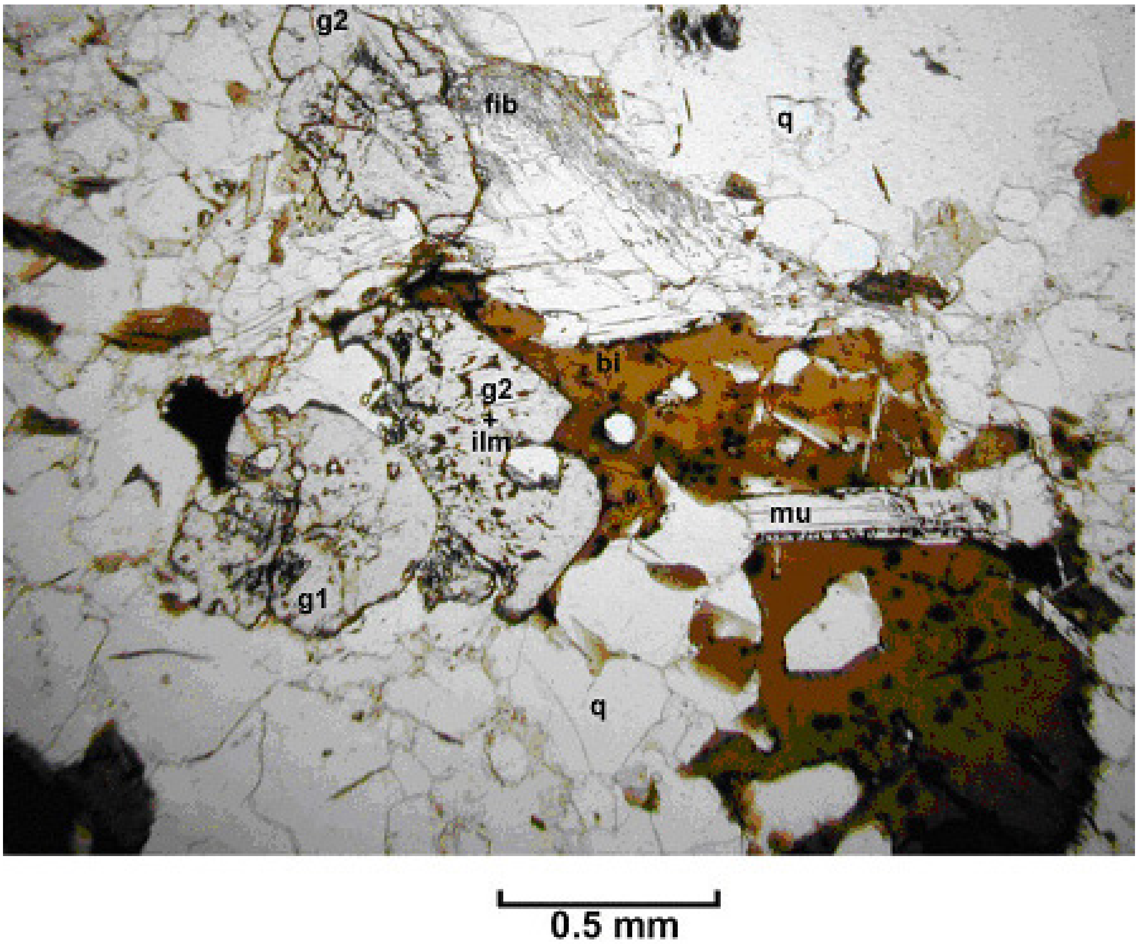


Plate 24 Garnet+ilmenite consuming biotite, Ameroo Hill. (Photo 049460)

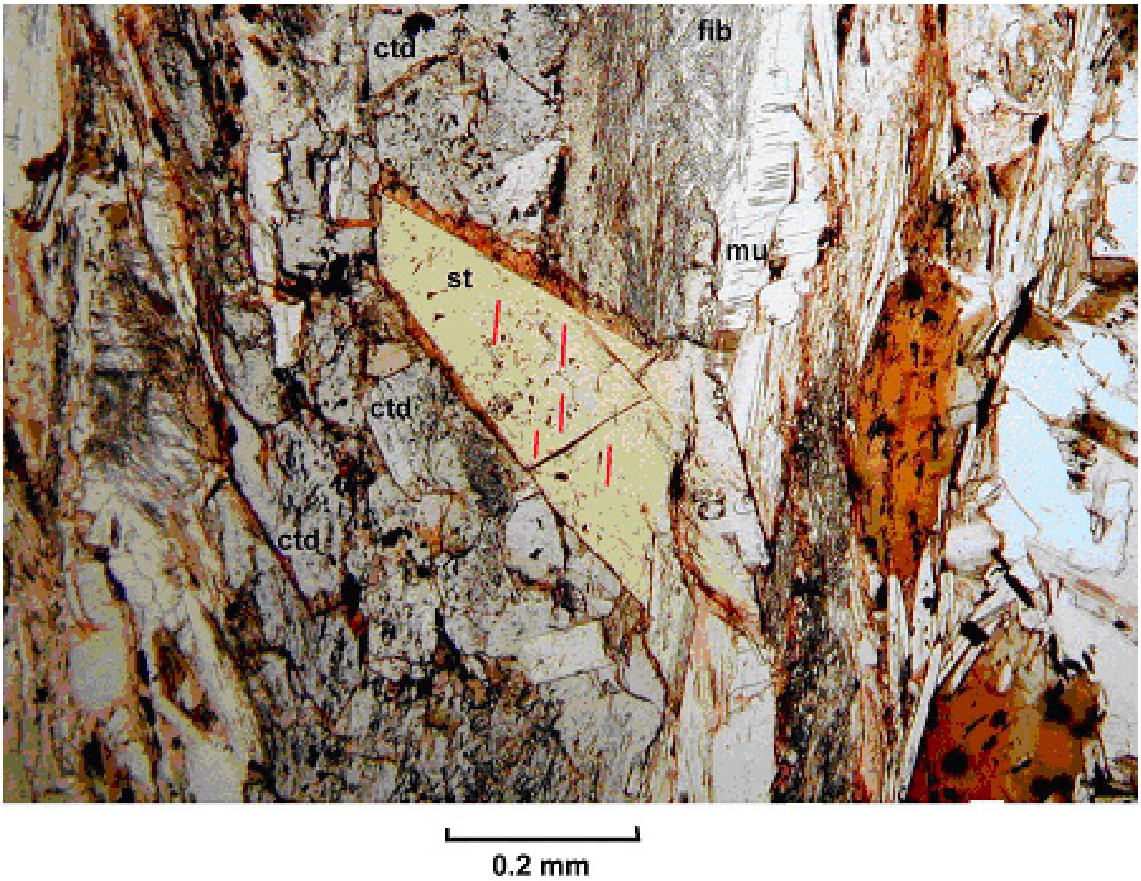


Plate 25 Late staurolite overgrowing 'local' S_2-parallel chloritoid, Ameroo Hill. (Photo 049461)

5.6 Cathedral Rock and Mulga Bore area (Clarke et al. (1987) — zone IIb)

This area (Fig. 4) was also not visited in this study but again Lachlan Rutherford and Martin Hand (University of Adelaide) provided several samples for petrographic analysis. Pelitic samples from this area are very similar to samples from Ameroo Hill. ‘Two growth stage’ garnets from Cathedral Rock, however, contain inclusions of fibrolitic sillimanite in both rim and core domains (e.g. sample CR2, University of Adelaide sample; plate 26). Furthermore, pelitic schist in this area often contains late chloritoid (R. Wiltshire, University of South Australia, pers. comm., 2002; Millar, 1994). Staurolite is not recorded from this area. Chloritoid (in the absence of staurolite) is also noted from pelite in the Oonarta Creek – Mary Mine area (Pepper, 1996).

Microprobe data, provided by Lachlan Rutherford from the University of Adelaide, provides compositional mapping data for a ‘two growth stage’ garnet from the Cathedral Rock area. This shows that the elemental zoning profiles of major cations (i.e. Fe, Mg, Ca, Mn) are very different in the two stages of garnet growth (Plate 27, 28). While the core of primary garnet contains no significant zoning at all, the secondary rim preserves a strong compositional zoning profile. This zoning pattern suggests that the core domain of garnet has been affected by intra-crystalline diffusion (probably due to prolonged heating at temperatures above ~650˚C) prior to the growth of the rim domain of garnet.

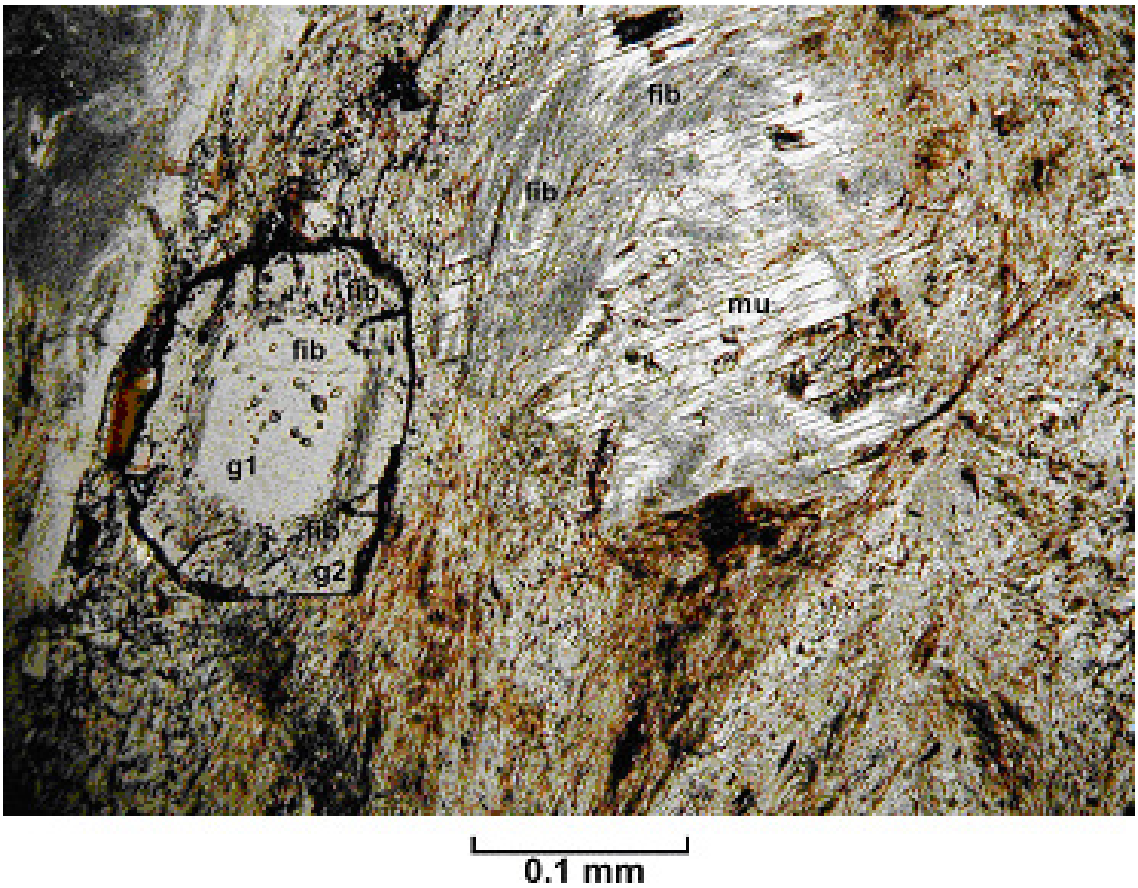


Plate 26 Fibrolite inclusions in two-stage garnet, and muscovite, Cathedral Rock (Photo 049462)

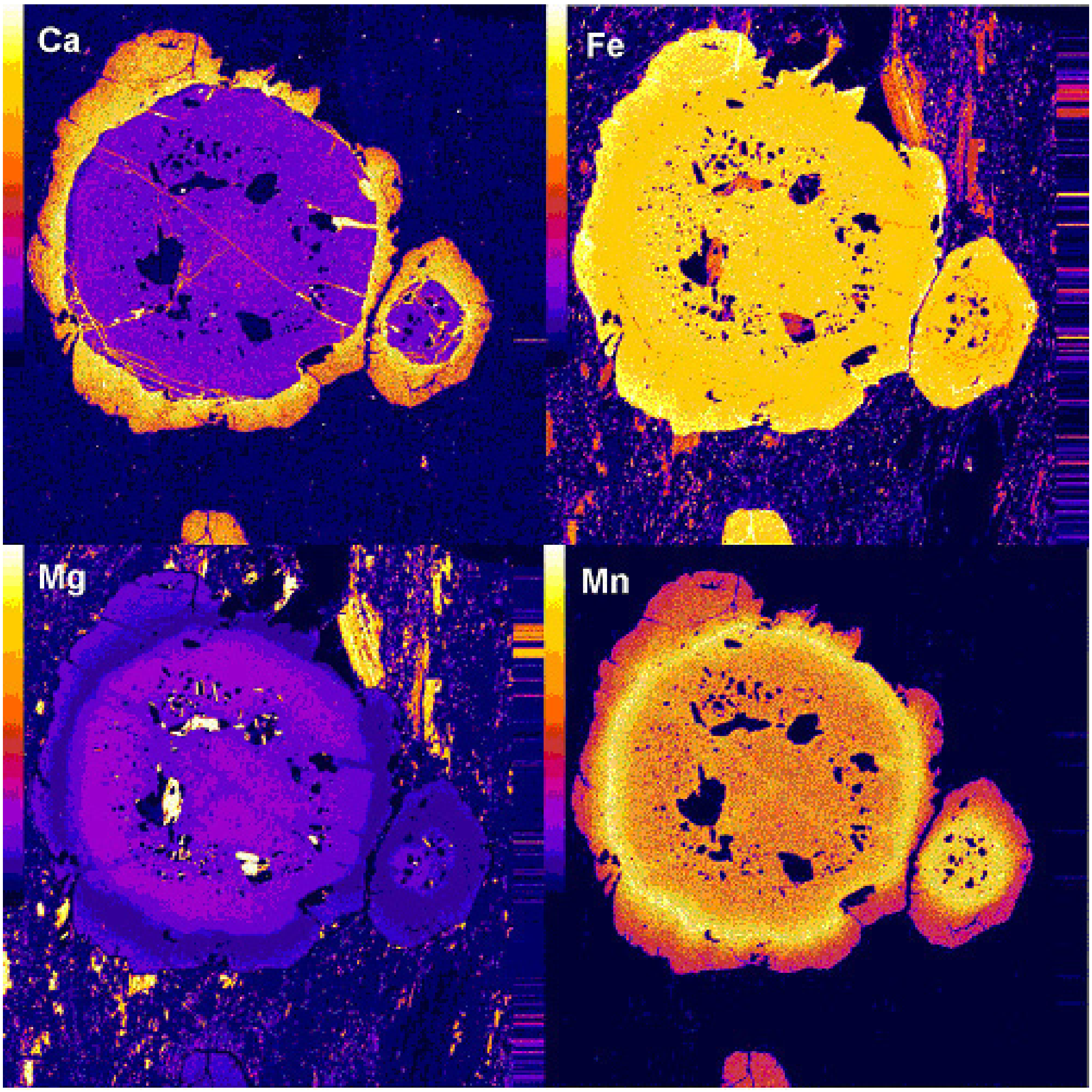


Plate 27 Composition maps of garnet from Cathedral Rock (Photo 049463)

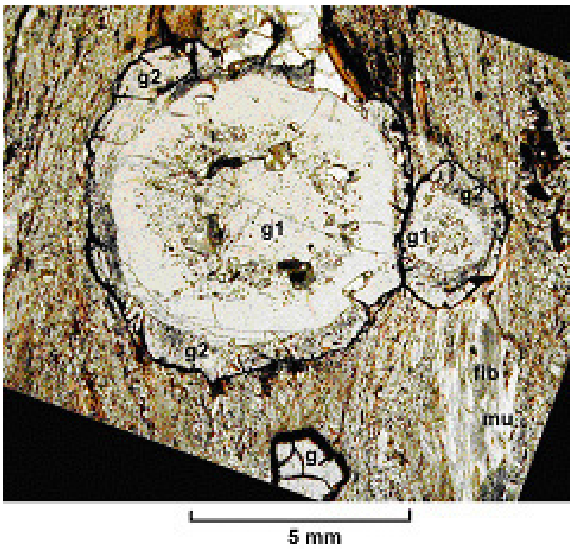


Plate 28 Photomicrograph of above image, Cathedral Rock (Photo 049464)

5.7 Wiperaminga Hill (Clarke et al. (1987) — zone IIa/IIb)

Reconnaissance fieldwork was carried out in the Wiperaminga Hill area (Fig. 4) to groundtruth mineral occurrences (mainly andalusite, sillimanite, and kyanite) recorded on annotated aerial photographs. Of the small number of photo localities visited, the mineral occurrences noted were found to be as described, giving confidence that this data could be included in the metamorphic mineral occurrence database. In addition, the following field relationships from the Wiperaminga Hill area were noted:

- Pristine chiastolites, semi-transparent with some crystal faces intact, occur in a carbonaceous schist unit. The chiastolite porphyroblasts defined a strong mineral lineation reflecting a top-to-the-northwest shearing (Plate 29). It is unclear whether the chiastolites grew within their present alignment or if they were aligned post-growth (i.e. due to shearing deformation).
- Retrogressed sillimanite schist was found in a number of places. This rock has a very similar appearance to samples collected from Koolka Hill and discussed above.
- Kyanite was found in a psammitic unit on the northern flanks of Wiperaminga Hill. The kyanite is flattened in the main rock foliation plane (Plate 30). Blades of kyanite were also found radiating out from relatively late, (undeformed) quartz veins (Plate 31).

Almandine garnet with homogenised, compositional zoning has been described from this area (Hutchings, 1990). This observation suggests that the terrane may have been hot for a long period after the growth of the garnet. This observation is in agreement with compositional maps of two-stage garnets found in pelite at Cathedral Rock (described above, see plates 27, 28). Hutchings (1990) also noted the presence of a migmatisation boundary (or a ‘migmatite-in’ isograd) immediately to the south of Wiperaminga Hill. This observation suggests that metamorphic grade increases rapidly southwards of Wiperaminga Hill, possibly due to the thermal effects of local intrusive bodies, but detailed fieldwork is required to test the hypothesis.

5.8 Mingary

Recent fieldwork has confirmed the presence of both mafic and pelitic, granulite-grade, metamorphic rocks in the poorly exposed outcrops of the South Australian portion of the Broken Hill Domain, south of the abandoned railway siding of Mingary (Fig. 12). Outcrops of the granulite-grade rocks occur in a linear belt that parallels the northeast–southwest-trending, linear gravity and magnetic feature that has been informally used by numerous authors (e.g. Stevens, 1986; Isles, 1983; Mills, 1986; Ashley et al., 1995) as a domain boundary between the Olary and Broken Hill Domains (see Crooks, 2001, for discussion). Inferred granulite-grade rocks have been found in a few localities both to the northwest and southeast of this linear feature (Fig. 7) extending to the New South Wales – South Australia border. The northeastern extent of the granulite-grade rocks is concealed by Tertiary and younger cover sequences.

The mafic granulites occur as isolated cores (5–20 m in diameter) to larger, elongate amphibolite bodies (up to 500 m long) that strike roughly northeast–southwest. These granulite to amphibolite-grade, mafic gneiss bodies are interpreted to have basic igneous precursors, probably dolerite dykes or sills, based on mineralogical considerations discussed below. The amphibolite – mafic granulite bodies are surrounded by granulite to amphibolite-grade, pelitic gneiss and quartzo-feldspathic gneiss that are correlated with gneisses of the Broken Hill and Thackaringa Groups of the Broken Hill Domain (Crooks, 2001). The metamorphic rocks at Mingary are generally different to the metamorphic rocks in other parts of the SAWI. The bulk rock textures from metapelite and amphibolite at Mingary are usually much coarser grained, mostly gneissic, than in other parts of the SAWI.

Plate 29 Lineation chiastolite, Wiperaminga Hill. (Photo 049465)

Plate 30 Kyanite on foliation plane, Wiperaminga Hill. (Photo 049466)

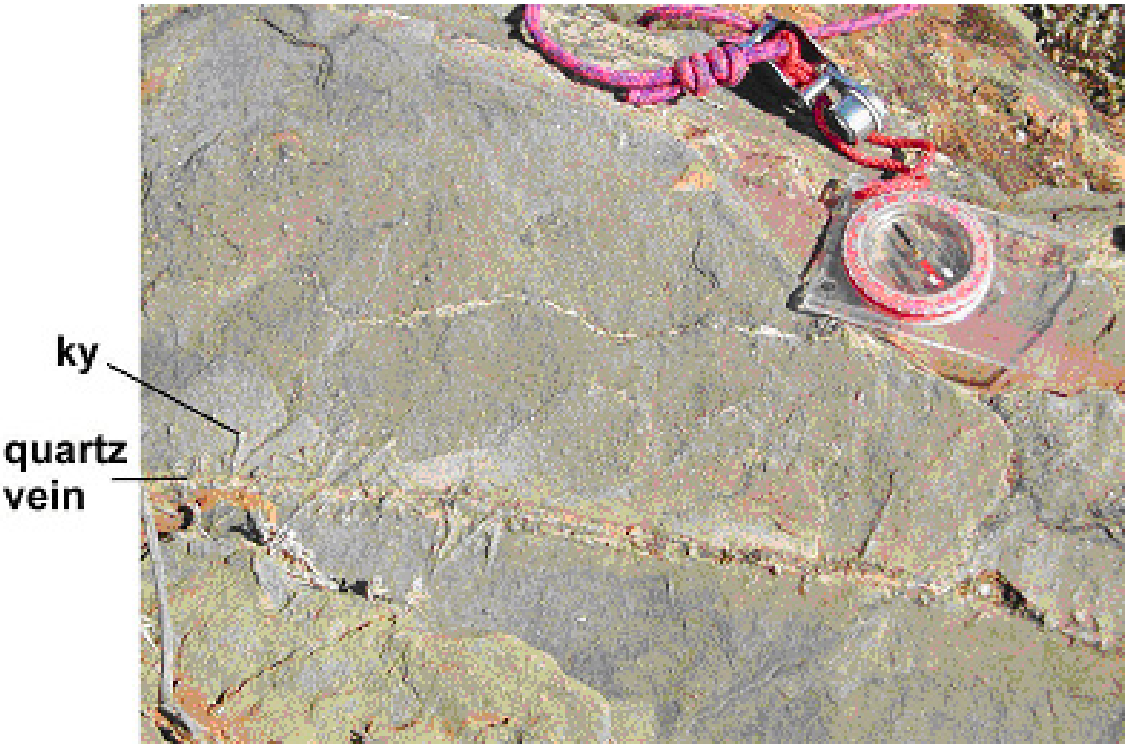


Plate 31 Kyanite growing from quartz vein, Wiperaminga Hill. (Photo 049467)

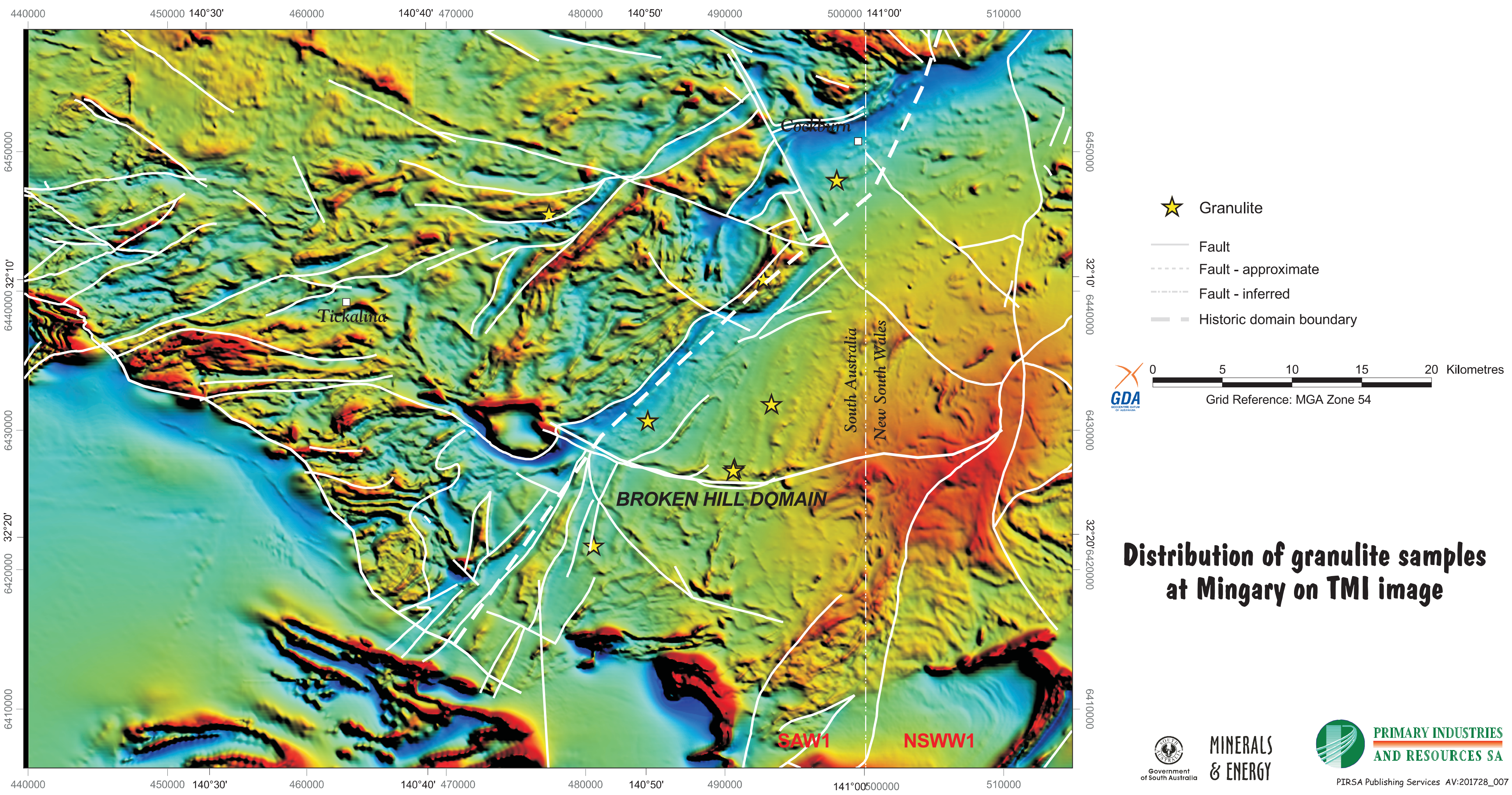
5.8.1 MAFIC GRANULITE AND AMPHIBOLITE

Three different mineral assemblages are found within the composite mafic granulite – amphibolite bodies. These include the two-pyroxene mafic granulite core, a zone of transitional alteration between granulite and amphibolite-facies rocks, and a zone of complete retrogression to amphibolite grade. Numerous amphibolite bodies outcrop throughout the area that have no associated granulite lithologies. It is possible that many of these bodies represent completely retrogressed equivalents of the composite granulite–amphibolite bodies.

The granulite cores of the composite granulite–amphibolite bodies generally contain the mineral assemblage orthopyroxene (hypersthene), clinopyroxene (augite), hornblende, and plagioclase (±ilmenite, and quartz). Plagioclase, pyroxene and hornblende form a granoblastic mosaic within the rock. Small amounts of ilmenite occur as inclusions in pyroxene and hornblende and as interstitial xenoblastic crystals in most samples (e.g. R495887 and R495900). Some samples (e.g. R495887) contain a moderately well-developed foliation defined by alternating plagioclase and hornblende–pyroxene-rich domains.

Actinolite and tremolite replace orthopyroxene and clinopyroxene along fractures that crosscut pristine granulite domains. These fractures occur at a high angle to a weak hornblende foliation present in a few samples (Plate 32). The concentration of fractures, and the degree of actinolite–tremolite growth along the fractures, increases towards the zone of transition between the pristine granulite cores and the surrounding retrograde amphibolite.

In one sample (R495900), cummingtonite is the dominant replacement mineral. This sample contains the granulite assemblage orthopyroxene (hypersthene), clinopyroxene (augite), hornblende, plagioclase and ilmenite. This assemblage is overprinted by the retrograde assemblage of perthitic K-feldspar, cummingtonite, garnet and quartz. Clinopyroxene crystals contain exsolution lamellae of orthopyroxene and, rarely, vice versa. The retrograde cummingtonite occurs as aggregates and coronas have replacing orthopyroxene. **Figure 7** Cummingtonite is usually separated from adjacent plagioclase by a corona of fine-grained garnet (Plate 33), demonstrating the instability of cummingtonite and plagioclase during


440000
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6430000
32°20' 6420000
6410000
Cockburn
Tickalina
South Australia
New South Wales
BROKEN HILL DOMAIN
SAW1
NSWW1
Granulite
Fault
Fault - approximate
Fault - inferred
Historic domain boundary
0
5
10
15
20
Kilometres
Grid Reference: MGA Zone 54
GDA
Distribution of granulite samples
at Mingary on TMI image
Government of South Australia
MINERALS & ENERGY
PRIMARY INDUSTRIES AND RESOURCES SA
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Figure 7

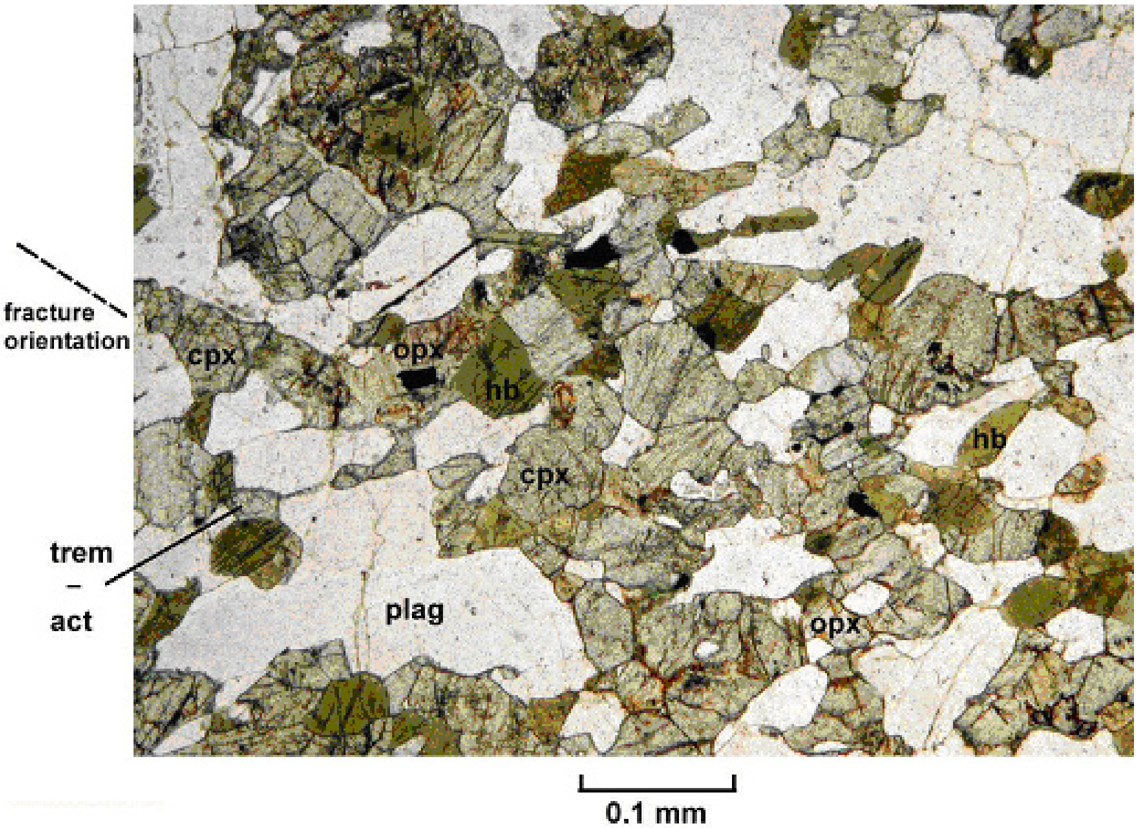


Plate 32 Tremolite–actinolite retrogressive alteration of a primary two-pyroxene granulite, Mingary.
(Photo 049468)

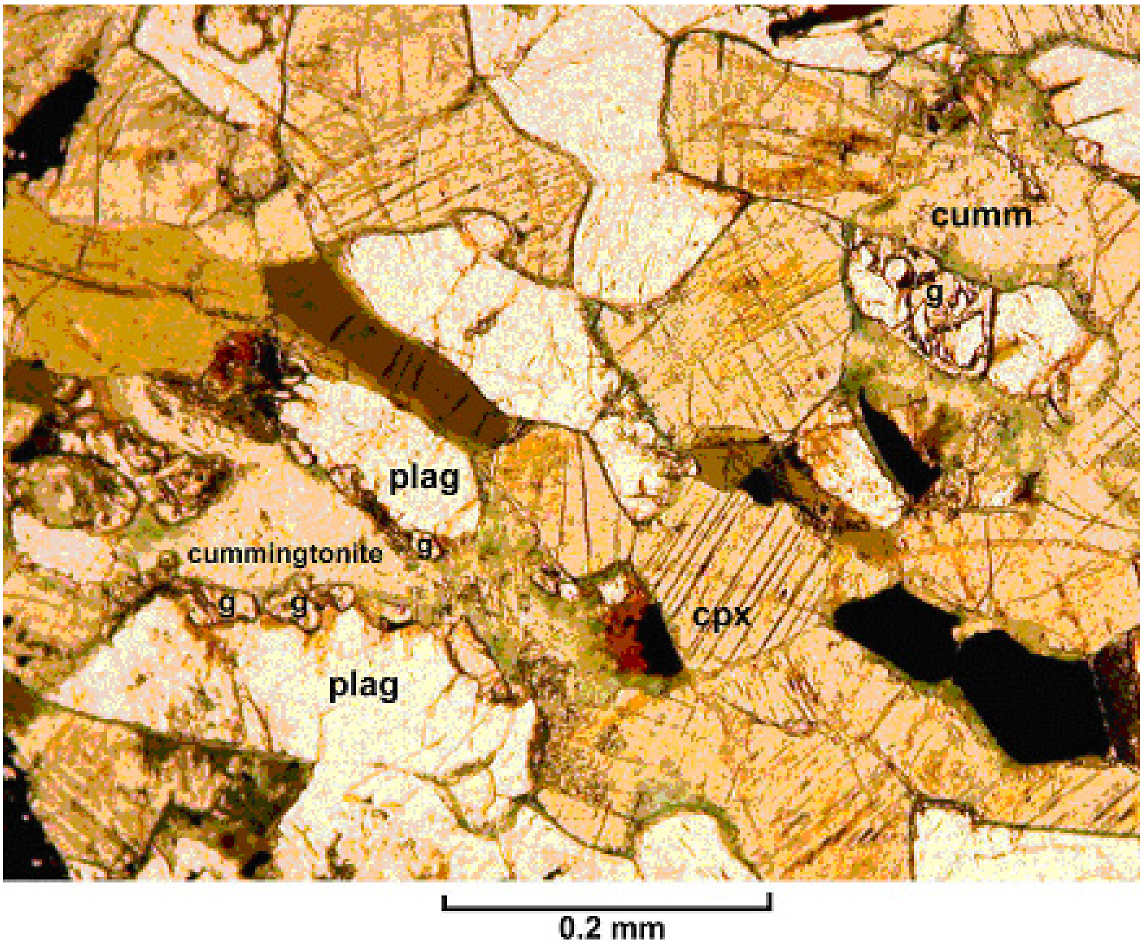


Plate 33 Cummingtonite separated from plagioclase by garnet corona, south of Cockburn. (R495900)
(Photo 049469)

retrogression (Corbett and Phillips, 1981; Tonel et al., 2001). Corbett and Phillips described this relationship in terms of the following relationship:

- Anorthite + cummingtonite => garnet + quartz + H2O

They stated that this reaction can be combined with the reaction that describes cummingtonite replacement of orthopyroxene, i.e.:

- Orthopyroxene +quartz + H_2O => cummingtonite

to give the vapour absent transition from orthopyroxene–plagioclase to garnet–quartz that adequately describes the formation of the garnet corona in these rocks:

- Orthopyroxene + anorthite => garnet + quartz.

Garnet also forms a corona reaction texture between plagioclase and ilmenite in some samples (e.g. R495900; plate 34). This texture may reflect the instability of plagioclase and ilmenite during anhydrous retrogression, similar to the scenario reported for cummingtonite and plagioclase described above.

A gradational alteration zone that varies between 0.10 and 1 m wide surrounds the pristine granulite cores. Orthopyroxene and clinopyroxene are increasingly replaced by cummingtonite, actinolite and tremolite, and the modal proportion of hornblende increases towards the outside of this zone. The amphibolite lithologies surrounding the two-pyroxene granulite cores generally have a mineralogy dominated by hornblende and plagioclase (±ilmenite and quartz). A strong foliation is generally defined by elongate hornblende grains and plagioclase aggregates and by alternating hornblende-ilmenite and quartz-plagioclase layers (Binns, 1965). Garnet is often present in varying amounts in amphibolite lithologies. However, unlike in the retrogressed mafic granulites, garnet often forms large (up to 4 mm) euhedral to subhedral (often poikiloblastic) porphyroblasts in the amphibolite rocks (Plate 35). Garnet-bearing amphibolite rocks often occur adjacent to a contact with surrounding felsic gneiss and metasediments (e.g. sample R495902). Furthermore, garnet-bearing amphibolites may have appreciable amounts of titanite and epidote. This suggests that the presence of garnet in these amphibolite rocks may be associated with metasomatism via fluids derived from the country rocks, as opposed to simple amphibolite retrogression of a granulite precursor. Biotite is often also associated with retrograde amphibolites.

The concordance of the granulite–amphibolite bodies with the surrounding gneiss and metasediments and their implied bulk composition indicate that the precursor lithology was likely to be a basic intrusive or extrusive (probably dolerite or basalt). Any primary structures indicative of the precursor rock type, however, have been obliterated by the subsequent metamorphism.

Hornblende defines a weak foliation in a few two-pyroxene granulite samples. This foliation is upright to inclined and roughly parallels the long axis of the granulite–amphibolite bodies in outcrop. A weak foliation has also been noted from a two-pyroxene granulite sample from diamond drillcore from the historic Mutooroo Mine (Flint, 1979). As the proportion of intact, granoblastic pyroxene grains decreases towards the outer margin of the alteration zone within the composite granulite–amphibolite bodies, the weak upright fabric found in the granulite cores becomes increasingly more developed. A prominent upright fabric (striking approximately northeast–southwest) is defined by aligned hornblende in the surrounding amphibolite hornfels and schist.

5.8.2 PSAMMITIC AND PELITIC GRANULITE GNEISSES

Pelitic granulite gneisses occur adjacent to the composite, mafic granulite-amphibolite bodies in a number of locations. The pelitic granulites generally contain the following mineral associations:

a) garnet, sillimanite, plagioclase, biotite, quartz and K-feldspar
b) garnet, spinel, plagioclase, biotite, sillimanite
c) sillimanite, biotite, quartz (± spinel)

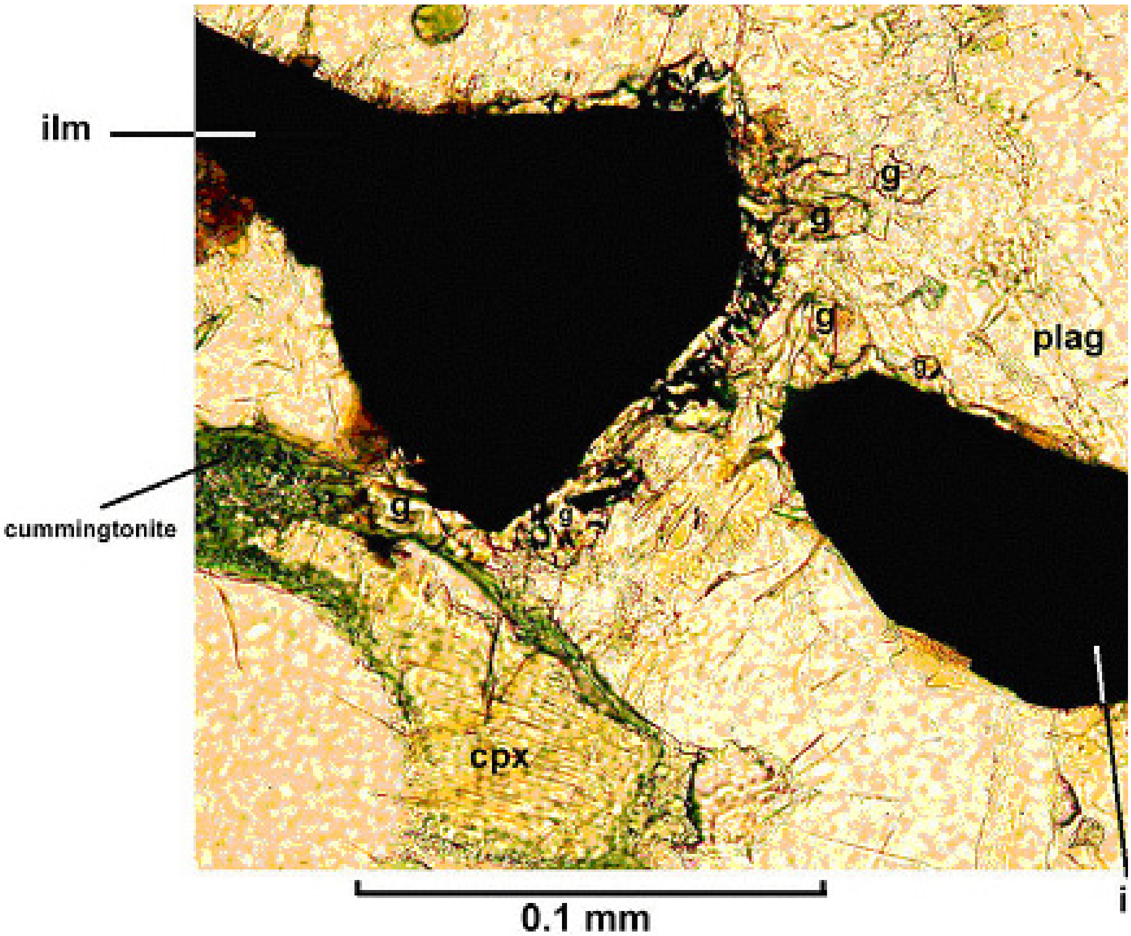


Plate 34 Garnet corona between ilmenite and plagioclase, south of Cockburn. (R495900) (Photo 049470)

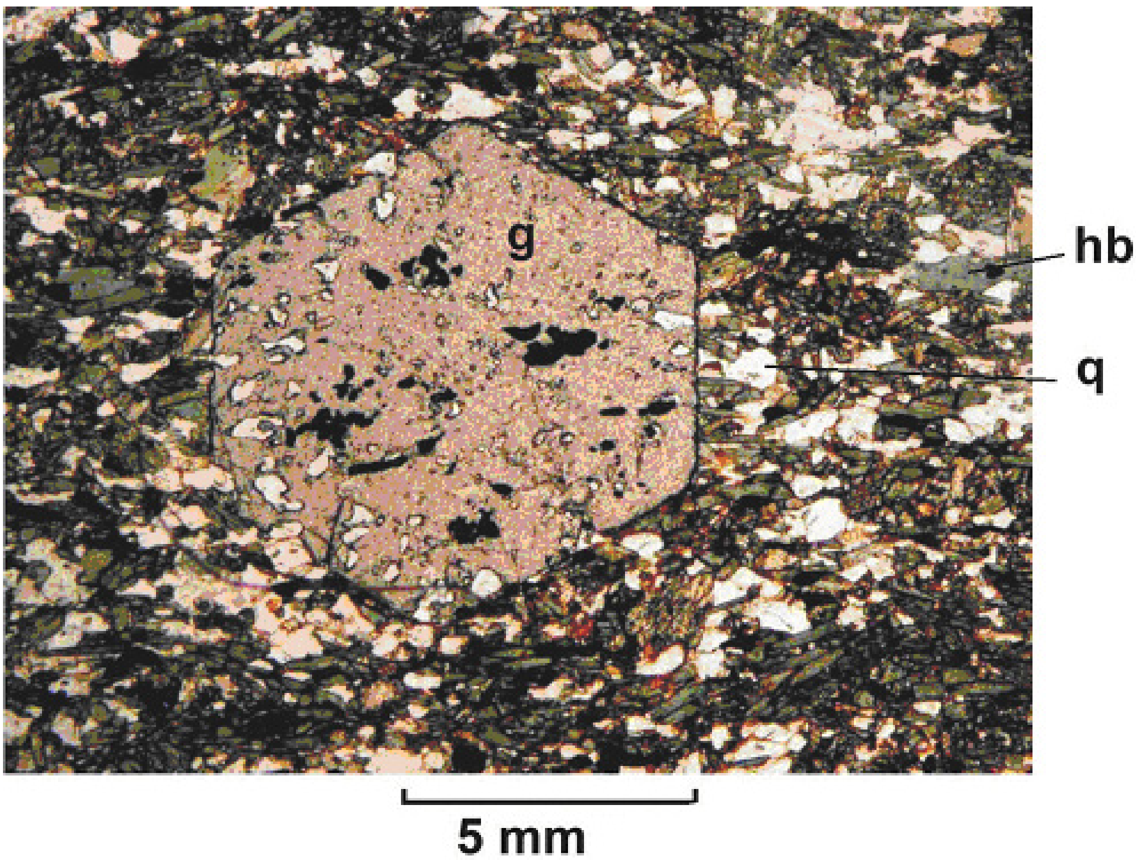


Plate 35 Garnet–hornblende schist, Mingary. (R185204) (Photo 049471)

The first two mineral associations (a and b) were most useful for pressure temperature determination (using THERMOCALC, see section 9.2) due to their relatively low thermodynamic variance and their readily decipherable textural associations. Assemblage c) contains textural evidence indicating growth of prismatic sillimanite prior to and during the later stages of folding deformation. This suggests that either sillimanite was stable throughout deformation or that sillimanite grew during two discrete events (before and late in the deformation). Evidence from other parts of the Willyama Inliers supports the occurrence of two distinct cycles of sillimanite generation (G. Webb, PIRSA, unpublished data, 2002; Flint and Parker, 1993; Amad and Wilson, 1982).

Garnet occurs as large (2–10 mm) subhedral porphyroblasts wrapped by a high-grade fabric primarily composed of plagioclase, quartz and biotite. A few samples contain garnet porphyroblasts with inclusions of fine-grained sillimanite (Plate 36, 37). The sillimanite needles are orientated within the garnet and appear to wrap around the inclusion-free core of the garnet. This suggests that the garnet overgrew a pre-existing, anastomosing, sillimanite-bearing fabric. Intergrowths of randomly orientated sillimanite, spinel, and secondary biotite overgrow a matrix of plagioclase and primary biotite adjacent to large garnet porphyroblasts (Plate 38). This is interpreted as a reaction texture, associated with retrogression of a high-grade pelitic granulite assemblage consisting of garnet, biotite, plagioclase, and sillimanite (and possibly cordierite, see below). Fractures in large garnet porphyroblasts are often filled with retrograde chlorite (Plate 37). This may reflect retrogression under greenschist facies conditions.

Despite the common occurrence of garnet–cordierite-bearing gneiss in the Broken Hill area (Jones, 1997; Corbett and Phillips, 1981; Phillips and Wall, 1981) no cordierite is known from SAWI; the South Australian part of the Broken Hill Domain or the Olary Domain. In the NSWWI, Corbett and Phillips (1981) noted the occurrence of quartz–biotite–sillimanite intergrowths, often adjacent to garnet porphyroblasts, in pelitic gneiss as a high-grade form of cordierite retrogression. This same mineral association, of quartz–biotite–sillimanite intergrowths adjacent to garnet porphyroblasts, is found in a number of pelitic gneiss samples from Mingary (e.g. R495900), suggesting that cordierite may have been present in the area prior to retrogression.

Mesoperthite is now known from three localities at Mingary (Plate 39). Mesoperthite, a lamellar intergrowth of plagioclase and K-feldspar, is thought to form under granulite-facies conditions (Purvis, 1996). Mesoperthite forms when an intermediate composition feldspar (i.e. between the plagioclase and alkali end-members in the ternary feldspar system) crystallises above the solvus, and is slowly cooled through the solvus (Deer et al., 1992). The resulting texture involves the exsolution of microscopic lamellar intergrowths of approximately equal parts of alkali and plagioclase feldspar (Plate 39).

Some of the samples containing mesoperthite occur on the western side of the Olary Domain – Broken Hill Domain boundary (as defined on geophysical grounds; see preface above), that is, within the Olary Domain, indicating that the western portion of the Olary Domain also experienced granulite-grade metamorphism.

5.8.3 OTHER IMPORTANT MINERAL RELATIONSHIPS AT MINGARY

In earlier regional, metamorphic-grade studies (Clarke et al., 1987), much of the SAWI covered by the Mingary 1:100 000 map area was described as being of sillimanite–muscovite grade due to the early (M_1) metamorphic event (see Fig. 2). However, no early muscovite was observed in any of the samples documented in this study. The only muscovite observed in these rocks was late, retrograde muscovite, overprinting primary sillimanite-bearing assemblages. However, sillimanite sometimes occurs in association with early K-feldspar, providing collaboratory evidence that this area attained granulite-facies conditions during the early metamorphic event (M_1).

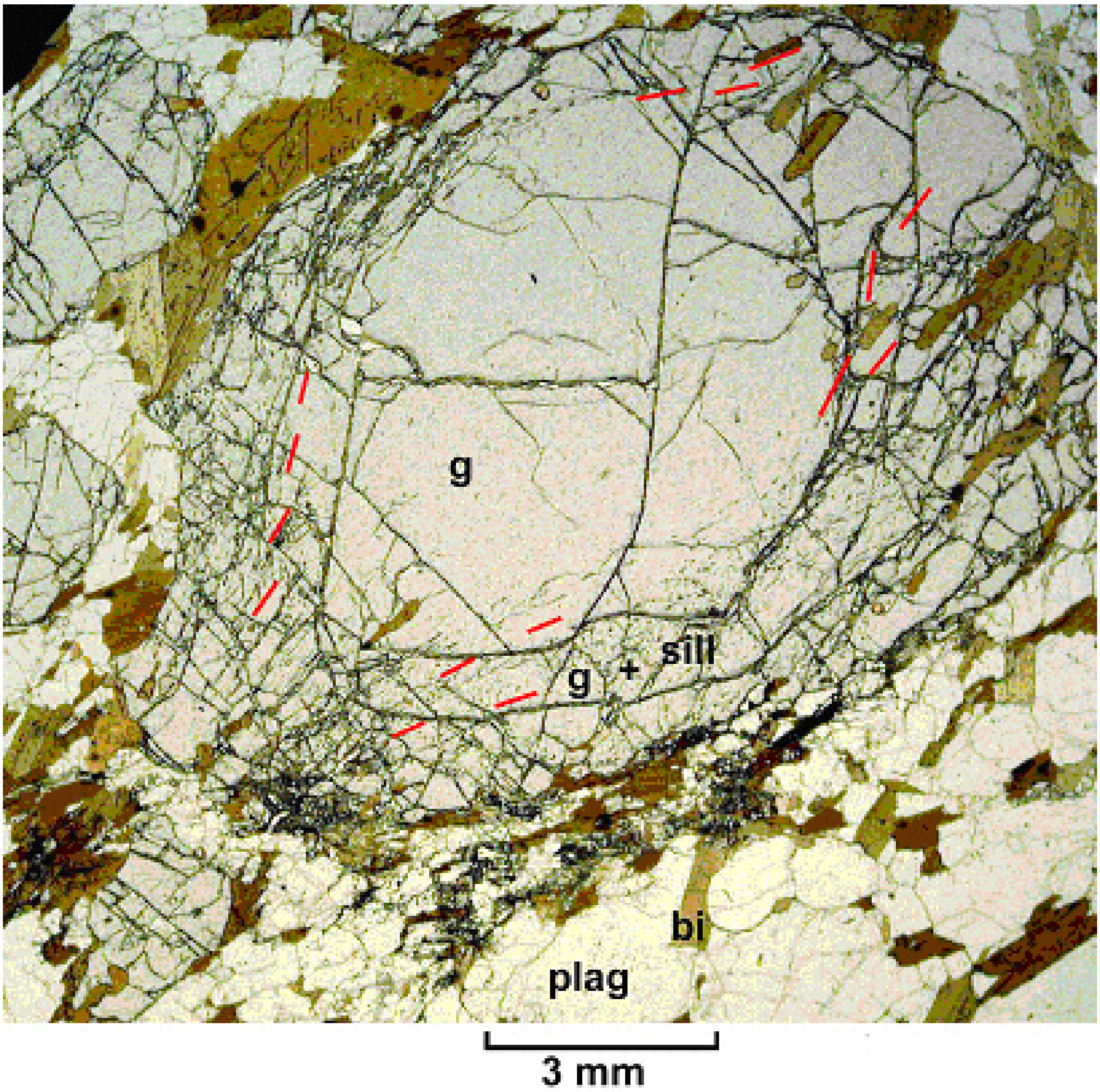


Plate 36 Garnet–sillimanite–chlorite relationships in pelitic granulite gneiss. (Photo 049472)

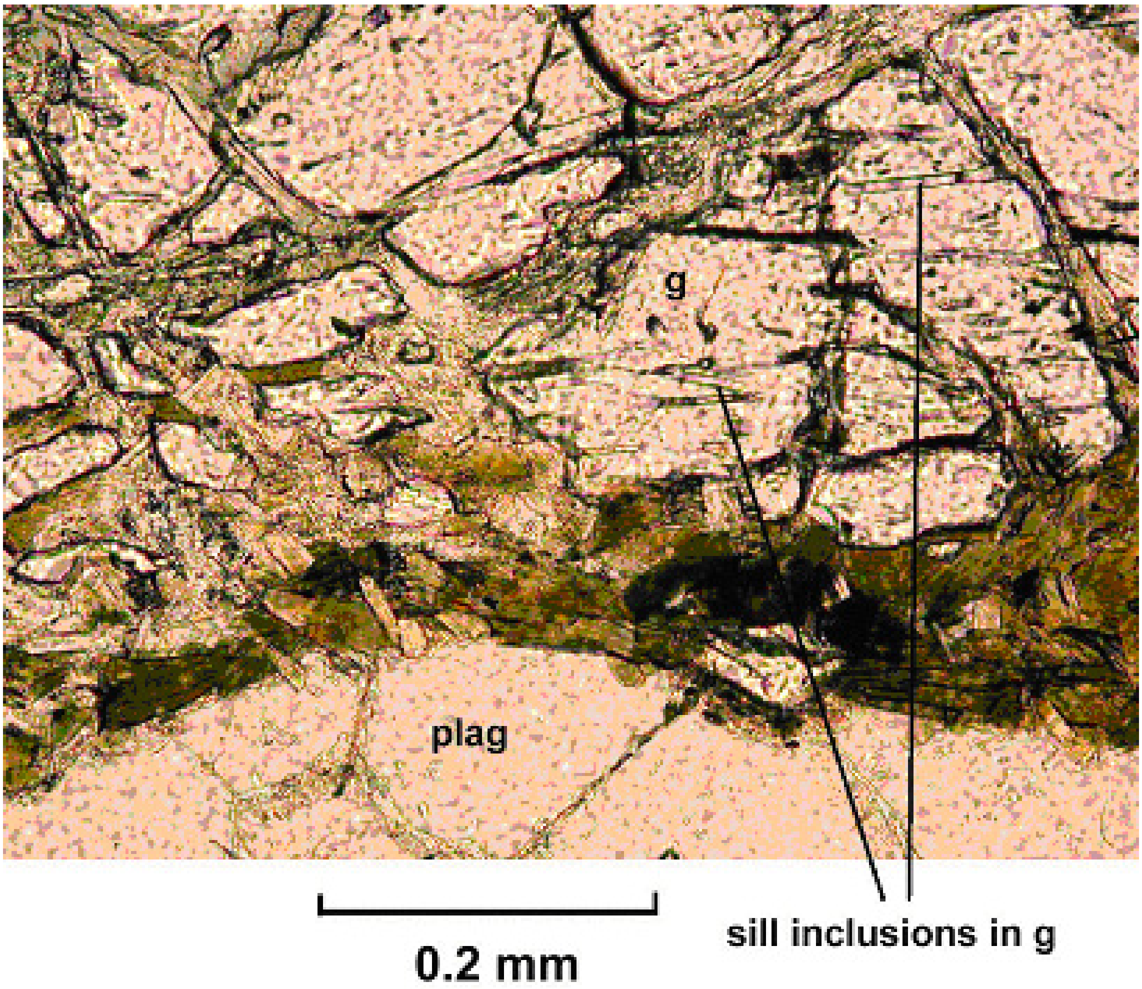


Plate 37 Garnet–sillimanite–chlorite relationships in pelitic granulite gneiss (enlargement of part of plate 36 above; R495901). (Photo 049473)

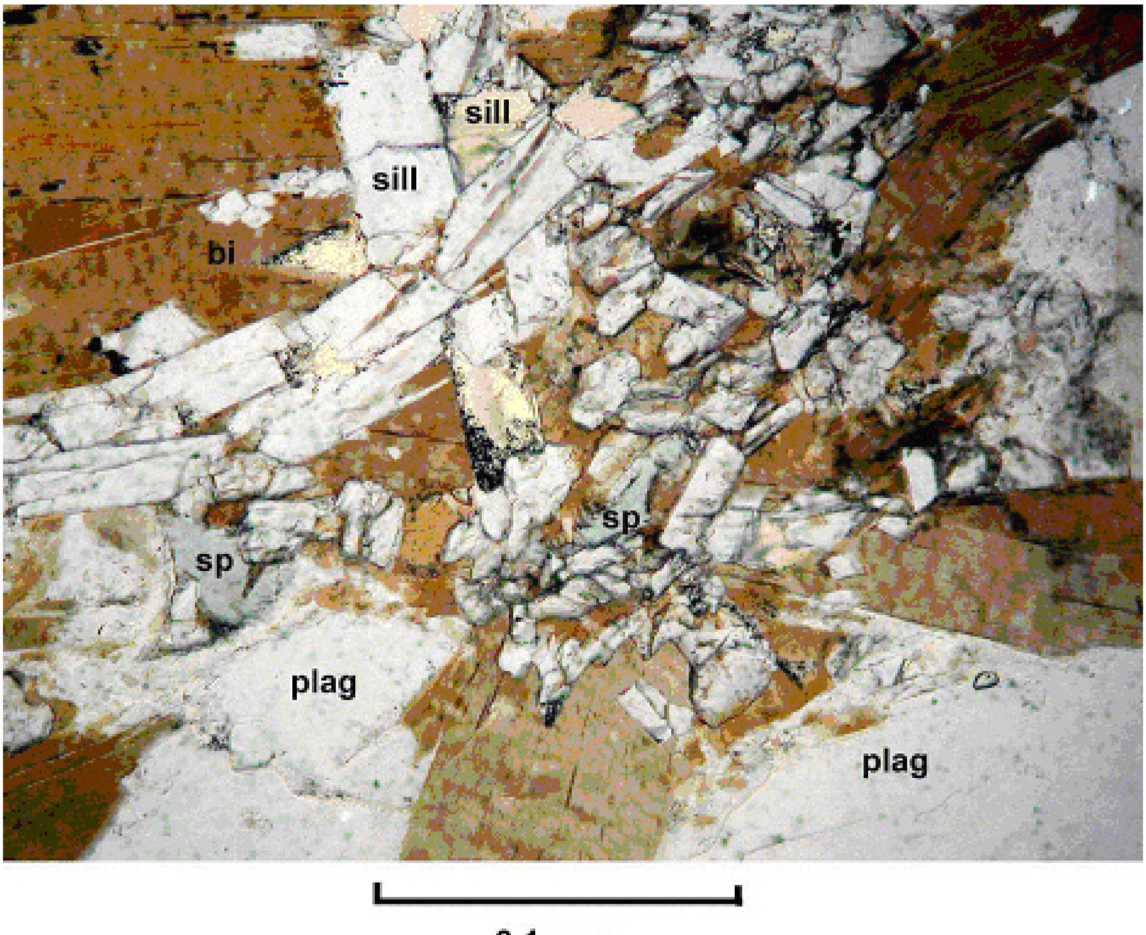


Plate 38 Complex reaction texture adjacent to garnet in pelitic granulite. (R495901) (Photo 049474)

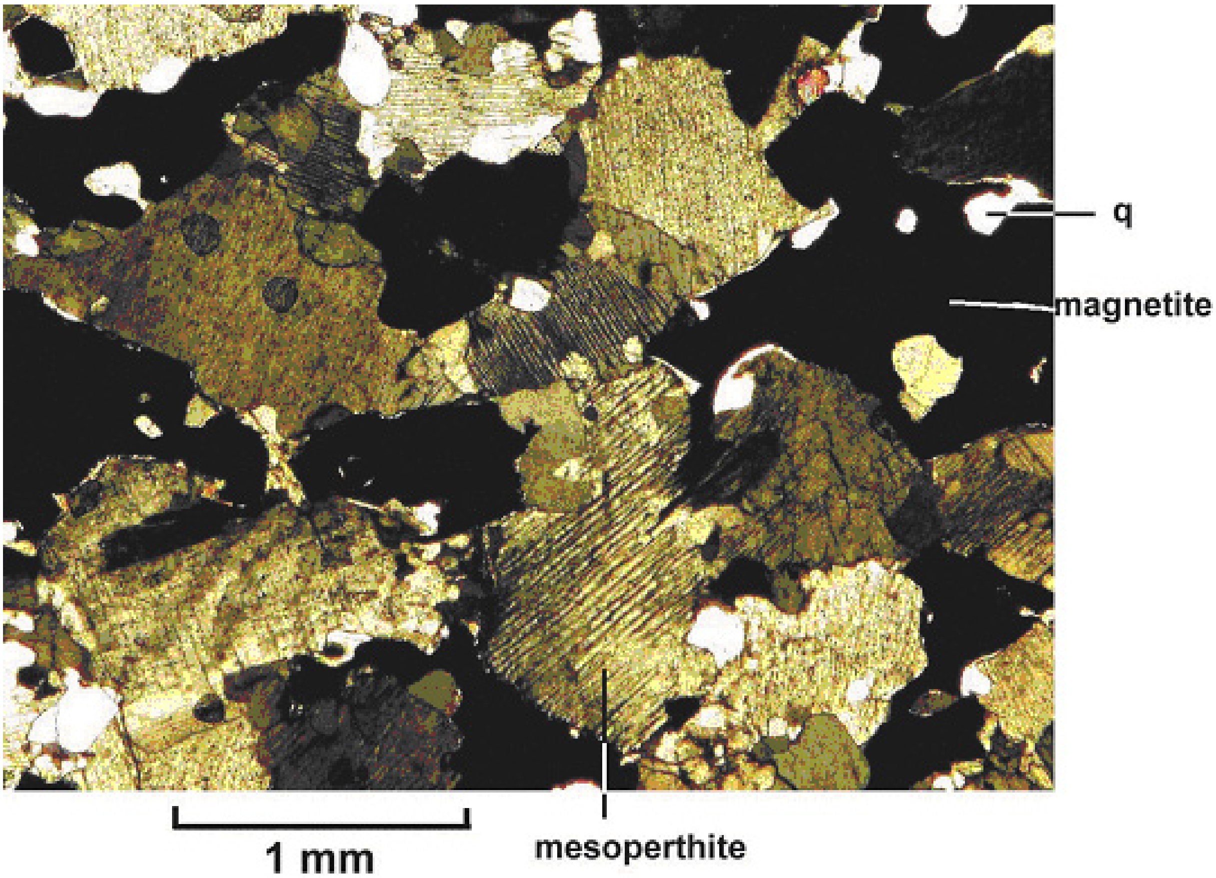


Plate 39 Mesoperthite from Mingary. (Photo 049475)

Kyanite and staurolite occur together in coarse schist and gneiss at Radium Hill and at several locations along the Kings Dam shear zone (Fig. 4). These rocks generally contain a matrix mineralogy of chlorite, biotite and quartz (±muscovite, fibrolite, K-feldspar and plagioclase). Kyanite varies in orientation from randomly orientated in the foliation plane, to strongly aligned, defining a L-S tectonic fabric (Plates 40, 41), and is often folded, exhibiting undulose extinction under crossed polarisers (Plate 42). On the other hand, the staurolite is generally randomly orientated with respect to the rock fabric, and contains folded inclusion trails and no undulose extinction (Plate 43). This suggests that the growth of the two minerals is genetically unrelated and that kyanite growth predates staurolite growth in some of these samples.

5.8.4 LATE RETROGRADE SHEAR ZONES

Several dextral shear zones, trending roughly east–west, bisect the Mingary map area (e.g. the Kings Dam shear zone, Fig. 4). These shear zones appear to truncate and deform several major structures associated with the Olarian deformation events (Crooks, 2001). The surface expression of these shear zones is usually outcropping, coarse-grained garnet (±staurolite)–chlorite schist or garnet–staurolite–biotite–muscovite schist (e.g. University of Adelaide samples MA1 and KD1A, collected by Lachlan Rutherford). Adjacent pelite and mafic rocks are metamorphosed to lower granulite facies (e.g. sample R495899 and R495900), suggesting that the dextral shear zones are retrograde features. Recent Sm–Nd garnet dating by the University of Adelaide returned a Cambrian age for the Kings Dam shear zone (Rutherford and Hand, pers, comm., 2002) indicating that the shear was active at least at that time.

5.8.5 BROAD COMPARISONS BETWEEN THE EASTERN MINGARY AREA AND THE SOUTHWESTERN BROKEN HILL AREA

Rocks of the southeastern Mingary map area share several features with high-grade rocks of the southwestern Broken Hill Domain. These similarities suggest that this area can be allied more closely with the Broken Hill Domain across the border, instead of with the Olary Domain to the west. These similarities include:

- mafic granulite and amphibolite bodies have similar outcrop distribution and abundance in both areas
- almost identical mineral assemblages and retrograde reaction textures occur in the mafic and pelitic gneisses in the southeast portion of the Mingary 1:100 000 map area and the granulite-grade metamorphic rocks surrounding Broken Hill (e.g. Phillips and Wall, 1981; Stroud et al., 1983; Edwards, 1958; Binns, 1964, 1965)
- metamorphic isograds (such as the sillimanite–kyanite isograd) can be correlated on both sides of the state border (Fig. 13)
- an identical metamorphic history can be described for rocks on both sides of the state border. This history involves low-pressure, high-temperature metamorphism and the evolution of the terrane through an anti-clockwise P–T–t evolution (see discussion below)
- gravity and magnetic data suggest that the southeastern part of the Mingary map area is more closely allied with the Broken Hill Domain than with the Olary Domain
- both areas contain pelitic and felsic gneiss lithologies that are believed to belong to the Thackaringa Group of the Broken Hill stratigraphy (Crooks, 2001)
- the presence of characteristic quartz–gahnite(Zn-spinel)-bearing rocks; in the Broken Hill area this lithology is used as an indicator of potentially mineralised stratigraphic horizons.

Rocks of the southern Broken Hill Domain lie within the ‘two-pyroxene’ zone of Phillips (1978; Fig. 2). However, Clarke et al. (1987) defined the Willyama Supergroup rocks covered by the Mingary 1:100 000 map area as belonging to a relatively lower grade sillimanite–muscovite zone. This classification ignores the presence of two-pyroxene bearing (i.e. orthopyroxene and clinopyroxene) mafic granulites and the absence of primary muscovite in metasedimentary rocks from this area. The two-pyroxene zone of Phillips should be

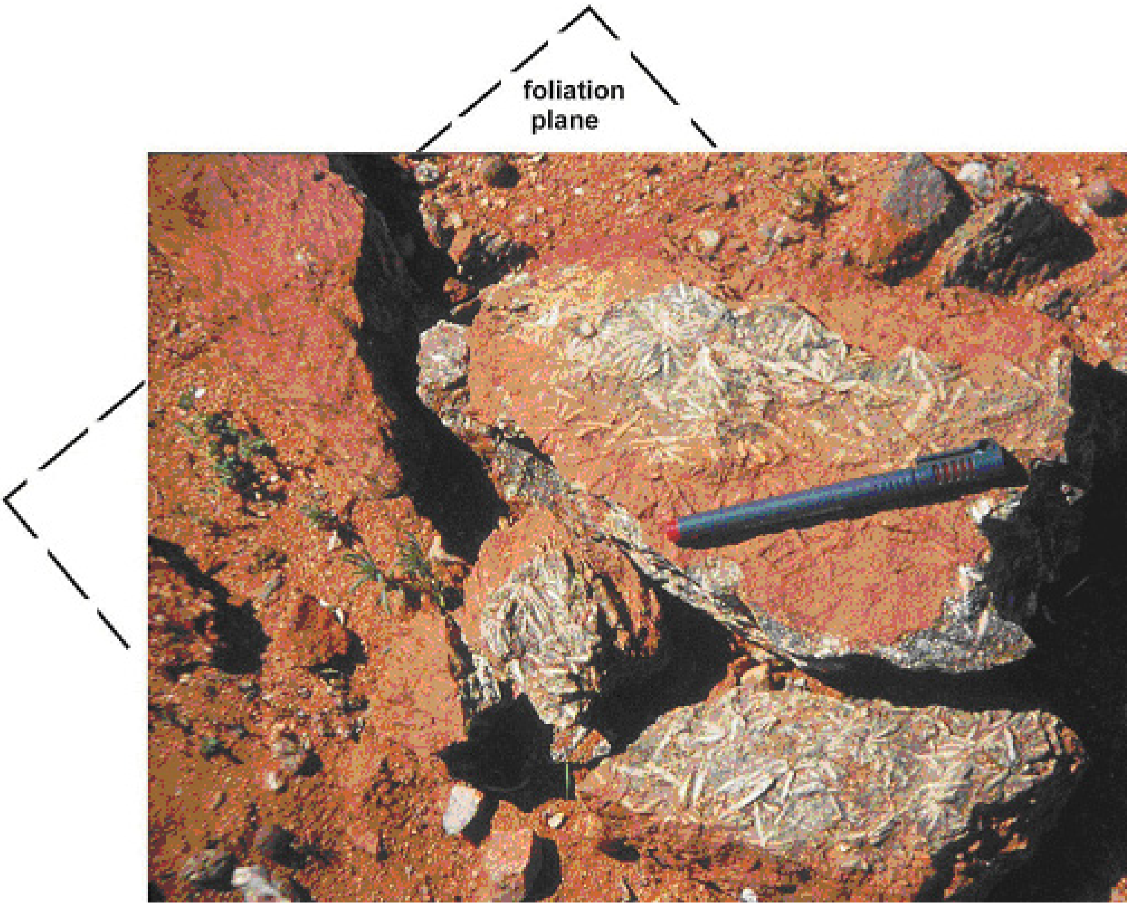


Plate 40 Kyanite flattened in foliation plane, east of Trinity Dam. (R397379) (Photo 049476)

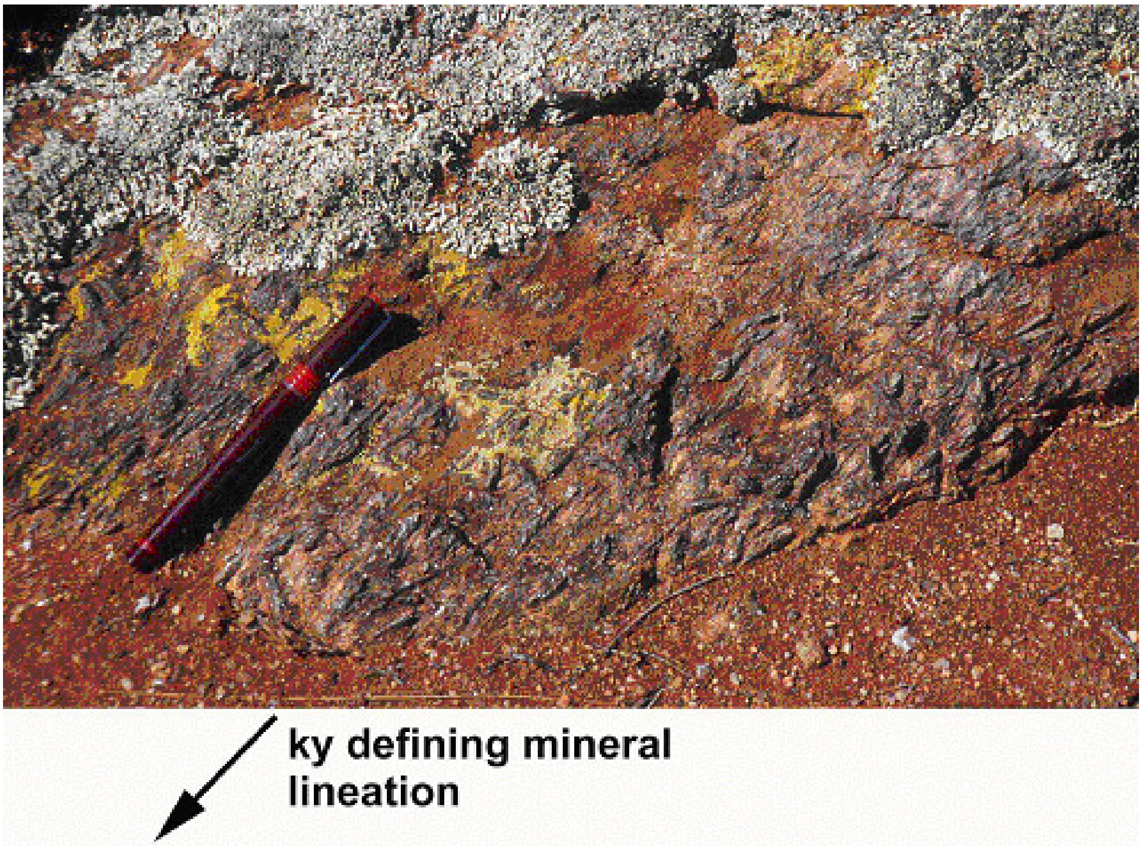


Plate 41 Kyanite defining strong mineral lineation, west of McBride's Dam. (R454666) (Photo 049477)

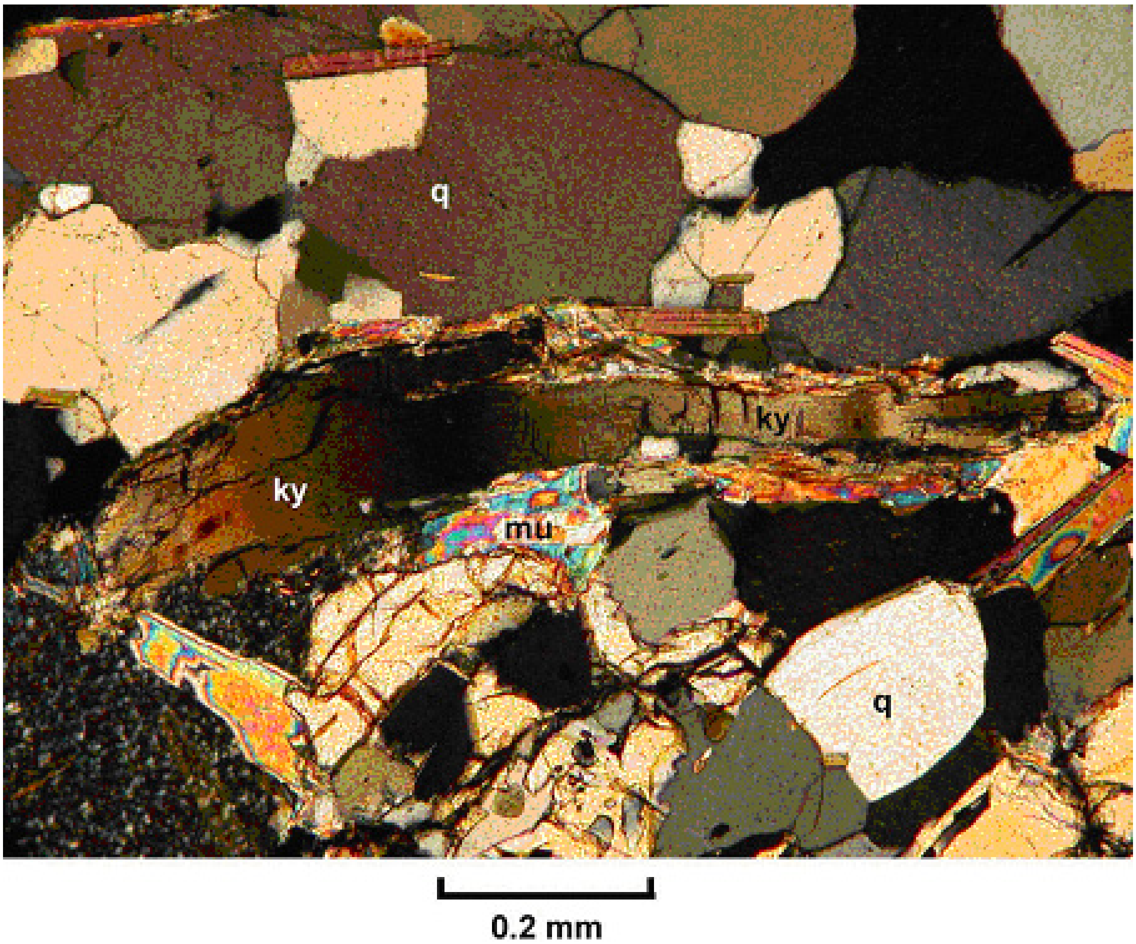


Plate 42 Kyanite displaying undulose extinction (crossed polars; R495903). (Photo 049478)

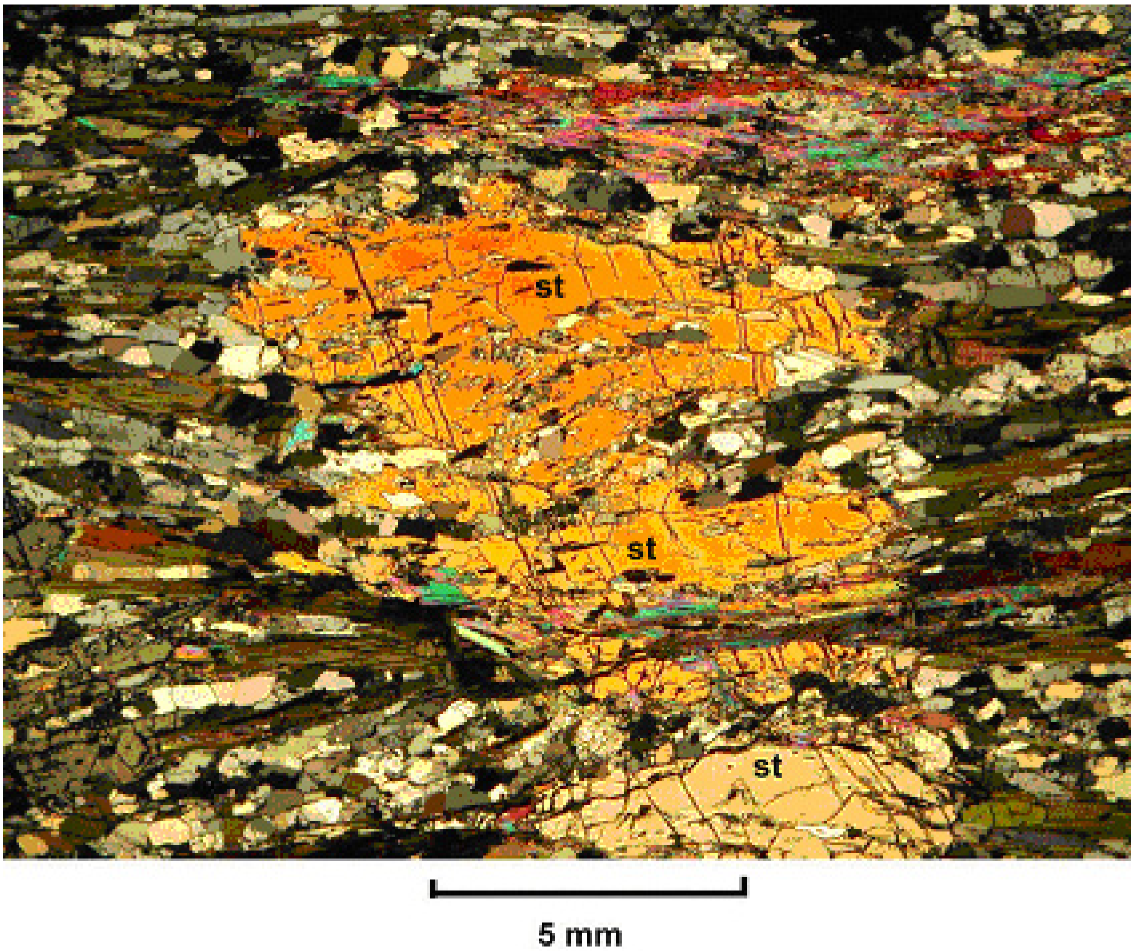


Plate 43 Staurolite, no undulose extinction (crossed polars; R495903). (Photo 049479)

extended to include the granulite-grade rocks at Mingary. This assessment is based on the presence of identical lithologies and metamorphic character on both sides of the state border.

Rocks of the southern Broken Hill Domain lie within the 'two-pyroxene' zone of Phillips (1978; Fig. 2). However, Clarke et al. (1987) defined the Willyama Supergroup rocks covered by the Mingary 1:100 000 map area as belonging to a relatively lower grade sillimanite–muscovite zone. This classification ignores the presence of two-pyroxene bearing (i.e. orthopyroxene and clinopyroxene) mafic granulites and the absence of primary muscovite in metasedimentary rocks from this area. The two-pyroxene zone of Phillips should be extended to include the granulite-grade rocks at Mingary. This assessment is based on the presence of identical lithologies and metamorphic character on both sides of the state border.

6 GIS DATA ANALYSIS OF THE METAMORPHIC MINERAL DATABASE

GIS analysis of the metamorphic mineral database allows determination of the spatial distribution of useful metamorphic minerals across the SAWI. Furthermore, GIS analysis allows for mineral species to be correlated with each other, and with other spatial features (e.g. regional structures, magnetic anomalies, etc.). In turn, this allows for the delineation of qualitative paragenetic zones or domains that can be interpreted in terms of regional metamorphic patterns. In this study, spatial mineral data from the metamorphic mineral database is combined with detailed petrography to assess the distribution of metamorphic isograds described by Clarke et al. (1987).

6.1 The distribution of the aluminosilicate (Al_2SiO_5) polymorphs

The distribution of andalusite, sillimanite, and kyanite in SAWI rocks is shown in Figure 8. Andalusite (including chiastolite) is found in most aluminous pelites that crop out to the north of the Barrier Highway; it is not recorded south of the highway. The chiastolite variety of andalusite is found in carbonaceous schists in the north and northwest of the SAWI. The distribution of chiastolite most probably reflects the distribution carbonaceous pelitic rocks within the andalusite-stable zone, rather than an independent metamorphic constraint.

Both fibrolitic and prismatic sillimanite are ubiquitous across the SAWI. There is an increase in the abundance of prismatic sillimanite relative to fibrolitic sillimanite towards the southeast (Fig. 9). The inverse is generally true towards the northwest, however coarse prismatic sillimanite occurs at Billeroo Hill in the Morialpa Inlier.

Kyanite occurs in three distinct areas (Fig. 8). Firstly, very coarse kyanite is found in the scattered outcrops southeast of the Barrier Highway on the Mingary 1:100 000 map area. The kyanite is often flattened in the main foliation. Secondly, kyanite occurs in the northern Walparuta Inlier in close proximity to a syntectonic granite body. All three polymorphs are found in the pelites from this area. Finally, annotated aerial photographs suggested that Wiperaminga Hill has outcropping kyanite schist, later confirmed by reconnaissance fieldwork carried out during this study. Kyanite is not known to occur any further northeast than Wiperaminga Hill.

Apart from the occurrence of kyanite within the pelite schists, kyanite was also noted in undeformed, late-stage quartz veins both at Wiperaminga Hill (Plate 31) and on Mingary.

6.2 Staurolite and chloritoid distribution and relationships

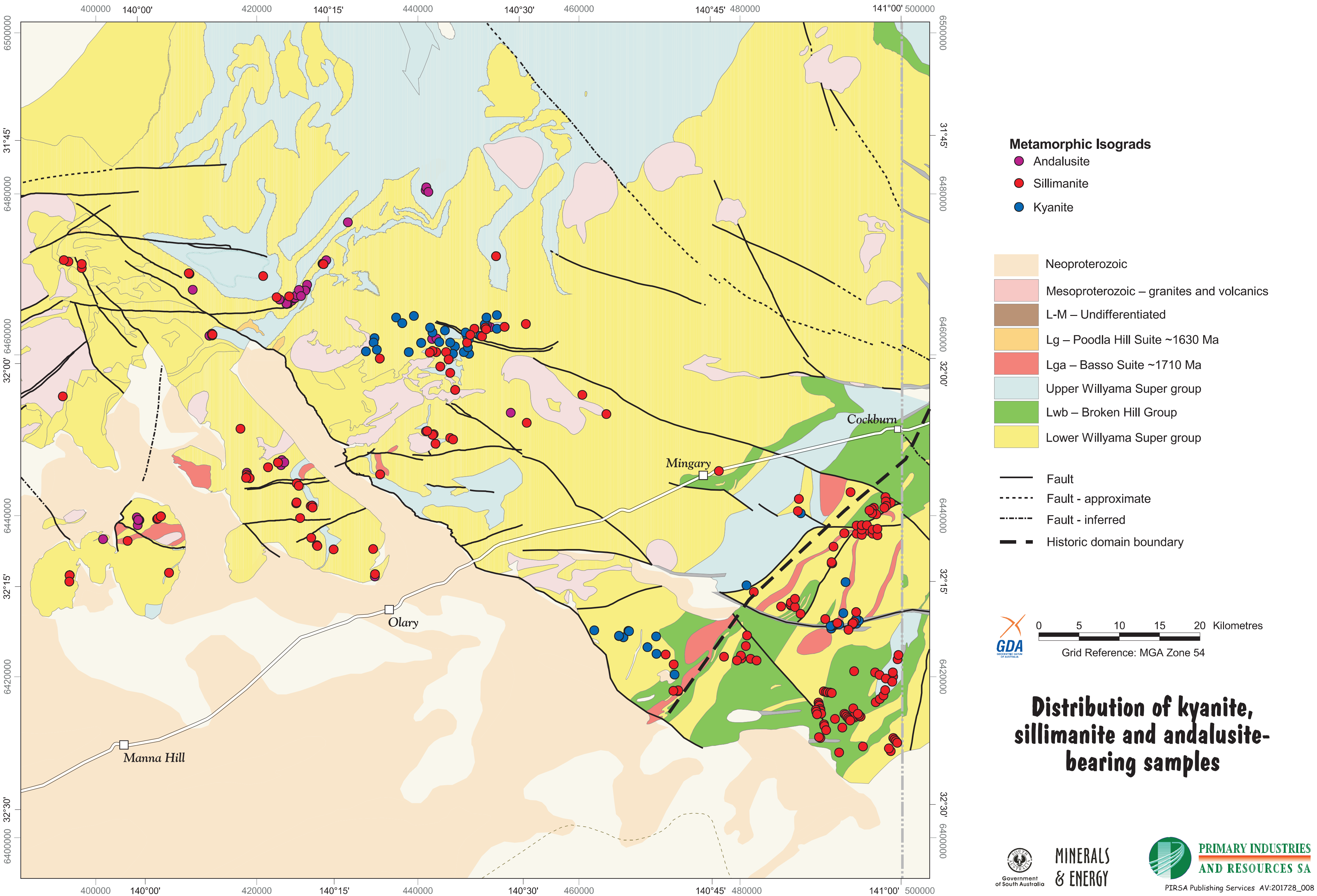
Field and petrographic relationships suggest that staurolite and chloritoid are paragenetically related in the SAWI. Staurolite and chloritoid are observed to grow late in relation to most other porphyroblastic minerals in pelite samples north of the Barrier Highway.

Staurolite is common in pelitic schist and gneiss in the southeastern SAWI (Fig. 10). The northwestern extent of staurolite occurrences is defined by an approximately linear mineral isograd trending roughly east-northeast. This can be considered to be the ‘staurolite-in’ isograd because metamorphic grade increases towards the southeast in the SAWI (Clarke et al., 1987). This isograd occurs to the north of the Weekeroo Inliers and crosses Ameroo Hill and Wiperaminga Hill. The exact location of the isograd is poorly constrained in the north due to the paucity of samples of pelite with recorded mineralogy from the northwestern Outalpa Inlier and to the west and southwest of Wiperaminga Hill. Furthermore, the paucity of pelitic outcrops to the north of the Weekeroo Inliers limits the precise determination of this isograd. However, staurolite is certainly absent from pelite samples from Mount Howden and further northwest (Fig. 10).

The vast majority of staurolite occurrences north of the Barrier Highway (i.e. in the Weekeroo and Outalpa Inliers and at Wiperaminga Hill) are late to post-kinematic. In several thin section samples it is clear that staurolite post-dates the ubiquitous sericite retrogression seen in aluminous pelite rocks from the Willyama Inliers.

Occurrences of chloritoid are found throughout the northwesternmost outcrops of the SAWI. The southeastern limit of chloritoid is a roughly linear isograd trending east-northeast (Fig. 10). The approximate position of this ‘chloritoid-out’ isograd cuts across the Weekeroo Inliers, through the Two Mile Inlier (southern Outalpa Inlier) to just south of Mulga Bore and Cathedral Rock (Fig. 4).

The ‘chloritoid-out’ isograd lies parallel to, but to the south of, the ‘staurolite-in’ isograd (Fig. 10) such that these two isograds define a corridor of pelitic rocks containing both staurolite and chloritoid (Fig. 10).



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141°00'
500000
6500000
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6460000
32°00'
6440000
32°15'
6420000
32°30'
6400000
Cockburn
Mingary
Olary
Manna Hill
Metamorphic Isograds
Andalusite
Sillimanite
Kyanite
Neoproterozoic
Mesoproterozoic – granites and volcanics
L-M – Undifferentiated
Lg – Poodla Hill Suite ~1630 Ma
Lga – Basso Suite ~1710 Ma
Upper Willyama Super group
Lwb – Broken Hill Group
Lower Willyama Super group
Fault
Fault - approximate
Fault - inferred
Historic domain boundary
GDA
0
5
10
15
20
Kilometres
Grid Reference: MGA Zone 54
Distribution of kyanite, sillimanite and andalusite-bearing samples
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Figure 8

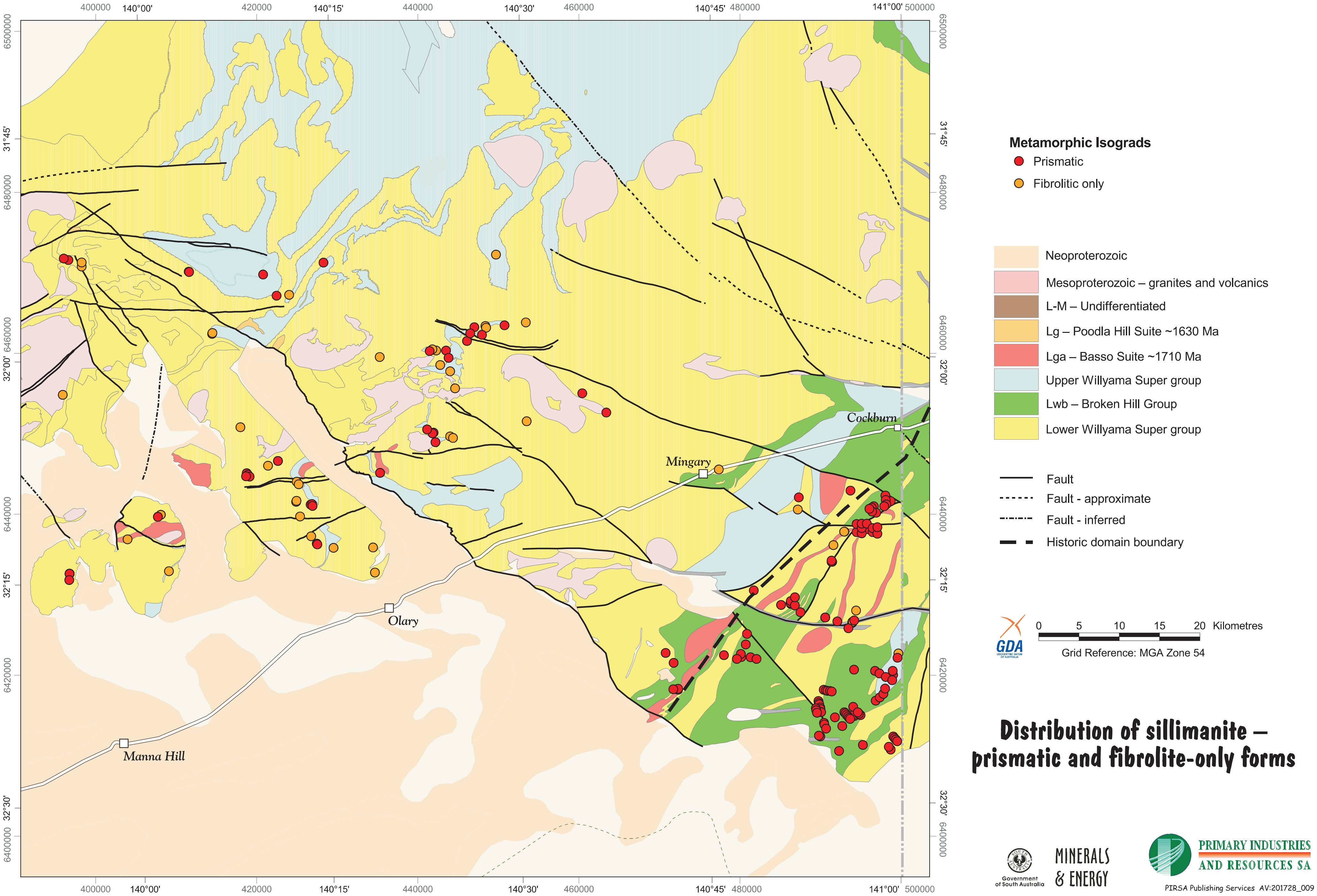
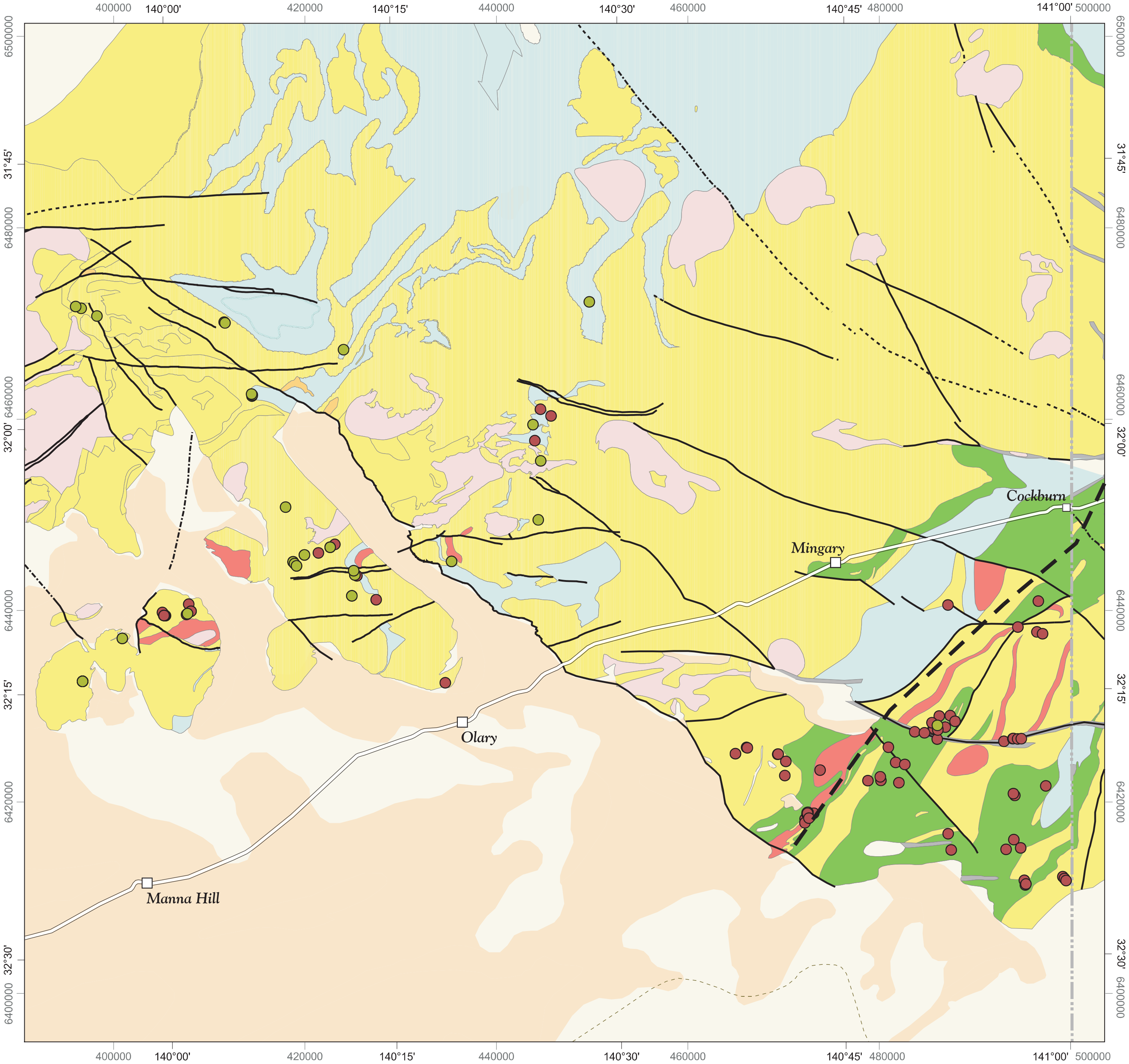

Metamorphic Isograds
Prismatic
Fibrolitic only
Neoproterozoic
Mesoproterozoic – granites and volcanics
L-M – Undifferentiated
Lg – Poodla Hill Suite ~1630 Ma
Lga – Basso Suite ~1710 Ma
Upper Willyama Super group
Lwb – Broken Hill Group
Lower Willyama Super group
Fault
Fault - approximate
Fault - inferred
Historic domain boundary
0 5 10 15 20 Kilometres
Grid Reference: MGA Zone 54
Cockburn
Mingary
Olary
Manna Hill
400000
420000
440000
460000
480000
500000
140°00'
140°15'
140°30'
140°45'
141°00'
6500000
6480000
6460000
6440000
6420000
6400000
31°45'
32°00'
32°15'
32°30'
Distribution of sillimanite – prismatic and fibrolite-only forms
MINERALS & ENERGY
PRIMARY INDUSTRIES AND RESOURCES SA
PIRSA Publishing Services AV:201728_009

Figure 9



Distribution of staurolite and chloritoid-bearing samples

Government of South Australia MINERALS & ENERGY PRIMARY INDUSTRIES AND RESOURCES SA

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Figure 10

6.3 Two-Stage Garnets

Early garnets are common throughout most of the study area. However, the extent of pelitic rocks that contain garnets showing the secondary growth rind within the SAWI is confined to the corridor defined by the 'staurolite-in' and 'chloritoid-out' isograds (Fig. 11). Petrographic analysis suggests that the secondary growth of garnet is late (similar to staurolite and chloritoid). Two-stage garnet occurrences are now known from the northern Walparuta Inlier, Ameroo Hill and the Mulga Bore – Cathedral Rock area. The special correlation of the two-stage garnet domain and the 'staurolite–chloritoid corridor' suggests that these two features are genetically related. However, such a relationship would have to be confirmed through more a detailed petrologic study.

6.4 Other Common Pelitic Minerals

Other minerals such as chlorite, biotite, muscovite, plagioclase, K-feldspar and quartz are broadly ubiquitous. Some important associations can be noted however. Firstly, aluminosilicate-rich lithologies of the Weekeroo Inliers often contain little or no quartz. Secondly, biotite is often isomorphically replaced by late chlorite in pelites across the Olary Domain. Thirdly, as described above, there is microtextural evidence indicating that muscovite was not stable in the southeast of the SAWI during the early M_1 metamorphic event associated with granulite formation. Muscovite found in rocks from this area is considered to be of late retrograde origin. Much of this area has been previously described as of sillimanite–muscovite grade (e.g. Clarke et al., 1987) but should probably be redefined as sillimanite–K-feldspar, implying granulite grade based on the results of this study.

6.5 Granulite-Grade Rocks in the South Australian Willyama Inliers

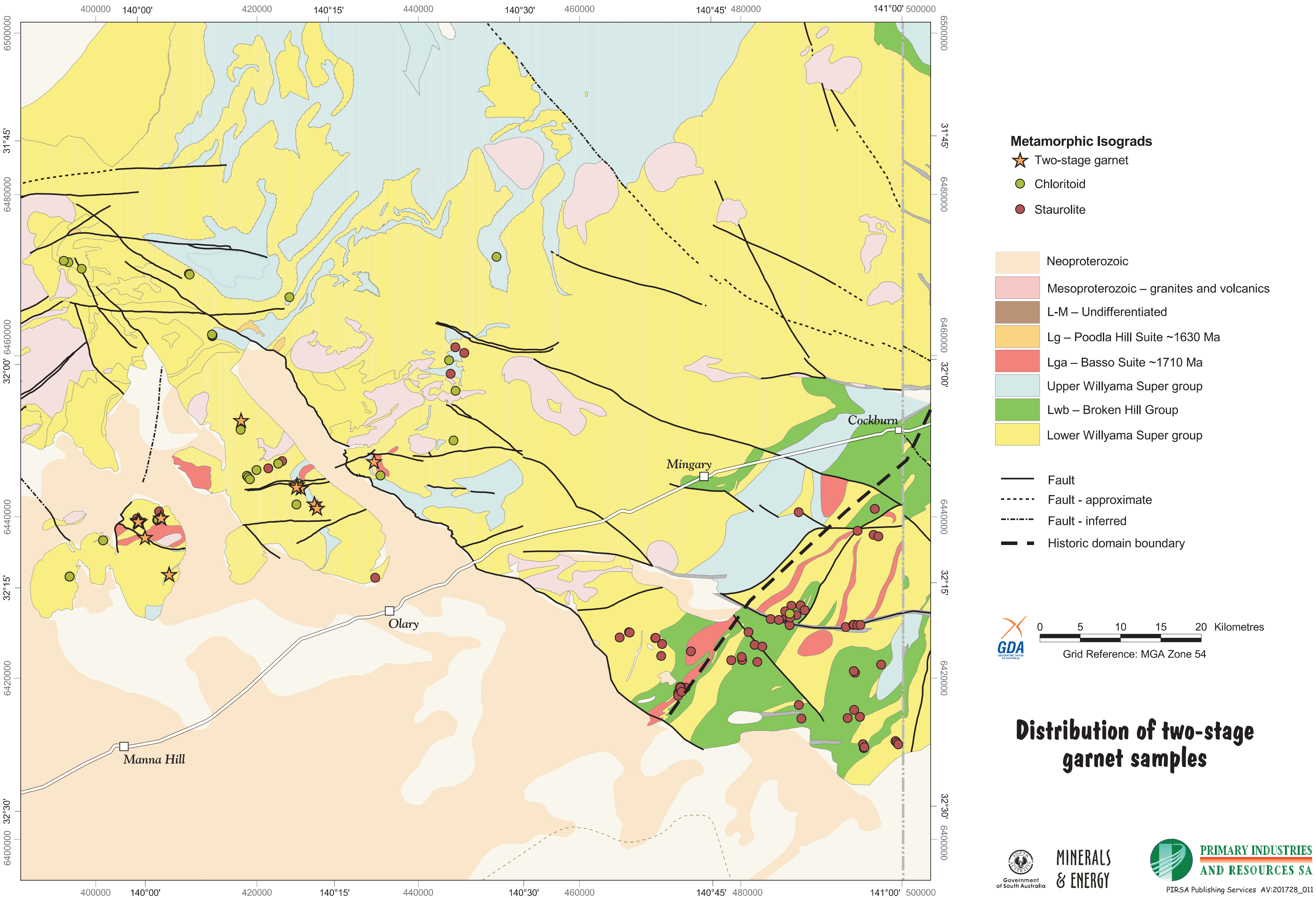
The distribution of granulite-grade rocks is shown in Figure 12. Mesoperthite-bearing samples are included with other granulite samples (pelitic and mafic) in the GIS analysis results (Fig. 12; Appendix A). These granulite rocks are considered to be the remnants of a precursor granulite terrane that probably had a much larger extent.

As discussed above, outcrops of the granulite-grade rocks occur in a northeast–southwest-trending linear belt that parallels a linear gravity and magnetic feature that has been used as a domain boundary (Fig. 7). With evidence for granulite-grade metamorphism to the west of this feature, it is apparent that parts of the Olary Domain reached granulite-facies metamorphic conditions.

7 METAMORPHIC ISOGRADS IN THE BROKEN HILL AND OLARY DOMAINS

There are several reported characteristic differences between the rocks of the Broken Hill and Olary Domains (Flint and Parker, 1993; Conor, 2000; Robertson et al., 1998; Rutherford et al., in prep). However, most of these differences are considered to be stratigraphic or sedimentary facies controlled (Conor, 2000). This observation has been borne out by this current study, with the metamorphic evolution of the two domains seemingly strongly related. Metamorphic mineral isograds, determined in this study for the SAWI, show apparent direct linkages with corresponding isograds reported for the NSWWI (Fig. 13). This indicates that, from the perspective of metamorphism, outcropping rocks of the two domains can be treated as a single entity. Furthermore, detailed mapping of isograds in the NSWWI can be employed to extrapolate isograd locations in poorly outcropping areas of the SAWI. Some of the linkages and extrapolated isograds include:

- The 'staurolite-in' isograds in both domains can be linked across the Mundi Mundi Plain via an approximately straight line. This can be done without any modification to the topology of this isograd.



Metamorphic Isograds
Two-stage garnet
Chloritoid
Staurolite
Neoproterozoic
Mesoproterozoic – granites and volcanics
L-M – Undifferentiated
Lg – Poodla Hill Suite ~1630 Ma
Lga – Basso Suite ~1710 Ma
Upper Willyama Super group
Lwb – Broken Hill Group
Lower Willyama Super group
Fault
Fault - approximate
Fault - inferred
Historic domain boundary
0 5 10 15 20 Kilometres
Grid Reference: MGA Zone 54
Cockburn
Mingary
Olary
Manna Hill
400000
420000
440000
460000
480000
500000
140°00'
140°15'
140°30'
140°45'
141°00'
6500000
6480000
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31°45'
32°00'
32°15'
32°30'
Distribution of two-stage garnet samples
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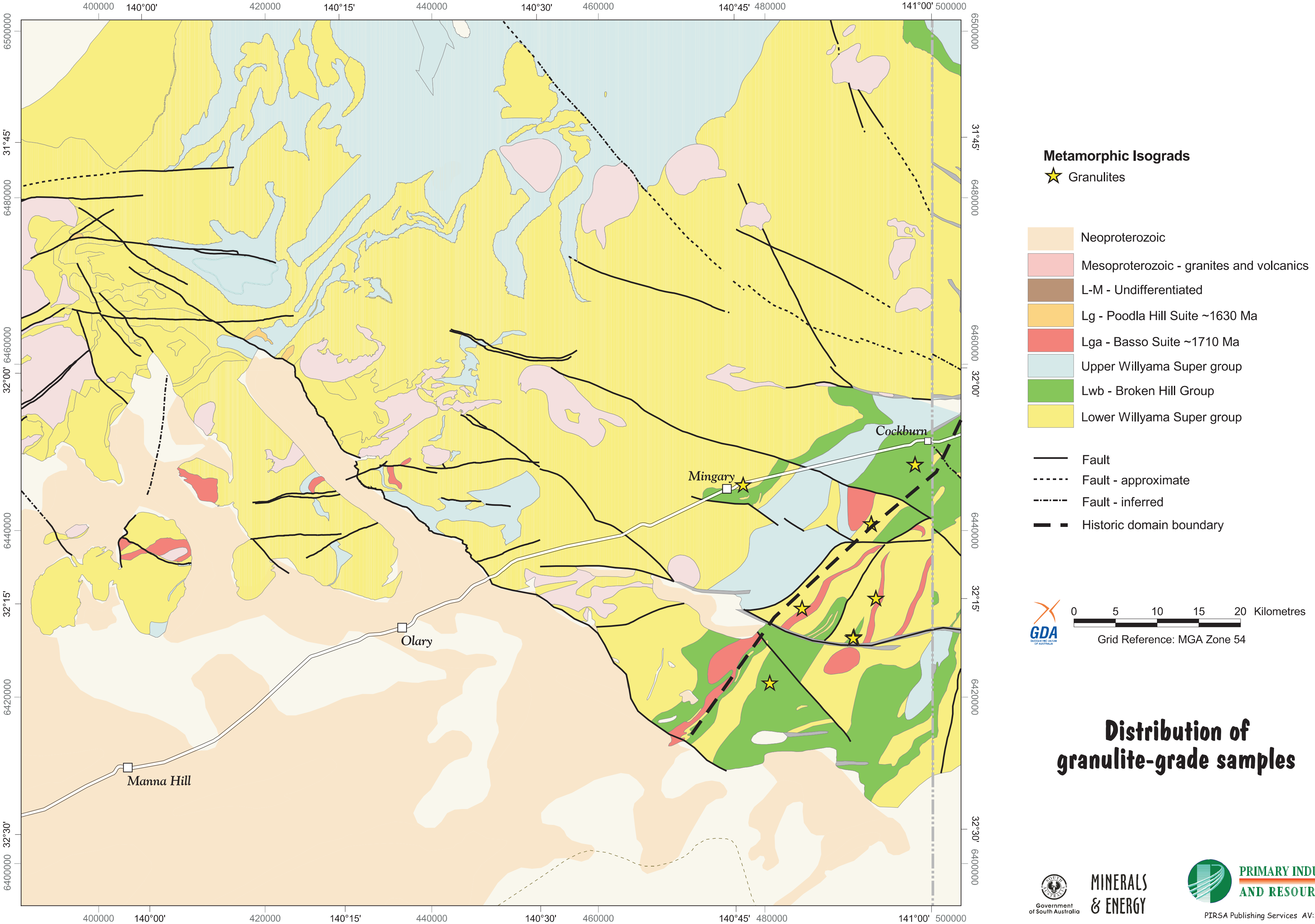
Government of South Australia
PIRSA Publishing Services AV:201728_011

Figure 11



Distribution of granulite-grade samples

Figure 12

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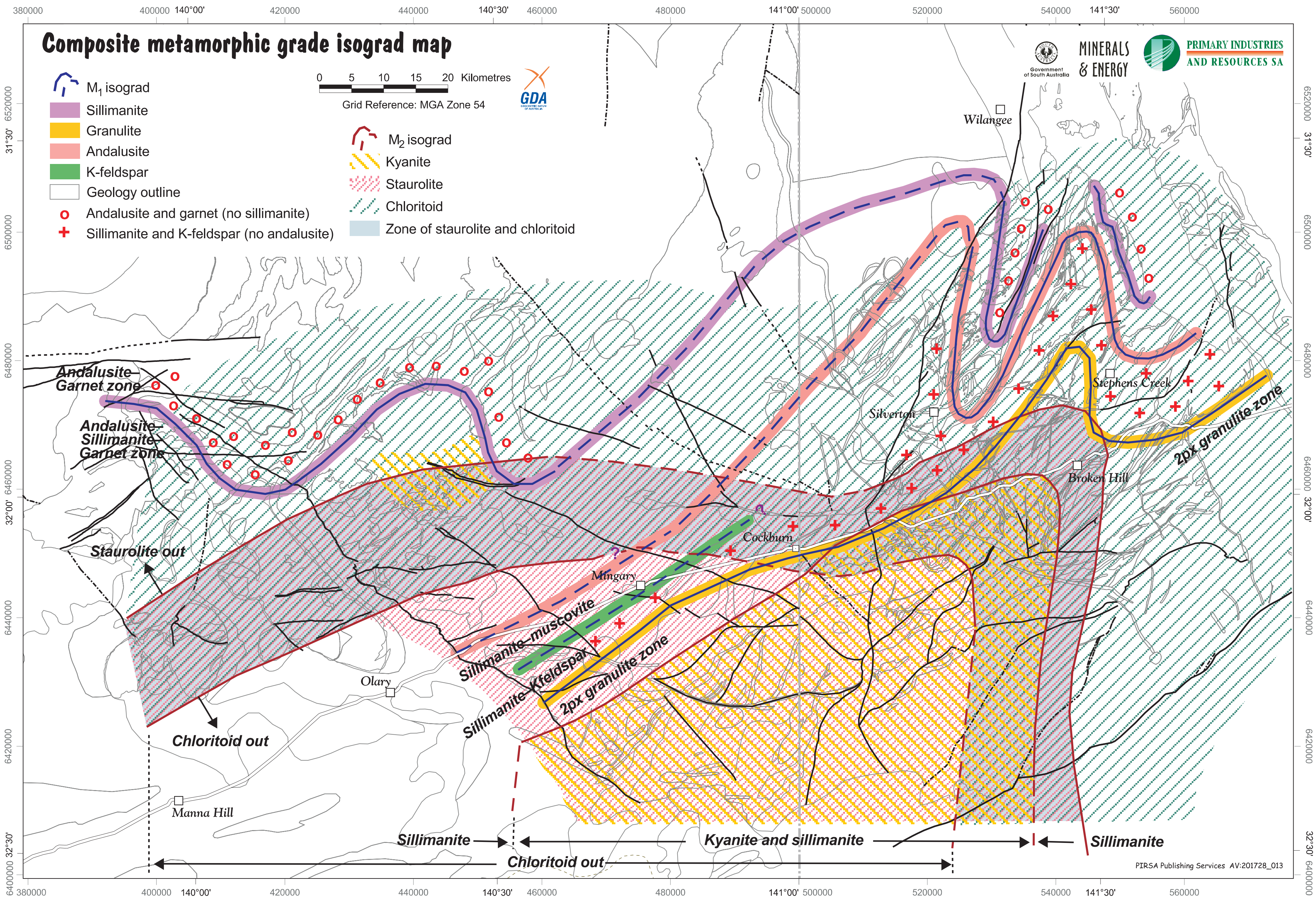


Composite metamorphic grade isograd map
M_1 isograd
Sillimanite
Granulite
Andalusite
K-feldspar
Geology outline
Andalusite and garnet (no sillimanite)
Sillimanite and K-feldspar (no andalusite)
0 5 10 15 20 Kilometres
Grid Reference: MGA Zone 54
GDA
M_2 isograd
Kyanite
Staurolite
Chloritoid
Zone of staurolite and chloritoid
MINERALS & ENERGY
PRIMARY INDUSTRIES AND RESOURCES SA
Government of South Australia
Wilangee
Silverton
Stephens Creek
Broken Hill
Cockburn
Mingary
Olary
Manna Hill
Andalusite–Garnet zone
Andalusite–Sillimanite–Garnet zone
Staurolite out
Chloritoid out
Sillimanite–muscovite
Sillimanite–Kfeldspar
2px granulite zone
Sillimanite
Kyanite and sillimanite
PIRSA Publishing Services AV:201728_013

Figure 13

- The ‘chloritoid-out’ isograd can also be linked, in a similar fashion to the ‘staurolite-in’ isograd. This isograd is not well mapped in the NSWWI, but is believed to occur to the southwest of Broken Hill (G. Corbett, geological consultant, pers. comm., 2002).
- The ‘kyanite-in’ isograd is poorly constrained in the Mingary kyanite-bearing domain due to the paucity of outcrop and suitable lithologies. However, the well-defined ‘kyanite-in’ isograd in the adjacent southern NSWWI can be readily extrapolated across the border.
- The boundary of the two-pyroxene granulite domain of the southern NSWWI can be extrapolated into the SAWI to provide a quasi-minimum constraint on the extent of this domain in South Australia.
- It would appear that the granulite domain and the coincident ‘kyanite-present’ domain also define a zone in which the Mesoproterozoic Bimbowrie Suite granite is absent. On the SAWI, these isograds also define a transition from a gross ‘migmatisation-absent’ to a ‘migmatisation-present’ domain. This may represent a subdivision between ‘melt-source’ and ‘melt-destination’.

8 THERMOBAROMETRY AND P-T DATA

8.1 Olary Domain P–T data

The following published P–T data is available for the Olary Domain.

Chubb (2000) reported the following P–T data from the White Dam area:

- garnet–biotite thermometry (method of Ferry and Spear, 1978):
  core = 531°C ± 28°C
  rim = 498°C ± 99°C
- plagioclase–amphibole thermometry:
  507°C ± 50°C.

Clarke et al. (1995) analysed the composition of KFMASH (K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O) bearing minerals from the Waterfall Creek andalusite schist and determined that the M_1 assemblage formed at 645°C and 6.1 kbar.

Laws (1990) reported temperature data based on arsenopyrite compositional data from an area to the east of Kalabity Station. The arsenopyrite thermometer yielded a temperature of 500–580°C. The inferred significance of this result was not made clear.

8.2 P–T estimates on mineral assemblages at Mingary

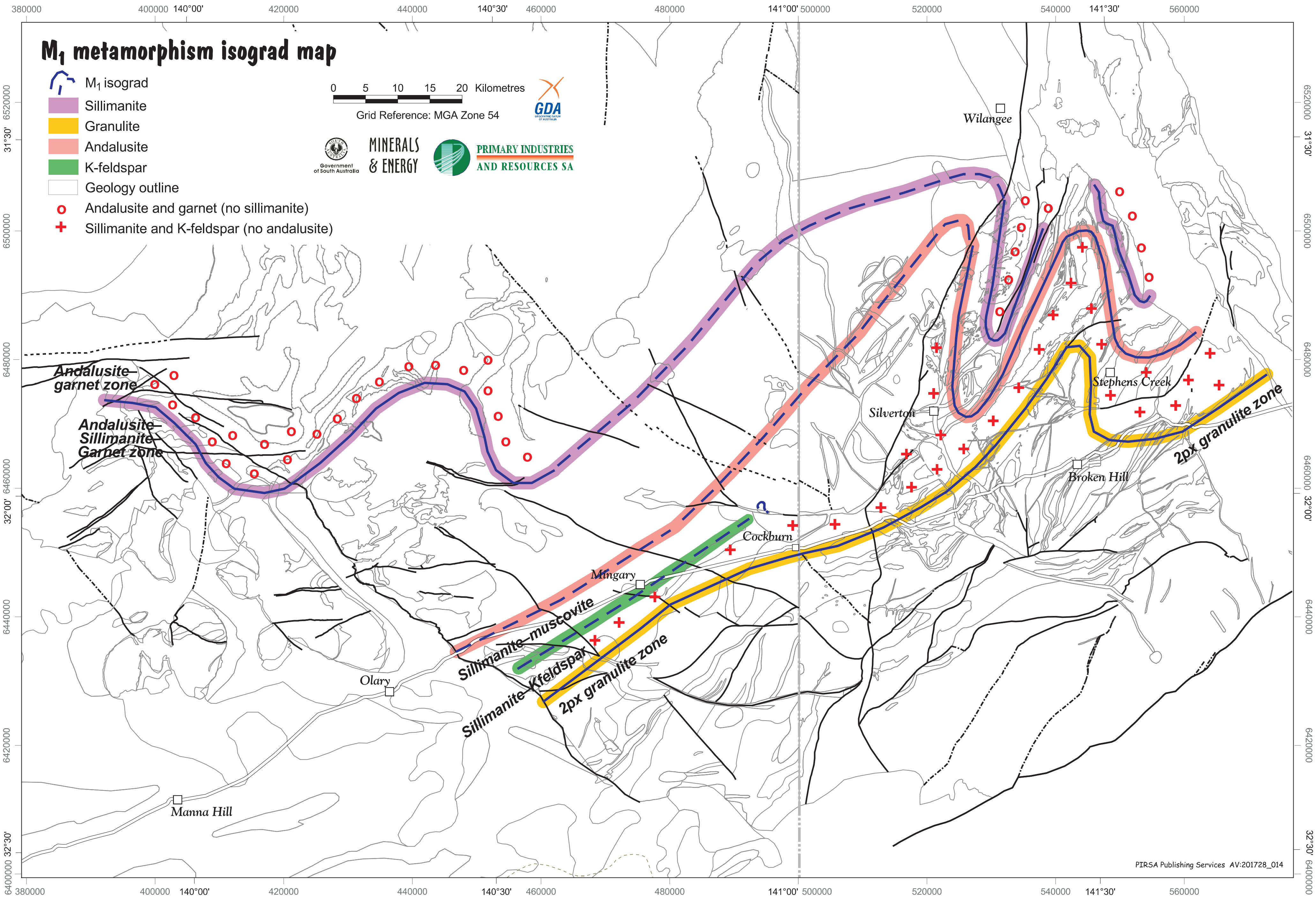
Using electron microprobe compositional data derived from the garnet–plagioclase–sillimanite-bearing pelitic gneiss, the garnet–aluminosilicate–quartz–plagioclase (GASP) geobarometer was employed to constrain the peak metamorphic pressures for the inferred M_1 assemblage. Assuming a peak temperature of 700–800 C (±125°C), representing lower granulite grade temperatures, the GASP geobarometer returned a pressure range of 4.6 to 5.6 kbar (±1.22 kbar). This complements the pressure data of Phillips and Wall (1981) for NSWWI that gives M_1 pressures in the range 4 to 6 kbar. Their pressure estimates were based on the use of three barometers; one from the mafic granulites and two from pelitic gneisses. Evidence from other parts of the Willyama Inliers indicates that prograde M_1 metamorphism involved near isobaric heating at relatively low pressures under high geothermal gradient conditions (Phillips and Wall, 1981; Clarke et al., 1987; Stuwe and Elhers, 1997). Peak temperatures for M_1 metamorphism are not well constrained in these rocks.

Retrograde metamorphism (M_2) of the area is thought to have occurred at slightly higher pressures than the M_1 metamorphism (Corbett and Phillips, 1981; Clarke et al., 1987). Corbett and Phillips used the g-opx-plag-q geobarometer to calculate a retrograde pressure minimum of 5 kbar (during M_2) for retrogressed, mafic granulites near Broken Hill. Similar pressures were reported by Stuwe and Elhers (1997), who P–T pseudosection analysis to determine M_1 and M_2 P–T conditions for staurolite–chloritoid-bearing pelitic rocks in Nine Mile region of the Broken Hill Domain. The P–T path dictated by this style of metamorphism is an anticlockwise P–T path (Phillips and Wall, 1981; Clarke et al., 1987). Low-pressure, high-temperature metamorphism and anticlockwise P–T paths are characteristic of many Proterozoic terranes (Oliver, 1997). This is opposed to a clockwise P–T path typified by Alpine-style continental collisional orogens.

9 CONCLUSIONS

The results of this study generally agree with the metamorphic isograd mapping of Clarke et al. (1987). However, from the data, the SAWI appears to show systematic variation in metamorphic character involving mineral paragenesis developed during at least two metamorphic events (M_1 and M_2). This evidence for a poly-metamorphic history in the Willyama Inliers is similar to the model proposed by Stuwe and Elhers (1997) for the NSWWI. This is at variance with the single P–T–t path proposed by Clarke et al. (1987) and Phillips and Wall (1981). While more comprehensive field-based research is needed to constrain such an hypothesis, it has important implications for the integrated tectonic studies of the South Australian and New South Wales Willyama Inliers.

This mineral paragenesis is depicted in tabular form (Table 2), with the subdivision into metamorphic zones based on mineral assemblages attained. A possible notation system is also shown in brackets. Metamorphic isograds, based on the outcrop pattern related to this zonation of the metamorphic minerals of these two events, is depicted in Figures 14 to 16.



M1 metamorphism isograd map
M1 isograd
Sillimanite
Granulite
Andalusite
K-feldspar
Geology outline
Andalusite and garnet (no sillimanite)
Sillimanite and K-feldspar (no andalusite)
0 5 10 15 20 Kilometres
Grid Reference: MGA Zone 54
GDA
Government of South Australia
MINERALS & ENERGY
PRIMARY INDUSTRIES AND RESOURCES SA
Andalusite-garnet zone
Andalusite-Sillimanite-Garnet zone
Sillimanite-muscovite
Sillimanite-Kfeldspar
2px granulite zone
2px granulite zone
Wilangee
Silverton
Stephens Creek
Broken Hill
Cockburn
Mingary
Olary
Manna Hill
380000
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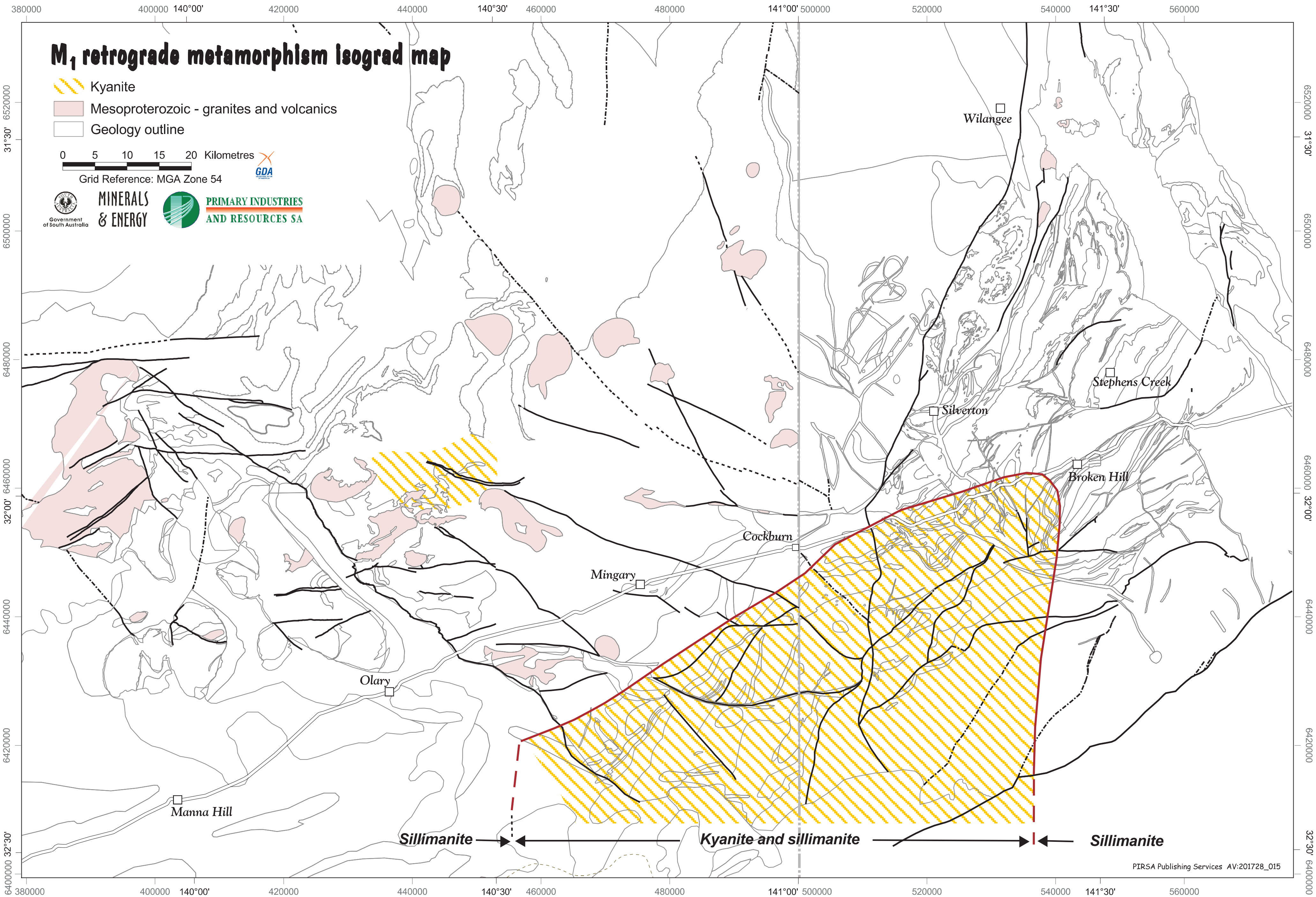
Figure 14



M1 retrograde metamorphism isograd map
Kyanite
Mesoproterozoic - granites and volcanics
Geology outline
0 5 10 15 20 Kilometres
Grid Reference: MGA Zone 54
GDA
Government of South Australia
MINERALS & ENERGY
PRIMARY INDUSTRIES AND RESOURCES SA
Wilangee
Stephens Creek
Silverton
Broken Hill
Cockburn
Mingary
Olary
Manna Hill
Sillimanite
Kyanite and sillimanite
Sillimanite
380000
400000
140°00'
420000
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140°30'
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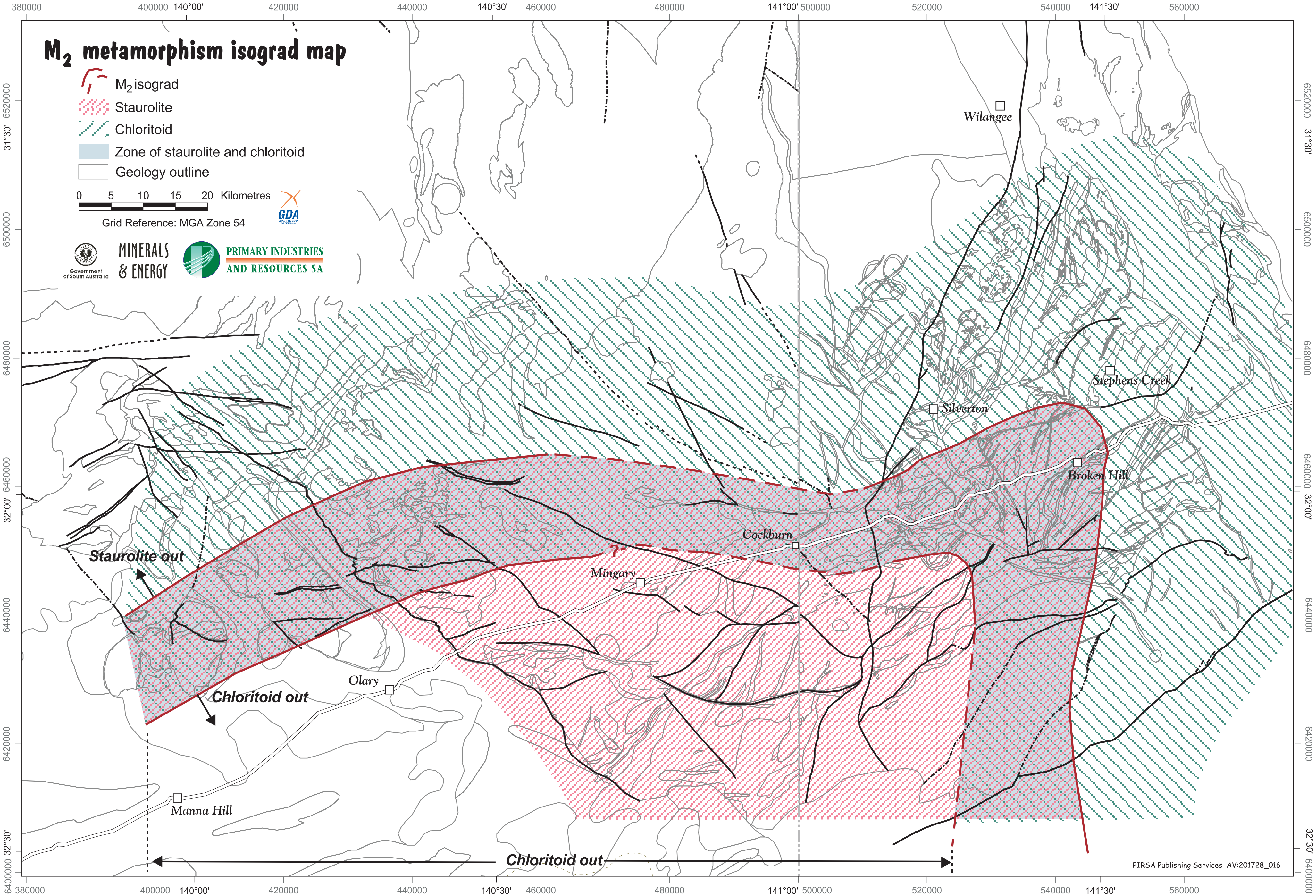
Figure 15



M2 metamorphism isograd map
M2 isograd
Staurolite
Chloritoid
Zone of staurolite and chloritoid
Geology outline
0 5 10 15 20 Kilometres
Grid Reference: MGA Zone 54
GDA
Government of South Australia
MINERALS & ENERGY
PRIMARY INDUSTRIES AND RESOURCES SA
Wilangee
Stephens Creek
Silverton
Broken Hill
Cockburn
Mingary
Olary
Manna Hill
Staurolite out
Chloritoid out
Chloritoid out
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Figure 16

Table 2 Two-stage metamorphism, southern Curnamona Province

M_1 peak metamorphism (syn D_1 to D_2; Fig. 14)	
Andalusite–garnet zone	**(M_1-zone I)**
Andalusite–sillimanite–garnet zone (including cores of two growth stage garnets)	**(M_1-zone II)**
Sillimanite–muscovite zone	**(M_1-zone III a)**
Two-pyroxene granulite zone	**(M_1-zone III b)**
M_1 retrograde metamorphism (late to post-D_3; Fig. 15)	
Ubiquitous sericite retrogression	**(M_1-Retro)**
This is possibly also when kyanite grows in the southeast of the SAWI.	
M_2 peak metamorphism (late to post-D_3; Fig. 16) (and possibly Delamerian)	
Chloritoid zone	**(M_2-zone I)**
Chloritoid – staurolite zone (possibly including rims of two growth stage garnets)	**(M_2-zone II)**
Staurolite zone (and possibly amphibolite overprinting of the M_1-zone IIIb assemblages)	**(M_2-zone III)**

This study, by design, was regional in scope. It has provided some indicators for directing future studies to further refine the isograd positions. These include:

- As mentioned in the text, the MacDonald Fault is a major structure with the potential for bringing blocks with differing metamorphic histories into juxtaposition. Other shears, like the Walter–Outalpa and the King Dam shear, are also major through-going structures. However, the regional isograd map appears to show no signs of major displacements along these long-lived structures. More detailed studies are required to investigate this further at a local scale.
- Thermal perturbations adjacent to late Olarian Orogeny granites appear to have caused local variations in metamorphic mineral assemblages. Further study of these minerals with respect to the known age for these intrusive granites may assist the understanding of the timing of metamorphic events.
- The timing of the development of zones of migmatisation across the SAWI was outside the scope of this study. Flint and Parker (1993) considered these to be related to intrusion of late Olarian Orogeny granites, but the folding at Koolka Hill within the migmatites (Plate 8) implies an earlier timing for some migmatisation. The location and timing of these thermal events should have influenced the location and timing of metamorphic mineral growth and, hence, should be reflected in the position of the mineral isograds.
- More detailed assessment of the extent of both the granulite-grade rocks and the retrograde kyanite on both sides of the border, but particularly near the Mingary siding, would appear to be required to confirm the geometry of the granulite isograd in more detail.

The granulite to amphibolite-grade lithologies on the Mingary 1:100 000 map area are petrologically identical to the high-grade metamorphic rocks around Broken Hill. In particular, mafic granulites from both areas preserve identical prograde and retrograde metamorphic assemblages. This supports the notion that these two areas are part of the same high-grade domain. Other similarities between the two areas include the continuity of gravity and magnetic signatures across the state border, the presence of Thackaringa Group sediments in both areas, and the occurrence of gahnite-bearing quartzite (indicative of Broken Hill-style mineralisation). A significant amount of exploration that has been carried out on the New South Wales portion of this economically important, high-grade terrane. However, the same is not equally true for the South Australian part of this terrane. In short, the high-grade metamorphic rocks at Mingary are highly prospective.

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APPENDIX A

MINERALOGICAL DATA, SOUTHERN CURNAMONA PROVINCE, SOUTH AUSTRALIA (Excel file)