



**Aeromagnetic interpretation of a section of the Willyama Inliers in the  
Curnamona Craton, South Australia**

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## Statement

To the best of my knowledge and belief, and except where reference is made herein, this thesis contains no material previously published or written by another person, nor any material that has been accepted for the award of any other degree or diploma in any University.

If this thesis is accepted for the award of the degree, I consent to the thesis being made available for photocopying and loan.

Mohammad Reza Haidarian

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## Abstract

This research provides maps which show in detail the position of different geological rock types and structures of the Willyama rocks that are totally covered by younger sediments to the north of the outcrop on the Olary Block and west of the Broken Hill Block. This is possible because the Quartzofeldspathic Suite, the Calcsilicate Suite and the calcalbitite rocks (the gradation between the two Suites) of the Willyama sequence provide a magnetic marker horizon which allows mapping of folds whose axes trend NE-SW and major faults which strike NW-SE and NNE-SSW.

The Quartzofeldspathic Suite shows a bi-modal distribution of susceptibilities with the lower peak similar to the Calcsilicate Suite and the higher peak one to several orders of magnitude greater than the lower. Thus it is not possible to map the Calcsilicate Suite magnetically and the previous definition of the Calcsilicate Suite as the magnetic marker is called into question. However the position of the weakly magnetic and sulfidic Bimba Suite may be deduced from the location of the quartzofeldspathic magnetic marker. It is difficult to distinguish the Bimba and the Pelite Suite magnetically and the amplitude of the anomalies of the composite gneiss and migmatite Suite lies between the amplitude of the anomalies of the magnetic marker; the Bimba Suite and the Pelite Suite.

The depth to the magnetic sources on the eastern three quarters of the Benageri 1:100,000 sheet is less than 350 metres and almost half of them are less than 200 metres deep. Magnetic interpretation shows that no Willyama rocks are present at relatively

shallow depths in the western half of the Benageri 1:100,000 sheet. This is consistent with the drill hole data.

The interpreted lineaments map shows cross cutting faults which strike NW-SE and NNE-SSW in the Olary Block. This pattern is similar to the pattern of cross cutting faults in the central province of the Broken Hill Block. Extension of the Mundi Mundi Fault and the Thackaringa Fault can be followed from the Broken Hill Block to the Olary Block.

The Willyama rocks are the source of half of the anomalies in the Curnamona 1:250,000 sheet; the volcanic rocks in the Curnamona 1:250,000 sheet is restricted to the Benageri 1:100,000 sheet and continues towards north to the Frome area; and the Adelaidean rocks which are essentially non-magnetic and occupies mostly the northern part of the Curnamona 1:250,000 sheet represent three different magnetic domains in the Curnamona section of the Olary Block.

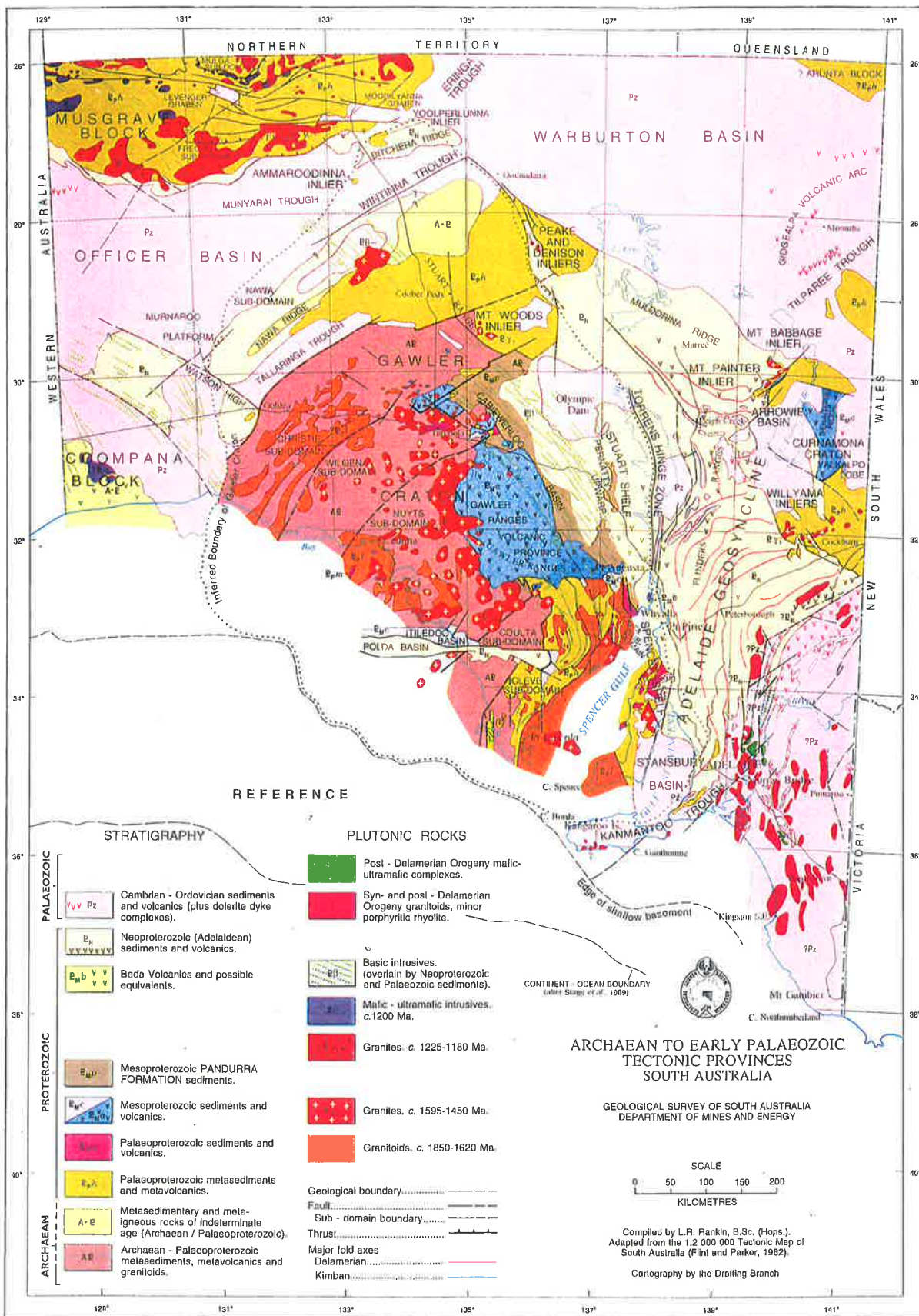


Fig. 1.1 Archean to Early Palaeozoic tectonic provinces of South Australia (after Drexel et al., 1993).



## **1. Introduction**

### **1.1. Preamble**

The Curnamona Craton and the Willyama Inliers are located on the eastern and north eastern margins of the Adelaide geosyncline (fig 1.1) and form a major paleo- to Meso-Proterozoic province of substantial economic importance, being host to the large Broken Hill Pb-Zn-Ag orebody (Flint and Parker, 1993). There are few outcrops of the Curnamona Craton, since it is covered by platformal sediments of the Arrowie basin (Cambrian), Frome embayment (Mesozoic) and Cainozoic basins.

The Craton is well defined on aeromagnetic images (fig 1.2) as a large semi-circular crustal block, approximately 250 km in diameter, with a regionally high total magnetic intensity. Composition of the Curnamona Craton is similar to that of the eastern edge of the Gawler Craton. Meso-Proterozoic volcanics and sediments in the central area overlie late Paleo-proterozoic metamorphic sequences exposed in the south in the Willyama Inliers (Flint and Parker, 1993).

The present configuration and distribution of the Paleo-Proterozoic basement in the Willyama represent complex overprinting of Olarian (~1700-1580 Ma), Adelaidean (~850-570 Ma) and Delamerian (~500 Ma) structures. The combined effect of these

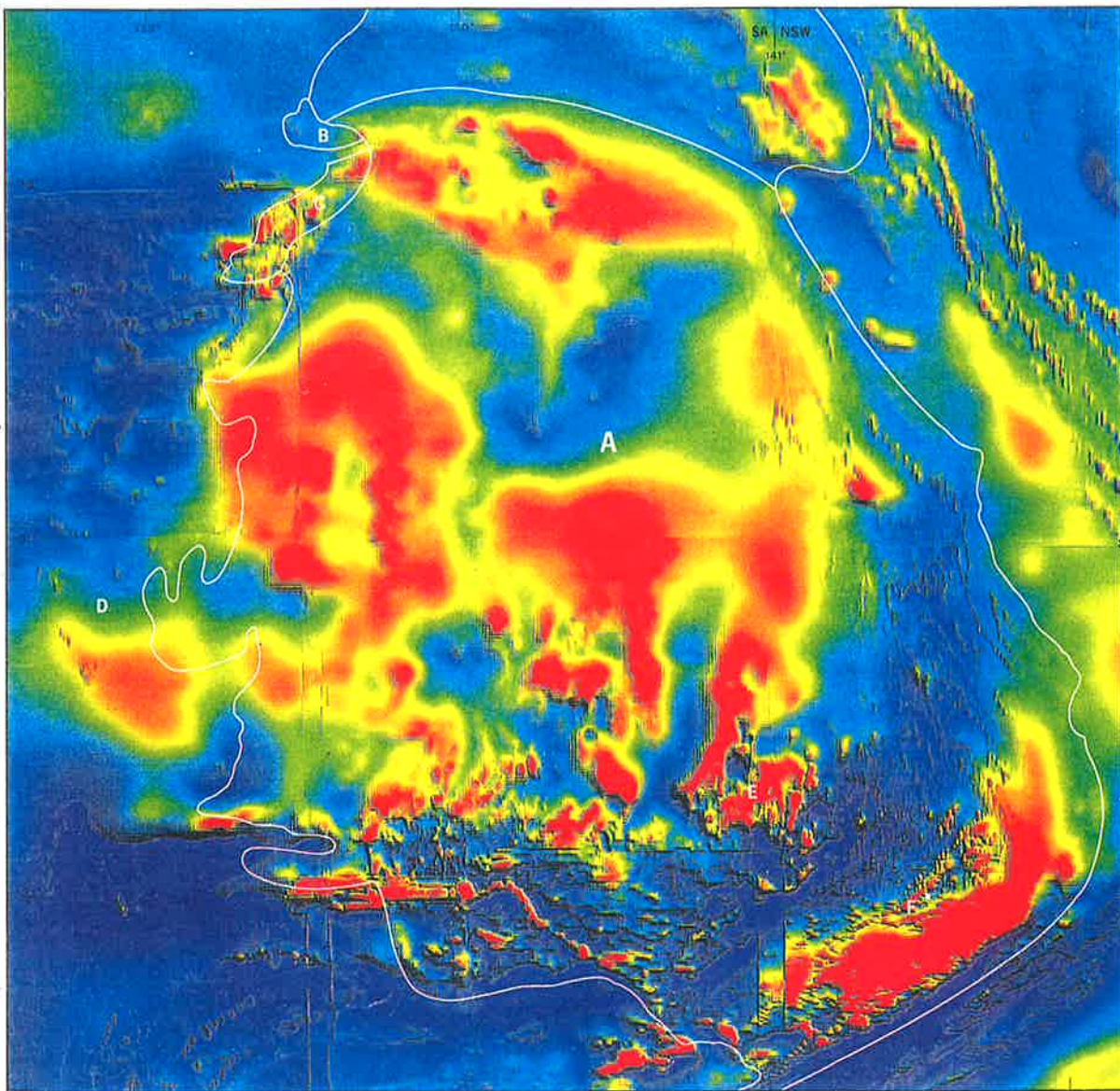
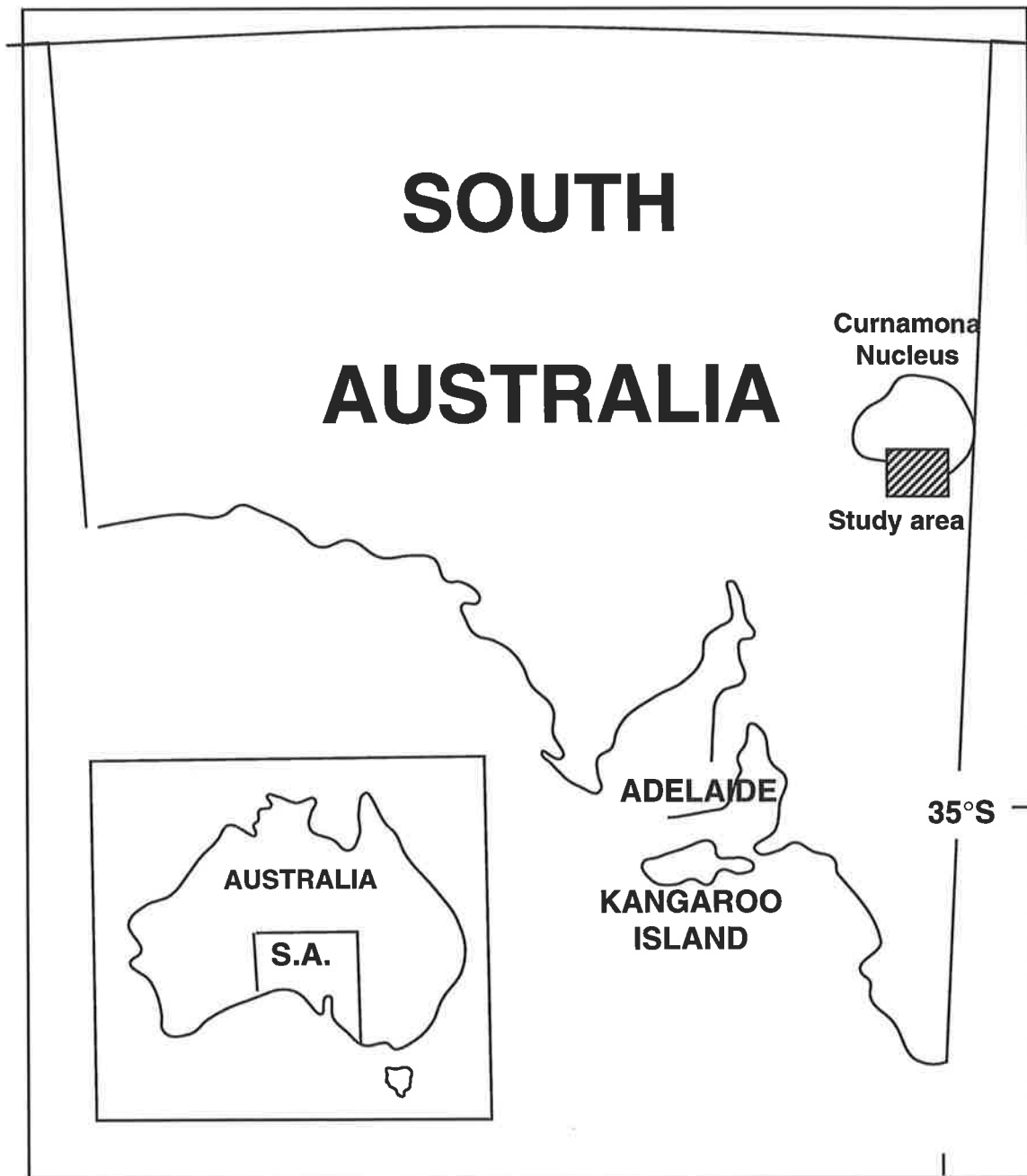


Fig. 1.2 Total magnetic intensity image derived from regional aeromagnetic data of the Curnamona Craton. A. Curnamona Craton. B. Mount Babbage Inlier. C. Mount Painter Inlier. D. Adelaide Geosyncline. E. Willyama Inliers. F. Broken Hill. Scale 1:2,200,000. (after Drexel et al., 1993).



**Figure 1.3** Location maps showing the position of the state of South Australia within Australia (inset) and the location of the study area within south australia.

overprinted events was to produce a number of semi-isolated, partially fault-bounded blocks that now constitute the Willyama Inliers.

Those inliers which are in South Australia are collectively referred to as the Olary Block, which is separated from the Broken Hill Block by a major sinistral, strike slip, north-northeast trending fault system. This is defined as the Mundi Mundi fault which manifests aeromagnetically as a north-northeasterly trending lineament. The latter separates high-grade gneisses south of the Broken Hill Block from the lower grade rocks of the Olary Block. The location of this study area is the Curnamona 1:250,000 sheet, that is the Curnamona section of the Olary Block (fig. 1.3).

A similar sequence of events and overprinting relationships is also evident in the Mount Painter and Mount Babage inliers on the north western part of the Curnamona Craton. There is no information on how extensive Paleo-proterozoic rocks and the Olarian Orogeny are within the Curnamona Craton. This thesis aims to establish a relationship between known Paleo-Proterozoic rocks and magnetic information and to use this as an aid for mapping these rocks where they are covered.

## **1.2. Aims of this study**

The Curnamona Cratonic Nucleus is almost completely hidden by younger sediments. In the Curnamona 1:250,000 sheet, geological information for the Proterozoic rocks which host the Broken Hill mineralisation comes from limited outcrops to the south, data from a few drill holes to the north and geophysics.

Drill hole data and aeromagnetic information suggest that the Proterozoic rocks extend to the north at relatively shallow depths for many tens of kilometres under cover along the Benageri Ridge towards the central part of the Curnamona Craton. Cover over these rocks to the north is mostly Cainozoic, but in places includes Cambrian and Adelaidean rocks, and possible equivalents of the Gawler Range volcanics (Callen, 1990; Flint and Parker, 1993). Therefore geophysics, and particularly aeromagnetism is the optimal tool for understanding the geology and mineralisation potential of the area.

The aims of this thesis are:

- 1) To investigate the relationship of magnetic information and Proterozoic rocks using the known geology in the area.
- 2) To use magnetic information to map these rocks over the unexposed areas.
- 3) To delineate structural features from the magnetic information.
- 4) The ultimate goal is mineral exploration which is not included in the detailed aims but considered in general terms.
- 5) To review and present a systematic approach to the interpretation procedures of magnetic data which could be applied elsewhere.

### **1.3. Thesis outline**

Chapter 1 presents the introduction along with the aims of the study and a review of previous investigations. The geology of the Proterozoic rocks in the Curnamona 1:250,000 sheet is described in chapter 2, in order to provide the reader with a background to the geology relevant to this project. An interpretation procedure along with the application and limitations of magnetic information in producing better geological maps is presented in chapter 3.

Processing and presentation used in the Curnamona 1:250,000 sheet, along with principles of rock magnetism and susceptibility measurements, are presented in chapter 4. The relationship of known geology with magnetic information is established in chapter 5. The results of using magnetic information and known geology to extend mapping of Proterozoic rocks under cover is discussed in chapter 6. The view of the geology of the Curnamona 1:250,000 sheet in the light of this new geophysical information will be presented in chapter 7. Chapter 8 is the summary and conclusion of the thesis. Appendix (1) presents the susceptibility measurements and appendix (2) the modelling parameters.

## 1.4. Previous investigations

### 1.4.1. Geology

Geological mapping and related investigations in the Olary Block have been modest in comparison with the extensive and very detailed investigations undertaken around Broken Hill (Flint and Parker, 1993). Most have been of limited regional extent except for the synthesis of Forbes and Pitt (1980), Grady et al. (1989), Clarke et al. (1986-1987) and Forbes (1991).

In the early 1990s the Olary and Curnamona 1:250,000 map sheets with explanatory notes were published by the South Australian Department of Mines and Energy (SADME) (Curnamona by Callen, 1990 and Olary by Forbes, 1991). These publications provide very useful summaries of previously published data on the Olary Block, although the map scale does not allow adequate subdivision of the metasediments. The geology of the Olary Block is also given by Flint and Parker (1993). Most of the geological information presented here and in chapter 2 comes from these two sources. The geological map of the Curnamona 1:250,000 sheet; the detailed geological maps of the Koolka South sheet, the Kalabity South sheet and the Kalabity North sheet at a scale of 1:25,000 were also used for this study.

Many unpublished exploration reports are also available for the Curnamona 1:250,000 sheet. Exploration for economic deposits of uranium, base metals and gold by various

companies has been continuous since the late 1960s, although, the exploration effort has been considerably reduced at times of recession.

All parts of the Olary Block are currently under exploration title. Most of the work has been completed in the vicinity of small mineral deposits, but regional studies have been undertaken by Carpentaria Exploration Company Pty Ltd (CEC), Esso Australia Ltd and Conzinc Riotinto Australia Exploration Pty Ltd (CRA).

Company exploration activities in the Curnamona 1:250,000 sheet were reviewed by Yates (1993). The Olary Block has been used as a geologic training area for many University groups. The University of Adelaide and Flinders University have run third-year mapping schools in the Weekeroo inliers, and many honours students from these institutions have spent time there.

In the context of mapping in the Olary Block, there has been a collaborative program. This commenced in 1990, and was initially between the Universities of Newcastle and New England and since 1992 the Universities of Melbourne and New England have cooperated. The results from the mapping program have assisted in the compilation of a series of new SADME 1:25,000 geological maps. These maps were used in this thesis to establish a relationship between high resolution aeromagnetic data and mapped rock units.

### 1.4.2. Geophysics

Aeromagnetic data can delineate magnetic markers, outline structures and sometimes provide a third dimension, and thereby yield much geological information which is not available from geological mapping alone. Of all the airborne geophysical techniques, the aeromagnetic method has by far the highest resolution to detect features down to the Curie point geotherm some 20 km or so beneath the earth's surface (Hood et al., 1979).

The aeromagnetic method makes an excellent mapping tool (Boyd, 1967) because the signal is unaffected by poor outcrop. The continuity of information provided cannot be matched by ground geophysical or geological surveys. However, in the Olary Block geophysical activities, particularly the application of high quality aeromagnetic data as an aid for mapping, have not been used as extensively as geological mapping programs.

Except for the regional interpretation of gravity and magnetic data by Mills (1986) on the Curnamona and Olary 1:250,000 sheet, and Ukaigwe's PhD thesis (1985) on the Olary 1:250,000 sheet, no detailed geophysical work has been done prior to imaging. Most aeromagnetic and ground magnetic work has been completed in the vicinity of small mineral deposits. At the time of writing this thesis SADME is collecting new higher resolution aeromagnetic data in collaboration with the Australian Geological Survey Organisation (AGSO) and the Geological Survey of New South Wales as part of the Broken Hill Exploration Initiative.

## **2. The geology of the Willyama Supergroup rocks**

### **2.1. Introduction and definition**

The stratigraphic sequence of metamorphic rocks in the Olary Ranges on the Olary Block have been labelled as the Willyama Supergroup by Willis et al., 1983. This stratigraphic sequence has been applied in a generalised form to the Curnamona 1:250,000 sheet. The Willyama complex which refers to Precambrian rocks in the Broken Hill, Olary, and Curnamona areas incorporates the Willyama Supergroup and comprises pre-Adelaidean granitoids and basic intrusives.

Geochronology of the Willyama Supergroup rocks has been summarised by Forbes and Pitt, 1980; Flint and Webb, 1980; and Rutland et al., 1981. Two sets of ages clustering around 1500 Ma and 1050-1200 Ma have been obtained. The former approximates the Mundi-Mundi granite dates from Broken Hill and the latter is similar in age to the Musgravian Orogenic phase (Thomson, 1980). These events have overprinted earlier metamorphic effects estimated at 1700 Ma from comparisons with the Broken Hill area.

Early deformation of the Willyama Supergroup rocks took place in three phases, constituting the Olarian Orogeny. Two phases of Delamerian deformation have also been recognised in these rocks. The outcropping of the Willyama Supergroup rocks in the Olary and Curnamona areas occurs naturally as a number of oval-shaped blocks

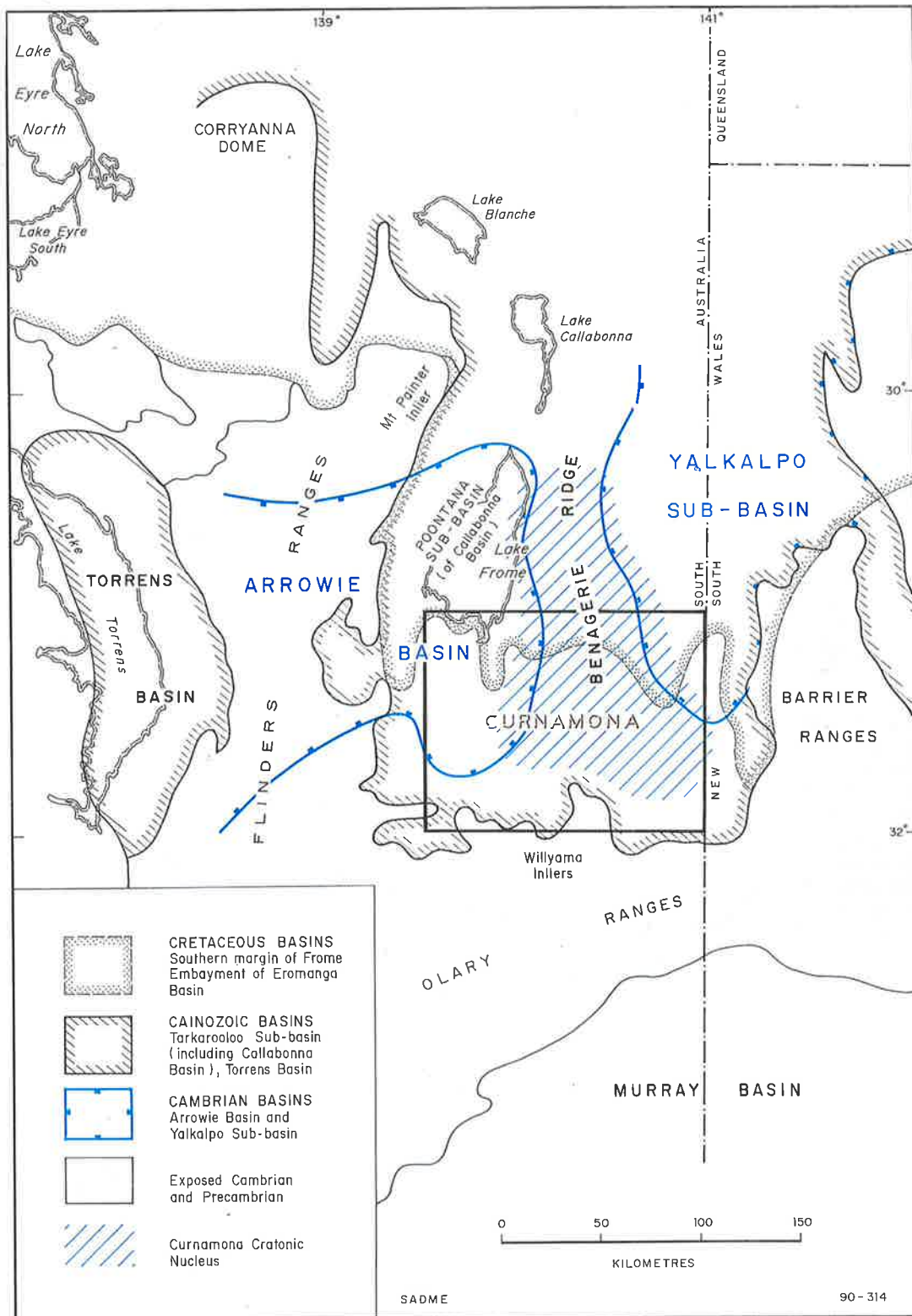


Fig. 2.1 Sedimentary basins in the lake From area (after Callen, 1990).

separated by large, curved fault zones. Outcrops of the Willyama Supergroup rocks are limited to the southern part of the Curnamona 1:250,000 sheet.

The rock description of the Willyama Supergroup (defined by Willis et al., 1983) of the Curnamona 1:250,000 sheet has been published primarily by Campana and King (1958), Wiltshire (1975), Clarke et al. (1986 and 1987), Callen (1990), Cook and Ashley (1992) and Flint and Parker (1993). Although a few correlations have been made between the Broken Hill and Olary blocks there are distinct similarities and differences between the two areas which have important implications for geological interpretation (Flint and Parker, 1993).

## **2.2. Regional geology**

Precambrian rocks crop out only on the southernmost parts of the Curnamona 1:250,000 sheet (Pitt, 1976). To the north, all of the Precambrian rocks disappear beneath onlapping sequences of Cambrian (Arrowie basin), Mesozoic (Frome basin) and Tertiary (Tarkarooloo basin) sediments. Province and basin elements on the Curnamona area are shown in figure 2.1.

The Willyama Complex was first defined by Mawson (1912) for Precambrian metamorphic, granitic and volcanic rocks of the Olary ranges region and later on referred to as the Olary Province (including Adelaidean rocks) by Campana and King (1958). Exposures of the early Proterozoic basement have been variously referred to as the Olary

PLUMBAGO	KALABITY (CEC.)	OLD BOOLCOOMATA (R. Wiltshire)	CURNAMONA (This Note)	OLARY (Forbes, 1989)	OLARY / CURNAMONA (Clarke <i>et al.</i> , 1986)	
( After Ashley <i>et al.</i> , 1978 )						
ESSO Nomenclature			SADME nomenclature			
Regional granite	Mica schist (Ps)	Upper schist	Bedded schist	Pws <sub>1</sub>	Mica schist and plagioclase-mica quartzite	
Schist (occasionally knotted) (Psk)	Knotted schist (Psk)	Pelitic-carbonaceous	Layered schist		Pwk	Carbonaceous mica schist, chialtolite-sillimanite rich schist
Missing	Cherty quartzite (Pq, Pnq) wollastonite rocks (Pq, Pet)	Bimba	Calcareous rocks			Metasiltstone gossan Pwt,g
Missing	Sericite (Pa) schist		Epidote schist Medium-grained mica schist	Pwe	Calc-silicate gneiss, amphibolite, breccia, mica-barite quartzite, layered calc-silicate, etc.	
Calc-albite rocks (Pea)	Layered albite rocks (Pnd)	Upper albite	Layered albite rocks	Pws <sub>2</sub>	Laminated plagioclase-pyrite-muscovite rock	
Layered albitite (Pnd)	Calc-albitite (Pea)		Calc-albitite		Pws	Quartzite-feldspathic gneiss with minor quartz-muscovite, mica schist/quartzite, aluminous schist, also mica-quartz-barite rock (near top) and quartz-magnetite (near base)
Missing	Feldspathic siltstone and mica schist (Pn, Ps)	Mixed schist	Albite rocks interbedded with mica schist			Pwg <sub>1</sub>
Missing	Remainder of sequence obscured by Adelaidean	Middle schist	Layered gneiss	Pwf	Composite gneiss suite	
Missing		Lower albite	Magnetite-quartz-feldspar rock Older migmatite			
Migmatite (Pm)			Layered hematite-albite rock	(Remobilised and reconstituted during metamorphism)		
Granodiorite (Prgd), Tonalite (Pel), Adamellite (Prgd, Prad), Trondhjemite (Pct) (Remobilised and reconstituted during metamorphism)	Gneissic basement	Granitic gneiss		Pwm, Pws		

Table 2.1 Comparison of basement lithostratigraphic terms for the Curnamona and Olary regions (after Callen, 1990).

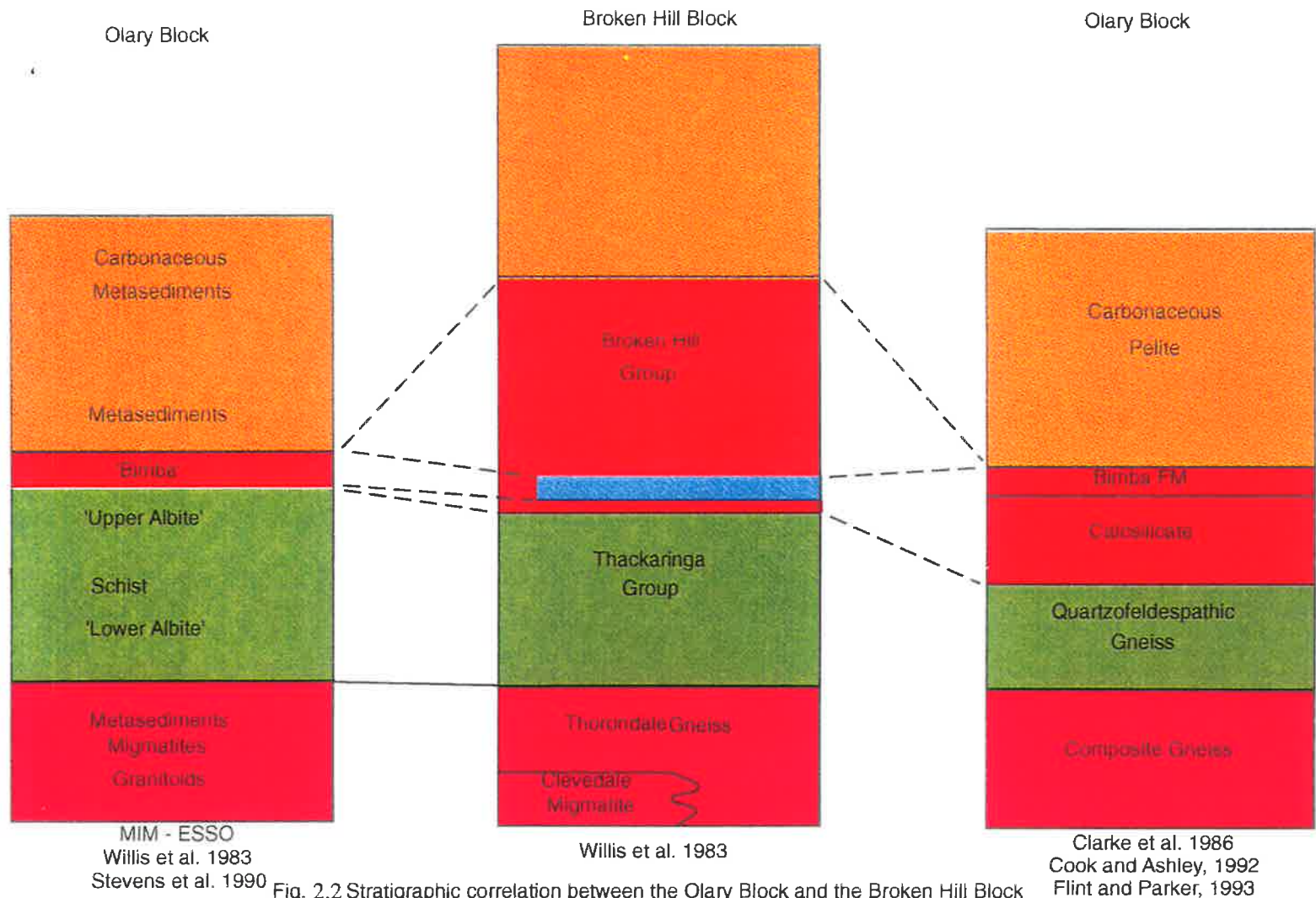


Fig. 2.2 Stratigraphic correlation between the Olary Block and the Broken Hill Block

Redrawn after Yates, 1993

subdomain of the Willyama domain (Glen et al., 1977), the Willyama inlier (Thomson, 1980; Flint and Parker, 1982), and the Willyama Inliers (Preiss, 1983).

Thomson (1976) recognised a stable block within the Cambrian basement which he called the Curnamona Cratonic Nucleus. The region of Adelaidean rocks in the Lake Frome area was named Coombalarnie Platform (Callen, 1990). Coombalarnie Platform rocks are overlain to the west by the Cambrian rocks of the Arrowie basin (Wopfiner, 1970). The northern boundary of the Curnamona area is overlain by the southern margin of Mesozoic rocks of the Frome embayment (Freeman, 1966; Wopfiner, 1966; Callen, 1981).

Correlation of the Willyama Supergroup rock units between the Willyama Inliers have shown that the upper units have proved to be more distinctive and able to be correlated than the lower quartzofeldspathic units as shown in Figure 2.2. U-Pb dating of the Hores Gneiss ( $1690 \pm 5$  Ma) which is closely associated with the Broken Hill orebody, places the Broken Hill Group in the middle of the Willyama Supergroup (Page and Laing, 1992). Metamorphism has been dated at  $1600 \pm 8$  Ma and sodic granites at Crokers well were dated at  $1579 \pm 2$  Ma (Ludwig and Cooper, 1984).

Undeformed volcanic rocks of the northern Curnamona in the Benageri area gave dates of  $1599 \pm 40$  Ma (Sheard et al., 1992). They concluded that this age is statistically indistinguishable from those obtained from the Gawler Range Volcanics of the Gawler Craton. In his recent work Page (1993) showed that the Willyama Supergroup is of

similar age to the Mount Isa Group. This links the two areas together as proposed by Laing, 1990.

### **2.3. Detailed geology**

The stratigraphy, metamorphism, igneous history, structure, and mineralisation within the Curnamona area are summarised in this section.

#### **2.3.1. Stratigraphy**

The stratigraphic sequence of metamorphic rocks in the Olary ranges on the Olary sheet (Forbes, 1970; Forbes and Pitt, 1980; Pitt, 1971 and 1976), labelled the Willyama Supergroup (Willis et al. 1983), has been applied in a generalised form to the Curnamona sheet (Callen, 1990). Most stratigraphic studies of the Willyama Inliers have shown a broad subdivision into migmatitic and gneissic units at the base, structurally overlain by schistose and fine-grained metasediments at the top (Flint and Parker, 1993). The Willyama Complex incorporates the Willyama Supergroup; and pre-Adelaidean granitoids and basic intrusives.

Some of the key basement areas in the Olary region have been mapped by Robinson et al. (1978), Clarke et al. (1986), Ashley et al. (1978), and Pitt (1976). The schemes are compared in Table 2.1. Ashley et al. (1978) estimated that the thickness of original sediments in the Willyama supergroup was 4000 to 6000 metres. Callen (1990) has used several marker horizons such as the iron formation, quartzite, albite and calc-silicate

rocks, and aluminous schists in mapping the Willyama Supergroup rocks in the Curnamona area. Description of the sequences will be summarised in ascending order.

### **2.3.1.1. Iron Formations and equivalents ( F1-3)**

These units consist of magnetite, partly oxidised to haematite, with varying amounts of quartz, albite, sulphide, barite and apatite. In the region where folding is complex it is very difficult to distinguish these units from gossanous rocks developed above albitite (Callen, 1990).

### **2.3.1.2. Schist, quartzite ( $\rho\omega$ ), migmatite and gneiss ( $\rho\omega m$ )**

Schist and quartzite grade laterally and down-sequence into coarse-grained, quartz biotite-plagioclase migmatite and gneiss which may contain magnetite. The migmatite and gneiss are intruded by granite and pegmatite, and contain rare, stratiform amphibolites. Amphibolites have a similar stratigraphic relationship to the iron formations, analogous to the relationship between amphibolites and Banded Iron Formations (BIF) in the Broken Hill region (Pitt, 1976).

Mills (1986) interpreted the magnetic pattern of Olary and suggested differences between the (BIF) of the Broken Hill area and the Curnamona area. Ashley et al. (1978) supported the analogy but suggested that some parts of the section are absent (Rutland et al., 1981).

### 2.3.1.3. Albitic and calc-silicate rocks ( $\rho\omega\alpha_{1-4}$ , $\rho\omega e$ )

This group consists of a variety of rocks which are characterised by high sodic feldspar (albite) content, and is stratigraphically distinct from albitites associated with the iron formation. This suite, often referred to in part as the 'Upper Albite Formation', is characterised by massive, banded and finely-laminated calcsilicate and feldspathic rocks which are typically finer grained and better laminated than the quartzofeldspathic gneisses.

Calcsilicate gneiss is interlayered with metasilstone and potassic to sodic felsic gneiss. The presence of magnetite ( $\pm$ haematite) throughout the suite distinguishes it from the overlying Bimba Formation (Flint and Parker, 1993). Cook and Ashley (1992) suggested that the calcsilicate suite and parts of the overlying Bimba formation were formed from felsic volcanic-derived sediments in an evaporating saline, alkaline environment possibly analogous to the rift lakes of eastern Africa.

There are several base-metal prospects within the calcsilicate suite throughout the Olary Block. There is also extensive, low grade, often fracture-controlled chalcopyrite mineralisation in brecciated magnetite-albite calcsilicate rocks near the base of the unit while the upper parts contain regionally anomalous stratiform low-grade zinc mineralisation often over stratigraphic intervals of up to 100 m thick.

### **2.3.2. Metasiltstone and stratiform gossan (ρωt , g)**

The metasiltstone varies considerably in thickness, with a maximum of several hundred metres near the Waulkaloo Mine. Stratiform limonite-sulphide gossans are common throughout the area or at the same stratigraphic level when the metasiltstone is absent. The gossans may occur as a single horizon, or a set of several horizons within the metasediments (Pitt, 1976).

#### **2.3.2.1. Aluminous schist (ρωk)**

This is a highly distinctive unit which has been mapped throughout the Kalabity area (Pitt, 1976). It consists of grey, carbonaceous aluminous quartz-mica (feldspar-free) schist. Large porphyroblasts of andalusite and particularly, gem-quality chiastolite, are common in these rocks and for this reason localities such as Mt. Howden are well known throughout the world (Mawson, 1911; Pitt, 1976).

#### **2.3.2.2. Red -brown schist (ρωs<sub>1</sub>)**

This is the youngest meta-sedimentary unit recognised in the Curnamona area. It is red-brown weathered quartz-feldspar muscovite schist with minor quartz-rich beds that contain vague sedimentary structures (Pitt, 1976). Iron is present as disseminated haematite in these rocks.

### 2.3.2.3. Syn- to late - tectonic granitic bodies and amphibolites ( $\rho\gamma$ )

Granitoids are prominent around the Mt. Victoria area, but have not been mapped in detail on the Plumbago 1 : 63,360 Olary geological sheet (Callen , 1990). According to Mills (1986), they may extend towards the north below the Cambrian and Adelaidean sediments (See tectonic sketch of Callen, 1990). Based on mapping at the scale of 1:100,000 and 1:2000 around the Kalabity area, Ashley et al. (1978) subdivided the granitoids into different types. Mills (1986) identified a number of other granitoid bodies on the basis of gravity and magnetic interpretation.

Pegmatites of several generations are related either to the various metamorphic phases or, to a lesser extent, to the late tectonic intrusive granites. Oliver and Stevenson (1984) reported that albite, microcline-albite and other varieties of dyke structures are present in the area. Beryl, tourmaline, phosphates and radioactive minerals occur in trace to subeconomic amounts (Campana and King, 1958). Pegmatite bodies have not been distinguished in the Curnamona area (Callen, 1990).

### 2.3.2.4. Amphibolites ( $\rho\beta$ )

Discordant metadolerite dykes are present in the Kalabity Mt. Howden-Triangle Hill area (Callen, 1990; Pitt, 1976). They consist of albite with lesser amount of actinolite, and apatite, and up to 10% opaque oxides together with epidote, minor sphene and apatite . These dykes were intruded prior to the deposition of the Adelaidean but after the basement was folded (Callen, 1990).

### **2.3.2.5. Undifferentiated schist ( $\rho\omega_s$ ) and other basement rocks ( $\rho\omega$ )**

With further mapping it is probable that the subdivision of this unit mapped locally by Ashley et al. (1978) will be recognised. The symbol  $\rho\omega$  is used for various borehole samples of metamorphic rocks most of which are too poorly preserved or too small to identify. They include amphibolite-biotite gneiss, mica schist and biotite schist (Callen, 1990).

### **2.3.2.6. Adelaidean ( $\rho$ )**

The Adelaidean in the Curnamona area is known almost entirely from company reports of drilling (Callen, 1974; Pigot, 1969; Preiss, 1987; Ashley et al. 1978 ). A small outcrop of tillite is present west of Waulkaloo Dam which probably belongs to the Sturtian Pulco tillite. East of Toolaby, the Adelaidean sediments have all been assigned to the Wilyerpa Formation. They consist of laminated black slate and siltstone with interbeds of massive tillite and several sandstone beds. Some very thin iron sulphide beds occur at the top of the sequence (Callen, 1990).

A complete description of the Adelaidean sequence is not possible due to the lack of continuity. Lack of distinctive lithologies prevents definitive correlation with type units (Pitt, 1976). Lithotypes of isolated outcrops around Strathearn are siliceous metasilstone, impure sandstone quartzite, and diamictite or conglomerate. The metasilstone strongly resembles the Benda siltstone of northern Olary but confirmation of the correlation may not be possible.

According to Pitt (1976) the distinctive Braemar iron formation of Olary has not been observed, but may be present in the Toolaby hills of the Curnamona 1:250,000 sheet. Ashley (1978) described the Adelaidean sequence as consisting of low grade metamorphic rocks of shallow water and fluvio-glacial origin. These rocks are predominantly composed of siltstones, quartzites and tillites with interbedded dolomitic, and conglomeratic members in the Plumbago area.

#### **2.3.2.7. Mesozoic rocks**

Callen (1990) indicated that the Mesozoic sediments in the Curnamona area are poorly exposed and occur only in shallow, structurally controlled depressions along the northern margin of the area. Open file reports of uranium exploration do not show Mesozoic sediments in drillholes east of the Benagerie Ridge. The thickest known sequence is in the Black Oak well (Ker, 1966 and Truelove, 1980).

#### **2.3.2.8. Cainozoic rocks**

The rock relationship diagram for the Cainozoic on the Curnamona map sheet is shown by Callen (1990). The Eyre Formation deposited during Paleocene-Eocene time, covers a large area of the Great Artesian Basin (Anderson and Ellis, 1983). This formation is mainly composed of blanket and paleochannel sands. The Oligocene period was reported by Anderson and Ellis (1983) as a period of nondeposition. Miocene clays and fluvial sands lie unconformably above the Eocene which itself laterally grades to recent

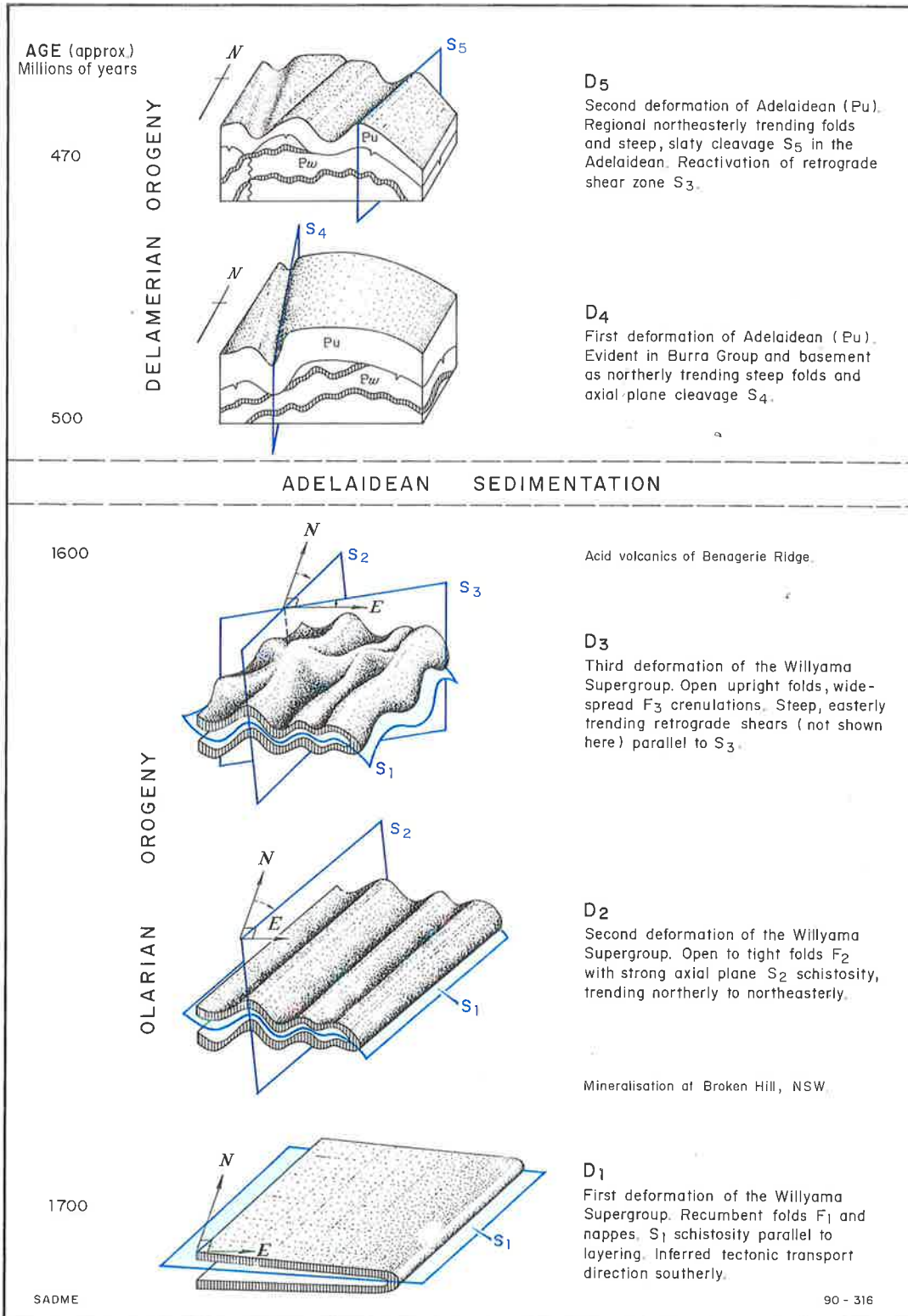


Fig. 2.3 Fold style development in the Curnamona area (after Callen, 1990).

sediments. For a detailed lithological descriptions of the Cainozoic rocks see Wopfiner et al. (1974), Anderson (1983), Callen et al. (1983), Callen (1986, and 1990).

### **2.3.3. Tectonics**

Two major periods of deformation have taken place throughout the history of the Willyama Inliers: The Paleoproterozoic Olarian orogeny and the Cambro-Ordovician Delamerian orogeny (Thomson, 1969; Glen et al., 1977 and Berry et al., 1978). Within the Paleoproterozoic basement, the Olarian orogeny was by far the more pervasive, of higher metamorphic grade and formed the majority of meso-and macroscopic structures. Three phases are commonly recognised, OD1 to OD3. Folding events D4 and D5 of Berry et al. (1978) and Grady et al. (1989) are part of the Delamerian orogeny as shown in figure 2.3 (Callen, 1990).

Rutland et al. (1981) provided a comparison between the Gawler Craton and the Broken Hill area. The most recent studies are those of Ashley et al. (1978) and Clarke et al. (1986). Although most of the structural studies of the area have been made in the Olary region (Forbes and Pitt, 1980), they are applicable to most of the Curnamona area.

The work of Clarke et al. (1986) was the first comprehensive regional study. Amongst their conclusion they suggested that the crust in the Olary ranges may have been around 50 km thick and was not subjected to uplift during a single continuous compression. They emphasised the first fold phase and used this concept to explain reversals in stratigraphy and repetition. Parker (1990) indicated that the present shape and distribution of Early

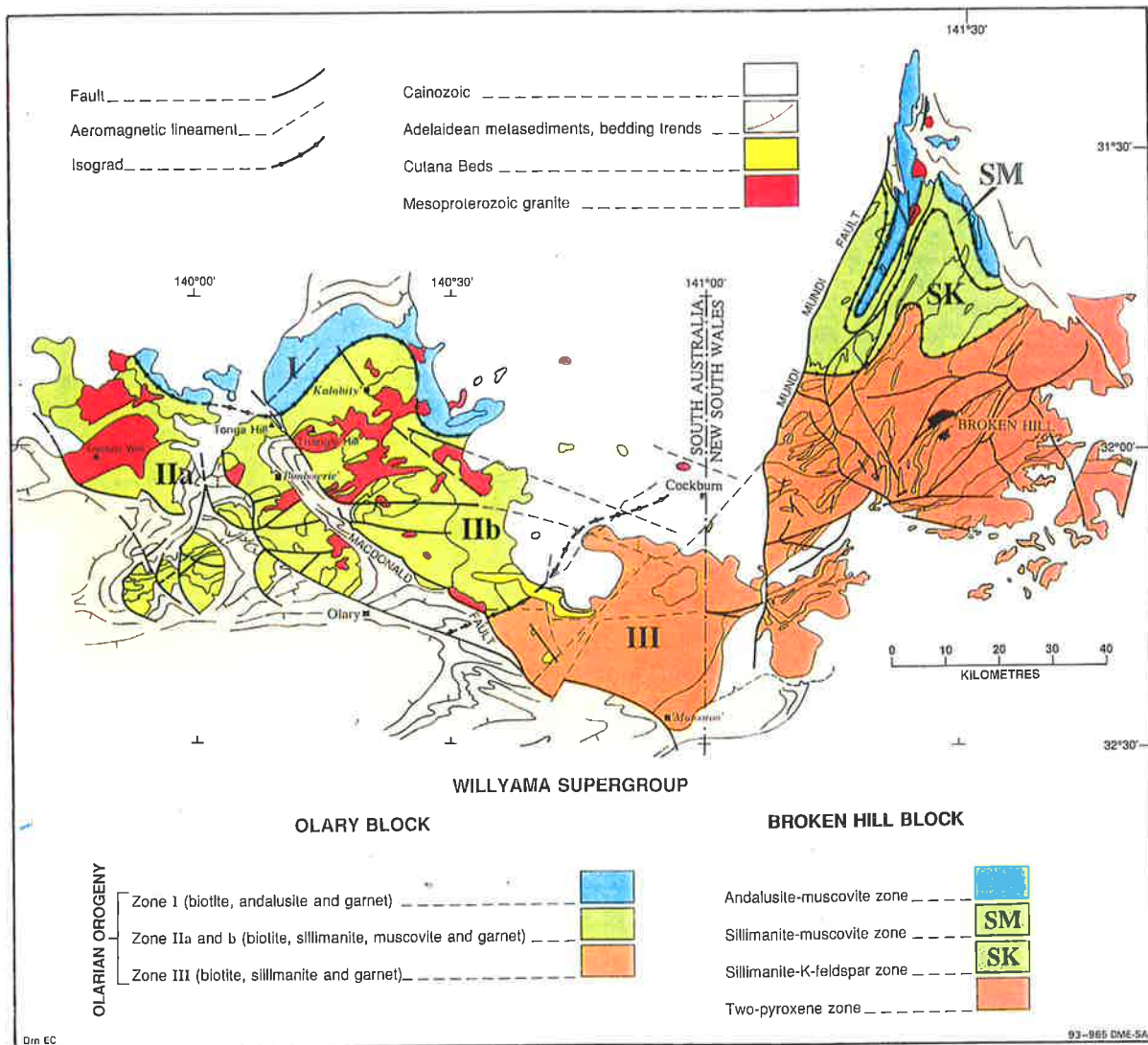


Fig. 2.4 Variation of metamorphic grade within the Willyama Inliers (after Drexel et al., 1993).

Proterozoic basement in the Willyama Inliers represents complex overprinting of Olarian and Delamerian orogenic structures. During the Olarian orogeny, early nappe-like structures were overprinted by at least two phases of progressively more upright folds trending N to ENE (Marjoribanks et al., 1980). The early events were accompanied by high grade metamorphism at Broken Hill and to the SE, but this decreased gradually in a N to NW direction towards the central Curnamona Cratonic Nucleus (Clarke et al., 1987).

Retrograde shear zones were formed during the later folding events, and were reactivated during the Delamerian folding at about 500 My. They mainly trend ENE and are truncated by NW striking faults. These structures controlled late Proterozoic deposition in narrow "corridors" which were fault bounded on their northern sides and uncomformable on their southwestern margins (Callen, 1990).

#### **2.3.4. Metamorphism**

Interpretation of the full metamorphic history of the area depends on a correct identification of deformational fabrics and their related recrystallization. Unfortunately this is not always clear in the Willyama inliers because the first and second deformational fabrics are generally parallel to lithological layering and are only rarely distinguishable, and the third and fifth are similar in orientation and style (Flint and Parker, 1993). Approximate timing and metamorphic grade of tectonic events during the Olarian and Delamerian orogenies is shown in figure 2.4.

Within the Olary and Broken Hill blocks, the maximum metamorphic grade increases towards the southeast (Binns, 1964; Spry, 1977; Phillips and Wall, 1981; Clarke et al., 1987). The exposed variation in metamorphic grade was interpreted as due to regional block tilting (Clarke et al., 1987), but the differences may relate to the variation in heat flow towards the Curnamona Craton which does not seem to have been greatly affected by the Olarian Orogeny

### **2.3.5. Igneous history**

#### **2.3.5.1. Acid Volcanics ( $\rho - v_1$ )**

Acid volcanic rocks are present in the subsurface in the northern part of the Benagerie ridge and beneath the Adelaidean platform rocks to the west (Callen, 1990). Mills (1986) reported a characteristic magnetic pattern indicative of volcanics where a thin Mesozoic-Cainozoic cover is present in the Benagerie area.

Reddish to brownish green porphyritic trachytes and rhyolites were first discovered in cuttings (Ker, 1966). Other cored sections are available from bores to the north on the Frome sheet (eg. Mudguard 1, Youngs, 1977a; Youles, 1981). U- Pb zircon age determinations by Fanning et.al. (1988) gave ages of  $1590 \pm 40$  Ma and equate the volcanics with the volcanic rocks of the Gawler Craton. Callen (1990) has suggested that the volcanic clasts of the northern Curnamona area are analogous to those of the Gawler Craton

### 2.3.5.2. Mafic volcanics ( $\rho - v_2$ )

Callen (1990) reported that basalts, with some pillow structures, are present in drillhole LNM 10. It should be noted that no outcropping basalts have been found. They are considerably altered by metamorphism, weathering and possibly hydrothermal action. The Adelaidean unconformably overlies the basalts, but their relationship with other volcanics and the Willyama complex is uncertain.

Mills (1986) suggested that the dykes to the east of LNM 10 were the feeders of volcanics. Giles and Teale (1981) reported a date of  $1360 \pm 40$  Ma and concluded that these basalts, which are interbedded with sediments, are related to the Gawler Range Volcanics. This suggests that a pre-Adelaidean sedimentary sequence may be interbedded with the volcanics in the Curnamona area (Youngs, 1977a).

### 2.3.5.3. Intrusives ( $\rho\gamma$ )

Flint and Parker (1993) have given a detailed description of the numerous foliated granitic gneisses, migmatitic gneisses, granodioritic to tonalitic gneisses, pegmatites and regional granitoids of the Olary block. Ashley et al. (1978) subdivided the granitoids into three types, mainly on the basis of mapping at 1 : 100,000 and 1 : 2,000 scale around the Kalabity area in the Curnamona 1:250,000 sheet. They were able to group these into a crude stratigraphic sequence, and suggested an unconformity between the second and third types.

Type 1 Rich in soda plagioclase, soda alkalite and pegmatite of predominantly intrusive type. These are present in axial zones of granitoid bodies.

Type 2 Adamelite, granite, granodiorite, often with crude layering, intermixed with rocks of type 1, but with a sharp, sometimes discordant contact with group 3.

Type 3 Metasediments and anatectic granitoids. These are less affected by high-grade metamorphism than the previous types. Callen (1990) has suggested that the granitoids that crop out, unfolded to poorly foliated on the Curnamona area, are thought to be Late tectonic intrusives.

Pegmatites of several generations are related either to the various metamorphic phases or to a lesser extent to the late tectonic intrusive granites. The pegmatite bodies have not been distinguished in the Curnamona area.

### **2.3.6. The sedimentation history of the Willyama Supergroup rocks**

Callen (1990) indicated that, stratigraphically, the oldest rocks of the Willyama Inliers on the Curnamona area are the arenitic derivatives of sodic gneiss at Ninnerie Hill. The source of sodium may have been tuffaceous material associated with the eruption of keratophyres or comendites in volcanic arcs (Stevenson, 1978), or from evaporites in the early rift-type environments. Potash-rich gneissic derivatives may have been derived from arkose and pelite (Callen, 1990).

The iron formations, banded and similar to typical Precambrian iron formations, were probably deposited 2000-1700 Ma (Glen et al., 1977). The iron formations are interbedded with metasediments that were originally derived from shales and sandstones. The presence of biotite and magnetite in these rocks indicates that the original sediments were iron rich. Calc-silicates represent impure carbonates, with magnesium and iron present. Iron-rich sulphides in mud and silt, now represented by the gossans, may indicate anaerobic conditions, suggesting stagnation of bottom waters.

These sediments grade upward into a sequence of interbedded quartzite, schist and quartz - rich schist, that was originally derived from interbedded sand bodies and sandy muds. The entire sequence was deposited in a shelf environment, either open marine or in a large lake. Extensive outpouring of acidic volcanic rocks in the study area are very similar to the intracontinental events of the Gawler Ranges and could be interpreted as an eastwards extension of the Gawler Ranges Province, or a portion of the Gawler Craton that has been broken by rifting (Callen, 1990).

Parker (1990) indicated that an incomplete history of early Proterozoic sedimentation and tectonism is present in the Willyama Inliers and the Curnamona Cratonic Nucleus. Ludwig and Cooper (1984) suggested that the post-tectonic granites with an age of 1580 Ma were emplaced in the Willyama Inliers as in the Gawler Craton and on the Curnamona Cratonic Nucleus. Acid volcanic rocks with an age of 1592 Ma (Fanning et al., 1988) were formed on the Curnamona Cratonic Nucleus and are similar in geochemistry to the Gawler Range Volcanics (Giles and Teale, 1979).

### **2.3.7. Mineralization**

#### **2.3.7.1. Uranium**

The hydrology of the region is discussed in detail (Ker, 1966; Taylor and Safta, 1978; and Waterhouse and Beal, 1978). Uranium occurs in the Tertiary sediments at the base of channel fill deposits of the Eyre Formation (Callen, 1976a and b; and 1977; Brunt, 1978; Ellis, 1980; Curtis and Moore, 1982). The deposits are of the roll front type. Uranium occurred as oxide and silicate in cavities between the quartz grains. It was precipitated from ground waters carrying uranyl complexes.

Precipitation occurred at the margins of the channels where movement was slowed. Reduction of the uranium complexes was caused by abundant organic matter. The passage of these groundwaters is recorded in the sediments by oxidation of pyrite and organic matter leaving yellow-orange to reddish iron oxides staining the sand grains. Uranium is thought to have entered the sediments during the latter part of the Cainozoic. In addition to the above references, other studies on the sedimentary uranium include Barbour (1983), Brunt (1973, 1974a and b), Brunt and Burns (1975), Bryan (1971), Ellis (1975a and b; and 1977), Middleton (1973), and Oilmin NL and Western Nuclear Australia LTD (1979a and b).

### 2.3.7.2. Base Metals

Recognition of the Diamantina Orogen of the Willyama Province with the Cloncurry Province (Laing, 1990) permits direct comparison of metallogenic styles. The Willyama Province at Olary is prospective for three styles of major ore deposits :

- 1) Broken Hill Pb-Zn-Ag, mineralogically complex in a sediment plus volcanic rocks.
- 2) Mount Isa Pb-Zn-Ag-Cu, mineralogically simple in shallow water sedimentary rocks.
- 3) Starra Cu-Au late tectonic, granite related mineralisation emplaced in stockworks, breccias and faults similar to Olympic Dam mineralisation.

The first type is proved but the two others have been predicted. Important stratiform copper mineralisation occurs at Mt. Howden, Waulkaloo, and Dome rock. All are closely associated with the gossan horizons immediately below the Aluminous Schist (Ashley et al., 1995). The presence of nearby Broken Hill and its silver-lead-zinc mines has always made the Olary Block prospective for exploration. Comparative works on stratigraphy, tectonics and mineralisation have been done by Stevens, 1986; Thomson et al., 1970; and Cooper and Tuckwell, 1971. A review of all open file reports of companies' exploration since 1960 has been carried out by Yates & Associates Pty Ltd, 1994.

The thin, distinctive, metal-rich Bimba Formation has been considered to be correlative with the Ettelwood calcsilicate of the lower Broken Hill Group (Willis et al., 1983). More recent workers have correlated the Bimba Formation and calcsilicate suite with the

lower Broken Hill Group (Flint and Parker, 1993). In contrast to the Broken Hill Block, the Olary Block which extends to the Curnamon area shows paucity of amphibolites and garnet-bearing quartzofeldspathic potosi gneiss and a greater proportion of sodic rocks.

To date, distinct metallogenic differences are the dearth of lead-zinc-silver occurrences and the abundance of uranium occurrences in the Olary Block as compared to the Broken Hill Block where the reverse applies (Yates, 1993). Because of no clear correlation of Bimba Formation between the Broken Hill and the Olary Blocks the continuation of this prospective marker unit to the Curnamona 1:250,000 sheet is more problematic.

### **2.3.7.3. Nonmetallic Minerals**

Nonmetallic minerals, such as clay, evaporites, feldspar, barite, and beryl have been sought by exploration companies. For further details see Callen (1990) and Yates(1994).

### **2.3.8. Depth to basement**

At least 70 percent of the interpreted Willyama Supergroup in the Olary Block is covered by Cainozoic continental sediments up to 120 meters thick in paleochanel sections, but averaging less than 100 meters (Yates, 1993). Open file data show only 11 significant diamond drill holes have reached the covered basement in the northern areas of the Curnamona sheet (Yates, 1993). Mills (1986) contour map to the basement shows that in the Curnamona 1:250,000 sheet depth changes from 100 to 600 metres. The depth to the magnetic basement increases towards the west and east from the Benageri area.

### **3. How magnetic information can be used to produce a better geological map**

#### **3.1. Introduction**

The magnetic method exploits the fact that variations in the susceptibility of rocks in-situ, a physical property, give rise to variations in a physical quantity, magnetic field, which may be measured remotely at the ground surface or above it.

The value of the method is that these observed variations, when corrected appropriately for predictable or measurable non geologic effects and presented as two dimensional maps of anomalies over the earth's surface, may be interpreted in terms of three-dimensional sub-surface variations of rock properties. Thus proper interpretation is essential to get the most information regarding the variation of the rock properties.

The variations in physical property must relate, to a greater or lesser extent, to what we term the "geology" of the sub-surface. It is widely acknowledged amongst exploration geoscientists that our skills in interpretation of geophysical data have developed far slower than our skills in acquiring the data (Boyd, 1967 and, 1979).

This may be attributed to a number of factors, particularly the traditional applications of utilising data. Geologic interpretation, or the identification of physical property

distributions in terms of realistic geologic models and processes, is still relatively neglected in practice and regrettably, in the geophysical literature. This chapter is presented to outline a systematic approach for aeromagnetic interpretation which can be applied in similar geologic problems elsewhere.

Major advances have taken place in the fields of data display and presentation, creating products of geophysical data showing greater detail than ever before. The improved presentations have been a major step in developing our methods of interpretation, but they have also widened the gap between quality of acquisition and our ability to understand the features we see in the data (Isles and Valenta, 1991).

### **3.2. Application of aeromagnetic data**

In addition to the early success in exploration directly for magnetite deposits, magnetic data were used over the past four decades indirectly, based on the association of economic minerals with particular host rocks, structures, or alteration zones in the search for ore deposits. Aeromagnetism has been the focus of many of the recent developments in mineral exploration geophysics and thus, ultimately, has provided a great benefit to the economy worldwide.

An important development has been the availability of multi-client data, or non-exclusive surveys as is the case in the Willyama inliers. These large surveys now cover most of the mineral fields in Canada, Western Europe and Australia. These countries have introduced regional data sets affordable to most explorers in these continents. It is the understanding

of these regional data sets that has contributed significantly to the knowledge base which enables the search for mineral deposits to be optimised.

Magnetic methods have proved to be an important reconnaissance tool for the majority of regional mineral exploration programmes. Typical exploration programmes for massive sulphides follow a sequence in which targets for drilling were defined by re-flying promising areas, selected from aeromagnetic and geological maps, with airborne electromagnetic systems.

The coincidence of magnetic and airborne electromagnetic anomalies was considered to be strong indication of sulphide mineralisation. This would not be achieved without accurate interpretation (the magnetic anomaly being due to pyrrhotite rather than magnetite). Drilling the target, after refinement of its position through ground-based surveys, including geochemistry, ground electromagnetic, and gravity, follows (Ward, 1958; Smellie, 1970; Witherly, 1979).

The ability of aeromagnetic and drill hole magnetic information to delineate basic and ultrabasic rocks has made them an important tool in exploration programmes for nickel (Zurbrigg, 1963; Pietila, 1991), chromium, and asbestos (Low, 1957), and for platinum group elements. The Archaean Yilgarn Block in Western Australia is a location in which the aeromagnetic method has been particularly effectively applied for such nickel and gold exploration.

The Yilgarn Block is very poorly exposed and because most of its favoured lithological hosts for Gold and Nickel contain magnetite, the interpretation of aeromagnetic surveys

has played a significant role in its exploration during the past 30 years. In particular, Bureau of Mineral Resources (BMR) now (AGSO) 1-mile surveys and their interpretation led the search for ultramafics during the 1960's Western Australia Nickel Boom.

Niobium and Tantalum bearing Syenite-Carbonate complexes, lamprophyres and Kimberlite, which commonly occur as pipe-like bodies in swarms, produce characteristic circular to elliptical magnetic anomalies. Exploration for diamond-bearing Kimberlite was used in Russia, Africa, India and Australia. Both existing regional aeromagnetic maps of geological survey of Canada and privately sponsored aeromagnetic surveys were properly utilized particularly in Saskatchewan for diamond-bearing kimberlite exploration (Lehnert-Thiel et al., 1992).

The association of Gold deposits and iron formation is well known (Stanton, 1979; Grant, 1985b). An example is the Dona lake Gold deposit in north western Ontario, Canada, discovered on the flank of a prominent aeromagnetic anomaly (Teskey and Hood, 1993). Drilling into a coincident magnetic, gravity and tectonic target identified the giant Olympic Dam Copper, Gold and Uranium deposits in South Australia (Esdale et al., 1987). The combination of high resolution data along with proper interpretation have led to many of the discoveries of mineral deposits.

Aeromagnetic surveys have been used successfully to map structures that are favourable for Gold mineralisation (Boyd, 1984; Svela, 1988; Isles, 1989; Leaman, 1992; Whitaker, 1992), and for base metals (Campbell, 1966; Mutton and McNerny, 1987). In the

majority of exploration cases, the primary use of aeromagnetic data is to extend and refine geological mapping in order to select optimal areas for further detailed exploration. Even when deposits can be detected directly, the probability of discovery is much greater when the geological framework is known.

It is evident that the major contribution of the aeromagnetic technique to mineral exploration is the improvement brought to geological mapping provided by analysis of aeromagnetic maps. This is not possible without proper interpretation. Successful exploration programmes, such as that which led to the 1989 discovery of gold resources in the Copper-Zinc Gold Louvicourt deposit in the Val-d'Or region of Quebec, are based on the integration of geological, geochemical and geophysical data of which regional and detailed aeromagnetic interpretation are an important component (Gill and Stockford, 1992).

Large aeromagnetic surveys have prompted the merging of structural geology and geophysical interpretation, although the principle of combining these two fields applies to all interpretations of geology from geophysics. Structural geology is a natural partner to aeromagnetic interpretation since it relies heavily upon recognition of geometry.

An image of aeromagnetic data shows only the distribution of magnetic minerals, from which the geometry of the magnetic rocks can be observed only after proper interpretation. Since the significance of features in the aeromagnetic data is sometimes ambiguous, we may be guided in our interpretation of them by using structural principles.

For mapping purposes, magnetic anomalies can be considered to be primarily due to the magnetite content of the rocks, although pyrrhotite can also be important especially in pelite schists (Teskey and Hood, 1993). Factors affecting the magnetite content of rocks, summarised by Grant (1985), include iron content, oxygen fugacity during formation, metamorphism, silica and aluminium content.

Knowledge of the relative susceptibility of various lithologies comes from an understanding of the above factors. However, the interpretation of these lithologies can be ambiguous and requires additional geological information as to which rock types are present. Hence, the merging of geological and geophysical data is emphasised.

Despite the inherent difficulty in identifying rock type from magnetic characteristics alone, magnetic maps have proved to be invaluable for tracing magnetic units beneath sediments, water, or overburden, and for locating faults by the offset or truncation of anomalies (Boyd, 1979 and Isles, 1989). Their low cost compared to other geophysical methods also has made them widely available.

Thus the proper interpretation of aeromagnetic data has played a major role in improving our understanding of the geology worldwide from exploration to continental scales. It is a fundamental tool for exploration particularly under cover such as the study area in this thesis and has contributed to numerous discoveries, most of which have not been documented (Hood, 1993).

### 3.3. Principles and styles of aeromagnetic interpretation

#### 3.3.1. Overview

Paterson and Reeves, 1985 stated: "There is a continuous large demand for gravity and magnetic surveys all over the world for a variety of exploration applications, all of which require the geophysicist to provide some new insight into the geology of an area at scales ranging from very large to very small. To achieve this objective, (a) surveys must be carried out accurately, and (b) their results must be interpreted in sympathy with what is already known of geology".

The methodology and instrumentation for acquiring and compiling data is in a very advanced stage (Teskey and Hood, 1993) and appears to be keeping pace with modern technology. Although aeromagnetic surveys continue to play a prominent role in mineral exploration, the interpretation of aeromagnetic data has been influenced by the geology and the ore occurrences of a given region (Tucker and D'Addario, 1987).

Interpretation of aeromagnetic data, like any type of geological interpretation, is subject to individual styles and will vary according to the end result required. Like air photography and Landsat interpretation, aeromagnetic interpretation should not be seen as an end in itself, but as a step towards geological interpretation (Isles, 1989).

The principles of aeromagnetic interpretation are very similar to those of photo interpretation with one important difference. Magnetic surveys measure only one

parameter of the geology in a uniform way, while air photos show several aspects of the geology and in different ways (Isles, 1991 and Pridmore et al., 1994). The mechanics of magnetic interpretation should therefore, be more straightforward than photo interpretation.

However it is important to remember the wide range of geological environments where magnetic information can be usefully employed. Like photo interpretation, aeromagnetic interpretation should not follow a strict recipe, but should change according to the geological problem at hand.

One of the most essential elements in getting the most information from aeromagnetic interpretation, is to let it tell its own story before drawing concrete geological conclusion. A common approach is to tie magnetic information into a pre-existing known geology; emphasising the magnetic features which agree with it and giving reasonable reason for those which do not. It should be stressed that except cultural noise there are very few non geological contributions to aeromagnetic data, so it is generally unwise to dismiss unexpected features as spurious.

There are very few who believe the old notion that you should interpret the aeromagnetic data before you look at the geology. Provided the interpreter remains open minded, much misdirected effort and time can be saved during an interpretation if the interpreter has a good understanding of the geology of the area.

The geophysicist is concerned not only with finding a physical property distribution that best fits the observed data, but also with a distribution that is consistent with what is

already known about the geology and what is geologically reasonable to speculate about the unknown. It is within these limits that new geologic information may be obtained from potential field data.

### **3.3.2. What geological information is contained in aeromagnetic data?**

In the magnetic method, the rock property is magnetic susceptibility and/or remanent magnetisation, both of which can only exist at temperatures cooler than the Curie point, restricting the sources of magnetic anomalies to the uppermost 30-40 km of the earth's interior. In practice, almost all magnetic properties of rocks in bulk reflect the properties and concentrations of a single accessory mineral, magnetite, which signals a caution in relating magnetic surveys to geology.

Ideally magnetic interpretation provides maps of rock units containing magnetic minerals. Rocks which in hand specimen would be regarded as non-magnetic (say, 0.02-0.5% magnetite) will show substantial aeromagnetic responses when they occur in large volume. Major benefits stem from the fact that aeromagnetic surveys can map this single geological parameter in a uniform and detailed manner.

Most importantly, the structural information which can be gleaned from aeromagnetic data gives it a unique place in the earth scientist's armoury. It is important to note, however, that the magnetic minerals are very widely distributed through all types of terrains and there are very few regional scale geological problems where aeromagnetic does not provide useful extra information.

### 3.3.3. Quality of the data

The surveying and processing parameters will govern the level of detail which can be extracted from the data. Boyd (1967 and 1979); Isles and Valenta (1991); Pridmore et al. (1994) and Gunn (1996) indicated that the main points to check are:

- Line spacing and flying height;
- Position recovery technique (visual or mechanical);
- Interpolated grid size;
- Compilation scale;
- Type of data presented (measured total field or filtered).

#### 3.3.3.1. Line spacing and flying height

In general a line spacing four times wider than the flying height is employed so that, in most cases, geological resolution along line is much better than in the across line direction. Financial considerations usually dictate that surveying is carried out along parallel lines of one orientation.

Occasionally grid surveys are flown and have been shown to be beneficial. The flying height is the parameter determining the maximum possible geological resolution. The basic rule is that two geological contacts spaced less than one flying height apart cannot be readily resolved using aeromagnetic information.

### **3.3.3.2. Position recovery technique**

In the last few years, flight path recovery and navigation have been revolutionised by the development of the Global Positioning System (GPS), a satellite system, which used in conjunction with inertial guidance or doppler systems is accurate to within 5-25 m during survey operations (Teskey and Hood, 1993).

### **3.3.3.3. Interpolating grid sizes**

Schemes for interpolating aeromagnetic data onto a regular square grid have been presented by Gallagher et al., 1987, and pioneered in Australia where by far the greatest volume of low level, detailed aeromagnetic surveys have been flown (Isles, 1991). The two basic types are Minimum Curvature and Bi cubic Spline. In both cases the continuous nature of the magnetic field and the extreme anisotropy in sample point distribution is taken into account.

As a general rule the Minimum Curvature schemes produce better looking maps but lose real high frequency geological information. The Spline schemes preserve more detail but are more prone to notchy or “fried egg” effects caused by wider line spacing.

The choice of grid cell size is a key factor in determining how much measured geological detail can be portrayed. The usual choice is between one third and one fifth of the line spacing. Not surprisingly, data processors/contractors prefer one third because the

resulting maps "look better" and interpreters/geologists prefer one fifth because there is more geological resolution.

Grid cell sizes outside this range should only be used in special circumstances. Reinterpretation of gridded data to very small cell sizes for the purposes of data integration is one such circumstance. Although this can be effective, the original aeromagnetic flight line spacing should always be borne in mind. These points should be considered by the interpreter to achieve a better outcome.

#### **3.3.3.4. Scale of presentation**

Two scales of presentation are highly desirable:

(i) A regional scale which allows the outside influences on the main areas to be portrayed at a manageable size.

(ii) A detailed scale which allows all of the required detail to be identified and resolved, while hopefully discriminating against irrelevant or excess detail (Isles, 1991).

These scales ideally should be different by a factor of around 4 or 5. If the difference is much bigger it becomes difficult to relate features from one scale to the other. If it is much smaller, there is considerable overlap and redundancy of information, which, although very useful, is also very costly. The rule of thumb generally used is that compilation scale should be such that one centimetre represents the approximately flight

line spacing. However, compilation scales are not necessarily the best interpretation scales.

In mineral exploration the most frequently used scales for aeromagnetic data are between 1:100,000 and 1:10,000. With a line spacing of 200 m or better, the same data set can have useful applications through this range of scales, but clearly the objectives of interpretation at 1:100,000 will vary considerably from those at 1:10,000.

At 1:100,000 scale the most common objective is to identify areas of exploration interest typically in the range of 10 to 100 km<sup>2</sup>. At 1:25,000 the areas of interest must be focused to around 1 to 5 km<sup>2</sup>. At 1:10,000 specific drill targets are usually identified. It is important to match the interpretation scale with the exploration problem. Many explorationists find this quite difficult-often expecting to define drill targets from a few hours spent with a 1:100,000 scale map. This raises the question of the time spent on the interpretation.

### **3.3.3.5. Presentation of data**

Data-enhancement processes such as filtering, reduction to the pole, continuation, etc. are often thought of as interpretation functions. They are useful processing techniques whereby information is displayed in a more interpretable manner (Paterson and Reeves, 1985). Much research has been carried out in methods of potential-field data enhancement and filtering in recent years.

In addition to the standard processes described, for example, in Spector and Grant (1970); Telford et al. (1992); Rajagopalan and Boyd (1989); Broom (1990); Teskey and Hood (1992 and 1993), useful work has been done in such areas as directional filtering, reduction to the pole at low latitudes and continuation of fields between different surfaces.

The important contribution of such processing methods is realised in the qualitative interpretation of contour maps; in particular, delineation of contacts between units of different physical properties, the recognition of faults and identification of shallow sources superimposed upon strong regional anomalies. Effective display of aeromagnetic data and a systematic approach in interpretation was presented by Rajagopalan and Boyd, 1989; and is dependent of the facilities available, the aims of the interpretation, the magnetic characteristics and the survey specifications.

### **3.4. Mechanics of interpretation**

The mechanics of interpretation are scale independent- the same tasks should be carried out on 1:1,000,000 maps as 1:10,000 maps. Where two scales are available, interpretation should proceed simultaneously at both scales. Boyd (1967 and 1979); Isles and Valenta (1991); Pridmore et al.(1994) and Jhonson et al. (1995) have indicated that there are three main activities involved in the interpretation:

(i) Forming the geometric skeleton

(ii) Grouping areas of common character

(iii) Looking into the third dimension. These are briefly described in the following steps.

### **3.4.1. Stage 1**

Stage 1 is fairly mechanical and as the first step in the interpretation, requires the identification of magnetic rock units, trend directions and pattern breaks. The drawing up of a structural skeleton is a mechanical activity with which most geophysicists and many geologists feel comfortable.

This has been made easier and more comprehensive by the now common use of mathematical filters and image display devices. The results is a skeleton structural interpretation depicting all the framework of the final product and it should be preserved for possible later redecoration. The meaningful geological picture will be portrayed by this and the other steps of interpretation.

### **3.4.2. Stage 2**

This step requires more interpretation and is best done over a period of time with maps pinned up on a wall. Areas of common magnetic character with common geological features are grouped into associations representing geological events. The degree of grouping or generalisation will depend on the purpose and scale of the interpretation.

The complex distribution of magnetite in the rock can yield important information on both the ancestral lithology and the metamorphic history. Such distributions cannot be

defined by any simple mathematical functions, but rather, require a qualitative or semi quantitative textural classification, commonly known as zoning.

Zoning or grouping involves the drawing of boundaries between units of different geophysical texture. Traditionally, texture is defined by such parameters as linearity, relief, and background level, and by features such as anomaly shapes and wavelengths. Usually, however, a great deal of subjectivity has been used in the zoning processes.

The temptation to assign a lithological type to each magnetic unit evident in the magnetic data such as cross cutting faults is not always appropriate. Sometimes this works, that is, it is appropriate. In many cases, however, this leads to credibility problems because the field geologist expects to encounter the specified lithology types and faults at the surface, and very often what is seen at the surface is not so straightforward.

For a number of reasons (see Grant, 1985 and McIntyre, 1980) it is not a straightforward matter to express aeromagnetic structures in terms of strict lithological groups and deformational structures. Grant and McIntyre allude to the fact that the distribution of magnetic minerals through a geological province is due to a complex convolution of depositional, diagenetic, deformational and metamorphic events with original rock chemistry.

These events rather than the rock chemistry, commonly dominate the picture and consequently the aeromagnetic interpreter should think as much about the events as about the rock types. A very important aside here, is that the accumulation of mineral deposits is usually in response to one of the above events.

As a consequence, the process of draping the geological meaning onto the structural skeleton involves substantial thinking time if it is to be done properly. The appropriate geological groupings or classifications will vary according to the scale of investigation. At detailed scales the differentiation of magnetic phases of a single lithology might be important, while at regional scales the distinction between basement and sediments might suffice.

One useful approach which parallels the geologist's approach to generalisation and grouping is the concept of "Lithological Associations". To a geologist a lithological association is a package of rocks corresponding to a geological interval, environment or event. It is a means of grouping rocks without committing to a stratigraphic or genetic interpretation.

The same style of generalisation is very convenient for aeromagnetic interpretation where frequently a package of rocks can be identified as having magnetic characteristics distinct from other packages. These "Lithological Associations" can be expressed in terms to which a geologist can directly relate without expecting the interpretation to differentiate the lithologies observed at the surface. As an example, the ultramafic association (Au) is a package of rocks dominated by ultramafic volcanics but including minor basalts, dolerites and sediments. The very strong magnetic response is almost entirely due to the magnetic phases of the ultramafics.

Applying the most appropriate groupings usually requires a sound geological understanding backed up with the best available surface control. Probably the most

important ingredient in the "Lithological Associations" is the commitment to resolving ambiguities by field observation and physical property measurements.

The fact that magnetic susceptibility is one of the most used physical properties, minimises the areas where observed geology and magnetic features are at odds. When conflicts of interpretation do occur, joint field investigation is undertaken. The end product is a map which both field geologist and aeromagnetic interpreter agree upon. It may not be perfect, but it benefits greatly from the balanced input of surface and remote observations (Isles and Valenta, 1991).

### **3.4.3. Stage 3**

Stage 3, the third activity in the interpretation of aeromagnetics, involves extracting specific detail in the third dimension. This goes well beyond the stage 2 activity of identifying 2D geometric relationships and asymmetry which suggest such things as dip, depth and plunge directions. Analysis of data in profile form is usually necessary to determine depth, dips and magnetite concentration information.

This is rarely done on an entire survey basis, largely because of the extra cost and the amount of time involved. It is usually confined to specific areas of interest. The cost of computing time will decrease sufficiently if routine automated computation of these parameters can be achieved but it always adds another layer or two of information to the geological interpretation.

### **3.4.4. Refinement**

Obviously, the quality of the interpretation will improve as more time is spent on it. It is also important to focus effort on the right problem. The amount of time to be devoted to interpretation depends on its ultimate use, but it is important to realise that interpretation is not a black box process - it does not happen at the flick of a switch.

The best interpretations seem to occur second time around after a preliminary effort has been pinned on the wall, stewed over and discussed with experts or colleagues. This of course applies to all types of data but historically aeromagnetic interpretations have been predominantly brief one pass efforts (Boyd, 1979; and Isles and Valenta, 1991).

It is worth reflecting on the size of the area covered and level of detail in an aeromagnetic data set before deciding how much time should be allowed for its interpretation. As with all data sets, the interpretation should be regarded as dynamic. It will change as new evidence and ideas come to light. It is most important, therefore, to be able to retrace the interpreter's steps back to the original data so that if necessary it can be refined.

The final interpretation map must attempt to depict boundaries of both individual bodies and larger units defined by the zoning process; it should contain structural information such as dips and strikes of interpreted physical property lineations and boundaries; and it should attach a geologic identification, however tentative, to each of these features.

In many cases as explained in Grant (1985a and b) and McIntyre (1980), geophysical boundaries will transgress mapped geologic contacts, because the geologic characterisation is based on a very different set of physical and chemical parameters and, in any event, no geologic map is truly complete.

It is the geophysicist's job to attempt an explanation for these differences in geologic terms so that potentially favourable environments can be identified and informed decisions can be made for further exploration or mapping. The fundamental points of presenting systematic procedures for the interpretation of aeromagnetic data have been discussed above and are now summarised in sequential order.

### **3.5. Summary of Steps in Aeromagnetic Interpretation**

1- Appropriate presentations of the data are normally chosen. Ideally, one image emphasising the shallower (structural) detail (e.g. vertical derivative map) and one image emphasising the broader, deeper features (eg. coloured total field map) are selected. A single map or image cannot adequately portray both of these aspects. At least two different maps will be required to see both local and regional features.

2- Suitable scales of interpretation are suggested. First is a working scale which will allow contact positions to be defined with sufficient accuracy and second, a regional scale which allows the big picture to be viewed on a single map of manageable size. These scales should differ by a factor of around 4 or 5. Inappropriate maps can easily hide some of the geological meaning.

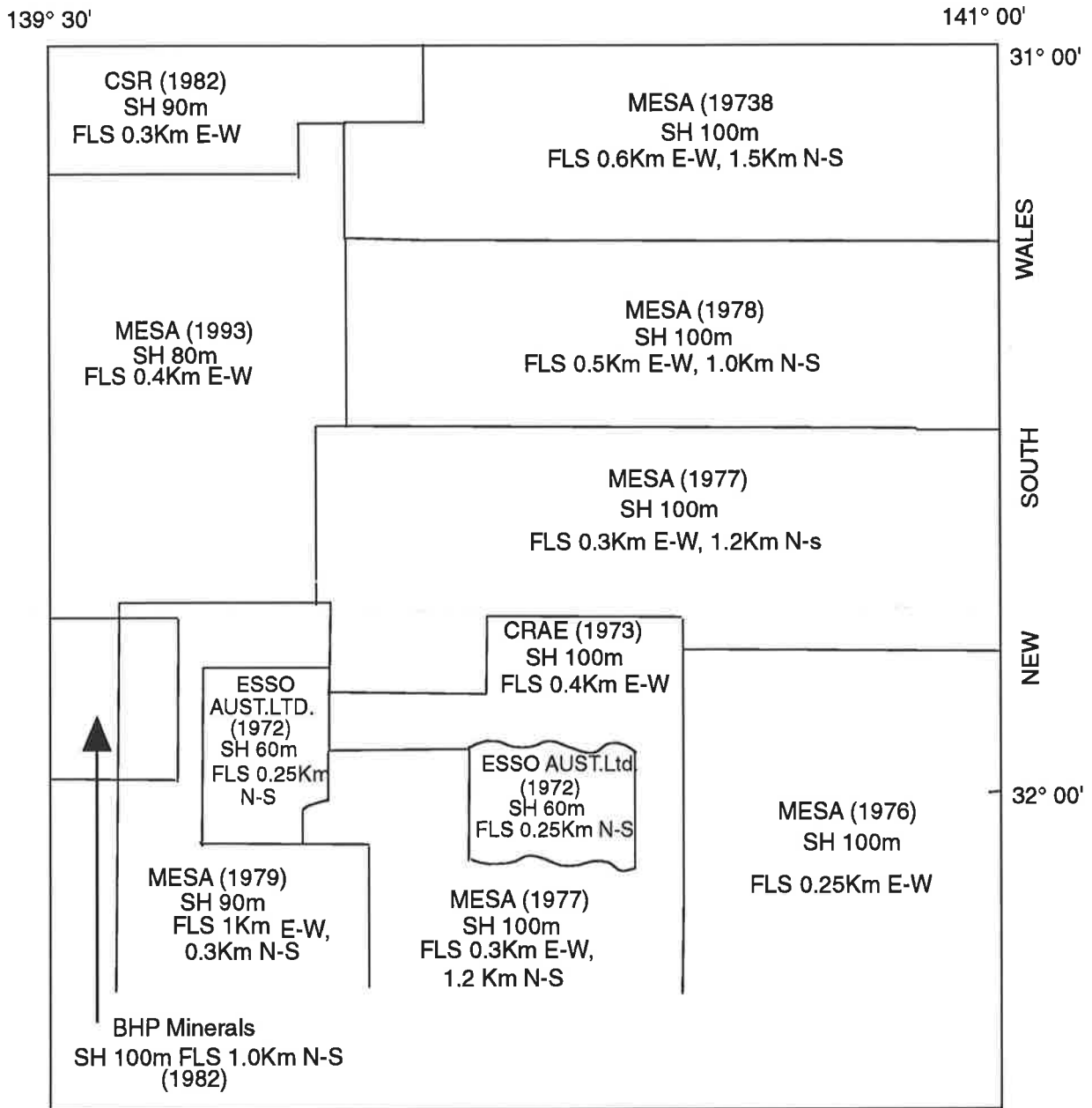
3- The relevant geological data at the same scale as the aeromagnetic information is essential.

4- The aeromagnetic interpretation must be treated like geological mapping. Observation is documented and gradually a geological interpretation is arrived at. Enough (uninterrupted) time to make careful observations and let their meaning be grasped is fruitful.

5- The geometric aspects of the data is initially considered. Magnetic bodies or geological units are outlined. The results will be blobs but should have some shape rather than featureless worms or straight sided polygons. Contacts, discontinuities and lineaments which are identifiable are delineated. Subtle features must not be forgotten in the presence of the obvious ones. Characteristics of gradients which may indicate dips or plunges are documented.

6- The resultant worm map should be regarded as a geometric or structural skeleton into which a geological classification can be built.

7- Analyses are carried out on selected profiles to determine depths, dips and magnetic concentration information; and to define a visualisation in 3D of the anomalous bodies.



SH : Survey Height

FLS : Flight Line Spacing

Fig. 4.1 Curnamona 1:250,000 Map Sheet

INDEX TO LOW LEVEL AEROMAGNETIC SURVEYS REDRAWN AFTER MESA

Curnamona 1:250,000 sheet.

## **4. Processing, presentation and susceptibility measurements from rocks in the Curnamona 1:250,000 sheet.**

### **4.1. Data specification**

Various surveys have been flown by Mines and Energy of South Australia (MESA) and private companies over the Curnamona 1:250,000 sheet. The specification of the magnetic data which have been interpreted in this study is shown in figure 4.1. The located aeromagnetic data of figure 4.1 were initially used for regional interpretation. However due to levelling problems of the located data, 75×75 metres gridded data obtained from Placer Exploration Pty Ltd. was used for the interpretation.

### **4.2. Processing**

The author was capable of processing the data but did not have the facilities for printing the large scale maps. A colour image of Total Magnetic Intensity (TMI) illuminated at azimuth 90° and inclination 45° at a scale of 1:250,000 covering all the Curnamona and northern two thirds of the Olary 1:250,000 sheet was provided by Placer Exploration Pty Ltd. This map along with 1:1,000,000 gravity and magnetic maps of South Australia were used for regional interpretation. Placer Exploration also provided three contour

**Curnamona 1:250,000 sheet.**

maps of TMI at a scale of 1:100,000 for the Kalabity, Mulyongari and Benageri sheets and these were used for detailed interpretation (discussed in chapter 6).

The author had access to a first vertical derivative grey image at a scale of 1:250,000 encompassing the Willyama Inliers in South Australia and Broken Hill which was provided by CRA Exploration Pty Ltd. This was the only map with a continuous coverage of magnetic responses of the Willyama Inliers between South Australia and New South Wales.

This first vertical derivative map of CRA was also used for delineation of contacts, lineaments and boundaries at the regional scale. Contouring and forward modelling; transformation and imaging programs written by J W Paine, Z Shi, and S Rajagopalan respectively were used by the author for processing and presentation. Contour maps of Total Magnetic Intensity (TMI) and Vertical Gradient (VG) at a scale of 1:25,000 were produced by the author using the software of the Geology and Geophysics Department of the University of Adelaide and were printed in the National Centre for Petroleum Geology and Geophysics (NCPGG) of the University of Adelaide. This scale was selected for detailed interpretation to be compatible with the three available geological maps which will be discussed in chapter 5. Contour maps of TMI and VG were superimposed on the colour image at a scale of 1:100,000 for easy comparison. The contour maps better show the gradient and the images easily identify lows and highs.

The results of the interpretation from the 1:25,000 map initially were transferred to the 1:50,000 map until the pattern of magnetic responses was recognised and then to the 1:100,000 map. Most of the tracing of the magnetic marker suite (discussed in chapter 6) outside the limited available mapped geology (the Koolka South, the Kalabity South and later the Kalabity North sheets) was carried out on the 1:100,000 scale.

Wherever confusion arise regarding the tracing of the Lithomagnetic suite, a larger scale map was produced to resolve the ambiguity. Quantitative interpretation was carried out on vertical gradient profiles. Due to the linearity of the anomalies and their strike length extent, the dike model was used for the interpretation.

### **4.3. Presentation**

A standard interpretation procedure was outlined in chapter 3. Almost all the steps previously mentioned for the presentation were followed in this study. The significance of the type of presentation has been reviewed by Paterson and Reeves, 1985; Broom, 1990; Teskey and Hood, 1991 and 1993. In this study both small scale presentation for identification of broad areas of possible interest and large scale presentation for the direct search for a particular magnetic horizon have been used.

Total Magnetic Intensity and its first vertical gradient were presented both at small and large scales. The vertical gradient at large scale allows the emphasis of detailed structure by resolving the edges of shallow magnetic bodies more precisely and the total magnetic

intensity provides crucial information on broad geological subdivisions and deeper magnetic sources.

#### **4.4. Rock magnetism**

In order to understand the geological significance of spatial variations in the earth's magnetic field, it is necessary to understand the geological features and phenomena which influence the magnetic response. The earth's magnetic field is a vector which varies in orientation and magnitude from place to place on the earth's surface, partly due to geographic position and partly due to the influence of sub surface materials.

The properties of subsurface materials which produce variations in the earth's magnetic field are susceptibility and remanent magnetisation. Magnetic surveys are useful because these properties vary in a geologically systematic way. In an area which contains no susceptibility contrasts and remanent magnetisation, magnetic surveys would not be useful.

In summary, magnetic surveys are carried out to map variations in the intensity of the earth's magnetic field due to induced and/or remanent magnetisation in relatively near-surface bodies. The earth produces a magnetic field, probably due to electric currents deep in the mantle and core, and small scale variations in the earth's field are due to the fields induced in near surface bodies.

Curnamona 1:250,000 sheet.

#### 4.5. Magnetic susceptibility

Rock magnetization characteristics in applied geophysical studies were presented by French et al., 1993; Clark and Emerson, 1991; and Clark, 1983. Magnetic susceptibility ( $k$ ) is the ratio of the induced field ( $I$ ) to the applied field ( $H$ ) (that is the earth in this and most cases). All materials have a magnetic susceptibility. Most materials show diamagnetic behaviour, which corresponds to a negative susceptibility and a small induced field opposing the applied field.

Substances containing unpaired electrons display paramagnetic behaviour which corresponds to a small, positive susceptibility which is independent of the applied field but dependent on temperature. Ferromagnetic materials show a natural alignment of magnetic moments in small domains in the presence of an applied field. In this case, susceptibility is a function of both the applied field and temperature

Main rock forming minerals such as quartz and feldspar display diamagnetic behaviour, meaning that they produce a weak induced field opposite to that of the earth's field. Materials such as clays display paramagnetic behaviour, and it turns out that they often have anisotropic susceptibilities which record strain fields, though this of little use in magnetic surveys.

There are relatively few minerals which show significant positive magnetic susceptibility. Of these, haematite, ilmenite and magnetite are by far the most common. Magnetite

**Curnamona 1:250,000 sheet.**

displays by far the highest magnetic susceptibility of these, to the extent were it is generally possible to assume that magnetic surveys essentially map the distribution of magnetite in the crust. In other words, the key to a geological understanding of a magnetic survey is an understanding of the connection between mapped geology and the distribution of magnetite. Pyrrhotite is an exception which can be important as in the case of the Elura orebody, Cobar, New South Wales (Emerson, 1980).

The distribution of magnetite is influenced by sedimentary and igneous primary depositional processes; metamorphism, alteration and deformation. This often makes interpretation difficult, but it also allows us to acquire information on aspects of all of these processes in the survey area. Susceptibilities of individual rock groupings are highly variable, spanning 2 - 3 orders of magnitude in some cases.

#### **4.6. Remanent magnetisation**

Ferromagnetic minerals display hysteresis, meaning that at some point during alignment of magnetic moments in an applied field, they reach saturation and then retain a permanent magnetisation when the magnetic field is removed. In rocks, this adds another vector quantity to a measurement of the earth's field at any point.

This can present problems for interpretation based on anomaly shape, but the existence of this permanent magnetisation has been a boon to Paleomagnetic researchers. This

**Curnamona** 1:250,000 sheet.

residual magnetisation is called Natural Remanent Magnetisation (NRM), and it can originate chemically, depositionally, isothermally and thermally.

#### **4.7. Koenigsberger ratio**

The Koenigsberger ratio is the ratio of remanent to induced magnetisation in materials. The orientation and magnitude of the induced field is a function of orientation and magnitude of the earth's field. On the other hand, remanent magnetisation is a record of previous magnetic fields and can be variable in orientation. In many deformed rocks, remanence is so variable in order and magnitude that its net effect on anomalies at survey scale appears to be negligible.

#### **4.8. Geological influences on the distribution of magnetic minerals**

Magnetic surveys map the distribution of magnetic minerals, particularly magnetite, in the crust. The distribution of magnetite in different rocks has been discussed by McIntyre (1980) and Grant (1985); and a summary is presented here from these two sources. Factors determining the distribution of magnetic minerals can be grouped into the categories of primary and secondary processes. Primary processes are those occurring during deposition of sedimentary rocks or crystallisation of magmas, while secondary processes encompass post depositional phenomena such as metamorphism, metasomatism and deformation.

Curnamona 1:250,000 sheet.

#### 4.8.1. Primary influences

**Total Iron** : All magnetic minerals contain iron. It is therefore obvious that the primary iron content of sedimentary and igneous rocks is a key factor in determining their magnetic susceptibility. McIntyre (1980) indicated that the composition and amounts of iron minerals in sediments depend firstly on the ways in which iron occurs in sediment source materials. This influence can of course be greatly modified by chemical and sorting processes preceding sedimentation. The following list gives a simple outline of ways in which iron occurs in sediment source materials.

- 1- Volcanic source rocks - iron occurs in silicates and oxides (magnetite more abundant than haematite or ilmenite).
- 2- In plutonic and metamorphic source rocks, iron occurs as silicates and as ilmenite, haematite and magnetite.
- 3- In sediments, iron is more abundant in fine grained rocks (often absorbed onto or closely associated with clays).
- 4- Soils are generally enriched in iron, which mostly occurs as amorphous ferric oxide.

**Geochemical environment** : In addition to total iron content, a key influence on susceptibility is the partitioning of iron into ferrous oxides, ferric oxides, sulphides and

**Curnamona 1:250,000 sheet.**

silicates. In any setting, stable iron phases will be determined by oxygen and sulphur fugacity; and temperature.

This general pattern can be applied to sedimentary depositional environments, in which it can be expected that high oxygen fugacity will favour haematite formation and haematite stability, moderate oxygen fugacity will favour magnetite formation and low oxygen fugacity will favour pyrrhotite or pyrite formation if sulfur fugacity is high enough.

**Crystallisation environment in igneous rocks** : In an igneous environment, the following sequence of iron phases is expected with increasing oxygen fugacity :

- 1 ) Iron silicates
- 2 ) Titanomagnetites
- 3 ) Titanohaematites
- 4 ) Haematite

In addition, the following trends can be observed with fractionation:

→ decreasing total iron; → increasing Fe/Ti ratios; → increasing oxygen fugacity.

The net effect of this trend is that mafic rocks often have higher iron content (5-10%) which are predominantly in iron silicates and iron-titanium oxides, while felsic rocks have

Curnamona 1:250,000 sheet.

lower iron content but a greater proportion of iron in high susceptibility Ti-poor magnetite.

#### 4.8.2. Secondary influences

**Metamorphism** : There are a number of magnetite producing reactions, beginning at lower green schist facies, which involve the breakdown of hydrous Fe-Mg silicates to form magnetite. Grant (1985) indicated that during progressive regional metamorphism secondary magnetite can be produced at all stages, but mostly it develops under rather low-grade conditions by the conversion of haematite, or under high-grade conditions from the breakdown of hydrous (Fe, Mg) silicates such as biotite and hornblende into simpler orthosilicates. The magnetite-producing capacity of a rock during metamorphism is determined by attributes which are largely inherited from the premetamorphic state, of which the most important are total iron content, oxidation state, and degree of silica saturation. Other influencing factors included magnesium, aluminum and carbon content. Magnetite is destroyed during granitisation and by low-temperature alteration. An implication of this is that the magnetic susceptibilities of most rocks generally increase with metamorphic grade. Once again, however, the increase will be a function of iron content in the case of isochemical metamorphism. However, ultra metamorphic processes such as granitisation generally destroy magnetite.

Curnamona 1:250,000 sheet.

**Metasomatism** : In most cases, the magnetite or pyrrhotite which allows direct detection of an orebody is the result of metasomatic alteration of host rocks or precipitation into open space from a fluid. A detailed discussion of the physiochemical conditions favouring transport and deposition of iron from a fluid is outside the scope of this study, although evidence of magnetite precipitation and magnetite dissolution associated with orebodies, faults and alteration zones is often clear in a magnetic data set.

**Deformation** : Deformation effects include disruption and reorientation of remanence, metasomatism associated with faults and the effects of grain-scale deformation processes. In high metamorphic grade ductile settings, grain growth associated with deformation will cause magnetite to grow through three different styles of domain behaviour. At small grain sizes ( $\leq 0.03$  mm) magnetite grains are super para-magnetic, displaying high susceptibility and zero remanence.

Above this grainsize threshold and up to 0.06 mm, magnetite grains display single domain behaviour, displaying lower susceptibility and high remanence. At larger grain sizes, magnetite displays multidomain behaviour, with moderate susceptibilities and low remanence. Thus, grain-scale processes have a profound effect on susceptibility and remanence. Of the influences listed above, primary variations in iron content and oxygen fugacity and possibly fault-related alteration are likely to be the most obvious in a survey, even in areas of intense deformation, metamorphism and metasomatism.

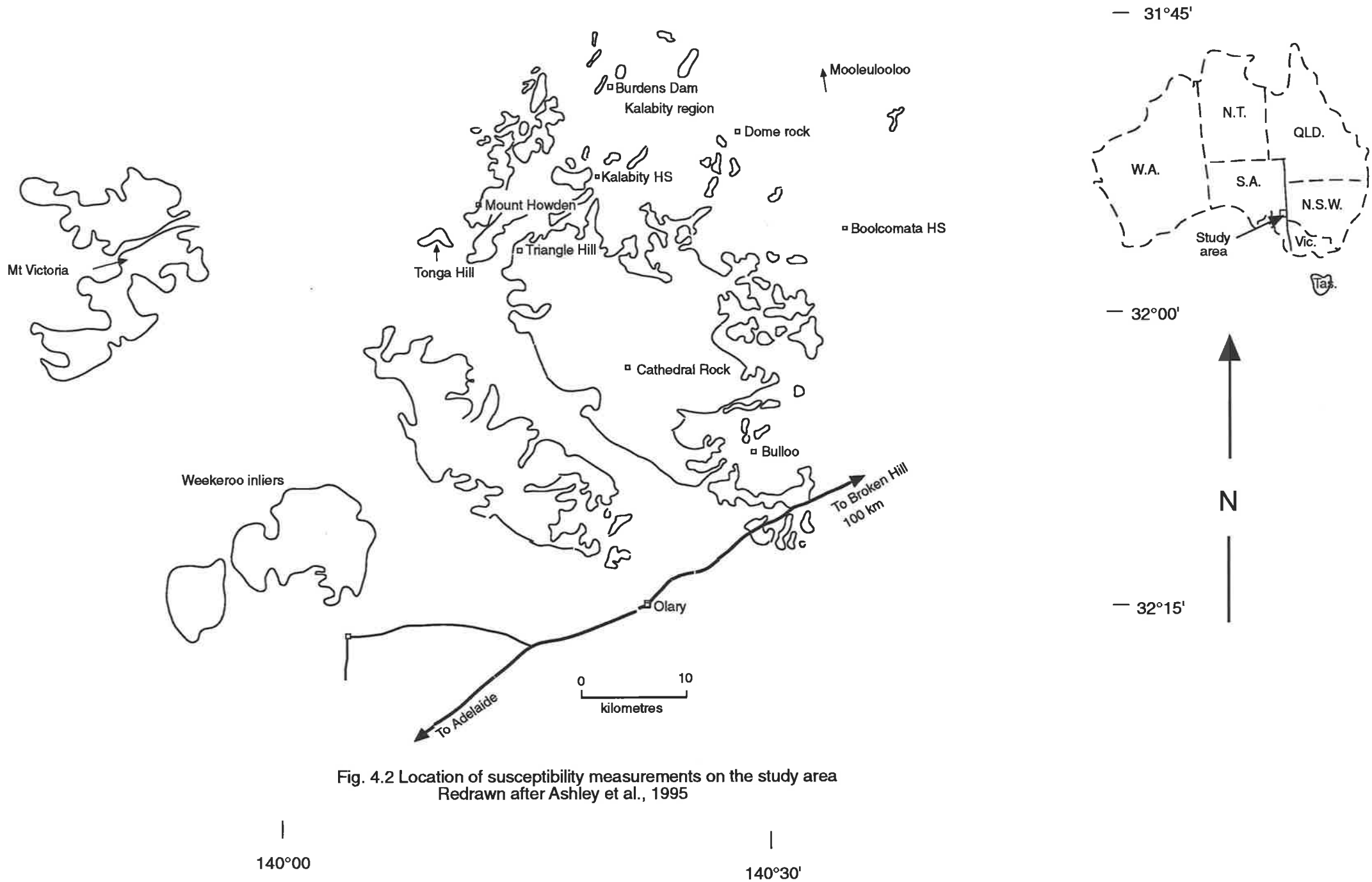


Fig. 4.2 Location of susceptibility measurements on the study area  
 Redrawn after Ashley et al., 1995

Curnamona 1:250,000 sheet.

#### **4.9. Susceptibility measurements**

One of the unknowns in the interpretation of magnetic anomalies is often the magnetic properties of the source rocks. These properties can, however, be measured independently at a cost that is very small compared with the cost of carrying out an airborne survey (Reeves, 1993). A review of previous magnetic studies and rock property measurements in the South Australian Mineral Resources References (SAMREF) and university theses indicated that except for the five drill holes to the north of the Curnamona 1:250,000 sheet which were drilled by MESA and were logged for susceptibility, no other susceptibility measurement has been done in the Olary Block.

Wood, 1972 and Everle, 1973 have done some susceptibility measurements on the granitic gneiss and amphibolite of the Broken Hill Mine area. Isles, 1983 has referred to previous susceptibility measurements which were carried out on different rocks over the Broken Hill Mine area.

The author had the opportunity to do some susceptibility measurements in the field over the representative rock units of the Willyama Supergroup in March, 1995. These measurements are summarised in table (4.1) and presented in appendix (1). The location of the measurements are shown in figure 4.2. The susceptibilities of the Albitite rocks which have been intersected by CRA Exploration Ltd in the Waulkaloo area and which will be discussed in chapter 5 are also presented in appendix (1).

Curnamona 1:250,000 sheet.

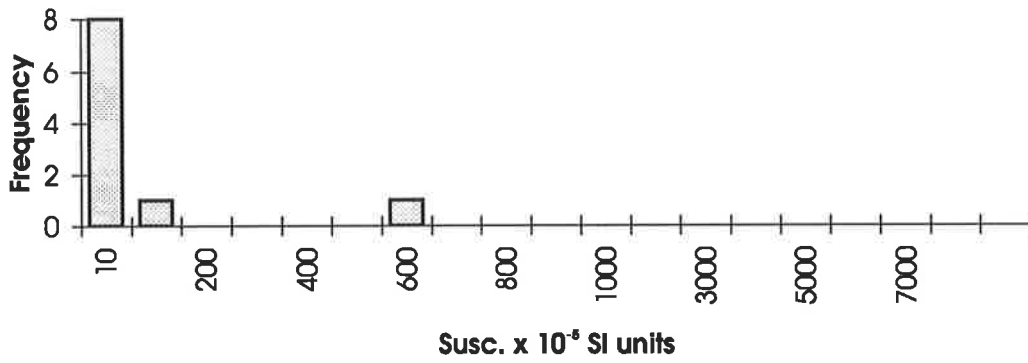
The susceptibility of the units in the sequence is given in this section and the units are taken in ascending order. Measured susceptibilities over the Composite Gneiss and Migmatite Suite placed them magnetically in the second rank in the Willyama Supergroup rocks. Susceptibilities of this suite in the Triangle Hill area were in the range of 0.0015 to 0.02 SI units with an average of 0.007 SI units.

Formation	Magnetic susceptibility $\times 10^{-5}$ SI units							Locality
	0-50	50-100	100-500	500-1000	1000-2000	2000-5000	> 5000	
PS			4					10
BS		6						9
CS	10	5		1				6, 7, 8
QFS	4	3	6	2	5	4	3	3, 4, 5
CGS	2		5	2		1		1, 2

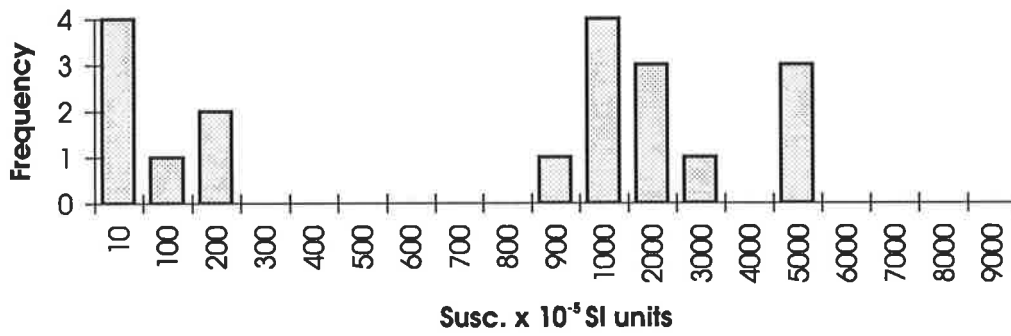
Table 1 Outcrop susceptibility measurements; Abbreviations are as follows; PS : Pelite Suite; BS : Bimba Suite; CS : Calcsilicate Suite; QFS : Quartzofeldespathic Suite; CGS : Composite Gneiss Suite. Numbers under locality column are as follows; 1 : Triangle Hill; 2 : Tonga Hill; 3 : Dome rock; 4 : Mt. Howden; 5 : Toraminga Hill; 6 : Mt. Howden; 7 : Cathedral rock; 8 : Bulloo; 9 : Brooks Dam; 10 : Mooleulooloo

Measured susceptibilities of the Quartzofeldespathic Suite in the Mt. Howden Mine area of the Koolka South sheet (table 4.1) showed a bi-modal distribution with the range of values between 0.00006 SI units to 0.05 SI units. The lower values of susceptibilities of

### Calcsilicate Suite Histogram



### Quartzofeldspathic Suite Histogram



### Quartzofeldspathic drill hole histogram

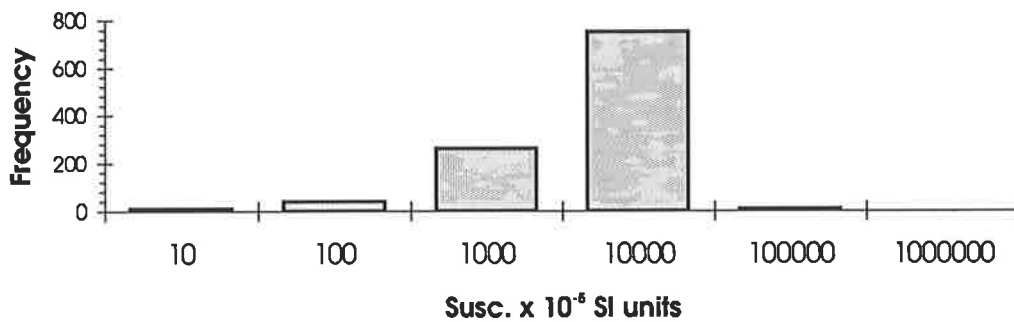


Fig. 4.3 Compared susceptibilities

**Curnamona 1:250,000 sheet.**

this suite falls in the range of susceptibilities of the Calcsilicate Suite and the higher values are one to several orders of magnitude greater than the lower ones (fig. 4.3).

This high magnetic response is related to the presence of disseminated magnetite, local concentration of iron formations and reconstitution of massive magnetite after brecciation in this suite (Cook, 1990 and Ashley, 1995). The lower range of susceptibilities may be related to alteration and the conversion of magnetite to haematite during the prograde metamorphism (Cook, 1990).

The measured susceptibilities (table 4.1) over two outcrops of the Calcsilicate suite in the Mt. Howden mine area varies from 0.00008 SI units to 0.0002 SI units which is, on average, one order of magnitude lower than the Quartzofeldspathic suite in the same general area (fig. 4.3). To further investigate the differences in the magnetite concentration level of the Calcsilicate Suite and the Quartzofeldspathic Suite, measured susceptibilities of the Calcsilicate Suite in the Cathedral rocks area (table 1) were compared with the 327 m hole, logged for susceptibility (four readings/m) of the Quartzofeldspathic suite. This hole was drilled by CRA Exploration Pty Ltd in the Waulkaloo area. Comparison confirmed the surface measurements and also demonstrated that the Quartzofeldspathic suite has a susceptibility of one to several orders of magnitude greater than the Calcsilicate suite (fig. 4.3) on average.

The Bimba suite is weakly magnetic and a few measurements over this unit in the Brooks Dam area showed low susceptibility (table 4.1). The non-magnetic character of the

**Curnamona 1:250,000 sheet.**

Bimba suite is related to the conversion of iron oxide in the Calcsilicate suite to iron sulphide in the Bimba suite (Bierlein et al., 1995). Susceptibility measurements over the Pelite suite (table 4.1) in the Mooleulooloo area were in the range of 0.002 to 0.0038 SI units.

Although the susceptibility measurements show considerable variation between and within the measurement suites, the most magnetic unit was always the Quartzofeldespathic suite, at least one to several orders of magnitude greater than the Calcsilicate suite. Thus the previous definition of the Calcsilicate suite as the magnetic marker unit (Yates, 1993; and Flint and Parker, 1993) has been called into question.

In conclusion, comparison of susceptibility measurements showed that the Quartzofeldespathic Suite has a bi-modal distribution of susceptibility with a lower range similar to the Calcsilicate Suite and a higher range one to several orders of magnitude greater than the lower one. This immediately implies that the two suites must produce a similar anomaly even though they are compositionally different. Because of considerable variation in susceptibility within and between the units, weathering problems and limited measurements, a large number of measurements from unweathered samples are necessary to draw a statistically sound conclusion.

Curnamona 1:250,000 sheet.

#### 4.10. Remanent magnetisation in the Willyama Supergroup rocks

Remanent magnetisation in the Willyama Supergroup rocks in the Olary Block is open to question. Limited studies regarding remanent magnetisation around the Broken Hill Mine by Evele, 1973 and Wood, 1972 did not show evidences for the presence of remanence or lack of it in the Willyama rocks. Isles (1983) indicated that the presence of a systematic remanent component in the Willyama rocks is unlikely because of the sedimentary nature of most of the magnetic horizons in question, and the subsequent metamorphism.

Opaque mineral study, whole rock analyses and also microprobe analyses (Cook, 1990) on the Quartzofeldspathic suite and the calclbitite rocks in the Kalabity area of the Curnamona 1:250,000 sheet have showed that magnetite is the most common opaque mineral within the Albitite, locally comprising up to 9 percent by weight. Magnetite grainsize varies from less than 10 microns up to a few millimetres, although the average is approximately 20 microns in many rocks.

His microprobe analyses of opaque mineral grains also indicated that they are titanomagnetites (ulvospinel-magnetite series) averaging 4.71 %  $\text{Tio}^2$ . Recalling the discussion in section 4.8.2 that magnetite grainsize smaller than 0.03 mm are super para-magnetic, and display high susceptibility and zero remanence, it is reasonable to assume no remanence for the Albitite rocks. However, Grant, 1985 indicated that magnetite

**Curnamona 1:250,000 sheet.**

which is contaminated with even small amounts of ulvospinel or ilmenite can acquire a significant magnetic remanence.

Modelling of linear anomalies in the Mt Howden Mine area arising from the Quartzofeldspathic suite (see section 5.2.6) required an average susceptibility of similar order to the measurements taken in the field which suggests that remanent magnetisation may not be significant. As stated above, in many deformed rocks remanence is so variable in order and magnitude that its net effect on anomalies at survey scale appears to be negligible.

To sum up all the above discussion concerning remanent magnetisation in the Willyama rocks, the presence of remanence in the Albitite rocks will be considered insignificant until further investigation proves it otherwise.

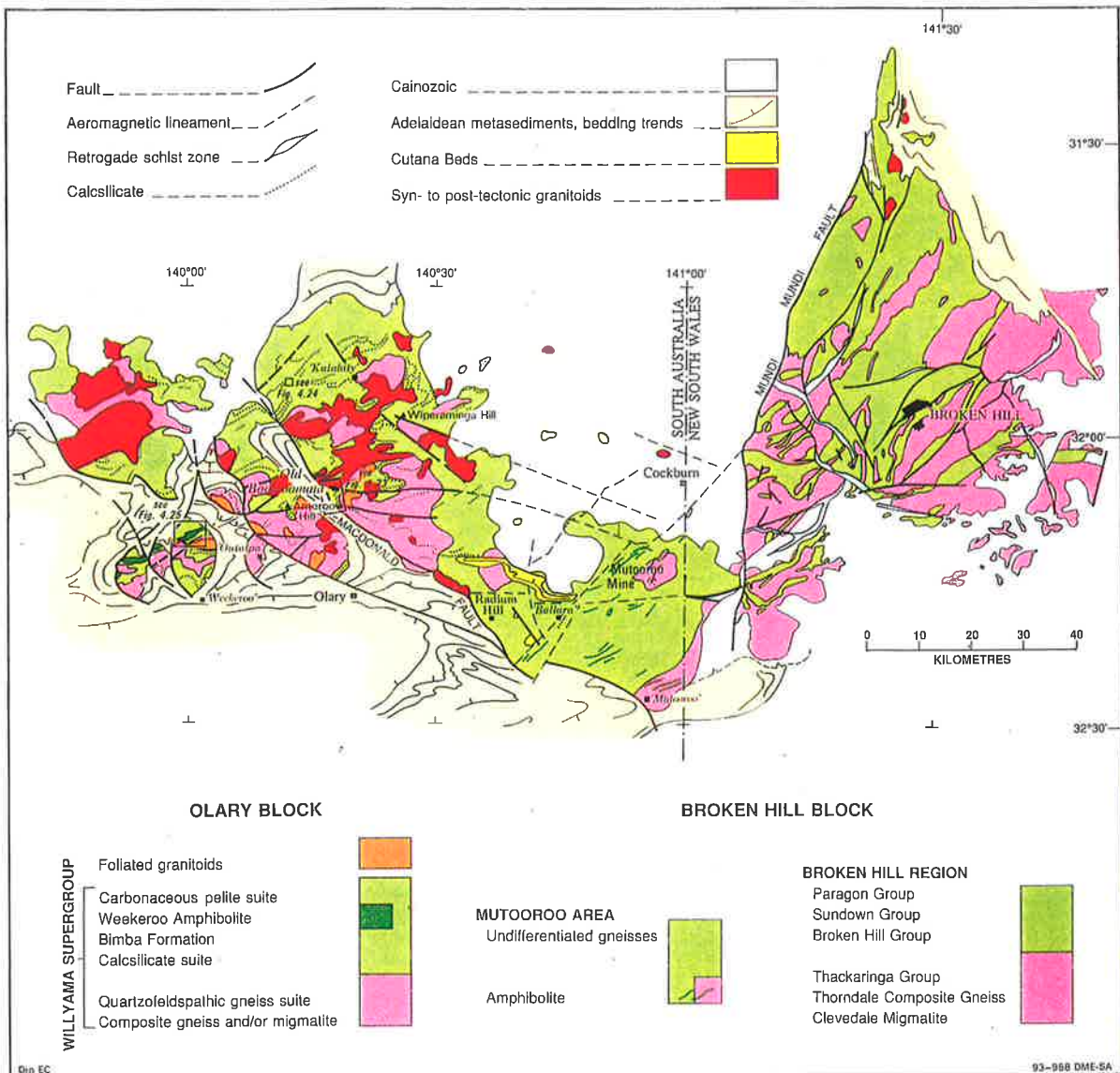


Fig. 5.1 Regional setting of the Willyama Inliers (after Drexel et al., 1993).

## 5. Relationship of magnetic information to known geology

### 5.1. Introduction

Paleo-Proterozoic rocks in the Willyama Inliers form a series of semi-isolated, partly exposed blocks which characteristically have faulted western margins and are unconformably overlain by Adelaidean sediments along their eastern margins (Flint and Parker, 1993) (fig 5.1). In the South Australian sector, basement is collectively referred to as the Olary Block and its rock succession is called the Willyama Supergroup.

The Willyama Supergroup rocks, which are extensively deformed and metamorphosed, outcrop sporadically in the Kalabity area in the southern part of the Curnamona 1:250,000 sheet but are concealed by Adelaidean and recent sediments elsewhere. Geological information in the Curnamona region for the Willyama Supergroup rocks, which host the giant Broken Hill mineralisation, comes from limited outcrop, drill hole data and geophysics.

High resolution aeromagnetic data is available for the Curnamona 1:250,000 map sheet but the interpretation is difficult due to the absence of outcrop. Good geological maps or actual susceptibility measurements in situ are essential for the establishment of a meaningful relationship between magnetic information and known geology. Often a geological understanding of the source of an anomaly is more important than a

sophisticated magnetic modelling. Both measured susceptibilities and available detailed geological maps were used here to constrain the interpretation.

A series of new 1:25,000 preliminary geological maps (see fig 6.2 for the index map sheet) which have been compiled from honours student projects, companies' exploration data and independent sources have been published by SADME (the first available were the Kalabity South and Koolka South sheets in 1994; followed by the Kalabity North sheet in 1995). The Kalabity South 1:25,000 sheet of this series was initially selected for establishing the relationship where known geology could be tied to aeromagnetic interpretation. The Calcsilicate suite of the Willyama Supergroup rocks has been previously reported as a magnetic marker unit (Yates, 1993; and Flint and Parker, 1993) which underlies the target, economic, non magnetic, sulphidic Bimba suite.

Evaluation of the mapped rock units in the Kalabity South 1:25,000 sheet showed that there is less than 2% mapped Calcsilicate unit and most of the map area is occupied by the composite gneiss and migmatite. However in the eastern third of the Koolka South 1:25,000 sheet around the Mt. Howden Mine area there is a complete mapped sequence of the Willyama Supergroup rocks and this area was chosen for the comparison which will be called Koolka South.

Total Magnetic Intensity (TMI) contour maps with different contour intervals were prepared. One, with a 25 nT contour interval, and its first vertical gradient (VG) contour map with 0.5 nT/m contour interval with the same scale as the geological map (1:25,000) were produced as these seem to show most features. They were prepared at the same

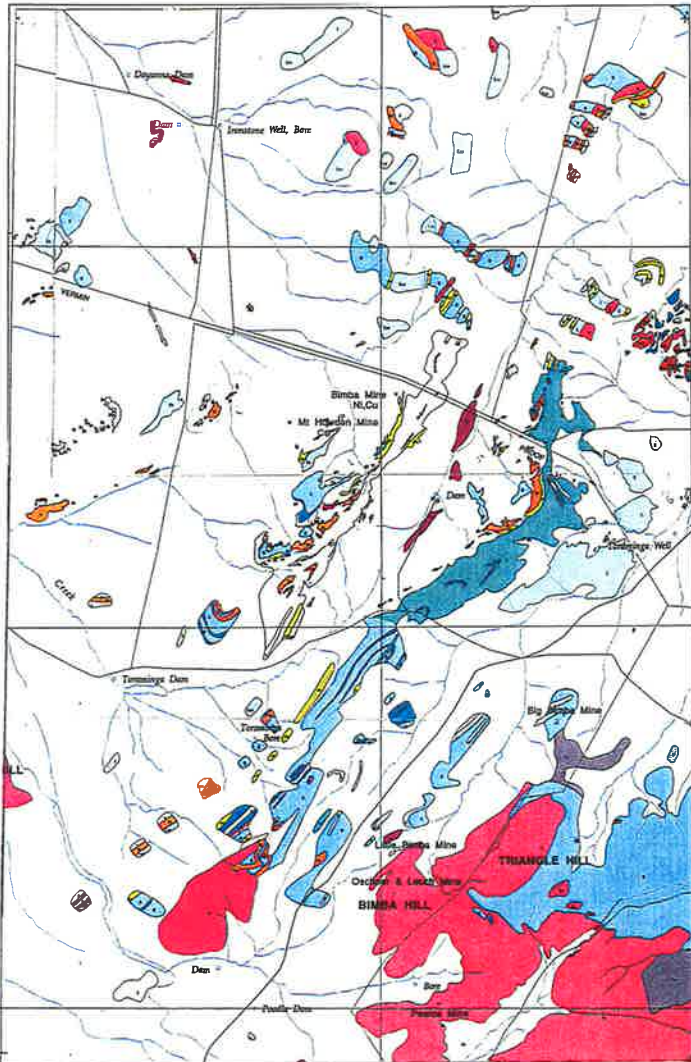
scale as the geological maps so that the maps could be compared directly by overlaying. The magnetic maps, geology map and the interpretation (figs 5.2, 5.3, 5.4 and 5.5) all are shown here for easy comparison. The scale is 1:100,000.

Clarke et al. (1986) proposed a stratigraphic sequence for the Olary Block (fig. 2.2) which was discussed in chapter 2 and was broadly correlated with that recognised in the Broken Hill Block (eg. Willis et al., 1983 and Stevens et al., 1990). Five lithological suites were defined which consist of the Metasedimentary Composite Gneiss and Migmatite suite, Quartzofeldspathic suite, Calcsilicate suite, Bimba suite and Psammopelitic suite.

The Mt. Howden Mine area of Koolka South was particularly selected because of the well mapped Calcsilicate suite striking northeast-southwest and extending for at least 1000 metres (fig 5.3). Because the flight line spacing is between 250 m in the N-S direction with 100 m sensor height; and 400 m in the E-W direction with 60 m sensor height (fig. 4.1 specification of the data) the Calcsilicate unit is crossed by at least two flight lines and it is unlikely not to be picked up on the magnetic data provided susceptibility contrasts with that of the adjacent units.

Comparison of the magnetic contour maps with the detailed geological map of Koolka South and outcrop susceptibility measurements (section 4.9) revealed that the Calcsilicate suite is not strongly magnetic but the Quartzofeldspathic suite has a pronounced magnetic signature. Comparison of TMI profiles through mapped areas of the Quartzofeldspathic and the Calcsilicate suites with the same strike direction (figs

6472980 N



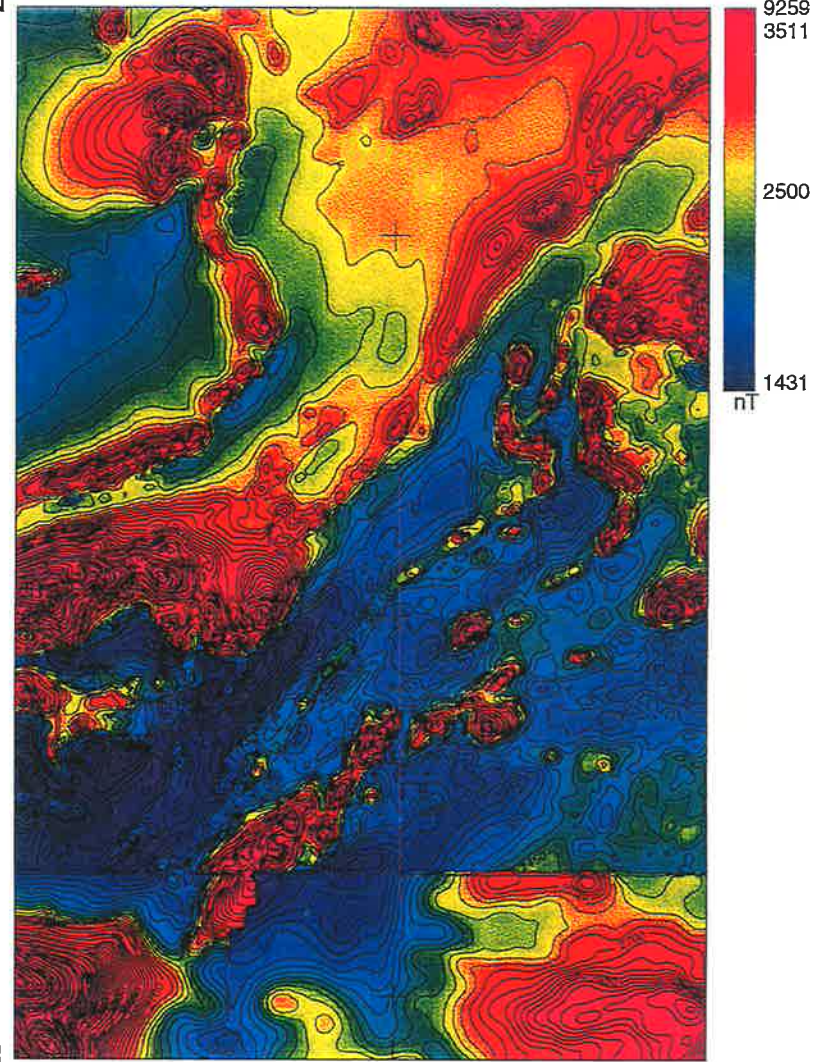
6459180 N

420025 E

429100 E

Fig. 5.3 Mapped geology of Mt Howden Mine area  
Map scale 1:100,000

6472980 N



6459180 N

420025 E

429100 E

Fig. 5.2 TMI contour map of Mt Howden Mine area  
Contour interval 50 nT  
Map scale 1:100,000

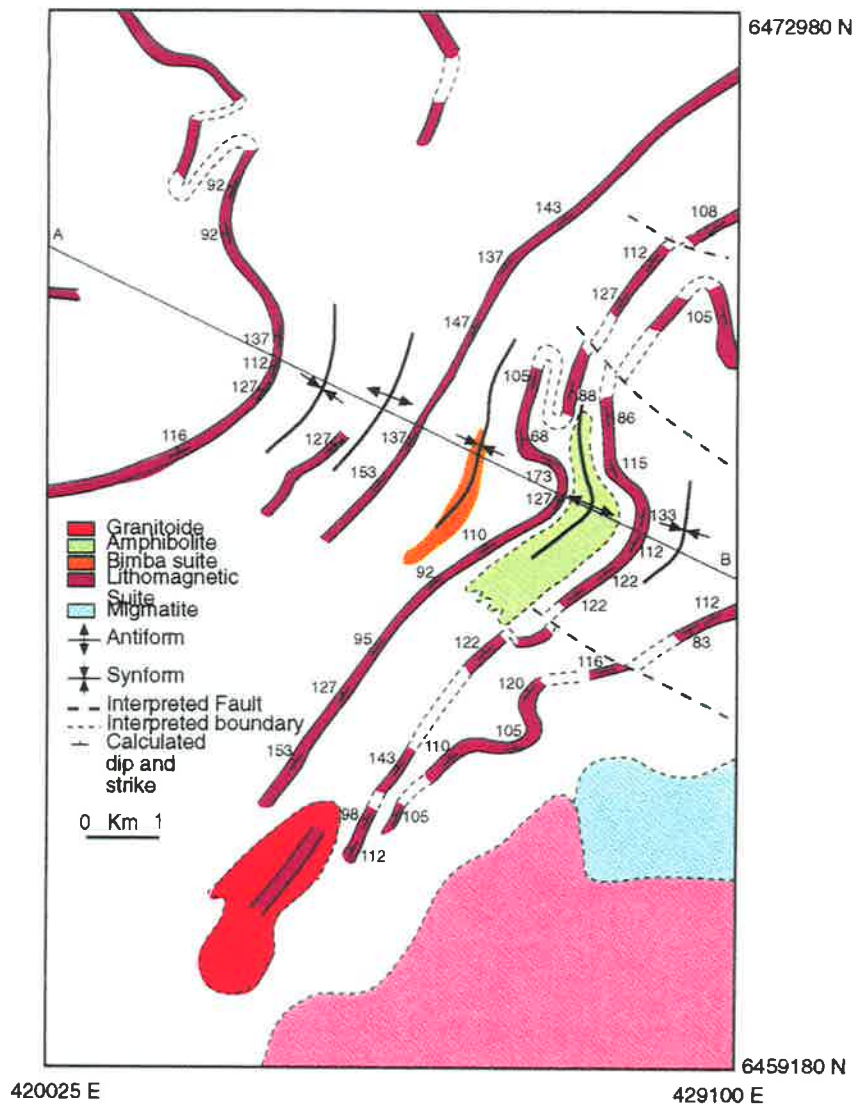


Fig. 5.5 Interpreted Willyama Supergroup rocks on the Mt Howden area.

a

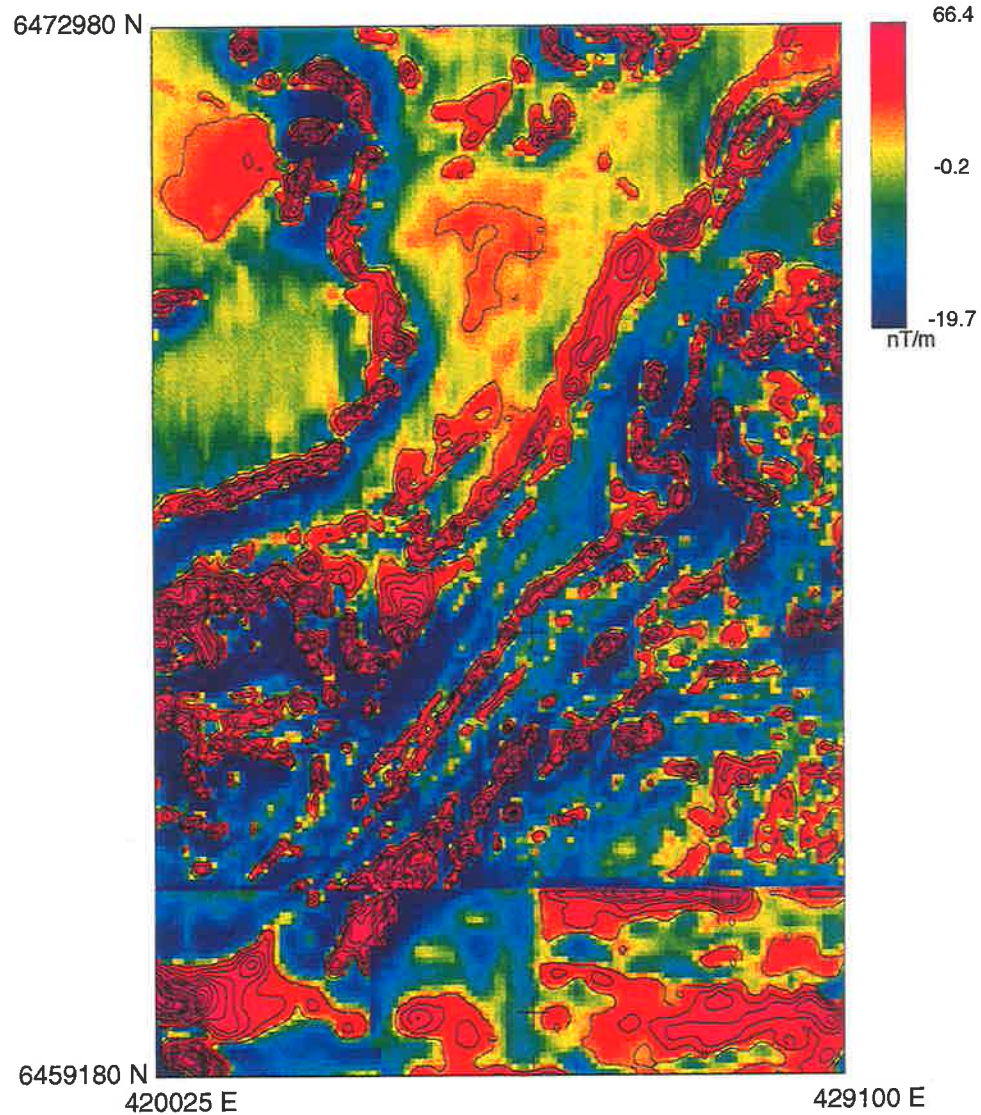


Fig. 5.4 VG contour map of the Mt Howden Mine area  
Contour interval 0.1 nT/m  
Map scale 1:100,000

5.6a and b) also revealed that the anomaly produced by the Quartzofeldspathic suite has an amplitude of between 400 to 1600 nT greater than the anomaly of the Calcsilicate suite (this is about 50 percent higher than the amplitude of the anomaly of the Calcsilicate suite).

Comparison of the field susceptibility measurements (table 4.1) over the representative outcrop also showed that the Quartzofeldspathic suite is the dominant magnetic unit in the sequence of the Willyama Supergroup rocks in the Olary Block and it was further confirmed by logged susceptibility of drill hole data. Recalling the discussion of 4.9, that the Quartzofeldspathic suite has a bi-modal distribution of susceptibility with the lower range similar to the range of the Calcsilicate suite and the higher range one to several orders of magnitude greater than the lower, it is not possible therefore to locate the Calcsilicate suite directly from the magnetic information.

Although showing considerable variation between and within measurement suites (table 4.1 and fig. 4.3), the most magnetic unit was always the Quartzofeldspathic suite, with one to several orders of magnitude greater than the Calcsilicate suite. Thus the previous definition of the Calcsilicate suite as the magnetic marker unit (Yates, 1993; and Flint and Parker, 1993) has been called into question.

Comparison of the magnetic maps with the detailed geology map (compare figs 5.2, 5.3 and 5.4) showed that where the Calcsilicate suite is mapped beside the Quartzofeldspathic suite they appear as one linear magnetic anomaly. This could be explained because of similar susceptibility of the Calcsilicate suite to the lower range of

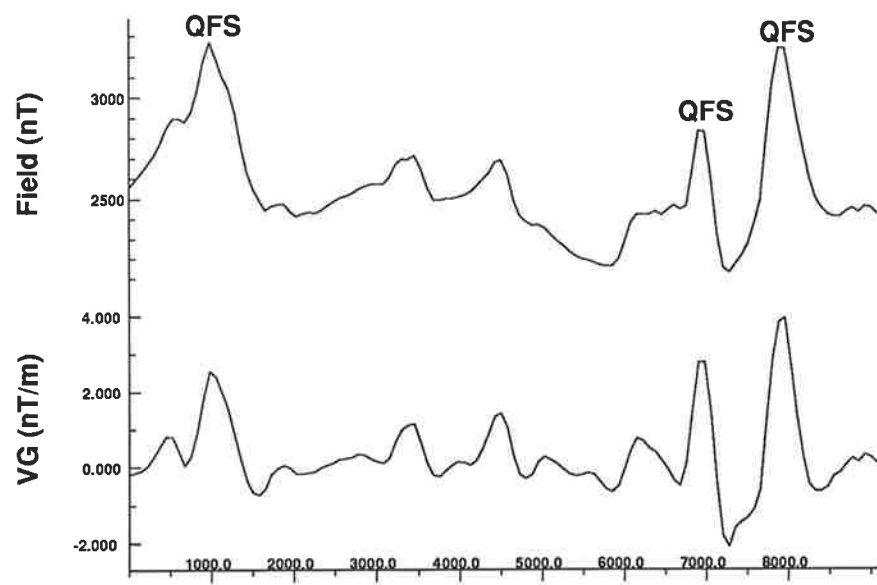
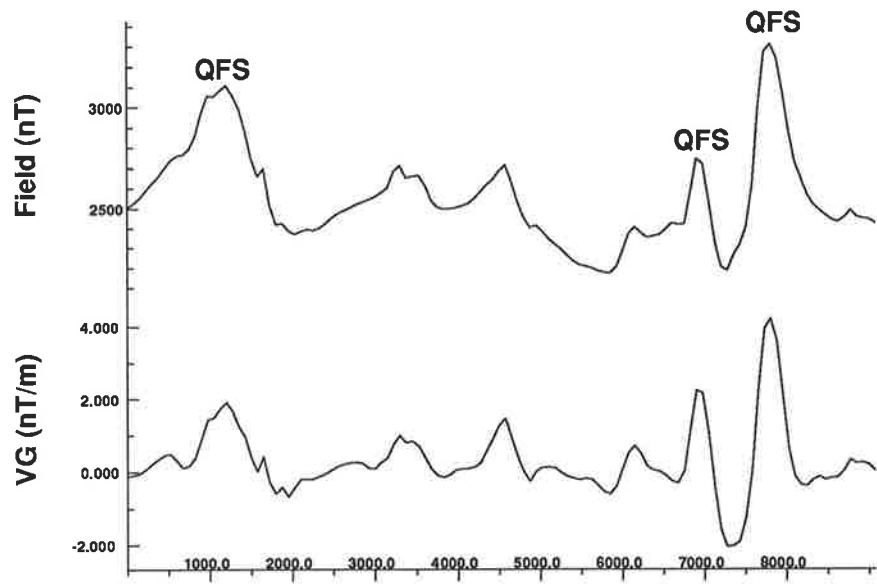
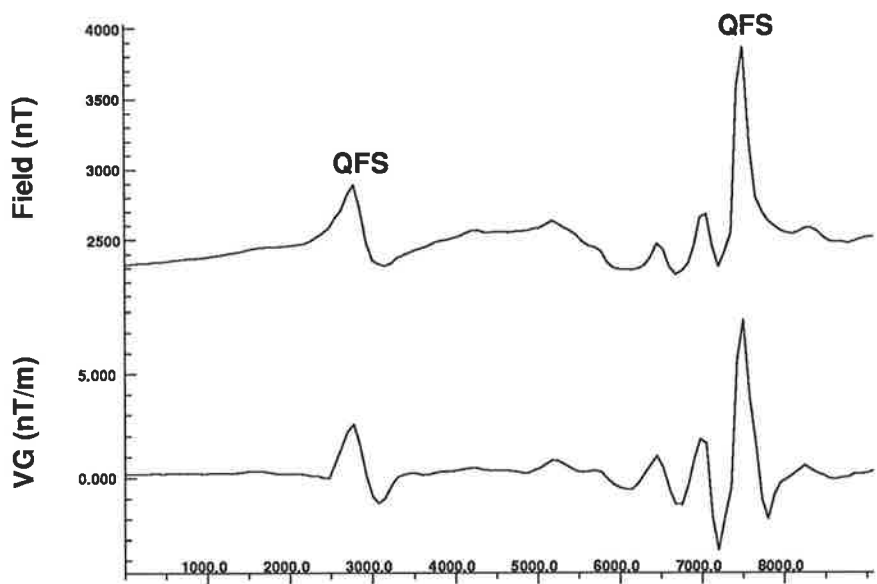


Fig. 5.6a Quartzofeldspathic suite "QFS" anomalies

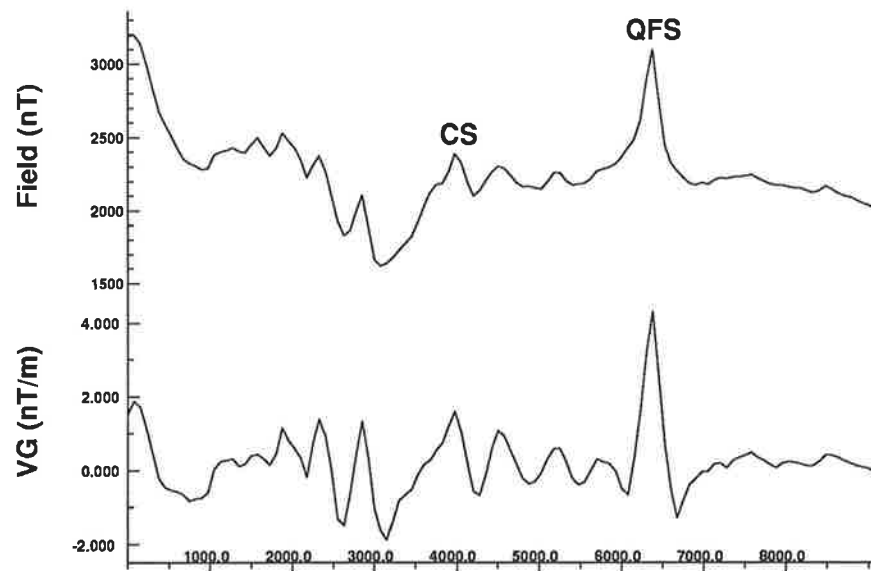
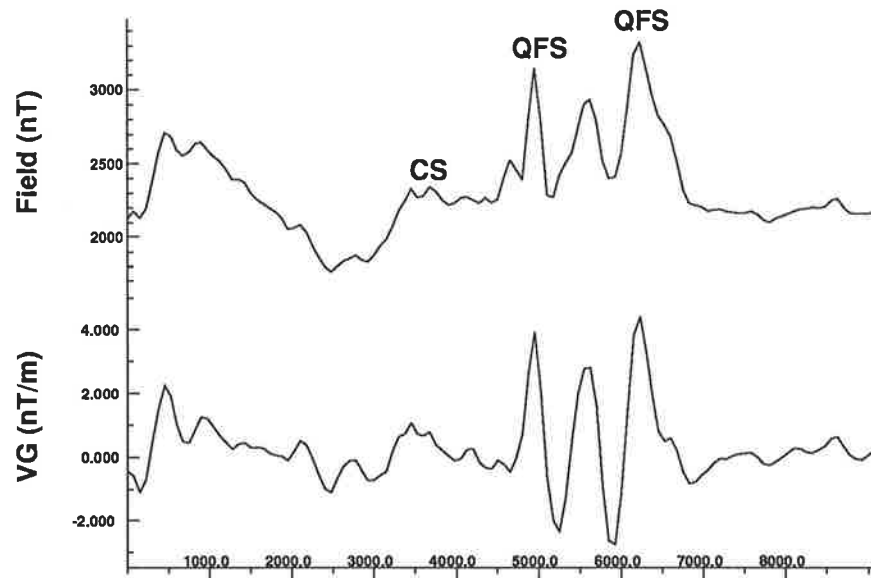
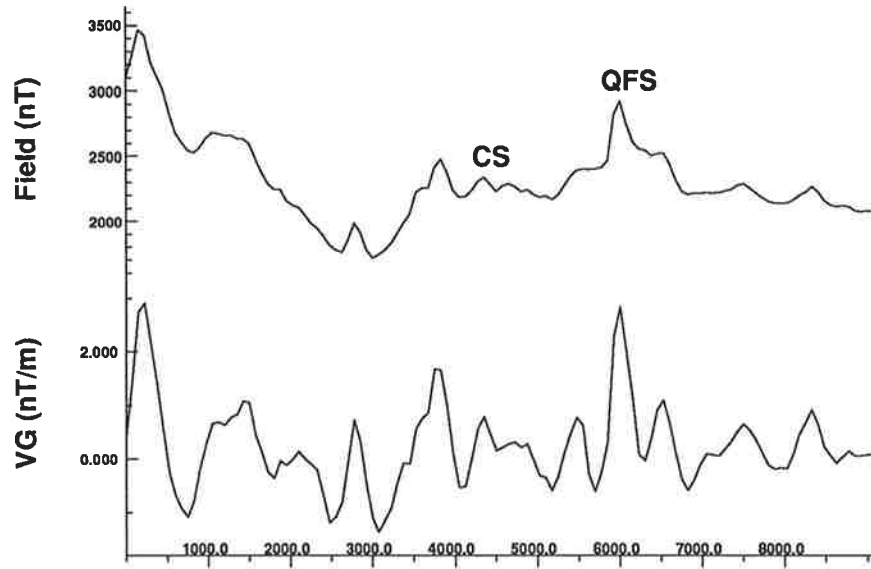


Fig. 5.6b Calcisilicate "CS" and Quartzofeldspathic suites "QFS" anomalies

the Quartzofeldspathic suite. These two suites are compositionally different while having a common population of susceptibility values.

It is also found that where the mapped Quartzofeldspathic suite grades to the mapped Calcsilicate suite along strike the magnetic signature is scarcely altered. An example can be sighted east of the Mt. Howden Mine and Toraminga area (compare figs. 5.2 and 5.3) which strikes northeast-southwest and extends for about 3750 metres. This could be explained by the facies change of the Quartzofeldspathic suite to the Calcsilicate suite through the calcalbitite rocks (Ashley, pers. communication). This indicates that there is probably a problem in mapped geology.

Cook (1992) in comparison of stratigraphy between the Olary Block and the Broken Hill Block noted "It was found that the stratigraphy erected by Clarke et al.(1986) was lacking essential detail. Furthermore, use of the Clarke et al. (1986) stratigraphic nomenclature is hampered by poorly defined units (suites), especially those for which the base or top is not adequately defined. The gradation of the Quartzofeldspathic suite into the overlaying Calcsilicate suite makes distinction of these suites difficult in the field".

He also noted "The Quartzofeldspathic suite is the predominant unit in the middle to low portions of the Willyama Supergroup in the Olary Block. The Quartzofeldspathic suite grades up to the Calcsilicate suite, or, due to absence of the Calcsilicate suite, may be overlain directly by the Bimba suite".

The function of an aeromagnetic survey is to map the distribution of magnetic minerals mainly magnetite in the sub surface. Magnetite is a minor accessory mineral which is

present in most rocks only in very small amounts-rarely more than one percent by volume of the whole rock. The presence of magnetite, or the lack of it, reveals little about what minerals make up the other 99 % of the rock.

Thus magnetic properties will not by themselves identify rock type, at least, not in a conventional classification system that is based principally upon silicate and carbonate mineralogy. Moreover changes in magnetite concentration levels often do not correlate with lithological division which are defined by the conventional silicate-carbonate nomenclature. This is exactly the case in the Calcsilicate suite and the Quartzofeldspathic suite of the Willyama Supergroup rocks. The former is compositionally different from the latter, while it has a susceptibility similar to the lower range of the other.

With the above mentioned problems in mind the author decided to produce an interpretation map considering the Quartzofeldspathic suite, the calcalbitite rocks (the gradation from the Calcsilicate suite to the Quartzofeldspathic suite) and the Calcsilicate suite make up one Lithomagnetic suite. This uses the Lithomagnetic suite as a magnetic marker horizon in the Mt. Howden Mine area of Koolka South. It was able to be traced to the other two thirds of the Koolka South 1:25,000 sheet and other covered areas in the Curnamona 1:250,000 sheet (7,200 Km<sup>2</sup>). Although there is inherent difficulty in distinguishing a stratigraphic unit (the Calcsilicate suite) from the magnetic data alone, the ability to trace the lithomagnetic unit under cover is beyond dispute.

## **5.2. Magnetic characteristics of rock units**

Referring to the stratigraphic correlation of figure 2.2 the magnetic responses of the rock units will be discussed in this section. The units are taken in ascending order:

### **5.2.1. Metasedimentary composite gneiss and migmatite**

Although no magnetic minerals have been reported on the geological map for this unit, it is moderately magnetic as observed in the field (section 4.9) and is evident from the comparison of the preliminary geological map and the magnetic maps (figs 5.2, 5.3 and 5.4). There are gradations into psammopelitic and pelitic schist; and Quatzofeldespathic rocks.

Magnetic amplitude varies from the background value of 2500 nT to 3150 nT in the south eastern part of the Koolka South sheet over the Triangle Hill granitoids (fig 5.3). This variation is probably related primarily to the depth of the related sources and the intermixing of the magnetic marker suite within the granitoids. The anomalies are smooth and simple where the intensity is low and complex in the higher amplitude areas.

Composite gneiss and migmatite are easily identified from their moderately low magnetic signature and the pattern of circular to semi circular anomalies on the colour image of TMI map (fig. 6.2). The boundary of these rocks may be traced by the disruption of linear to curvilinear anomalies of the surrounding Lithomagnetic marker suite.

Susceptibilities measured (table 4.1) in the field in March 1995 for these rocks in the Triangle Hill area of the Koolka South sheet showed them as less magnetic than the Lithomagnetic marker in the Willyama Supergroup rocks. Overall these rocks have an easily identifiable magnetic character which is evident on the total magnetic intensity contour map (fig. 5.2) of the Koolka South sheet and the colour image of TMI magnetic map of the Curnamona 1:250,000 sheet (fig. 6.2).

### **5.2.2. The Quartzofeldspathic suite**

The Quartzofeldspathic rocks are an extensive and important constituent of the sequence in the northern portions of the Olary Block (Cook, 1993). They are also common throughout the remainder of the Olary Block, occurring generally in the lower parts of the stratigraphy. Many of the Quartzofeldspathic rocks of the Olary Block are unusually rich in sodium, others (a minority) are enriched in potassium, and contain, a very little mica. Albitite, a term used frequently by exploration companies, is used for the Albite-rich Quartzofeldspathic rocks.

Progressing up-section through the Albitites there is an increase in the proportion of the Calcsilicate minerals. Albite-rich Quartzofeldspathic rocks in which the Calcsilicate minerals are prominent are termed calcalbitites. These rocks form the bulk of the Quartzofeldspathic suite, as defined by Clarke et al. (1986), in the northern Olary Block and probably are the correlative of the Thackaringa group in the Broken Hill Block (Willis et al., 1983; Ashley, 1984a; Stevens et al., 1990). The new 1:25,000 series

geological map of SADME which are used here for comparison are based on this classification.

Ukaigwe (1985) in his PhD thesis reported that the Quartzmagnetite rocks are strongly magnetic in the northern part of the Olary 1:250,000 sheet. Mills (1986) indicated that the massive to layered Quartz-Plagioclase-magnetite "Quartzite" is the most strongly magnetic unit in the Olary Block.

Flint and Parker (1993) placed both the Quartz-magnetite of Ukaigwe (1985) and the Quartz-Plagioclase-magnetite "Quartzite" of Mills (1986) in the Quartzofeldspathic suite. Isles (1983) reported that the major persistent magnetic intervals in the Broken Hill area are located in the upper suite 3 to lower suite 5. His subdivision of the suite is based on Stevens et al. (1979) with suite 3 as the Quartzofeldspathic rocks, suite 4 as the mine sequence and suite 5 as the pelite rocks..

Comparison of the magnetic maps with the mapped geology of Koolka South (figs 5.2, 5.3 and 5.4) and physical property measurements in this study revealed that the Quartzofeldspathic suite is the strongest magnetic unit in the stratigraphic section of the Willyama Supergroup rocks. This high magnetic response is related to the presence of disseminated magnetite, local concentration of iron formations and reconstitution of massive magnetite after brecciation in this suite (Ashley et al., 1995). Measured susceptibilities of all representative Willyama Supergroup rock suites (table 4.1) which were discussed in chapter 4.9 also indicated that the Quartzofeldspathic suite is the dominant magnetic unit in the sequence (fig. 4.3).

The Quartzofeldspathic suite shows a bi-modal distribution of susceptibilities in which the higher values are one to several orders of magnitude greater than the lower. It also has the highest magnetic intensity values in the Koolka South 1:25,000 sheet in the sequence of the Willyama Supergroup rocks. Susceptibility values which were measured for this suite in the Mt. Howden Mine area were in the range of 0.00006 to 0.05 SI units.

Fifty anomalies were selected for modelling over the interpreted Lithomagnetic suite (fig. 5.5) which was discussed in section 5.1. Observed strike from the magnetic map and measured susceptibilities from the outcrops were initially used for the analyses. The results showed that the magnetic body has a minimum 15 m and maximum 440 m thickness with an average of about 75 m. Cook (1992) and Yates (1993) reported data from a drill hole of CRA in the Waukaloc area which penetrated more than 400 m of laminated and massive Albitites without intersecting the base of this suite. The susceptibilities of the rocks from the drill hole also indicate a bi-modal distribution and confirm the surface measurements which was discussed in section 4.9.

The calculated susceptibilities used for modelling were of similar order to the measurements which were taken in the field and this suggests that remanent magnetisation may be negligible. Differences can be related to the use of a constant susceptibility value whose estimate was based on limited and variable field measurements, possible remanence which was discussed in section 4.9 and possible variation in model parameters.

### 5.2.3. The Calcsilicate suite

The Calcsilicate-bearing rocks and impure marbles (carbonate-bearing rocks) are mostly found within the Calcsilicate and Bimba suites (Cook, 1990). These rocks occur as two major types; firstly, as laminated to massive quartzofeldspathic rocks with variable calcsilicate component (the calcalbitites gradational from the albites); secondly, as banded to laminated calcsilicate rocks; and thirdly as banded impure marbles. A fourth type comprises calcsilicate bearing pelites. Flint and Parker (1993) and Ashley et al. (1995) have correlated the Calcsilicate suite of the Olary Block with the Ettelewood Calcsilicate member of the Broken Hill Block (fig. 2.2).

Lateral and vertical variation of the calcsilicate bearing rocks were presented by Cook, 1990, and Ashley et al., 1995. James (pers. communication) mentioned that the calcalbitite rocks are problematic for mapping the Quartzofeldspathic suite and the Calcsilicate suite in the Willyama Supergroup rocks of the Olary Block. Recalling the discussion of section 5.2.2 and the opinion of the experts mentioned above, the author now presents the magnetic character of the mapped Calcsilicate suite in the Koolka South 1:25,000 sheet.

The magnetic responses of the mapped Calcsilicate unit hardly alters where it grades to the Quartzofeldspathic suite east of Mt. Howden mine and the Toraminga area in the preliminary geology map of the Koolka South sheet (compare figs 5.2, 5.3 and 5.4) which suggests that there is probably a problem in mapped geology. This was explained

(section 5.1) due to the facies changes of the Quartzofeldspathic suite to the Calcsilicate suite through the calcalbitite rocks.

The Calcsilicate suite and the Quartzofeldspathic suite both represent one curvilinear magnetic anomaly where they are mapped beside each other. This was also explained (section 5.1) because of similar range of susceptibilities of the Calcsilicate suite to the lower range of the Quartzofeldspathic suite. The measured susceptibilities (table 4.1) over two outcrops of the Calcsilicate suite in the Mt. Howden mine area varies from 0.00008 SI units to 0.0002 SI units which is one to several orders of magnitude lower than the Quartzofeldspathic suite measured in the same general area.

The magnetic effect of the Calcsilicate suite cannot be separated from the lower Quartzofeldspathic suite which has a similar range of susceptibilities to the Calcsilicate suite in the lower range (discussed in 5.1 and 4.9). It is the author's opinion that the Quartzofeldspathic suite, calcalbitite rocks and the Calcsilicate suite represent one lithomagnetic marker and causes all of the curvilinear anomalies in the Koolka South 1:25,000 sheet and in other areas where the Willyama Supergroup rocks are found.

After the Lithomagnetic marker suite was traced to the covered areas of the Willyama Supergroup rocks the author received the 1:25,000 geological map of the Kalabity North sheet from SADME in July 1995. This map showed a similar problem of nonseparable magnetic responses of the Calcsilicate suite from the Quartzofeldspathic suite where they were mapped.

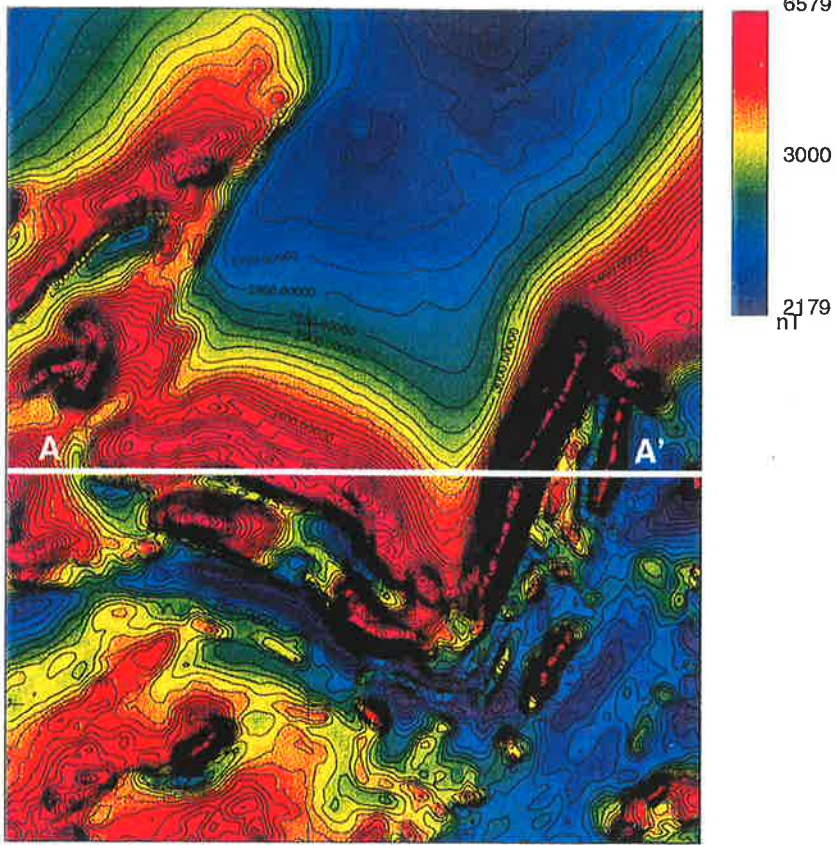
A band of the Calcsilicate suite, about 50 m thick and 1000 m long in a northeast-southwest strike direction, is correlated with an anomaly in the TMI contour map (fig. 5.7). This is mapped in the north central portion of the Kalabity North 1:25,000 geological map sheet (fig 5.8). A much thicker band of the Quartzofeldespathic suite is also mapped east of the Calcsilicate suite and was correlated with the same anomaly on the TMI contour map.

The TMI contour map (fig 5.7), the geology (fig. 5.8), the VG contour map (fig. 5.9) and the interpretation map (fig. 5.10) are shown at 1:100,000 scale. Both the TMI and VG profiles through these mapped suites show hardly any change in the magnetic character and are modelled with a single source (fig 5.11a and b).

This is another good example of the manifestation of one curvilinear magnetic anomaly by both the Calcsilicate suite and the Quartzofeldespathic suite and is similar to the Mt. Howden Mine area of the Koolka South sheet. Considering the discussion of 4.9 and 5.1 that, there is a common magnetic responses between the Quartzofeldespathic suite and the Calcsilicate suite in the lower range of susceptibility, it is not unusual not to be able to map magnetically two chemically different rock suites which have similar range of susceptibilities.

This leads to the conclusion that the lithomagnetic marker suite appears as (i) the Quartzofeldespathic suite, (ii) the calcalbitite rocks (the gradational changes from the Quartzofeldespathic suite to the Calcsilicate suite), and (iii) the Calcsilicate suite,

6484150 N



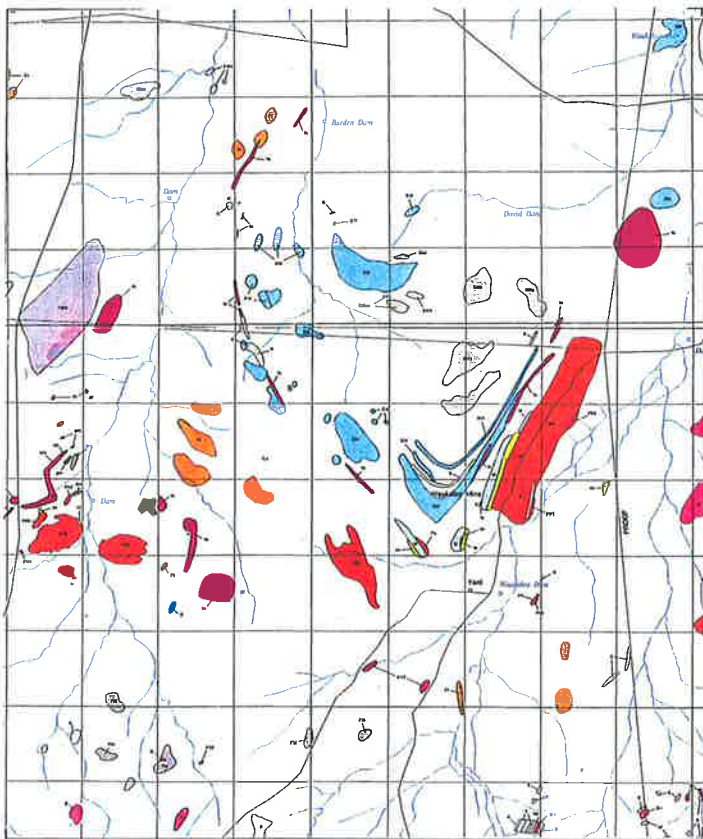
6473200 N

436000 E

445150 E

Fig. 5.7 TMI contour map of the Waukaloo Mine area  
Contour interval 50 nT  
Map scale 1:100,000

6484150 N



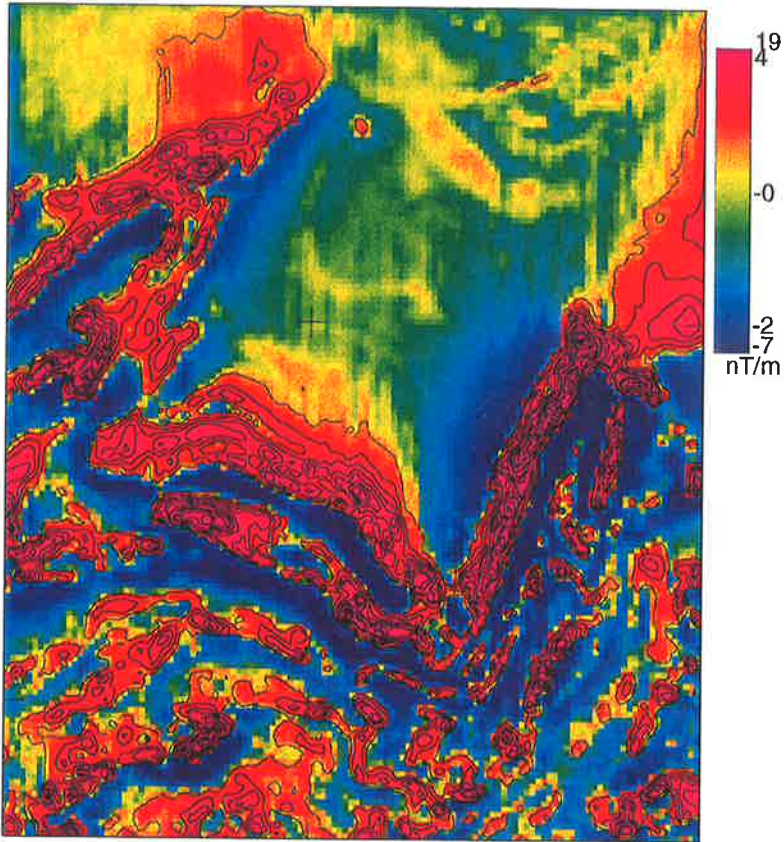
6473200 N

436000 E

445150 E

Fig. 5.8 Mapped geology of the Waukaloo Mine area  
Map scale 1:100,000

6484150 N

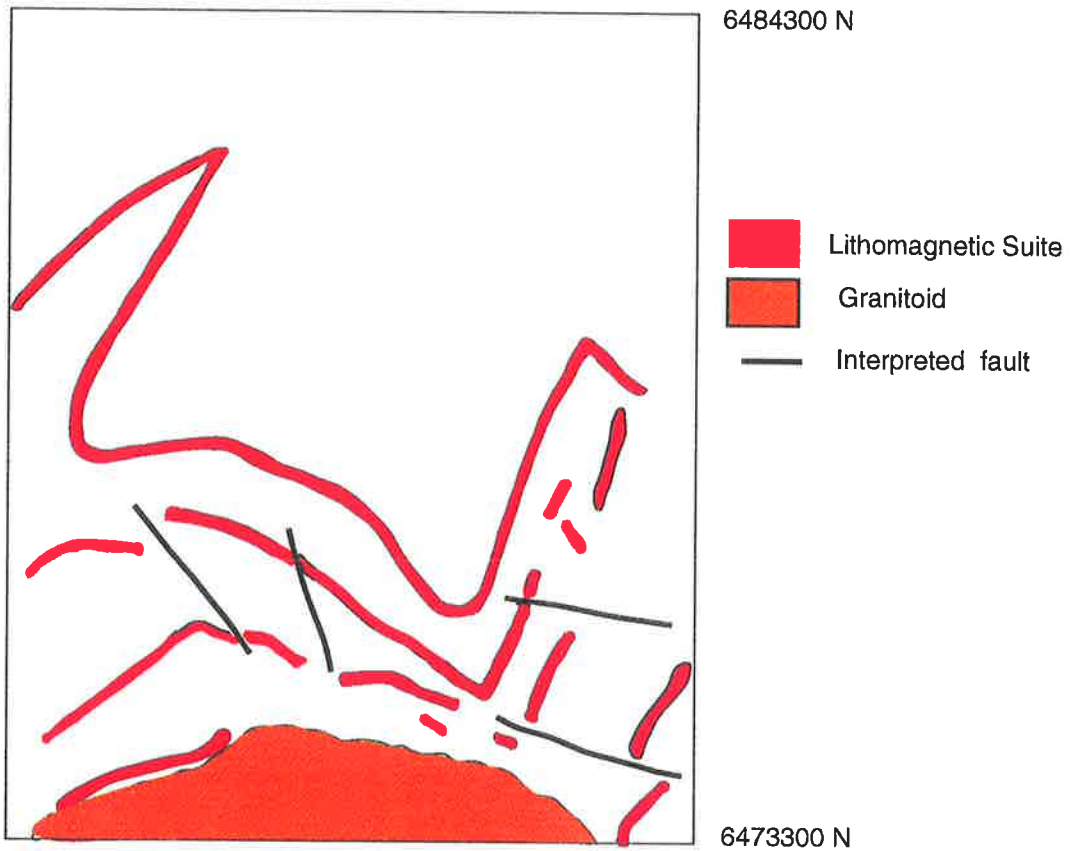


6473200 N

436000 E

445150 E

Fig. 5.9 VG contour map of the Waukaloo Mine area  
Contour interval 0.1 nT/m  
Map scale 1:100,000



6484300 N

436000 E

445190 E

Fig. 5.10 Interpreted folds and Granitic intrusion in the Waukaloo Mine area

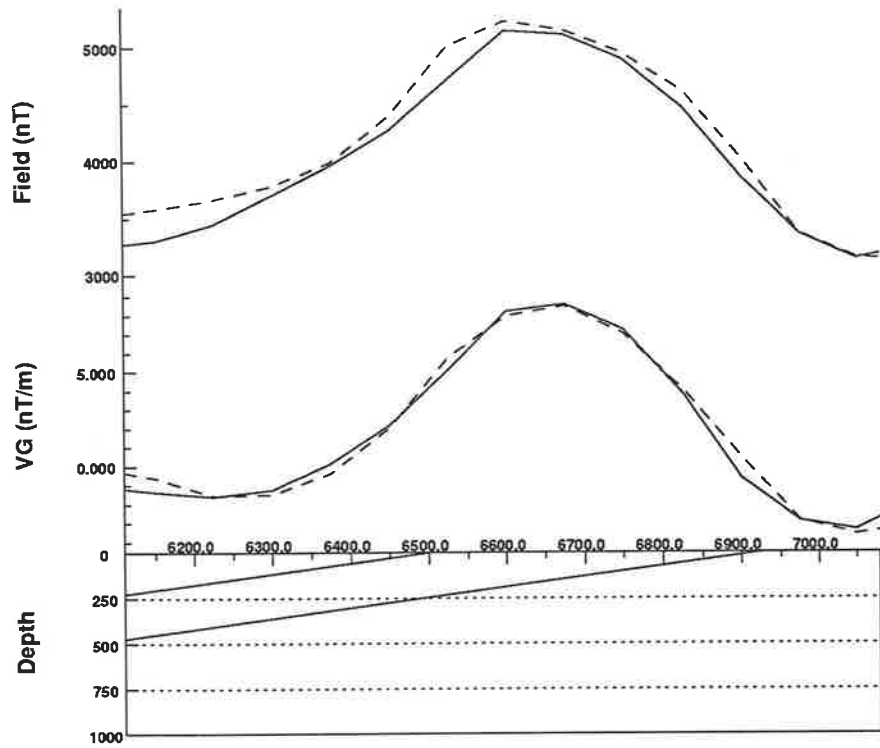


Fig. 5.11b Model of the anomalies of the Calcisilicate and Quartzofeldspathic suites

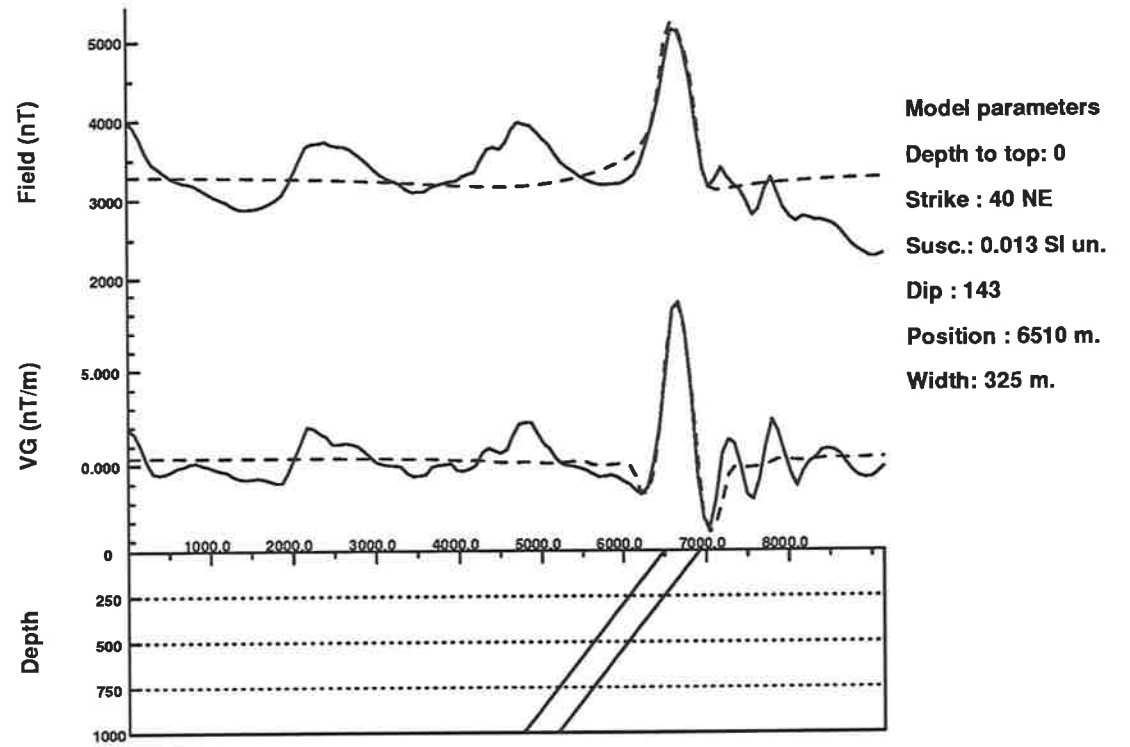


Fig. 5.11a TMI and VG profiles through the anomaly of the Calcisilicate and Quartzofeldspathic suites in the Waukaloo Mine area

depending on the location. This is similar stratigraphically and spatially to the distribution of magnetic horizons in the Broken Hill area (Isles, 1983).

#### **5.2.4. The Bimba suite**

The Bimba suite has also been correlated with the Etelewood Calcsilicate member in the Broken Hill Block (fig. 2.2) (Flint and Parker, 1993; Cook et al., 1994) and is likely to have a gradational contact with the underlying Calcsilicate and Quartzofeldspathic suites. The Bimba suite has a similar isotopic signature to that from the Broken Hill orebody and points to an approximate formation age of 1660-1780 Ma (Bierlein et al., 1994).

The Bimba suite is characteristically heterogenous and consists of Psammopelitic to Pelitic Schists grading into laminated Calcsilicate-rich rocks and rare iron formations. All rock types contain disseminated, laminated and vein sulphides and there are uncommon occurrences of massive sulphides which rarely contain magnetite.

Magnetically this unit is very weak (compare figs. 5.2, 5.3 and 5.4) and a magnetic profile through an outcrop in the Mt. Howden Mine area of the Koolka South sheet, extending for about 2000 metres, has no appreciable magnetic response. This is related to the conversion of iron oxides from the Calcsilicate suite to iron sulphide in the Bimba suite (Bierlein et al., 1995).

The large contrast in magnetic character between the Bimba suite and the underlying Calcsilicate suite, which has been reported previously (Yates, 1993; and Flint and Parker,

1993), causes the difference in the magnetic responses of this suite and the lithomagnetic marker below it, as was described in sections 4.9, 5.1 and 5.2.3. The position of the Bimba suite in covered areas may be deduced from the location of the lithomagnetic marker using the interpreted maps of this study (figs 6.7 and 6.33).

### **5.2.5. The Pelite suite**

Metamorphosed Pelites, Psammopelites and Psammites are common in the Olary Block. They form the bulk of the Pelite suite, are common in the Quartzofeldspathic suite, especially in its middle portions, and are minor components of the Calcsilicate and the Bimba suites. Psammites and Psammopelites are also inferred to have formed much of the composite gneiss suite, but as migmatite development is extensive in these rocks, many of the Pre-metamorphic characteristics useful in interpreting their origin have been destroyed (Cook, 1992).

The Pelite suite is weakly magnetic in the Koolka South 1:25,000 sheet. Laffen (1994) reported several occurrences of well laminated manganiferous banded iron formation in the pelite suite in the Meningie area. These contain magnetite and are compositionally similar to the banded iron formations in the Broken Hill orebody.

No anomalous feature can be correlated with the pelite suite in the Koolka South geological map (compare figs. 5.2, 5.3 and 5.4). The relatively low, smooth magnetic character between the distinct curvilinear magnetic anomalies in the Koolka South area, particularly in the synform areas which will be discussed in the next section, corresponds

to the mapped Pelite suite. A few susceptibility measurements (table 4.1) over this suite in the Mooleulooloo area were in the range of 0.002 to 0.0038 SI units.

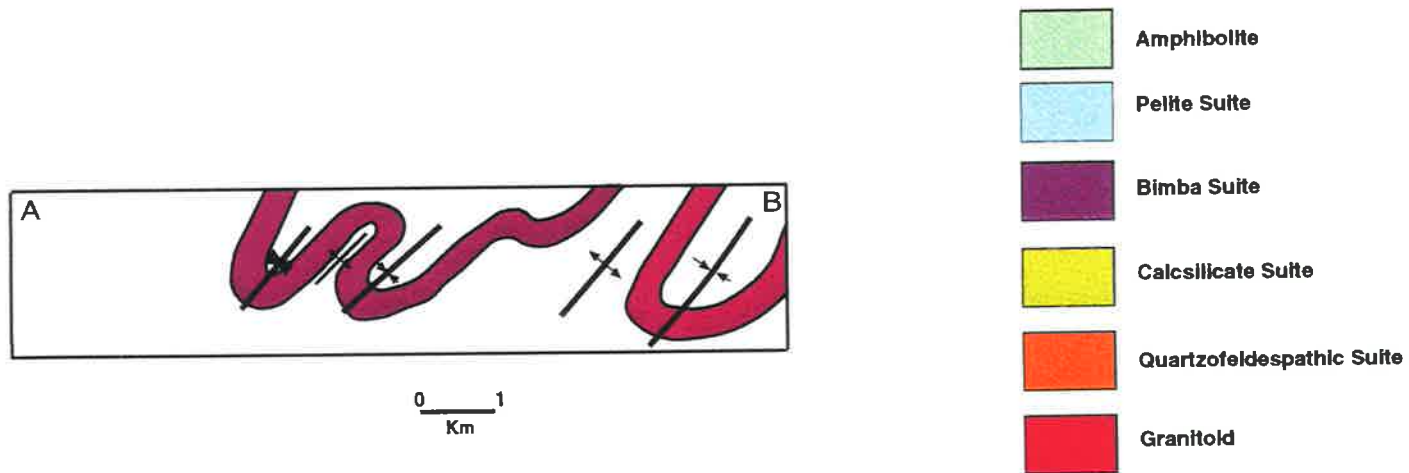
### **5.2.6. Structures and lineaments**

The magnetic maps of the Willyama Supergroup rocks in the Olary Block contain a considerable amount of significant geological information, and if carefully integrated with other available geological data, are a cost-effective means of resolving structural and stratigraphic problems in many areas. The Lithomagnetic marker horizon which is a distinctive feature in the magnetic maps allows mapping of folds and faults.

The curvilinear magnetic anomalies in the magnetic contour map (fig. 5.2) of Koolka South have been interpreted (fig. 5.5) as the Lithomagnetic markers as well as stratigraphic markers. Therefore they probably contain valuable structural information. While this information would primarily be concerned with the lateral continuity of individual horizons, defining strike directions, fold closures and dips of horizons may also be obtainable from the aeromagnetic profiles.

Structural geologists use available outcrop observation and aerial photographs to map structures on a macroscopic scale. They are limited by lack of access to outcrops and by the amount of soil cover. Continuity of information and depth of penetration make the aeromagnetic method particularly sensitive to changes in structure.

It is stressed that the aim of the analyses in this section is not to produce detailed structural interpretations but rather to extract all of the valid structural information



**Fig. 5.12** Interpreted folded structures on the Mt Howden Mine area

contained in the magnetic anomalies and to present it in a form readily useable by the interpreter of structural geology.

The magnetic map showed that the Lithomagnetic suite has been folded and refolded over the Koolka South area. Six curvilinear magnetic anomalies showing repetition and folding of the Lithomagnetic suite are identified (fig 5.5). These folded structures are interpreted as three antiforms and four synforms with all axes trending northeast-southwest (fig. 5.12). A younger generation of folds with their axes trending east-west are superimposed on the earlier ones. The northeast-southwest and easterly fold axes may be related to the D2 and D3 deformations of the Olarian orogeny respectively.

This interpretation is consistent with the structural information of Clarke et al. (1986) for the Willyama Supergroup rocks. The identification of the Quartzofeldspathic suite, the calcalbitite rocks and the Calcsilicate suite as one Lithomagnetic suite leads to a structural and geological interpretation comparable to the one provided by Esso-CEC (Hemming, 1978) for this area. Their interpretation is based on drill hole information.

The curvilinear anomalies in the north eastern part of the Koolka South magnetic map (fig. 5.2) have been displaced by a major WNW-ESE fault which extends for about 65 km to the Broken Hill Block. This linear feature is recognised in all magnetic maps (colour image of the Curnamona 1:250,000 sheet, figure 6.2, contour map, figure 6.20 and the first vertical derivative map of CRA on the Olary and Broken Hill Block particularly in the TMI contour map of the Kalabity South 1:25,000 sheet part of which is shown in figure 6.20.

This fault is sub parallel to the Thackaringa shear zone in the Broken Hill Block. Two other, but less continuous, faults are mapped where the curvilinear anomalies show a break and discontinuity in the south eastern part of the Koolka South (fig 5.5) sheet.

The association of folding and shearing created boudin structures in the Lithomagnetic suite in the Koolka South sheet. Refolding and boudinage are evident from the magnetic contour map (e.g. at the Iron Stone Well in the north west, at Mt. Howden in the eastern central area of the Koolka South sheet and the Dome rock area in the Kalabity North sheet) (compare figs 5.2 and 5.3).

Modelling results with susceptibilities of the same order as the observed values over these folds showed a general north west dip. This is interpreted as a domain of overturned folds which is consistent with the interpretation of Dibben (1990) east of Mt. Howden Mine area. Possible remanent magnetisation which could affect the calculated dip from the magnetic data was discussed in section 4.10 and differences in the calculated and observed susceptibility were discussed in section 5.2.2.

### **5.2.7. Intrusive rocks**

In the Olary Block there are widespread suites of granitoids which are spatially related to regions dominated by the composite gneiss and migmatite suite. The granitoids form bodies up to several kilometres across, but range down to small masses directly associated with migmatite development. The most extensive granitoids in the Olary

Block are relatively leucocratic and are informally termed regional granitoids (Ashley et al., 1995).

The Triangle Hill granitoids to the south of Mt. Howden in the Koolka South sheet (fig. 5.3) are included in the regional granitoids (Ashley op. s.). The Poodla Hill and the Tonga Hill granitoids are also located to the south and southwest of Mt. Howden Mine in the geological map (fig 5.3). The pattern of folded curvilinear anomalies of the magnetic marker suite has been disrupted by the above granitoids. Semi-circular to elliptical anomalies corresponds with these intrusions in the magnetic map.

The granitoids in the Triangle Hill area have been reported to be less mafic than the Tonga Hill granitoids (Ashley, op. s.). A few susceptibility measurement over the former showed average susceptibility of 0.0072 SI units which is of the same order as the average value of 0.0024 SI units measured over the latter (table 4.1). The Triangle Hill granitoids, as well as the composite gneiss suite around it, have relatively moderate magnetic anomalies (fig. 5.2).

In the absence of the Lithomagnetic marker suite, which is sometimes intermixed with the granitoids and is usually curvilinear, the granitoids frequently show a smooth and rounded or equidimensional magnetic pattern. This characteristic pattern helps to identify the other intrusives where they do not outcrop and were not mapped. The distribution of interpreted granitoids in the covered areas will be discussed in 7.2.3.

The information on the magnetic map correlates with the available mapped geology and shows more a continuous magnetic body under cover. An example is the Tonga Hill

granitoids which show limited outcrop but the magnetic map of the Koolka South sheet shows two large semi-circular features with similar magnetic character. Part of the eastern one corresponds with the outcrop of the Tonga Hill granitoids whilst the western one is laterally displaced by the MacDonald fault (see figs 6.8, 6.9, 6.10 and 6.11).

The Tonga Hill intrusion, which comprises massive felsic meta igneous rocks, is compositionally and magnetically similar to the Poodla Hill granitoids. The elliptical anomaly to the south west of Mt. Howden (fig. 5.2) is correlated with a granitoid body in the Poodla Hill area which intruded rocks of the Lithomagnetic suite. This granitoid has also been reported to be more mafic than the typical regional granitoids in the region. The explanatory legend of the Koolka South, the Kalabity South and the Kalabity North geological map sheets used in this study is presented in figure 5.13.

## 6. Willyama Supergroup rocks under cover

### 6.1. Introduction

The relationship of magnetic information to known geology was established in the previous chapter. The aeromagnetic signatures reflect structural, lithological and alteration patterns arising from controls on detailed mapped and susceptibility measurements at prospect scale. At the regional scale (eg. 1:250,000) the magnetic data reflects the regional tectonics and divides the area into domains for the application of appropriate genetic models. At the prospect scale (eg. 1:25,000) the magnetic information allows the extrapolation of poorly outcropping geology to provide a cost effective mapping technique.

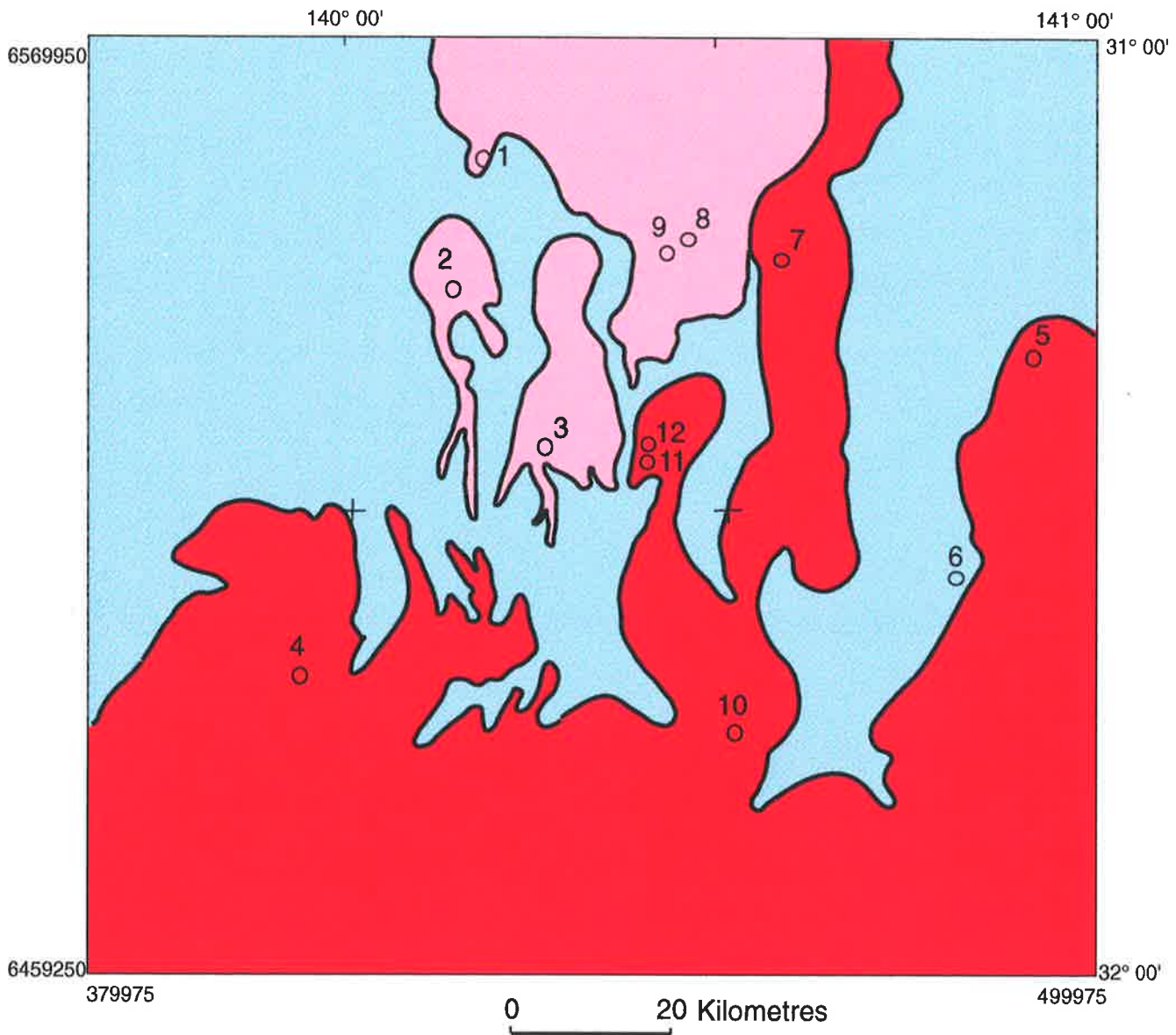
In this chapter the specific outcrop areas and shallow subcrops where the thickness of Adelaidean and recent sediments are less than 200 metres will be interpreted and presented along with the geology. The detailed interpreted geology from the outcrop areas will be traced to the shallow covered areas using the magnetic data. The extension of the Willyama Supergroup rocks to the deep areas where known geology is limited to few drill hole data will be followed later in the chapter. Contour maps of TMI and VG are superimposed on their colour images. Gradients, boundaries, lows and highs are all easily portrayed by this way of presentation.

## 6.2. Regional interpretation

### 6.2.1. Magnetic zones

From a magnetic view point, the Curnamona 1:250,000 sheet is divided into three domains or "Magnetic Zones" : (i) the Willyama Supergroup Magnetic Zone (WSMZ); (ii) the Volcanic Magnetic Zone (VMZ) and (iii) the Adelaidean Magnetic Zone (AMZ) (figure 6.1). This division is based on the magnetic characteristics, mapped geology and drilling information.

The subdivision of aeromagnetic maps into zones of characteristic response is a common initial approach in the qualitative interpretation of such maps as discussed in chapter 3 and 4 (e.g. Boyd, 1967 and 1979; Emerson, 1973 ; Isles, 1989; and Isles and Valenta, 1991; and Pridmore et al., 1994). These zones may be defined by the abundance of anomalies, by their shapes, by preferred strike directions, by changes in the magnetic background or by many other subtle, systematic changes in the magnetic content within an otherwise uniform rock type. Volcanism or regional metamorphism may exert a strong influence on the distribution of magnetite over large areas as is the case in the Curnamona sheet (1:250,000) and these effects can impose a zoning on the measured magnetic intensity.






- |   |      |  |                                  |
|---|------|--|----------------------------------|
|  | WSMZ | 1 : LNM 10   | 6 : Drilled Bimba at Hunters Dam |
|  | VMZ  | 2 : BWM 1  | 7 : Drilled Meta pelites         |
|  | AMZ  | 3 : ETM 5  | 8 & 9 : Drilled Altered Basalt   |
|   |      | 4 : TWM 9  | 11 & 12 Drilled Metasediments    |
|   |      | 5 : MU 2   |                                  |
|   |      | 10 : Drilled Willyama Supergroup rocks at Johnny hill area |                                  |

Fig. 6.1 Magnetic Zones and location of deep drill holes in the Curnamona 1:250,000 sheet

Curnamona  
Total Magnetic Intensity

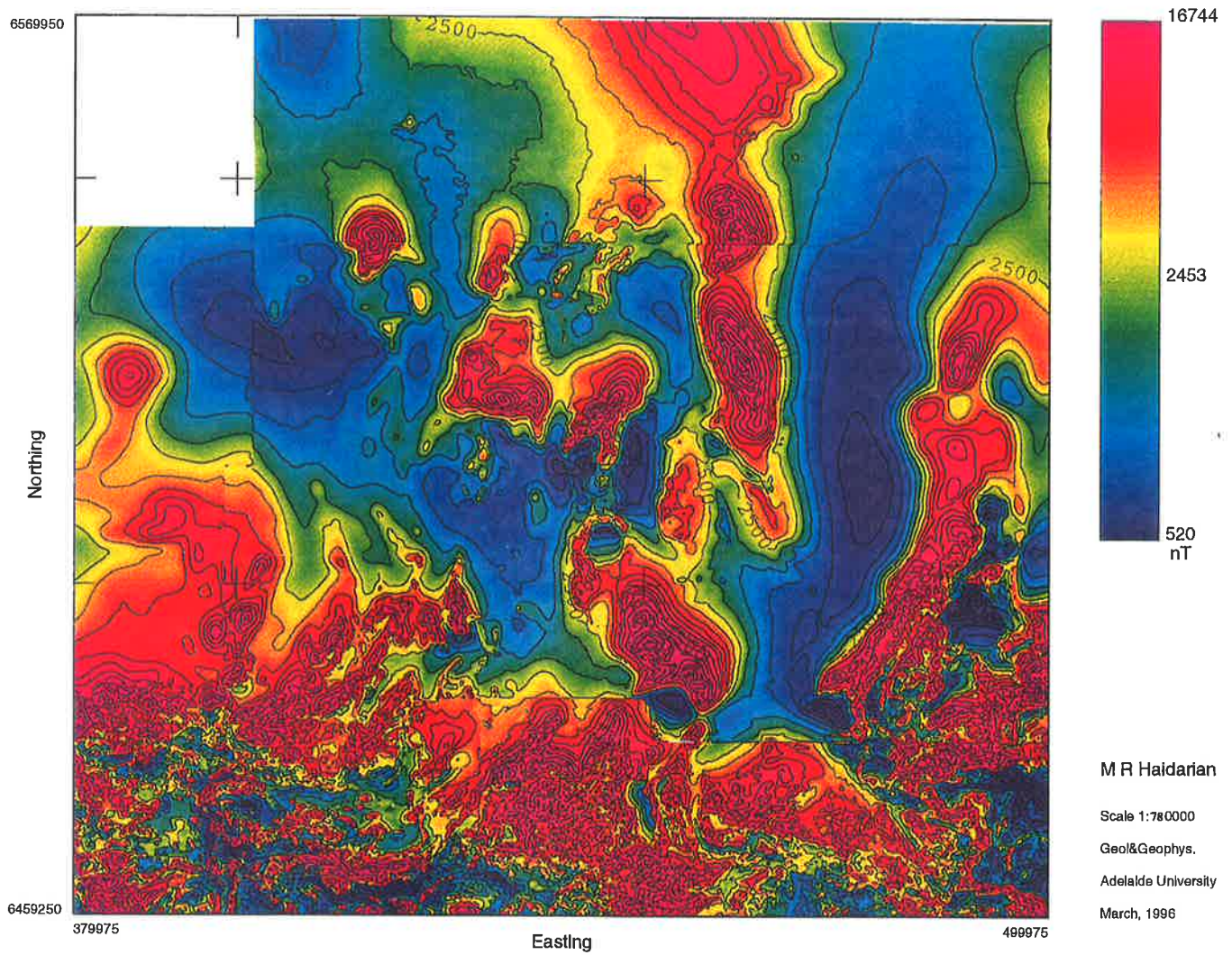


Fig. 6.2 Colour Image of Total Magnetic Intensity of the Curnamona area  
Contour interval 100 nT

M R Haidarian  
Scale 1:780000  
Geol&Geophys.  
Adelaide University  
March, 1996

### 6.2.2. The Willyama Supergroup Magnetic Zone (WSMZ)

The WSMZ in the Curnamona 1:250,000 sheet is characterised by narrow, elongated, high amplitude and curvilinear magnetic anomalies which represent intense deformation and metamorphism (fig. 6.2). These anomalies are cut by circular granitic intrusions and migmatites which normally show equidimensional shape and subdued magnetic character. Over half the anomalies in the Curnamona 1:250,000 sheet shows a single magnetic characteristic response reflecting the WSMZ either in outcrop/or near surface or covered.

The WSMZ continues to the south into the Olary 1:250,000 sheet and is terminated by the MacDonald shear zone separating the Adelaide geosyncline to the south. To the north the WSMZ extends through the eastern branch along the Benageri Ridge towards the Frome area of the Curnamona Craton (compare figs 6.1 and 6.2). The WSMZ extends east to the Broken Hill Block in New South Wales. The extension of the WSMZ towards the north and north east is accompanied by gradual deepening and bifurcation by Adelaidean rocks.

The northern margin of the WSMZ does not look like a faulted boundary but simply indicates the termination of this zone along a sinusoidal truncation by an unconformable boundary with the Adelaidean Magnetic Zone (AMZ). Modelling showed that the Willyama Supergroup rocks dipping gently towards the southwest to the order of a few degrees. The southwestern boundary of the WSMZ is a fault separating the highly

Curnamona 1:250,000 sheet

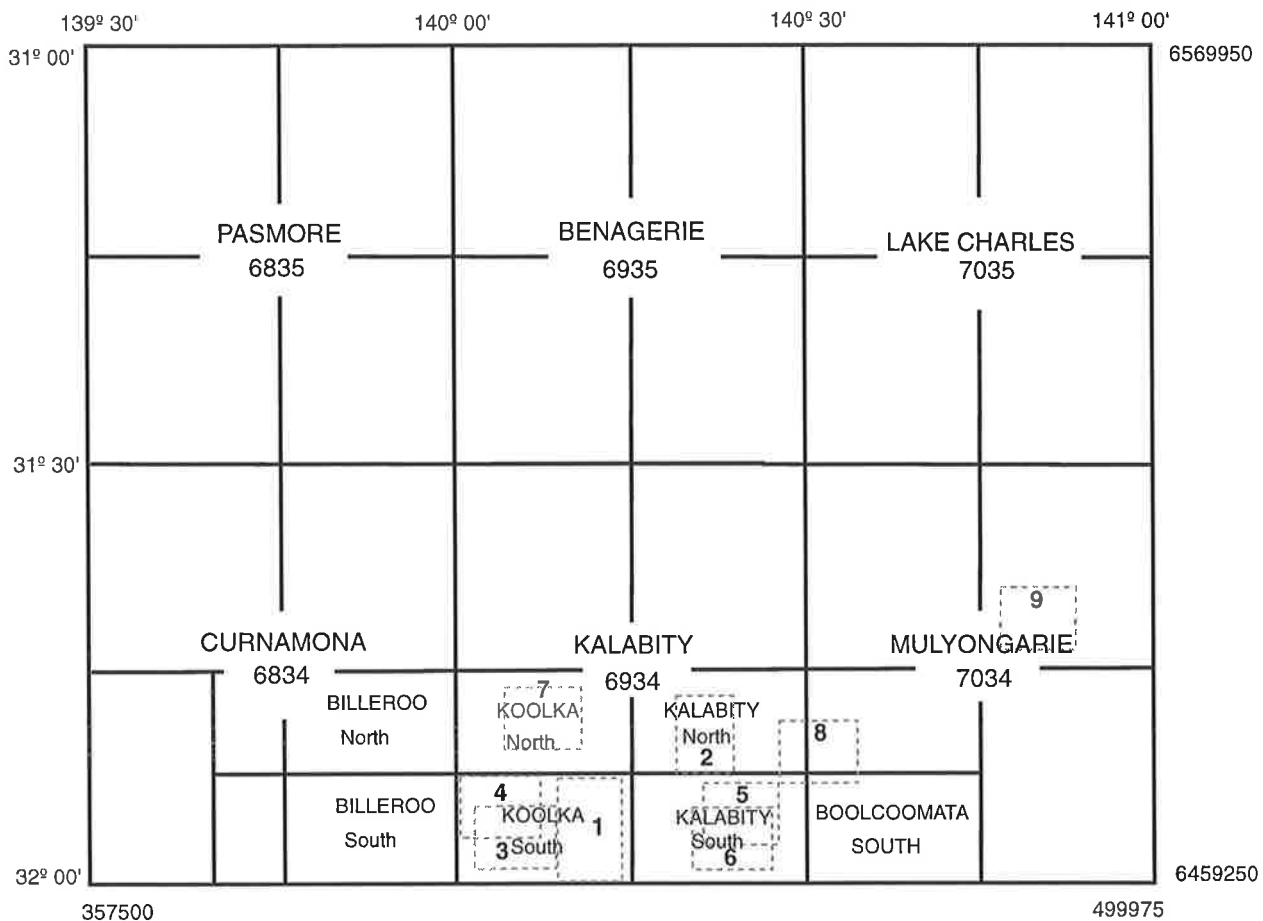


FIG 6.3 Curnamona province geological map index 1 : 100,000 and 1 : 25,000 Geological map sheets redrawn after MESA. The dashed quaderangles which are numbered from 1 to 9 show locations of the following areas:

- (1) Mt. Howden Mine area (figure 5.5).
- (2) Waulkaloo Mine area (figure 5.10).
- (3) Tonga Hill area (figure 6.11).
- (4) North West area of Koolka South (figure 6.15).
- (5) Dome rock area (figure 6.19).
- (6) Fault in the Kalabity South sheet (figure 6.23).
- (7) Koolka North area (figure 6.26).
- (8) North West of the Bolcomata South area (figure 6.32).
- (9) North East Mulyongari area (figure 6.36).

magnetic Willyama rocks of the Olary Block to the east from the Adelaide geosyncline to the west.

### **6.2.3. The Volcanic Magnetic Zone (VMZ)**

The VMZ shows a typical semi-circular to equidimensional anomaly with non-linear and undeformed pattern (compare figs 6.1 and 6.2). This zone constitutes three major anomalies in the northern part of the Curnamona 1:250,000 sheet; the eastern two are separated from the western one by the Adelaidean Magnetic Zone (AMZ). A smaller anomaly is located further north of the above mentioned three. Drill hole information for the volcanics is presented in 7.3. A WNW-ESE Lineament (see section 7.5) marks the south western boundary of the VMZ although there is evidence of possible thin lava flows extending south across this lineament.

The entire 1:100,000 Benageri sheet (see fig. 6.3 index map sheet) was selected for determination of depth to the top of the anomalous sources. Ignoring the effect of any possible magnetic sources in the Adelaidean this depth map shows either the volcanic or the Willyama Supergroup rocks according to the interpretation map (fig 6.1).

Randomly 115 anomalies were selected for depth determination and modelling assuming no remanence. The calculated depths to the top were plotted and contoured with 50 m contour interval (fig 6.4). This depth interpretation map shows that about 45 percent of the anomaly sources in the Benageri 1:100,000 sheet are less than 200 m deep. The shallow areas are located to the north eastern portion of a diagonal line in the NW-SE

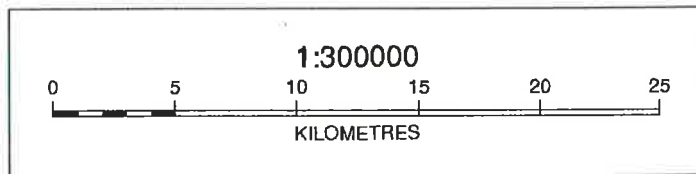
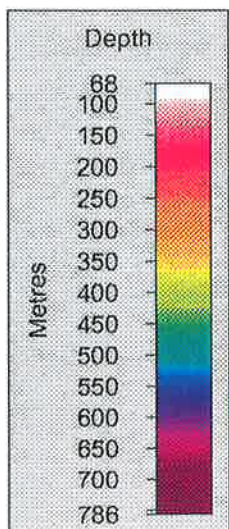
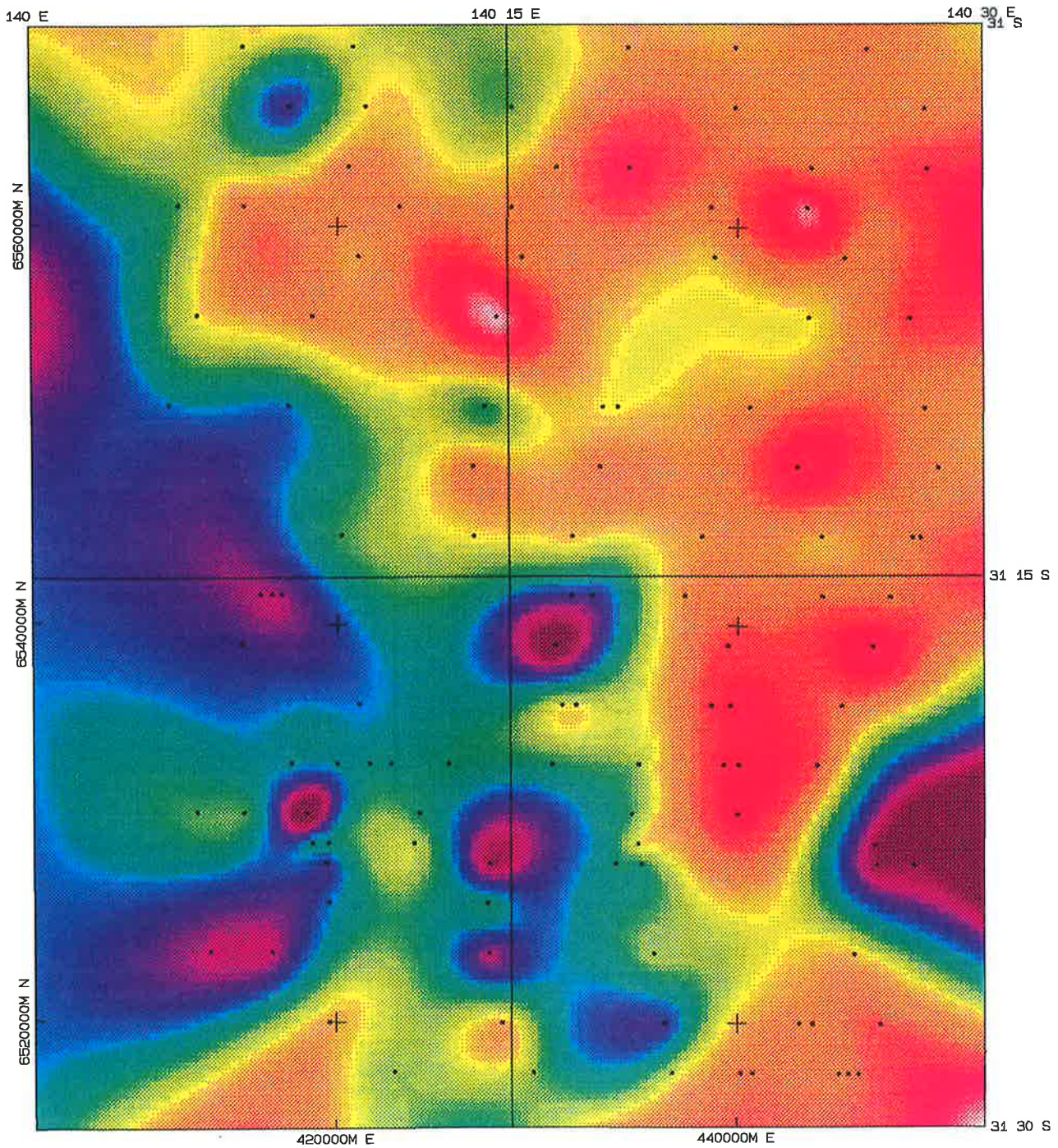


Fig. 6.4 Depth interpretation map in the Benageri 1:100,000 sheet.

direction (fig. 6.4). This direction of two different depths to the magnetic sources coincides with the more regional lineament of the Strathearn fault (see section 7.2.2).

It seems that the 200 metres contour line of depth to basement (fig. 6.4) follows a paleochannel meandering in the north west-south east direction. If this is the case then the direction of this paleochannel could represent a basement fault. The alignment of volcanic anomalies with some of the Willyama Supergroup anomalies in the northwest-southeast direction of the Benageri 1:100,000 sheet further confirms this interpretation.

#### **6.2.4. The Adelaidean Magnetic Zone (AMZ)**

The AMZ occupies mostly the northern part of the Curnamona 1:250,000 sheet. This zone is non-magnetic relative to the WSMZ and VMZ. There is no magnetic anomaly similar to the anomalies arising from the Braemar iron formation of the Olary 1:250,000 sheet in the Curnamona sheet. The AMZ on the north east corner of the Curnamona 1:250,000 sheet has a sharp eastern and a gentle western boundary with the WSMZ (figs 6.1 and 6.2). The former is interpreted as a thrust boundary (section 6.7) and the latter looks like a faulted one on the basis of the north south alignment of the anomalies. The AMZ has a sinusoidal unconformable contact with the WSMZ to the south. It is separating the VMZ to the south west from the WSMZ, although towards the north all three magnetic zones are overlying each other in ascending order.

A clear cut subdivision of these magnetic zones is apparent in the colour image of TMI of the Curnamona 1:250,000 sheet (fig. 6.2). The differences in magnetic response

between these zones are, in most cases, profound and the boundaries between zones are normally abrupt. Geological information (limited drilling) and magnetic characteristics certainly confirm that the magnetic zones represent distinctly different geological provinces.

### **6.3. Detailed interpretation**

#### **6.3.1. The Koolka South 1:25,000 sheet**

Detailed interpretation initially started from the southern part of the Curnamona 1:250,000 sheet and was constrained with the three preliminary geological maps at a scale of 1:25,000 and the outcrop susceptibility measurements as discussed in detail in chapters 4 and 5. The Koolka South sheet, Kalabity South sheet and Kalabity North sheet (fig. 6.3) are the only available geological maps at prospect scale. The geology on the other areas over the Curnamona 1:250,000 sheet was extrapolated from limited drill holes (fig. 6.1) and company exploration information (see section 7.2.1).

Although the interpretation is constrained by the available geological maps the problem of these maps is that in 80 percent of the areas (787.5 km<sup>2</sup>) rocks can be seen. In the following sections specific examples of the mapped geology which are reduced to a scale of 1:100,000 will be presented along with the interpretation map at the same scale for easy comparison.

Detailed discussion of the important magnetic features will be shown by the Total Magnetic Intensity (TMI) contour maps and Vertical Gradient (VG) contour maps superimposed on their images, along with the related interpretation and its geological map all at 1:100,000 scale. This type of presentation easily distinguishes the lows and highs; and better shows the gradients and boundaries. It will allow easy comparison between geology and its magnetic signature and also will demonstrate the amount of information contributed from magnetic data. It should be noted that the original interpretation was carried out at 1:25,000 scale as previously discussed in chapter 5.

The relation between geology where the rocks outcropped and magnetic information was established in chapter 5. This made it possible to trace the identified Lithomagnetic suite of the eastern part of the Koolka South sheet to the unexposed areas of the Willyama Supergroup rocks. The western two thirds of the Koolka South 1:25,000 sheet are more or less dominated by the northwest-southeast trending MacDonald shear zone.

The MacDonald fault trends roughly WNW-ESE (see section 7.2.2) through the Koolka South 1:25,000 sheet. All the magnetic anomalies in the vicinity of this linear feature have been truncated and oriented towards the strike of this fault zone. The fault is a major regional boundary separating the Adelaide Geosyncline from the Willyama inliers in the Olary 1:250,000 sheet. It has been mapped in the geological map of the Adelaide Geosyncline at the 1:600,000 scale (Preiss, 1983) and to the south on the Olary 1:250,000 geological sheet (Forbes, 1989).

The map of the Adelaide geosyncline was enlarged to 1:250,000 scale to be comparable with the colour image of the TMI of the Curnamona sheet (fig. 6.2) and overlain on it. Five aeromagnetic profiles were selected perpendicular to the strike of the fault and modelled to investigate the dip and location of this structural feature. The position of the fault is selected from the anomaly of the colour image of TMI (fig. 6.2) along the north eastern boundary of the highly magnetic Adelaidean and the relatively lower magnetic Willyama Supergroup rocks.

Considering the dip direction (recalling the discussion of remanence in section 4.10 and assuming no remanence) of modelled profiles ( $20^\circ$  to the north east) and knowing the relative age of the Willyama Supergroup rocks and the Adelaidean, the fault indicates a thrust fault. In all the profiles which were modelled the location of the interpreted fault correlates with the geological mapped fault of the Adelaide geosyncline map within a difference of  $\pm 300$  m. The portion of the fault which was selected for modelling is shown in figure 6.5 and one of the profiles and the model are shown in figure 6.6a and b.

The simplified interpretation map (fig. 6.7 the Kalabity sheet at 1:100,000) over the Koolka South sheet shows more continuous geology than the mapped geology. Two semi-circular to ellipsoidal anomalies with similar magnetic character (fig 6.8) are interpreted to the north-east and south-west of the MacDonald fault in the south central portion of the Koolka South sheet.

The Tonga Hill granitoids which have been mapped (fig. 6.9) on the 1:25,000 geological map of Koolka South are correlated with the eastern portion of the north eastern

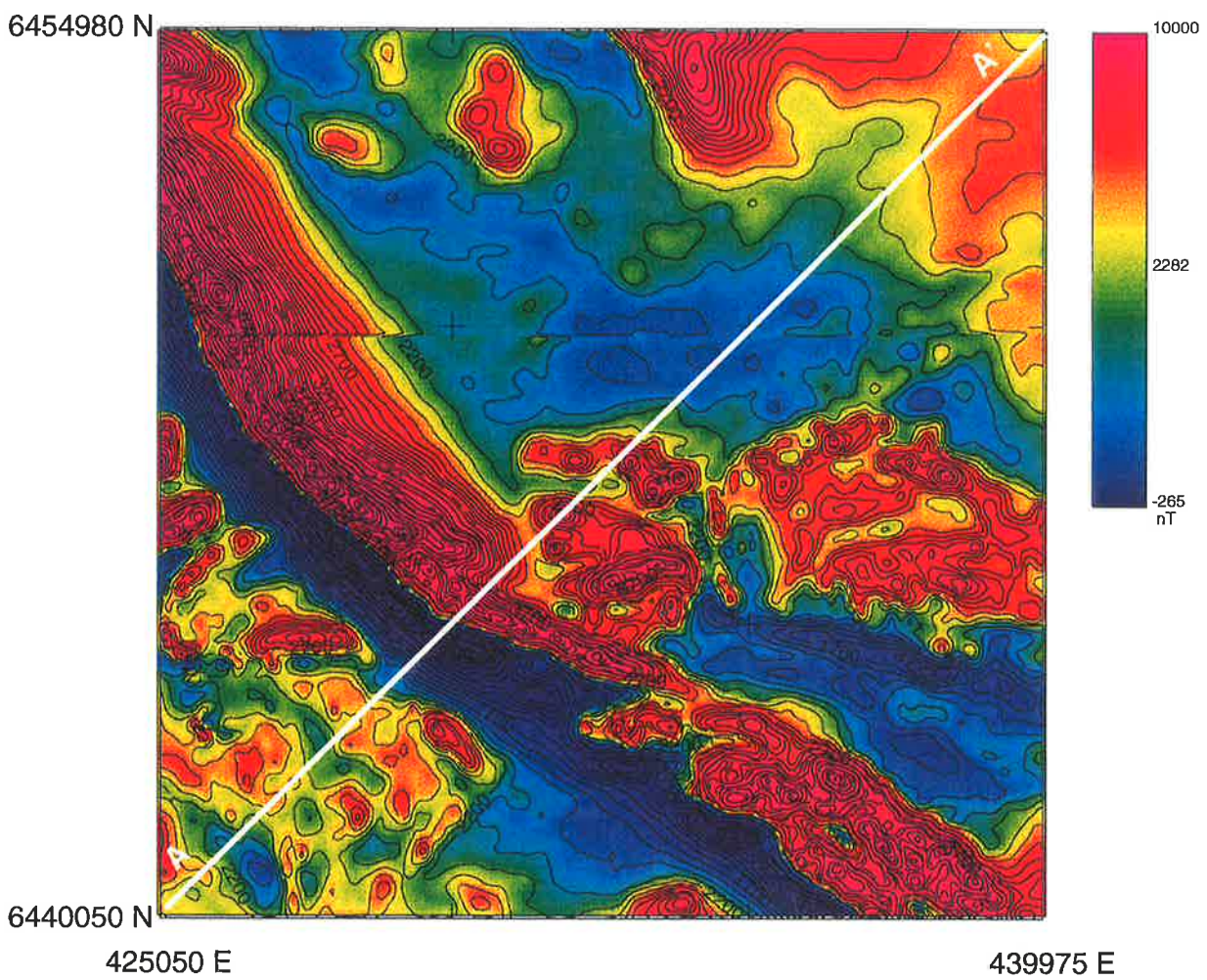
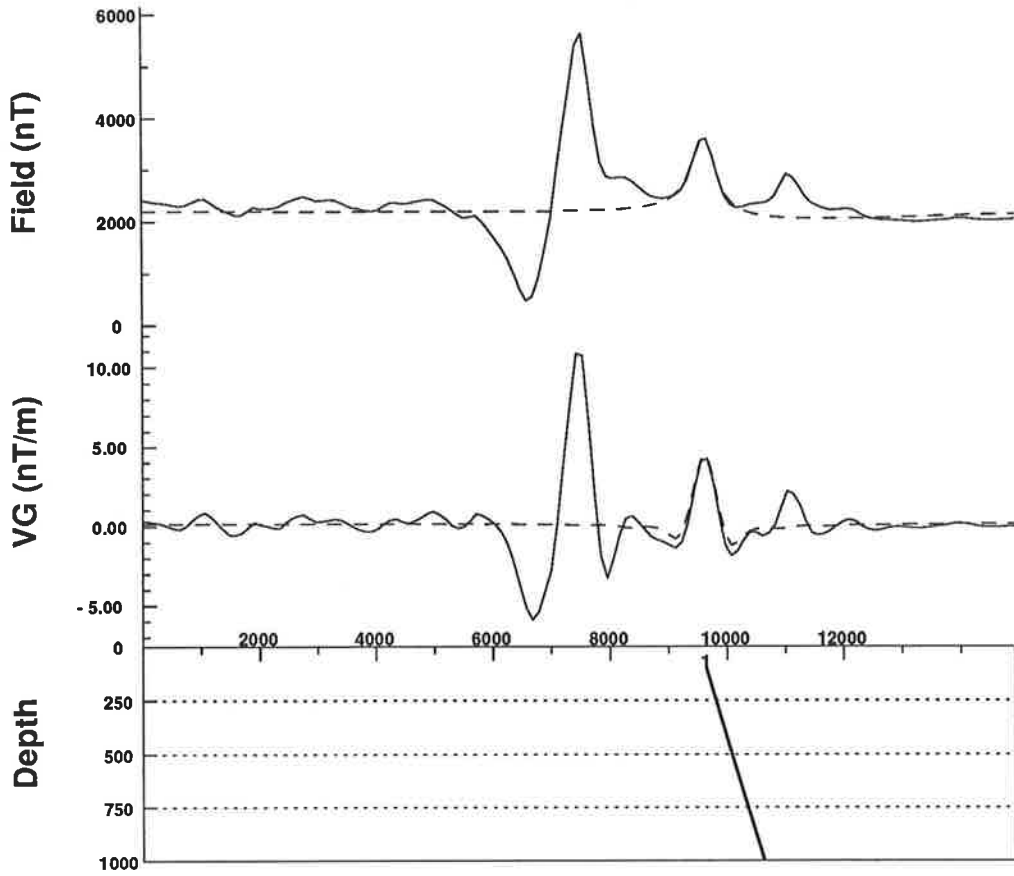


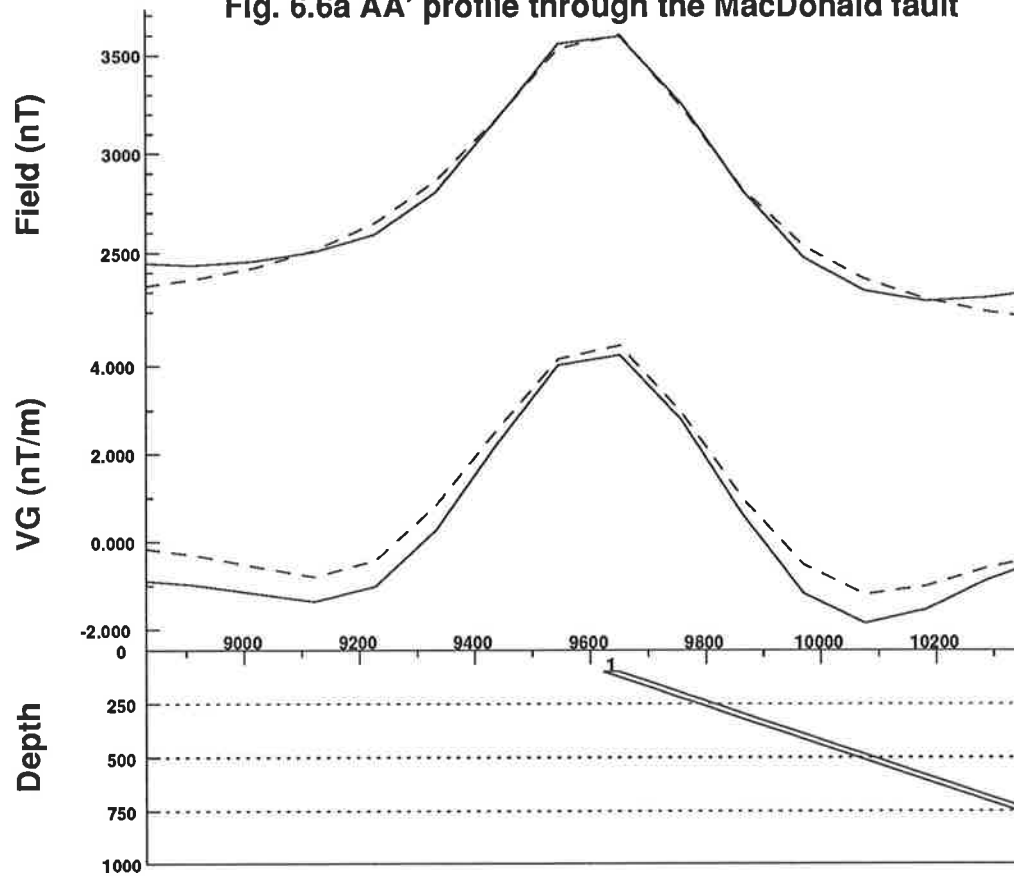
Fig. 6.5 TMI contour map over the MacDonald fault

Contour interval 100 nT

Map scale 1:80,000



**Fig. 6.6a AA' profile through the MacDonaldd fault**



**Fig. 6.6b Model of the anomaly of the MacDonaldd fault**



Fig. 6.7 Interpreted Willyama Supergroup rocks in the Kalabity 1:100,000 sheet

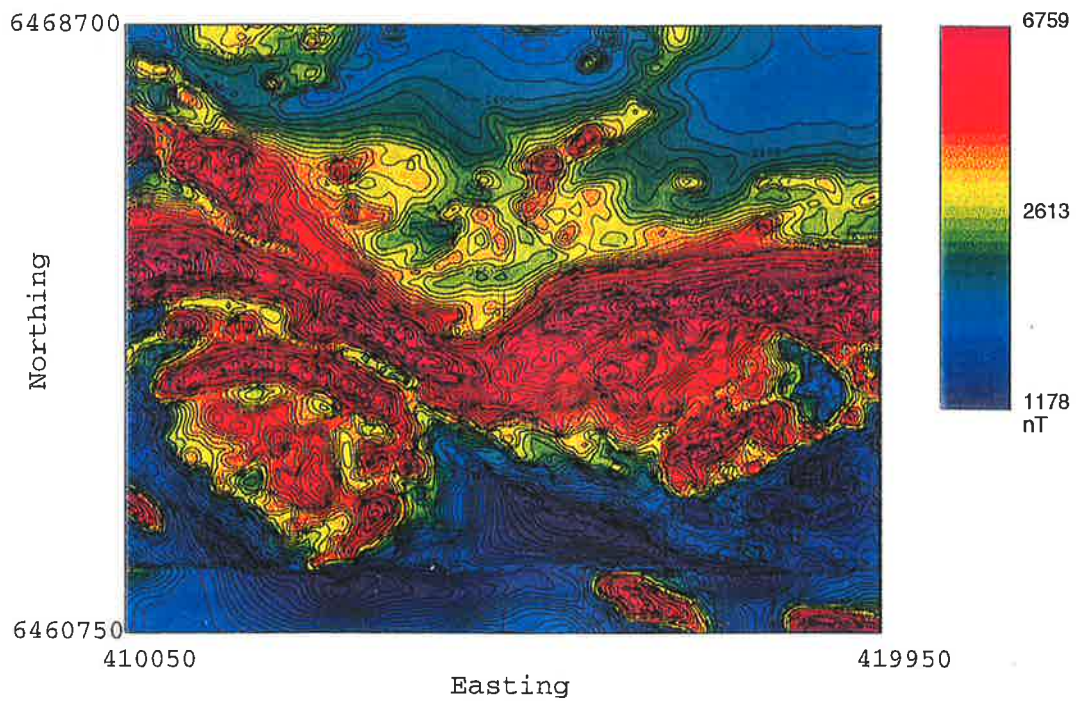


Fig. 6.8 TMI contour map of the Tonga Hill area  
 Contour interval 50 nT  
 Map scale 1:100,000

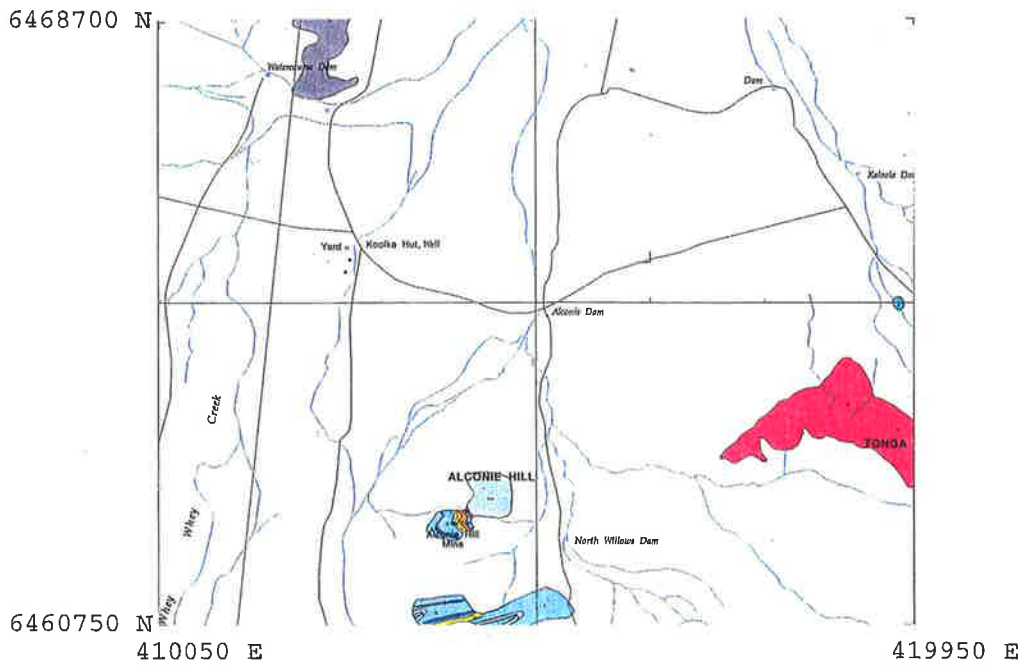


Fig. 6.9 Mapped geology on the Tonga Hill area  
 Map scale 1:100,000

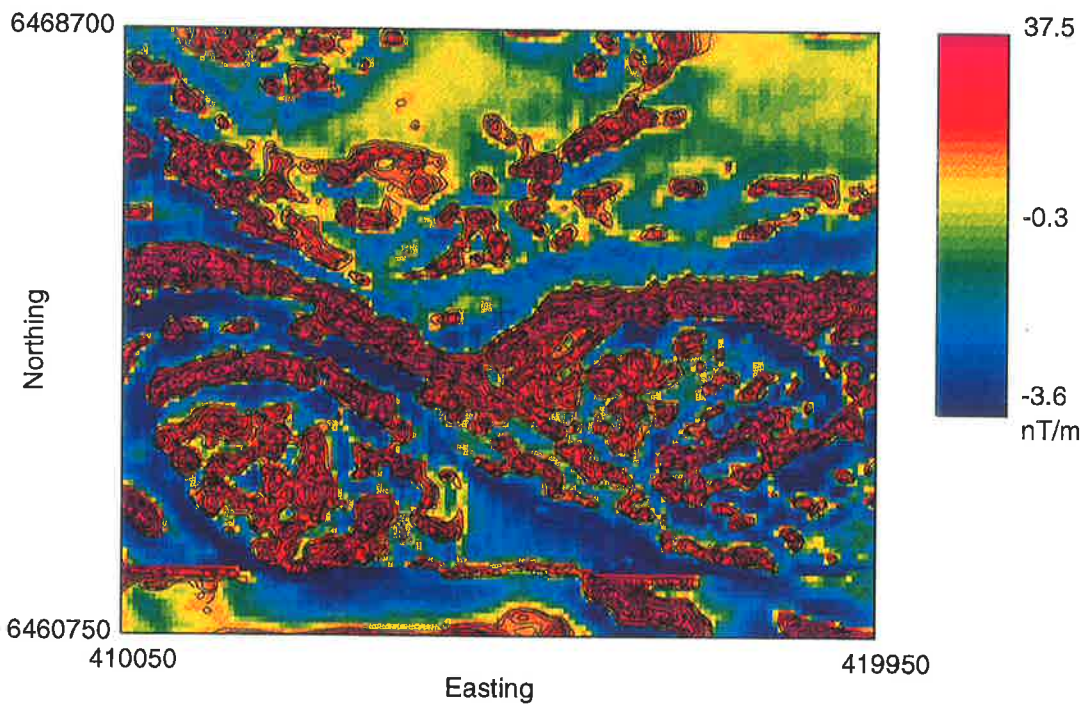


Fig. 6.10 VG contour map of the Tonga Hill area  
 Contour interval 0.1 nT/m  
 Map scale 1:100,000

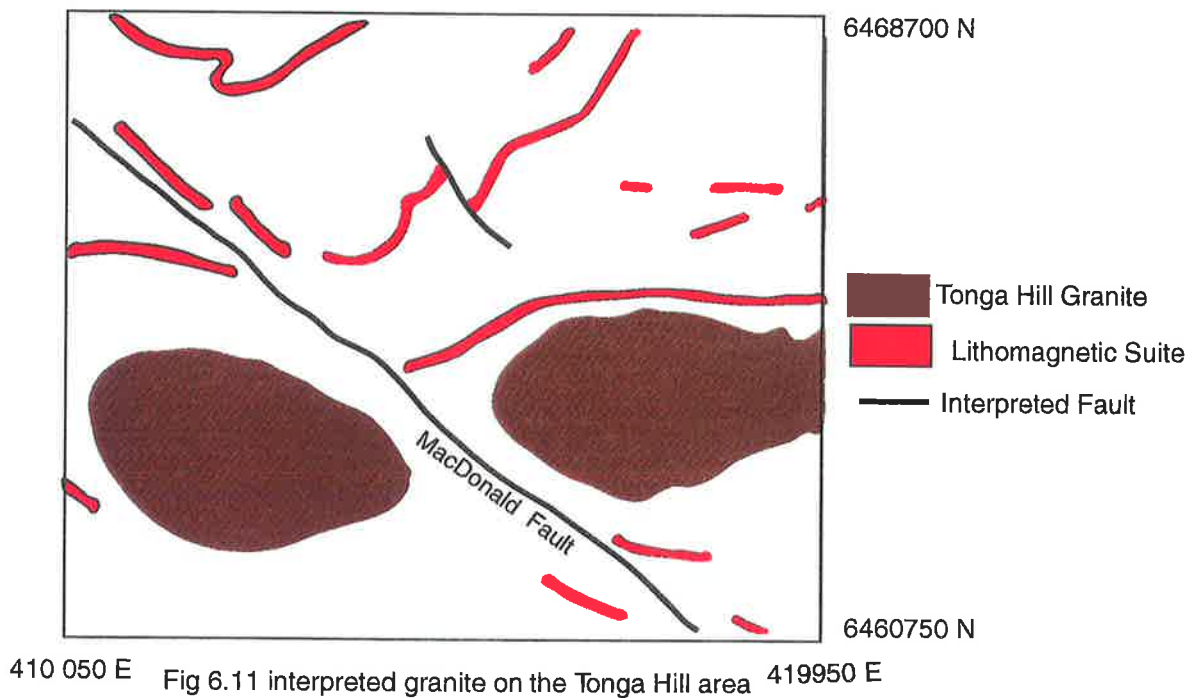


Fig 6.11 interpreted granite on the Tonga Hill area

anomaly. Much bigger ellipsoidal magnetic bodies than the mapped Tonga Hill granitoid were interpreted from the magnetic maps. Figures 6.10 and 6.11, the VG contour map and the interpretation map respectively, show the trend of the MacDonald fault and the two magnetic bodies.

These two ellipsoidal bodies are interpreted as one intrusion which has been dissected later by the MacDonald fault. The offset of these two bodies indicates that there has been a lateral slip component of motion along the strike of the fault. This may indicate that the MacDonald fault is not a pure thrust fault as modelled above.

The linear magnetic horizons, which are distinctive features of the area, allow mapping of folds and faults. The Lithomagnetic suite was traced as folded structures from the magnetic map (fig. 6.12) to the north central and north western parts of the Kooka South 1:25,000 sheet where it is not affected by the presence of the MacDonald fault. The main fold axis trends east west in the north central part and changes strike slightly to the north west as it approaches west. The southern limbs of these folds are either truncated by or aligned with the strike of the MacDonald fault.

A semi-circular to equidimensional feature with moderate magnetic character and surrounded by the curvilinear magnetic anomalies is correlated with the composite gneiss and migmatite. The oldest stratigraphic unit of the Willyama Supergroup rocks which is migmatite is mapped at the core of these folded structures (fig 6.13) on the geological map of the Koolka South sheet. The position of the migmatites may be located from the fact that they show relatively lower magnetic character than the Lithomagnetic suite and

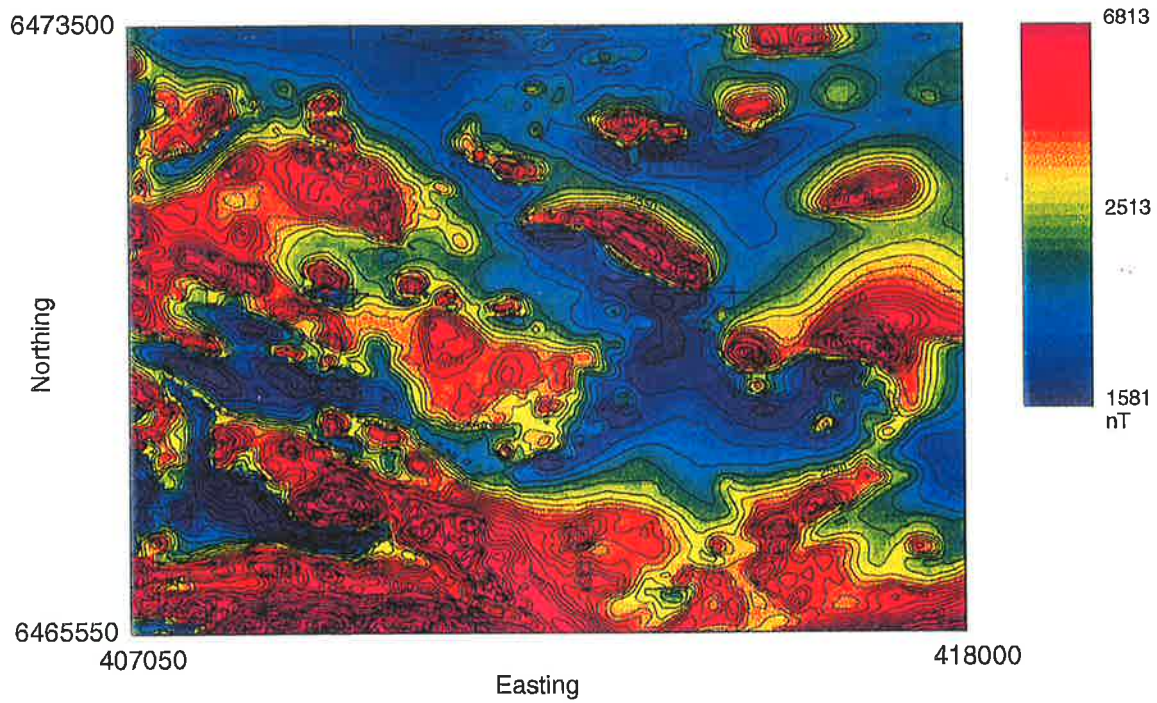


Fig. 6.12 TMI contour map of the north west of the Koolka South area  
 Contour interval 50 nT  
 Map scale 1:100,000

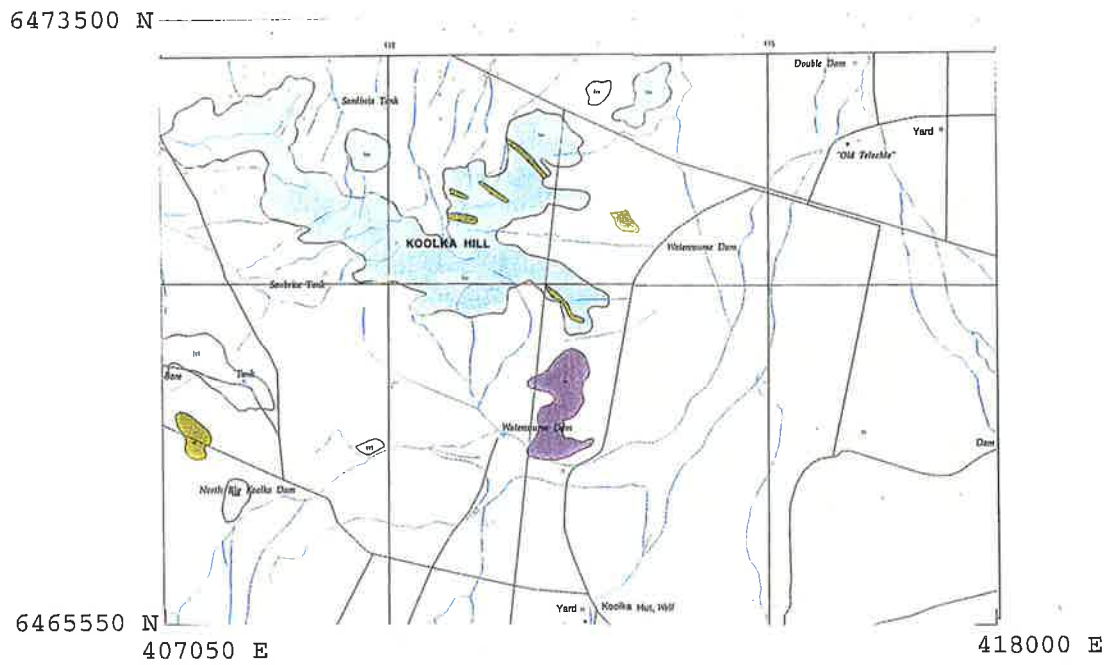


Fig. 6.13 Mapped geology on the north west of the Koolka South area  
 Map scale 1:100,000

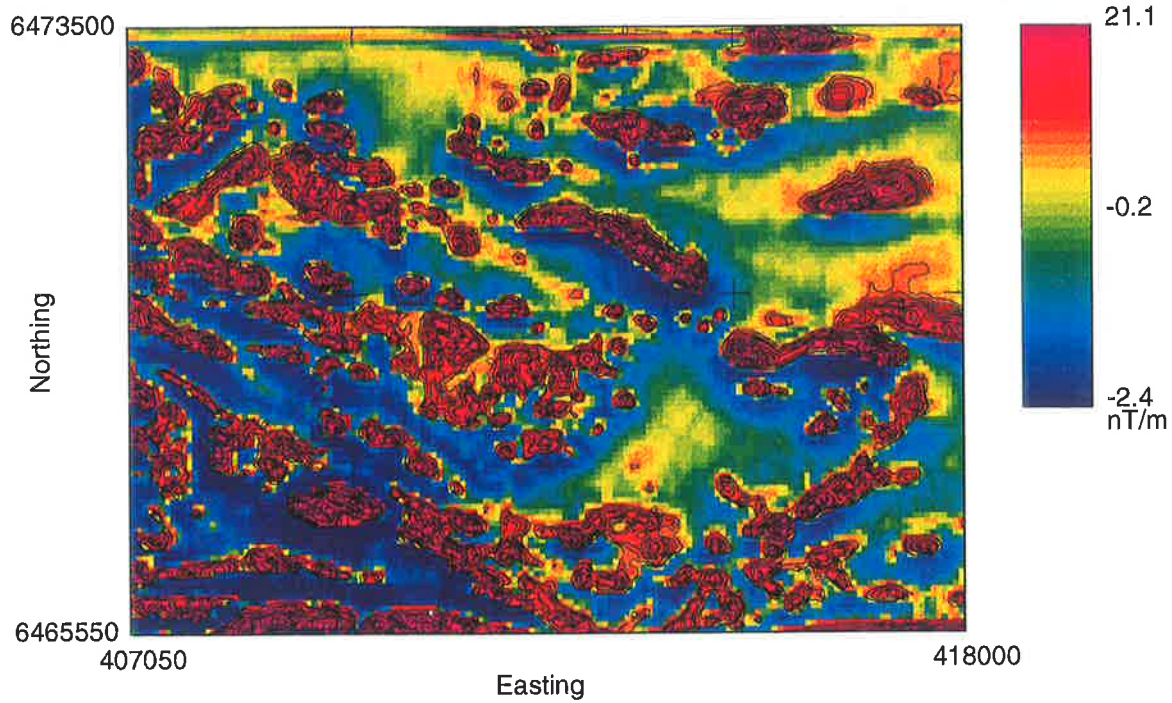


Fig. 6.14 VG contour map of the north west Koolka South area  
 Contour interval 0.1 nT/m  
 Map scale 1:100,000

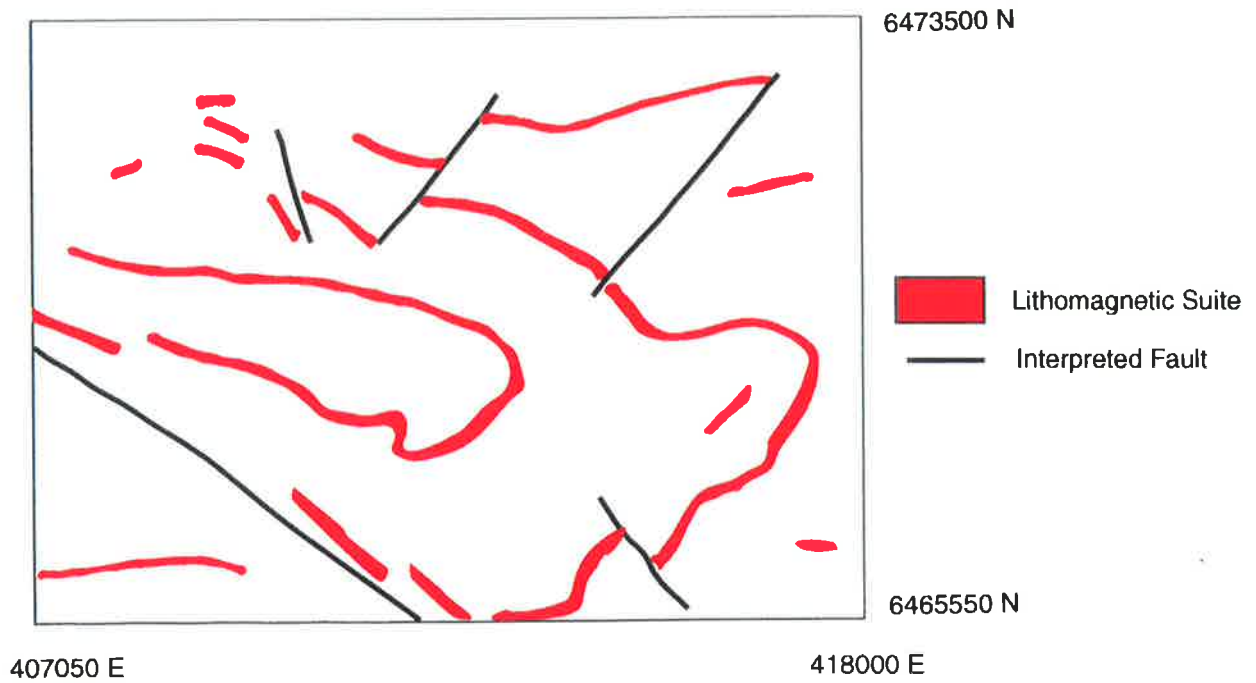


Fig. 6.15 Interpreted fold in the north west of the Koolka South sheet

higher amplitude magnetic character than the Pelite suite as discussed in chapters 4 and 5.

Lower magnetic areas between the folded Lithomagnetic suite were interpreted as the Pelite suite. In the Koolka South geological sheet most of the mapped Pelite suite corresponds with the low magnetic areas and confirms the above interpretation. The Lithomagnetic marker was accurately traced to the north eastern part of the MacDonald fault on the Koolka South sheet. Figures 6.14 and 6.15, VG contour map and interpretation map respectively, show the trace of these folded structures.

Migmatite and the Pelite suite were interpreted from the magnetic map to the south west of the MacDonald fault (fig. 6.7). All of the limited mapped Pelite suite (fig. 6.13) and migmatite correspond with this interpretation in the south west portion of the Koolka South sheet. The very limited mapped Calcsilicate suite (fig. 6.13) in the north western part of the Koolka South sheet was correlated with the Lithomagnetic suite (compare figs. 6.13 and 6.15).

Comparison of features on the TMI contours, VG contours and their images along with the ER mapping image of the magnetic data with the geological map of the Koolka South sheet showed that the Lithomagnetic suite is the dominating magnetic unit which appears as folded structures (fig 6.7) in the stratigraphic sequence of the Willyama Supergroup rocks.

Except in both the southern corners of the Koolka south sheet where mostly migmatite was interpreted (fig. 6.7), the remainder of the magnetic anomalies are

correlated/interpreted as arising from the Lithomagnetic suite. All the curvilinear magnetic anomalies which appear as folded and refolded structures correspond with the Lithomagnetic suite. Most low magnetic areas between the folded structures were interpreted as the Pelite suite (fig. 6.7). This interpretation correlates with all the limited mapped suites and extends them onto the Koolka south 1:25,000 sheet.

### **6.3.2. The Kalabity South 1:25,000 sheet**

The Kalabity South geological map (see fig. 6.3 index map sheet) shows that half of the mapped rocks are granitoids and migmatite. The interpreted map of this study over this sheet (fig. 6.7) indicates a greater concentration of granitoids and migmatite in the southern and central area. The TMI and VG contour maps were prepared at the same scale as the geological map of this sheet (1:25,000). ER mapping images of magnetic data over selected parts of this sheet along with the contour maps were compared with the mapped geology over the Kalabity south sheet. The Lithomagnetic marker of the eastern portion of the Koolka South sheet extends to the western part of the Kalabity South sheet where it corresponds to the mapped Quartzofeldspathic suite and the Calcsilicate suite (fig. 6.7).

The Lithomagnetic suite corresponds with the Quartzofeldspathic suite and Iron formation in the Dome rock Copper Mine area to the east and north eastern part of the Kalabity South sheet (see figs 6.16, 6.17, 6.18 and 6.19). Iron formations are the minor rock type in the Quartzofeldspathic suite (Ashley, 1995). Most central and northern parts of the Kalabity South sheet are interpreted as either migmatite or regional

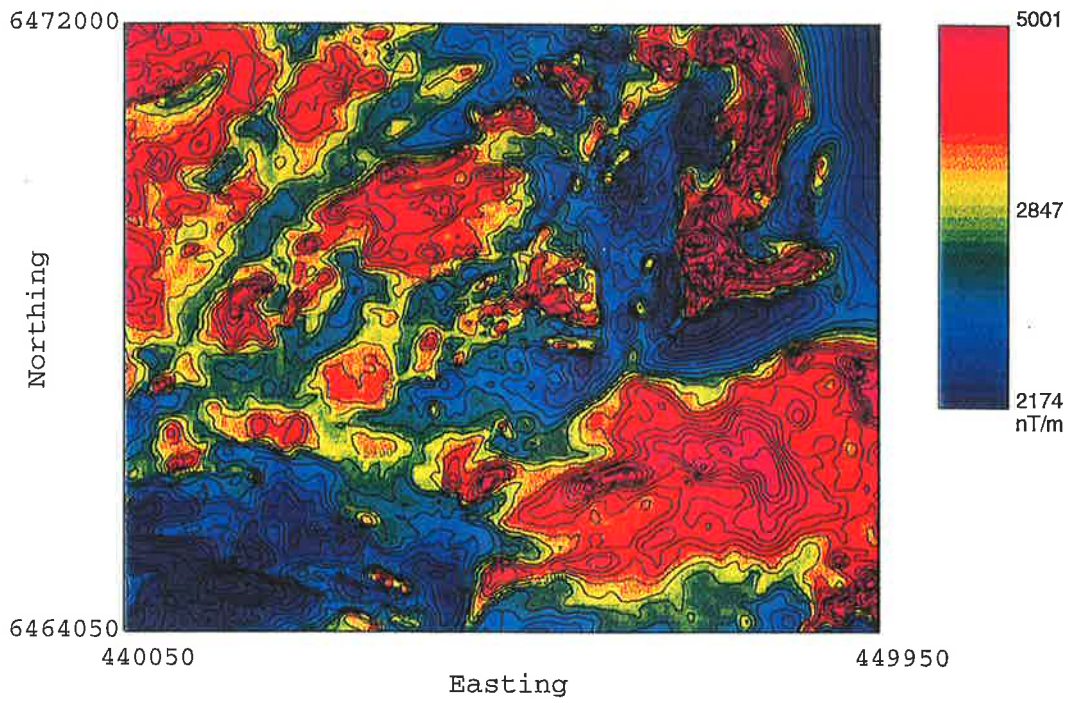


Fig. 6.16 TMI contour map of Dome rock area  
 Contour interval 50 nT  
 Map scale 1:100,000

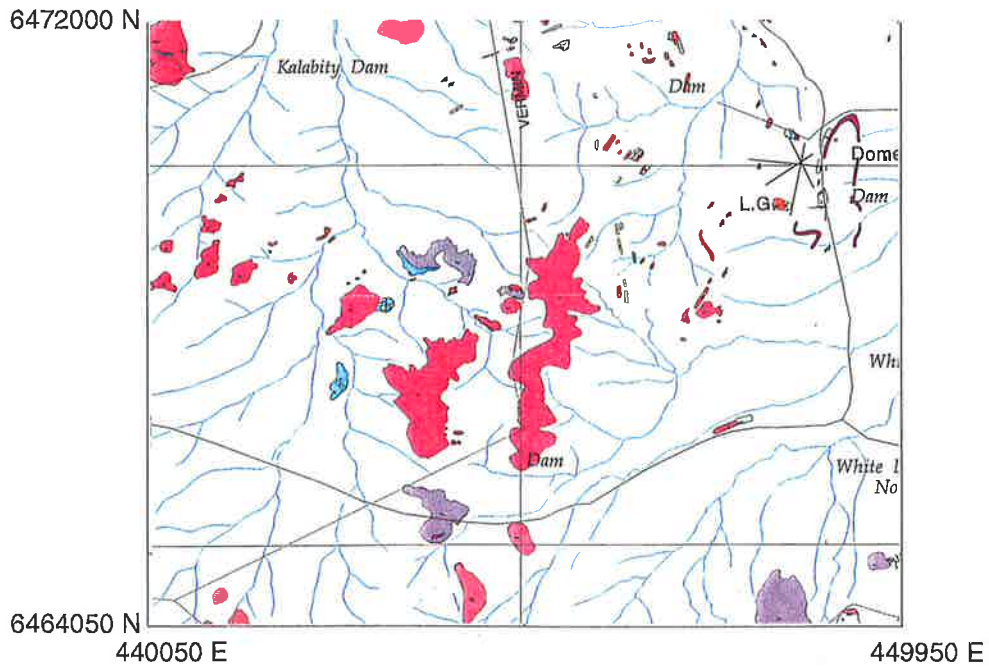


Fig. 6.17 Mapped geology of Dome rock area  
 Map scale 1:100,000

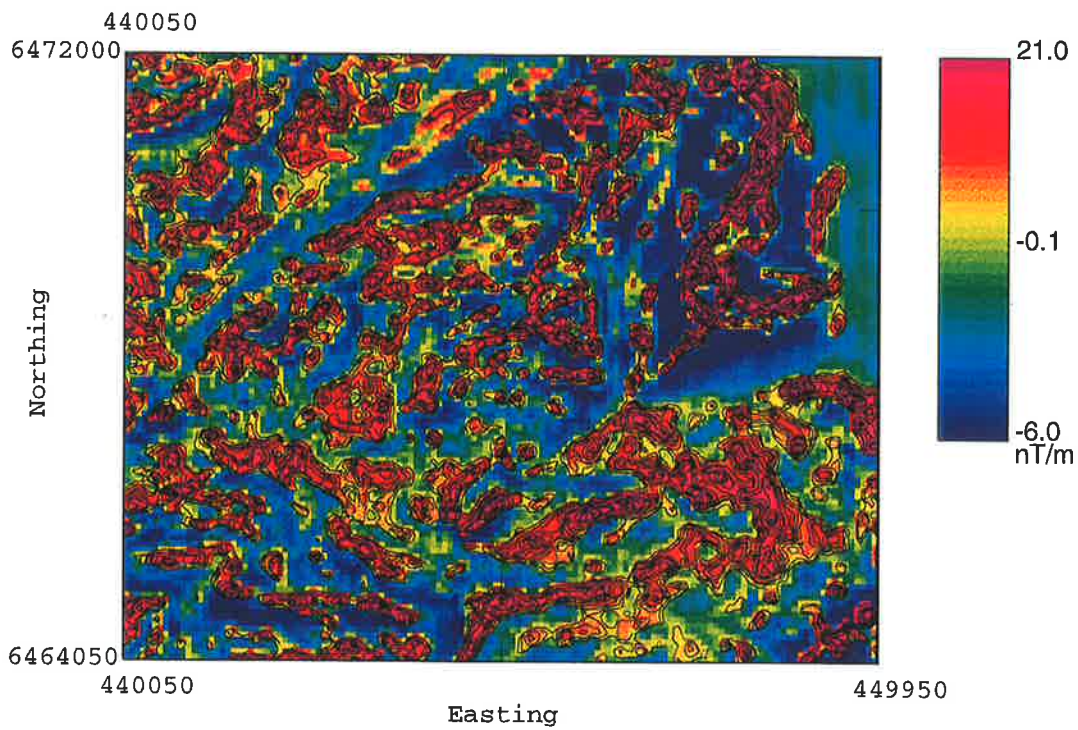


Fig. 6.18 VG contour map of Dome rock area  
 Contour interval 0.1 nT/m  
 Map scale 1:100,000

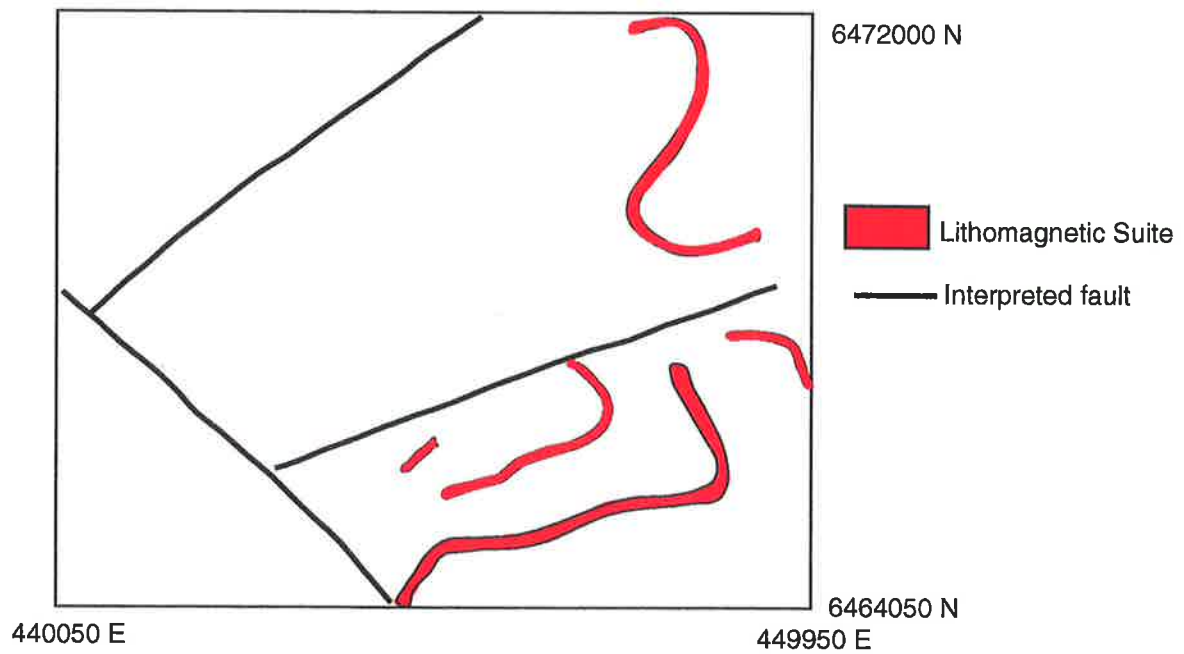


Fig. 6.19 Interpreted faults and folds in the Dome rock area

granitoids forming a dome shape structure extending to the Kalabity North sheet and with the lithomagnetic suite around it (fig. 6.7).

Migmatite and regional granitoids were identified from the semi-circular anomaly-shape of the magnetic images which are surrounded by the Lithomagnetic suite. Short linear and curvilinear magnetic anomalies which are intermixed with the migmatite and granitoids are interpreted as the Lithomagnetic suite. The relatively smooth magnetic texture of these migmatite and granitoids have been disturbed by the presence of the highly magnetic Lithomagnetic suite (fig. 6.7).

A WNW-ESE trend which is easily recognisable in the TMI contour map (fig. 6.20) continues to the Olary 1:250,000 sheet and extends for about 65 km, sub parallel with the Thackaringa shear zone, to the Broken Hill Block. This linear trend is interpreted as a fault which displaced some of the mapped Quartzofeldespathic gneiss laterally (fig. 6.21).

The TMI and VG contour maps (figs. 6.20 and 6.22 respectively) show the trend of the fault and the offset of the curvilinear anomaly. This interpreted fault (fig. 6.23) has not been mapped in the north western part of the Kalabity South sheet and magnetic data shows that it terminates to the west by the NE-SW regional interpreted fault at the south central area of the Curnamona 1:250,000 sheet (see section 7.2.2). Although the WNW-ESE interpreted fault is not exactly parallel to the MacDonald fault, they seem to be regionally related and both of them are terminated to the south east by the Mundi Mundi fault in the Broken Hill Block. This will be discussed in chapter 7.

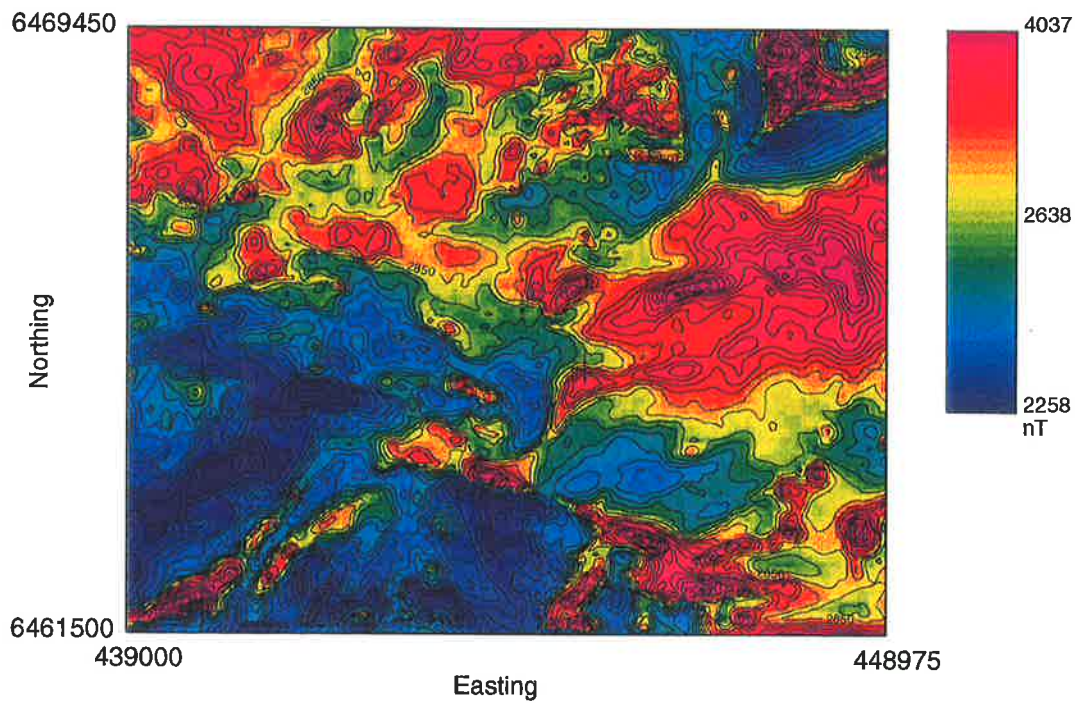


Fig. 6.20 TMI contour map of a WNW-SSE fault on the Kalabity South area  
 Contour interval 50 nT  
 Map scale 1:100,000

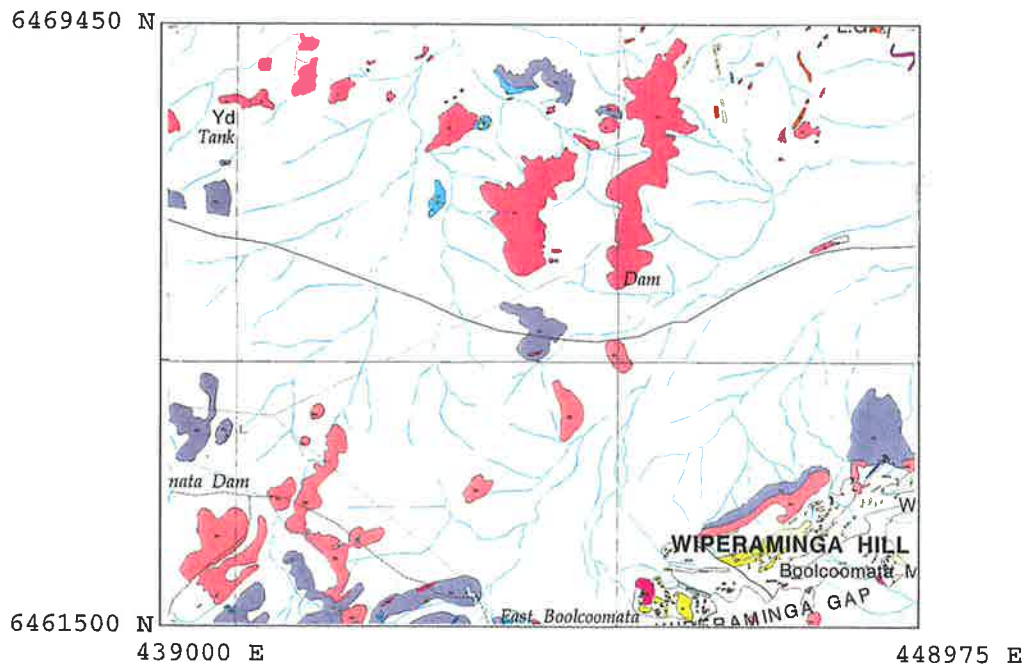


Fig. 6.21 Mapped geology of the Kalabity South area  
 Map scale 1:100,000

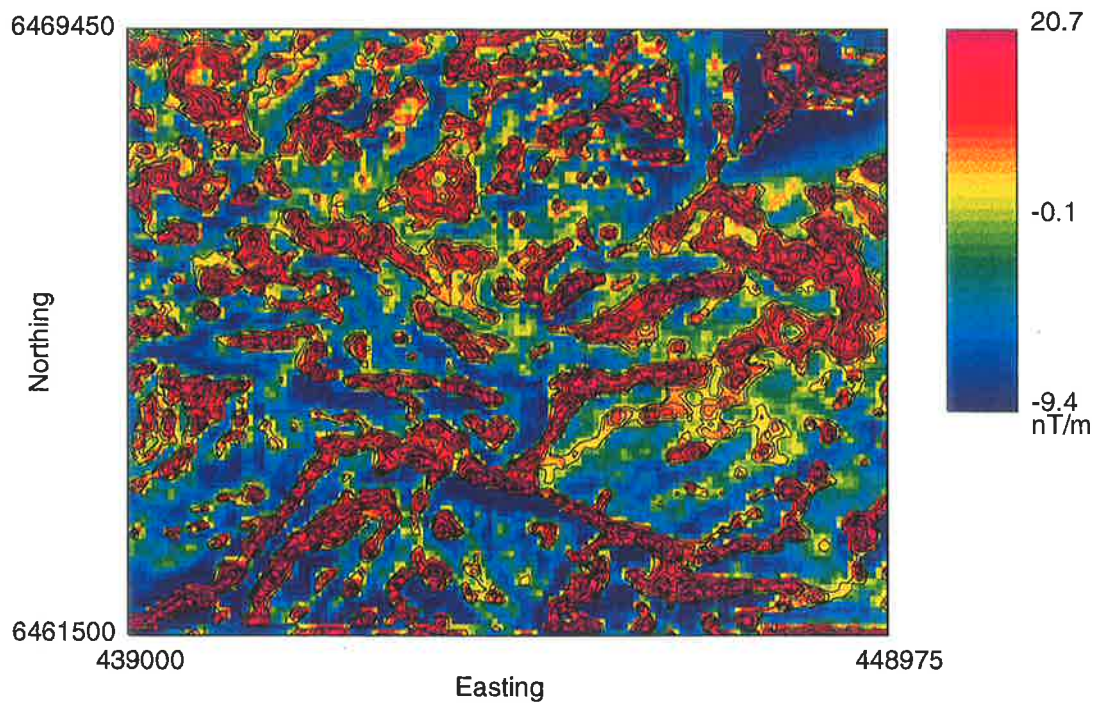


Fig. 6.22 VG contour map of a WNW-SSE fault On the Kalabity South area  
 Contour interval 0.1 nT/m  
 Map scale 1:100,000

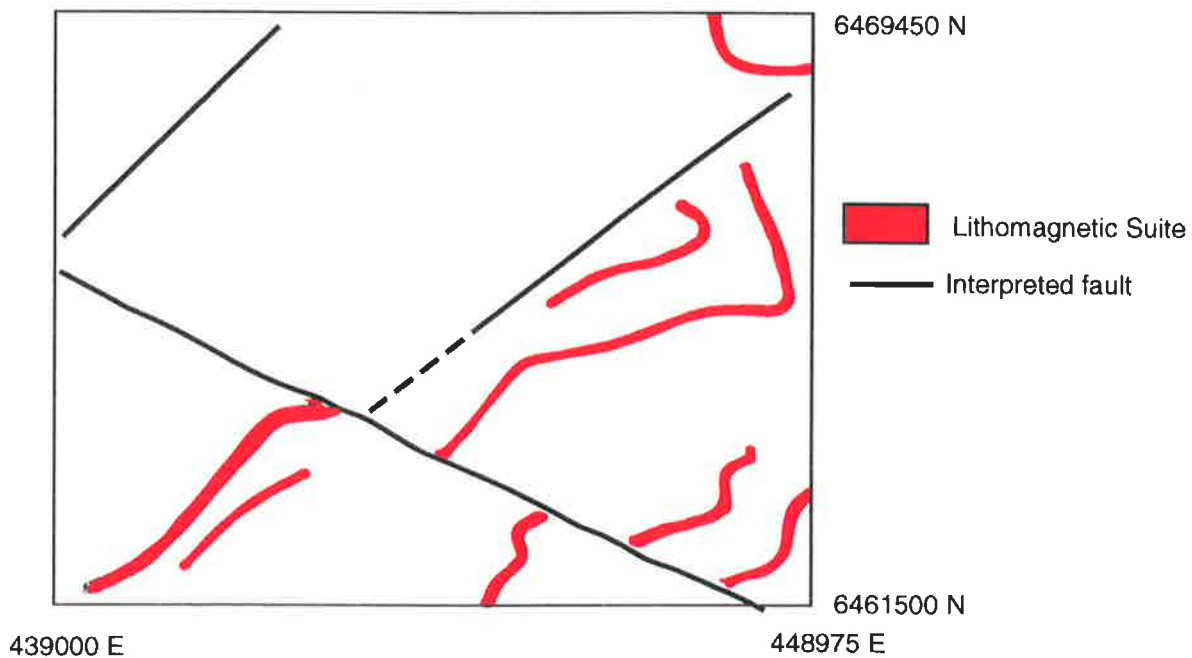


Fig. 6.23 Interpreted fault in the Kalabity South Sheet

A less continuous but sub parallel fault is running across the migmatite further south than the WNW-ESE interpreted fault (fig. 6.7). The linear magnetic anomalies over all these interpreted faults are probably related to the concentration of magnetic minerals in the fault zone. The WNW-ESE fault has been cross cut by at least three NE-SW interpreted shears over the eastern part of the Kalabity South sheet (fig. 6.7). These small local shears are also parallel to the regional faults. Two of these interpreted shears are shown in figure 6.19.

The above regional shears are interpreted from the colour image of Total magnetic intensity (fig. 6.2) and the first vertical gradient grey image of CRA on the Olary and Broken Hill Blocks. Delineation of subtle detailed structural features and distinction between weakly magnetic suites are not possible using a smaller scale map than 1:25,000. Small NE-SW shears can be better identified from the ER mapping image which has a better resolution.

The association of the intrusion, shear zone and folded Lithomagnetic suite which can all be identified from the magnetic data may be potential areas for mineralisation. An example is the Wiperaminga mine (fig. 6.21) which is located in the vicinity of the mapped Calcsilicate Suite and granitoid; NE-SW shear and the WNW-ESE interpreted fault (fig. 6.23).

### 6.3.3. The Kalabity North 1:25,000 sheet.

The Kalabity north 1:25,000 geological sheet (see fig. 6.3 index map sheet) shows that less than ten percent of the map area ( $32.8 \text{ km}^2$ ) is occupied by mapped rocks and 90 percent ( $295.5 \text{ km}^2$ ) is sand and soil. The Lithomagnetic suite which is traced as a folded structure in the Dome rock Copper Mine area of the Kalabity South sheet continues to the Kalabity north 1:25,000 sheet. The contour maps of the TMI and VG were prepared at the same scale as the geological map of the Kalabity North sheet (1:25,000); and overlain on it.

An anomaly on the TMI contour map (fig. 5.7) is correlated with a band of Quartzofeldspathic suite about 500 m thick and a thinner band of the Calcsilicate suite about 50 m thick striking NE-SW. These extend along strike for about 2500 m and were mapped in the south central part of the Kalabity North sheet (fig 5.8). Both of these mapped suites which were discussed in chapter 5 appear as one curvilinear anomaly similar to the Koolka South sheet. The VG contour map and the interpretation map are showed in figures 5.9 and 5.10 respectively.

A profile through the corresponding anomaly of both mapped suites was modelled with reasonably good fit using a single source (fig 5.11a and b) and the inherent difficulty of mapping the Calcsilicate suite was discussed in chapter 5. This demonstrates that the magnetic mineral concentration may not necessarily correlate with the stratigraphic units. This problem has been observed even with the new initiative surveys (100 metre flight

line spacing and 60 metre sensor height) over the Broken Hill Block (Denham, pers comm.).

The first vertical gradient contour map of the Kalabity North sheet, part of which is shown in figure 5.9, clearly shows the folded Lithomagnetic suite surrounding a moderately circular magnetic body which is interpreted as the regional granitoid (fig. 6.7). The migmatite and the regional granitoid, which were interpreted in the central portion of the Kalabity South sheet, continue to the Kalabity North sheet where they are surrounded by the highly folded Lithomagnetic suite (fig 6.7).

In the northern part of the Kalabity north sheet the termination of the Willyama Supergroup rocks is inferred as there is no continuation of the Lithomagnetic marker in this area. Magnetic modelling over this boundary (assuming no remanence) showed that the Willyama Supergroup rocks are dipping at about 45 degrees towards the west. The termination is also evident on the colour image of TMI at a scale of 1:250,000 (fig. 6.2).

Comparison of the total magnetic intensity contour map, first vertical gradient map and ER map images of the Koolka South sheet, Kalabity South sheet and Kalabity North sheet with their equivalent detailed geological maps were made at the same scale. This allowed not only a very good correlation of the Lithomagnetic suite with the mapped geology but a far better continuation of rock suites under cover to be traced using the magnetic maps.

Although there is inherent difficulty in distinguishing the stratigraphic suite (Calcsilicate suite) from the magnetic information alone, the ability to trace the Lithomagnetic suite

under cover is beyond dispute. This has been verified through the comparison of mapped geology with the equivalent magnetic responses over the above three available preliminary geological maps and by exploration drill holes over the covered areas.

#### **6.3.4. The Koolka North 1:25,000 sheet**

There is no rock mapped on the Koolka North 1:25,000 sheet (see fig. 6.3 the index map sheet) at all. Although the magnetic maps indicate the termination of the Willyama Supergroup rocks in the northern part of the Kalabity North sheet, this is not the case over the Koolka North sheet. The TMI and VG contour maps (figs. 6.24 and 6.25) show folded structures over the northwestern part of the Koolka North sheet. The fold axes (fig. 6.26) mostly trend north east, similar to the other areas of the Willyama Supergroup domain.

The geology of the Willyama Supergroup rocks further north from the Koolka South sheet is only known from an interpolated cross section between the deep drill holes (fig. 6.1). The interpretation beyond the available preliminary geological maps (Koolka South, Kalabity South and Kalabity North) was carried out on a 1:100,000 scale (see fig. 6.3 the index map sheet) except over the complex areas that required a 1:25,000 scale.

The semi-circular moderately magnetic area surrounded by the Lithomagnetic marker in the south western part of the Koolka north sheet was interpreted as composite gneiss and migmatite (fig. 6.7). This interpretation correlates with the drill information reported by Yates (1993) further north west. Magnetically this area is similar to the central areas of

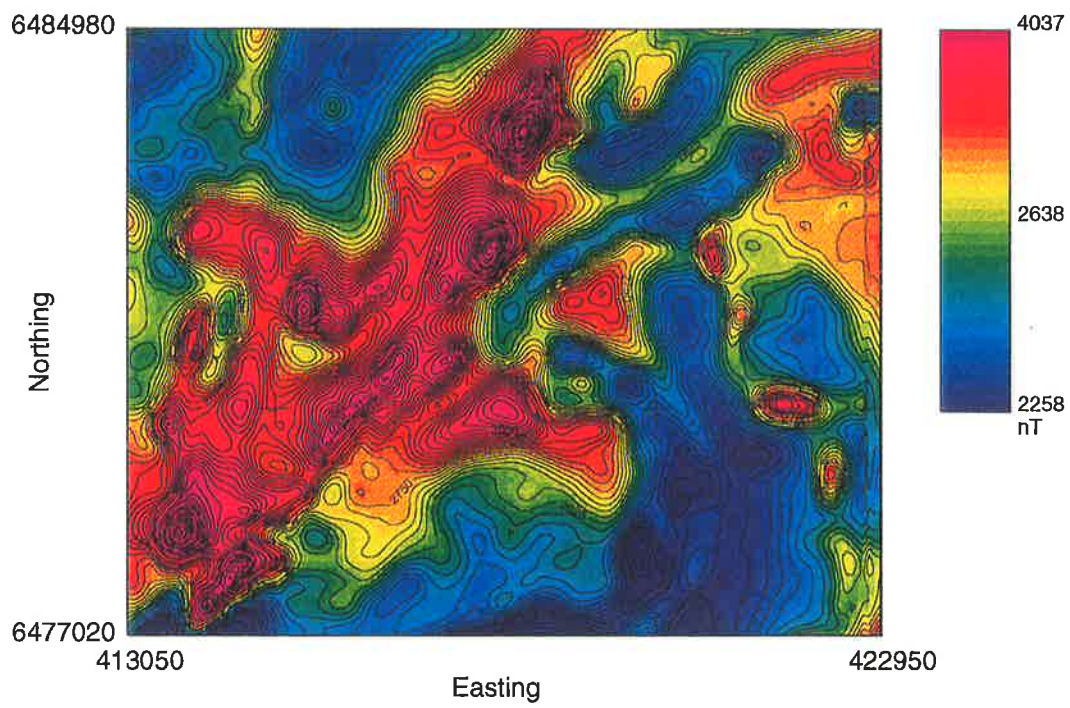


Fig. 6.24 TMI contour map on the Koolka North area  
Contour interval 50 nT  
Map scale 1:100,000

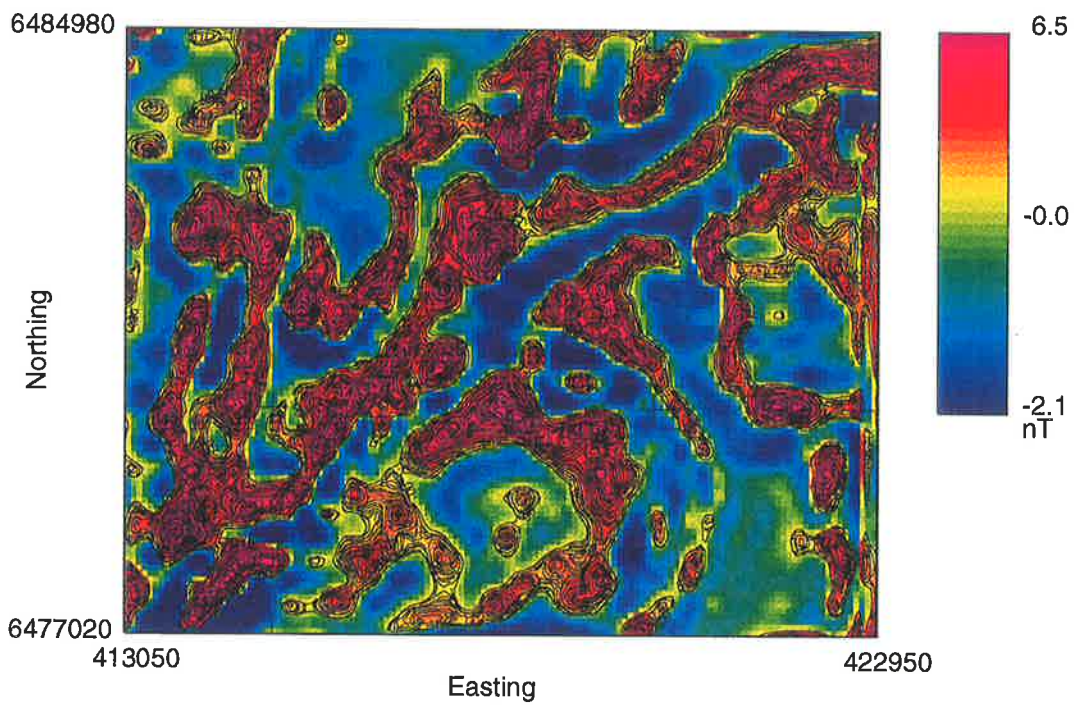


Fig. 6.25 VG contour map on the Koolka North area  
 Contour interval 0.1 nT/m  
 Map scale 1:100,000

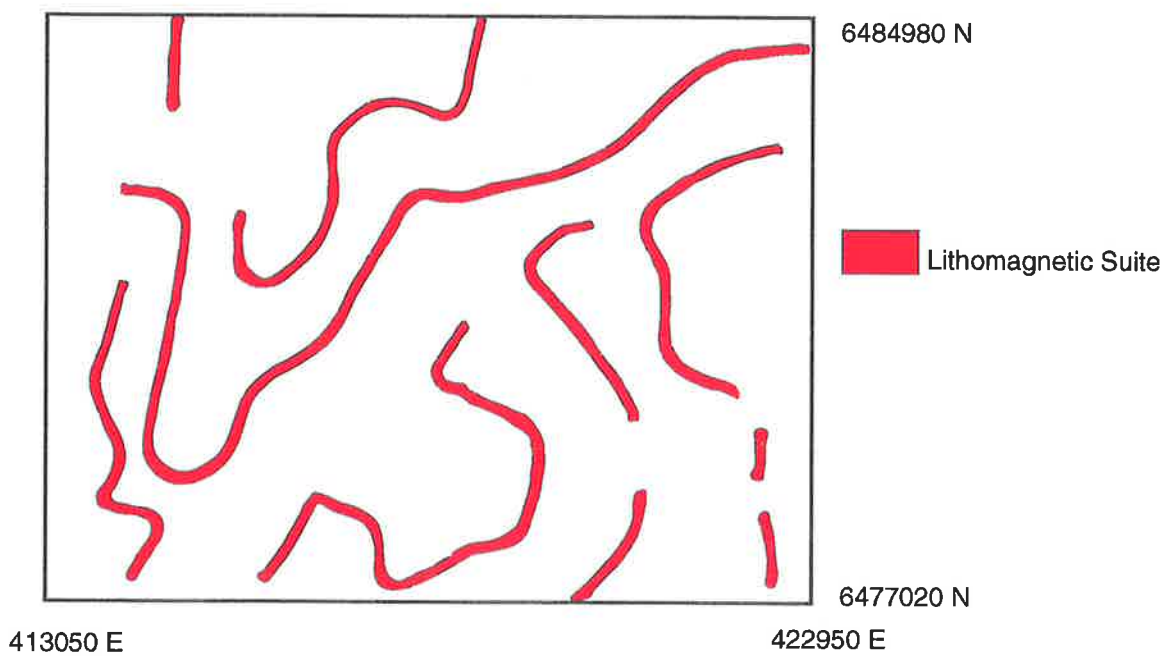


Fig. 6.26 Interpreted folds on the Koolka North area

the Kalabity North and Kalabity South sheet. Smaller and less continuous anomalies of the Lithomagnetic marker are intermixed with migmatite in this area. The geological implication is that migmatite and regional granitoids dominate the Koolka North sheet and deformation is reduced further north and north west.

The continuation of the Lithomagnetic suite was traced further to the north western part of the Kalabity 1:100,000 sheet (fig 6.7). Although this suite is continuing to the north and north west, the degree of folding and deformation is less than on the Koolka South and Kalabity South sheets. This possibly reflects the decrease of metamorphism, deformation and increase of the depth of the sources to the north west.

The position of the termination of the Willyama Supergroup rocks in the north western part of the Kalabity 1:100,000 sheet was interpreted from the colour image of the total magnetic intensity (fig. 6.2) and the first vertical gradient grey image of the Olary and Broken Hill Blocks. Although the termination of the Willyama Supergroup rocks is identified from the above magnetic maps, the nature of the boundary is not an easy problem.

An unconformable contact between the AMZ and the WSMZ is interpreted from the sinusoidal shape of the boundary (fig. 6.7) as was discussed in section 6.2.2. The question of the continuity of the Willyama Supergroup rocks in the north eastern part of the Kalabity 1:100,000 sheet is different than in the north west.

Thick anomalies similar in magnetic character to the Lithomagnetic suite in the Kalabity North area, but deeper, were traced to the north eastern part of the Kalabity 1:100,000

sheet.(fig. 6.7). These anomalies are identifiable from both images and contour maps particularly on the smaller scale magnetic maps. This indicates that the Willyama Supergroup rocks are continuing to the Benageri 1:100,000 sheet in the north east, while terminating on this sheet to the north west (fig. 6.1). The inferred extension of the Willyama Supergroup rocks from shallow areas in the south to deep areas in the north, using interpreted magnetic data, will be discussed in the next chapter.

Wide and deep anomalies extend to the north in a north south direction over the eastern portion of the Benageri 1:100,000 sheet and the western portion of the Lake Charles 1:100,000 sheet (compare figs. 6.1 and 6.2). This north south trend of the anomalies is interpreted as arising from Willyama Supergroup rocks. The colour image of TMI (fig. 6.2) clearly shows the continuation of the magnetic anomalies to the north which is interpreted as the Lithomagnetic suite (figs 6.1 and 6.7).

Drill holes into the metapelites (hole 7 in fig. 6.1) (Yates, 1993) confirm the continuation of the Willyama Supergroup rocks to the north. The colour image of the Curnamona 1:250,000 sheet (fig. 6.2) shows the continuation of a wide north south anomaly from the location of the drilled metapelites in the south without any noticeable change in the magnetic character.

The wider and deeper anomalies in the eastern part of the Benageri 1:100,000 sheet are interpreted as extensions of the Willyama Supergroup rocks (compare figs. 6.1 and 6.2). These are separated from the narrower and shallower altered basalt to the west by a low magnetic area (AMZ). This low magnetic area continues to the south and has similar

magnetic character to that of the north eastern part of the Curnamona 1:250,000 sheet which will be discussed later in chapter 7.

A rounded circular magnetic low is apparent in the north central area of the colour image of the Curnamona 1:250,000 sheet (fig. 6.2). Figures 6.27 and 6.28 show the TMI and VG contours respectively over this body. This low magnetic feature lies to the western side of a north south, wide and large magnetic anomaly. It has a clearly higher magnetic rim. Modelling results of a few profiles through the circular body required the following model parameters : susceptibility in the range 0.0018 to 0.0015 SI units, width of 2200 m to 3400 m, depth to the top of about 800 m and dip almost vertical (assuming no remanence) (figs 6.29a and b).

The rocks surrounding this circular body were also modelled with these parameters : susceptibility in the range 0.009 to 0.45 SI units, width 20 to 360 m, depth to the top of about 320 m to 600 m and dip of 104 to 173 degrees (assuming no remanence). Comparison of the above modelling results showed that the magnetic source of the circular feature is deeper and lower in magnetic intensity than the surrounding north south anomalies.

The circular feature is probably an intrusion which intruded into the north south striking Willyama Supergroup rocks. The coincidence of this low magnetic feature with a low gravity of -15 milligals on the Bouguer gravity anomaly map of the Curnamona 1:250,000 sheet possibly suggests a source of acidic intrusion.

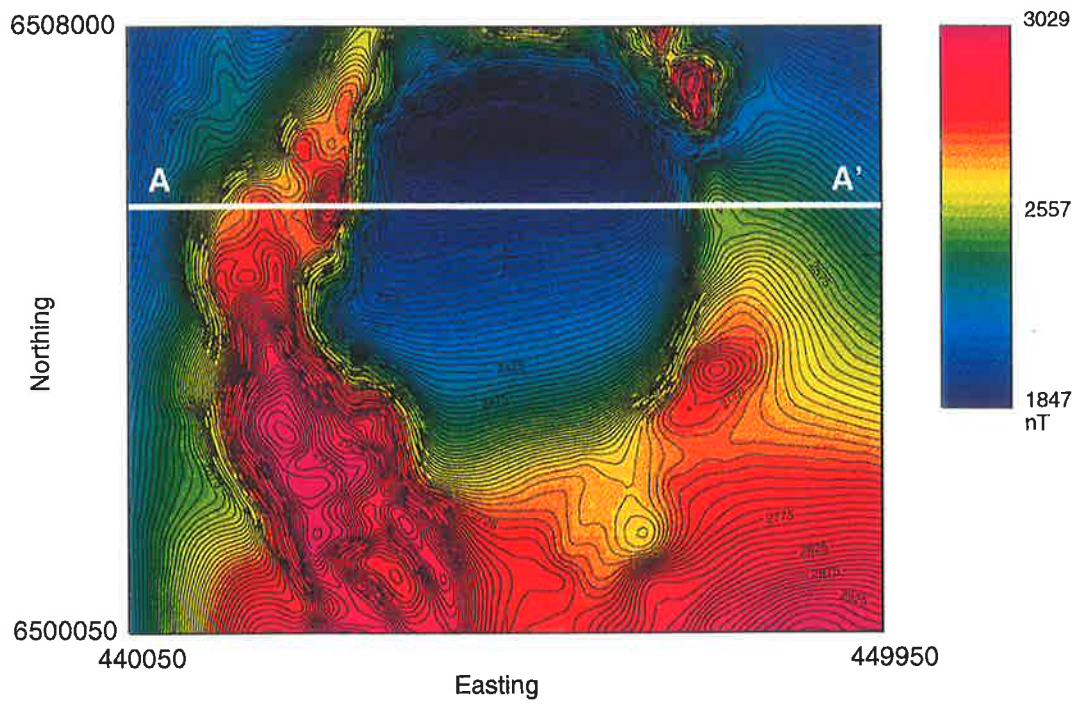


Fig. 6.27 TMI contour map of granitic intrusion on the north east Kalabity area  
 Contour interval 50 nT  
 Map scale 1:100,000

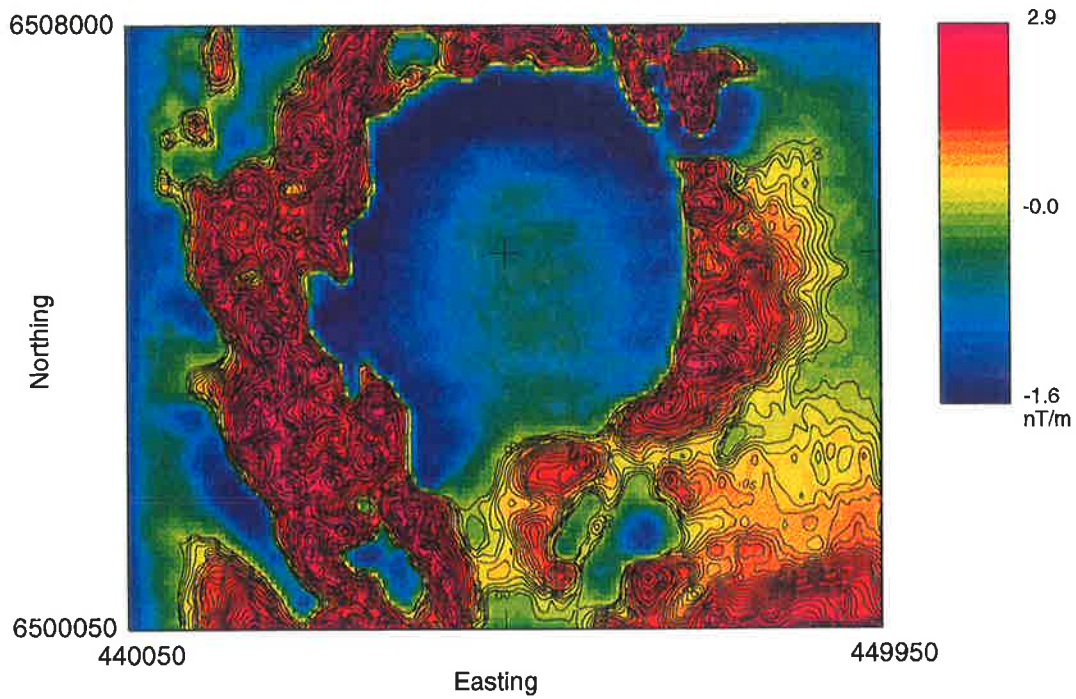
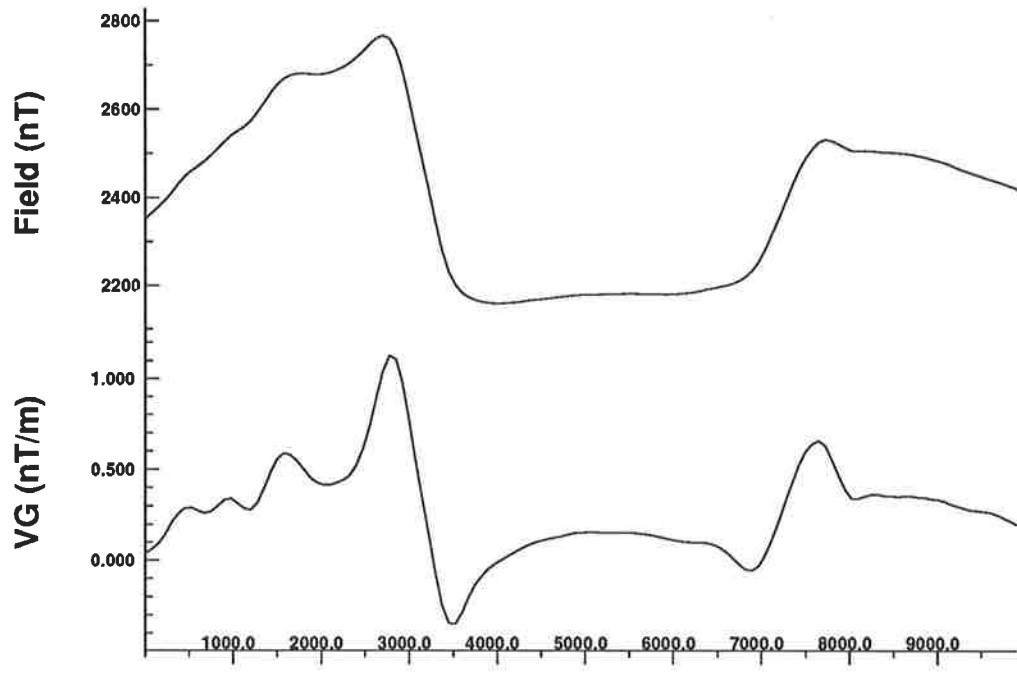
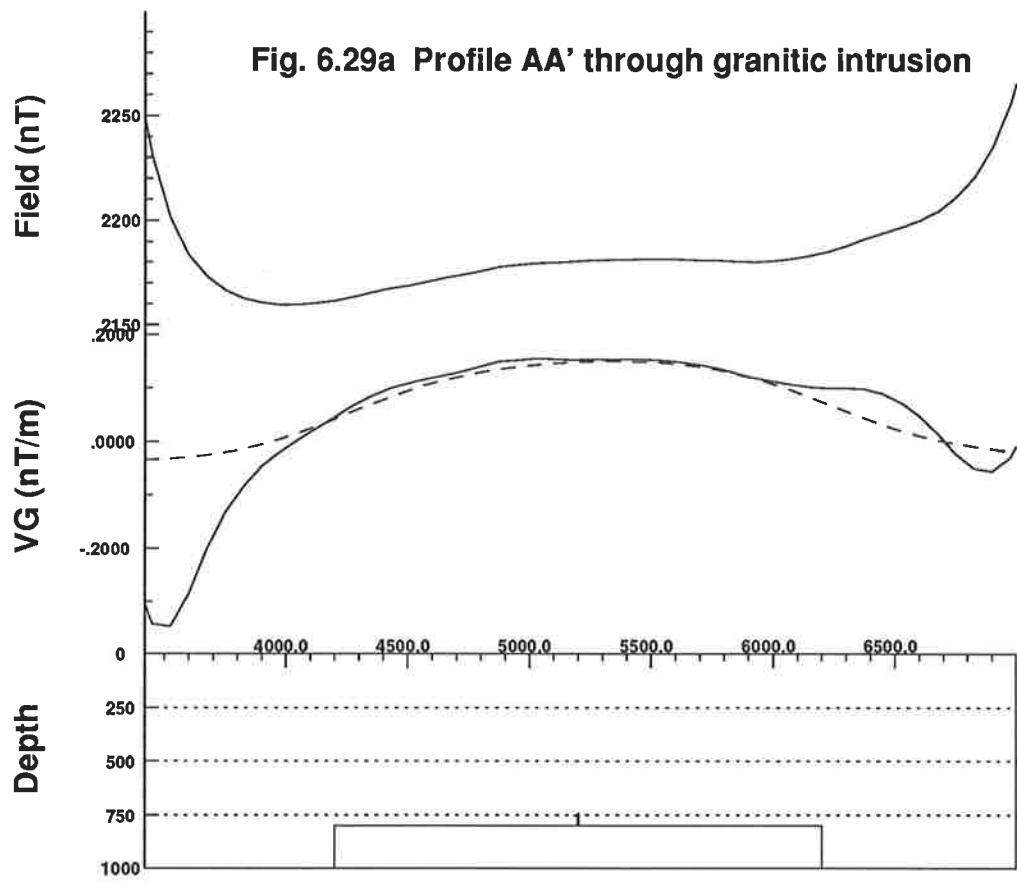


Fig. 6.28 VG contour map of granitic intrusion on the north east Kalabity area  
 Contour interval 0.1 nT/m  
 Map scale 1:100,000



**Fig. 6.29a Profile AA' through granitic intrusion**



**Fig. 6.29b Model of the granitic intrusion**

### 6.3.5. The Bolcomata South 1:25,000 sheet

Folded structures were interpreted from the TMI and VG contour maps (figs 6.30 and 6.31) in the North western part of the Bolcomata South 1:25,000 sheet. The fold axis trends NNE-SSW and N-S (fig. 6.32). Magnetically these structures look similar to the Mt. Howden and Waukaloo Mine area and are interpreted as the Lithomagnetic suite. Most of the southern and eastern portions of the Bolcomata South sheet are similar magnetically to the regional granitoids and composite gneiss in the central area of the Kalabity North sheet.

Composite gneiss and migmatite show moderately smooth magnetic character intermixed with non continuous anomalies of the Lithomagnetic suite where they are mapped. The south western part of the Koolka North sheet, the south central area of the Kalabity South sheet and the central area of the Kalabity North sheet are all magnetically similar to the southern and eastern part of the Bolcomata South sheet and are all interpreted as composite gneiss and migmatite (fig. 6.33 the Mulyongari at 1:100,000)).

A similar WNW-ESE linear feature parallel to the interpreted fault on the Kalabity South sheet is also running through the Bolcomata South sheet and is interpreted as a fault (see fig 6.33). This trend is recognisable in the colour image of Total magnetic intensity (fig. 6.2), first vertical gradient grey image of CRA on the Olary and Broken Hill Blocks to which the author had access and the contour map of the Mulyongari at a 1:100,000 scale.

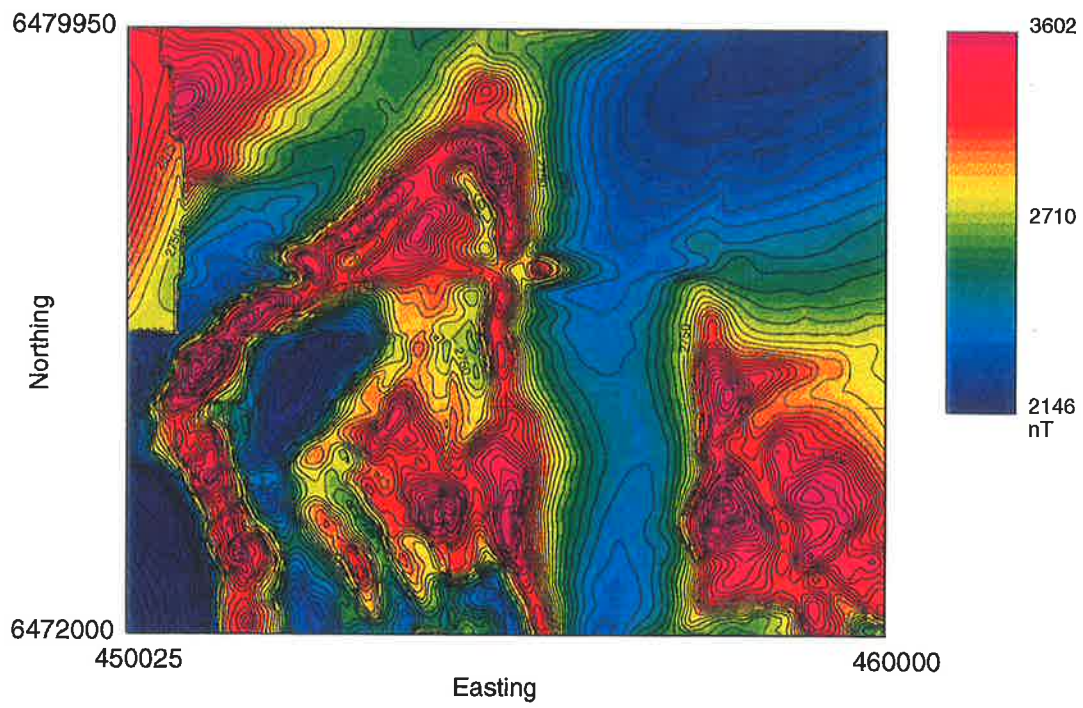


Fig. 6.30 TMI contour map of folds on the north west Bolcomata South area  
Contour interval 50 nT  
Map scale 1:100,000

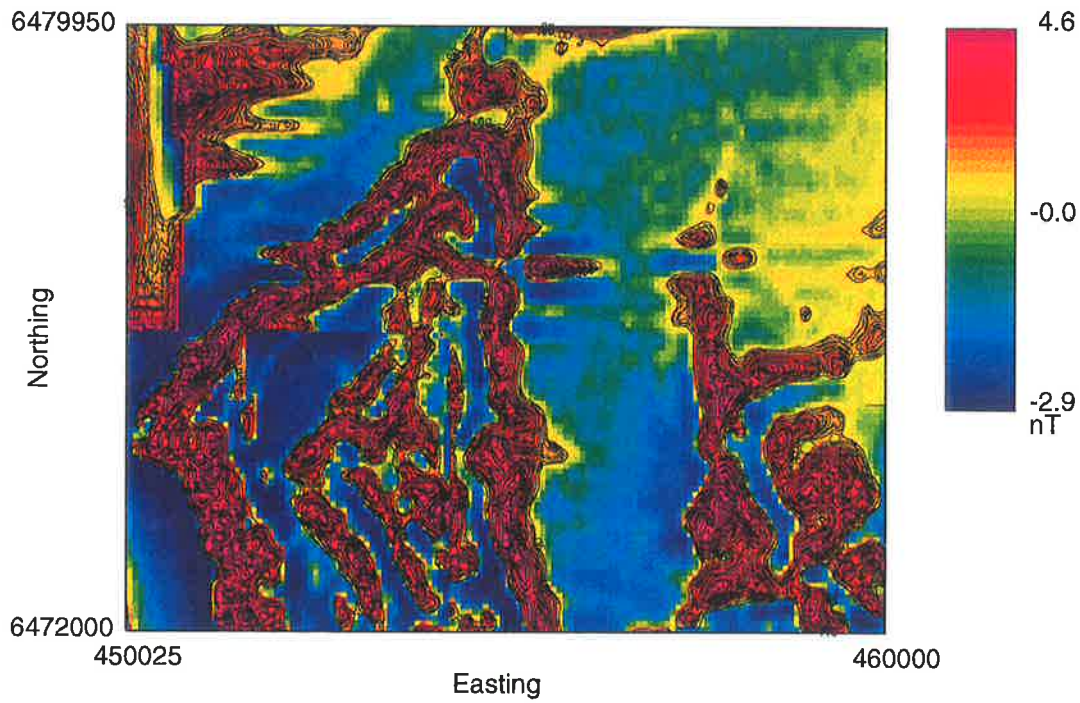


Fig. 6.31 VG contour map of folds on the north west of the Bolcomata South area  
 Contour interval 0.1 nT/m  
 Map scale 1:100,000

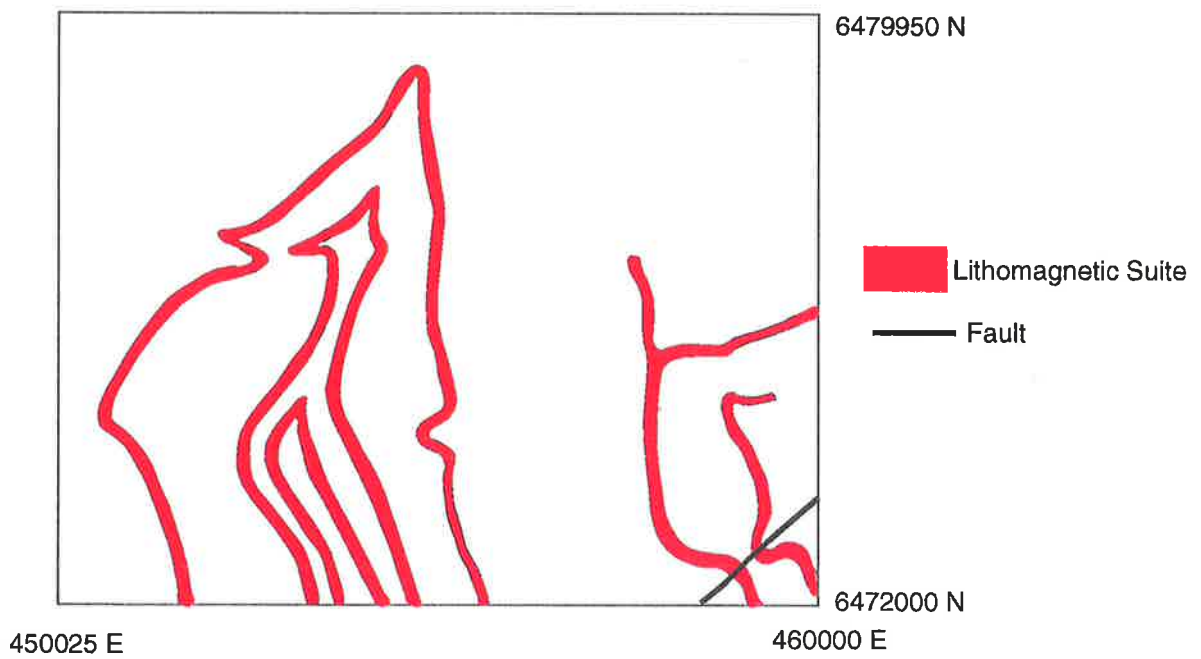


Fig. 6.32 Interpreted folds on the north west of the Bolcomata South area

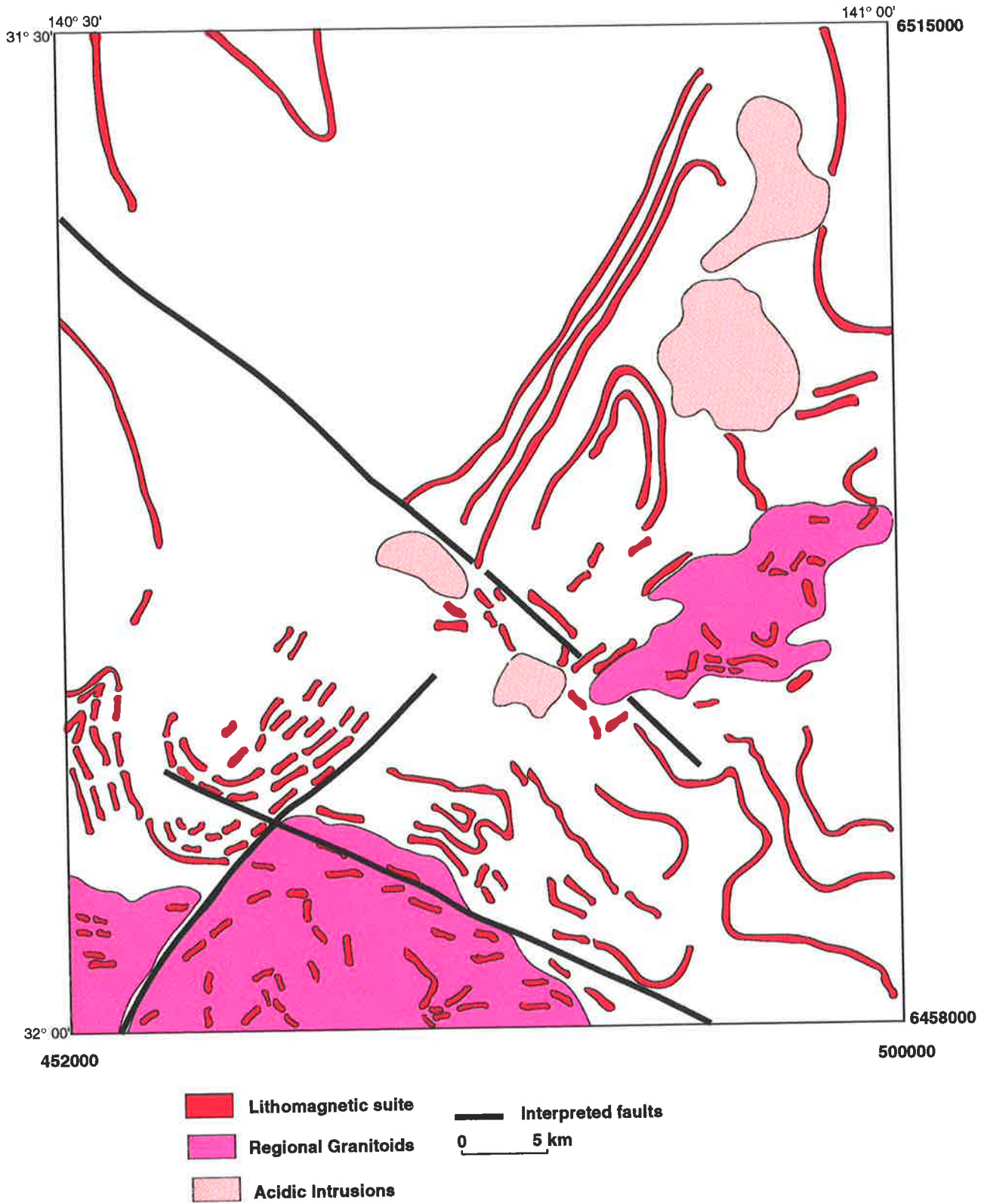
### **6.3.6. The Mulyongari South 1:25,000 sheet**

Continuous and persistent anomalies of the Lithomagnetic suite were traced on the south eastern part of the Mulyongari 1:100,000 sheet (see fig. 6.3 index map sheet) (fig. 6.33). These anomalies show clearly folded structures. The fold axis trends ENE-WSW. From the similarity of the magnetic character and continuation of the Lithomagnetic suite over the Mulyongari 1:100,000 sheet, less composite gneiss and migmatite are interpreted in the south eastern part than in the south west (fig. 6.33).

A lineament trends WNW-ESE which is parallel to the MacDonald fault and is interpreted as a fault (fig. 6.33). This trend is less clear than the other interpreted faults on the small scale images of the magnetic data. There are a few parallel conjugate shears which are all interpreted from the magnetic information in the southern part of the Curnamona 1:250,000 sheet (see section 7.5). These are interpreted from the displacement/truncation of the distinctive curvilinear anomalies and from their apparent trend.

### **6.3.7. The Mulyongari North 1:25,000 sheet**

The most elongated and undisturbed anomalies of the Lithomagnetic suite are traced to the east central area of the Mulyongari 1:100,000 sheet. A series of parallel NE-SW anomalies extending for at least 20 km are interpreted from the TMI and VG contour maps as the Lithomagnetic suite in this sheet. Lengthwise these are the most persistent



**Fig. 6.33** Interpreted Willyama Supergroup rocks in the Mulyongari 1:100,000 Sheet

anomalies in the whole Curnamona 1:250,000 sheet. Figures 6.34, 6.35 and 6.36 show the TMI, VG and the interpretation maps respectively.

These curvilinear anomalies were interpreted as folded structures of the Lithomagnetic Suite with the fold axis trending NNE-SSW. The western limbs of these folds have a very sharp boundary with the non magnetic area of the Mulyongari 1:100,000 sheet. The eastern limbs of these folds were possibly deformed by the presence of a rounded magnetically low intrusion type feature (see figs 6.33, 6.1 and 6.2).

This circular magnetic low coincides with a gravity low of -10 milligals on the Bouguer gravity anomaly map of the Curnamona 1:250,000 sheet. This is very similar to the intrusion in the north eastern part of the Kalabity 1:100,000 sheet (discussed in 6.6). The gravity and magnetic response of this anomaly indicates that the source is probably an acidic intrusion.

Interpreted folded structures in figure 6.36 show a NNE-SSW sharp boundary separating the highly magnetic Lithomagnetic suite sources in the south east from the low magnetic area in the north west. The possible sources for this low magnetic area, which is Adelaidean, will be discussed later. A few profiles were selected perpendicular to this boundary for modelling.

The results showed that the contact is dipping to the south east with an angle between 22 and 38 degrees, assuming no remanence. This boundary may be a thrust fault in which older Willyama Supergroup rocks thrust over the younger Adelaidean, similar to the MacDonald fault. However this boundary is not parallel to the MacDonald fault and it is

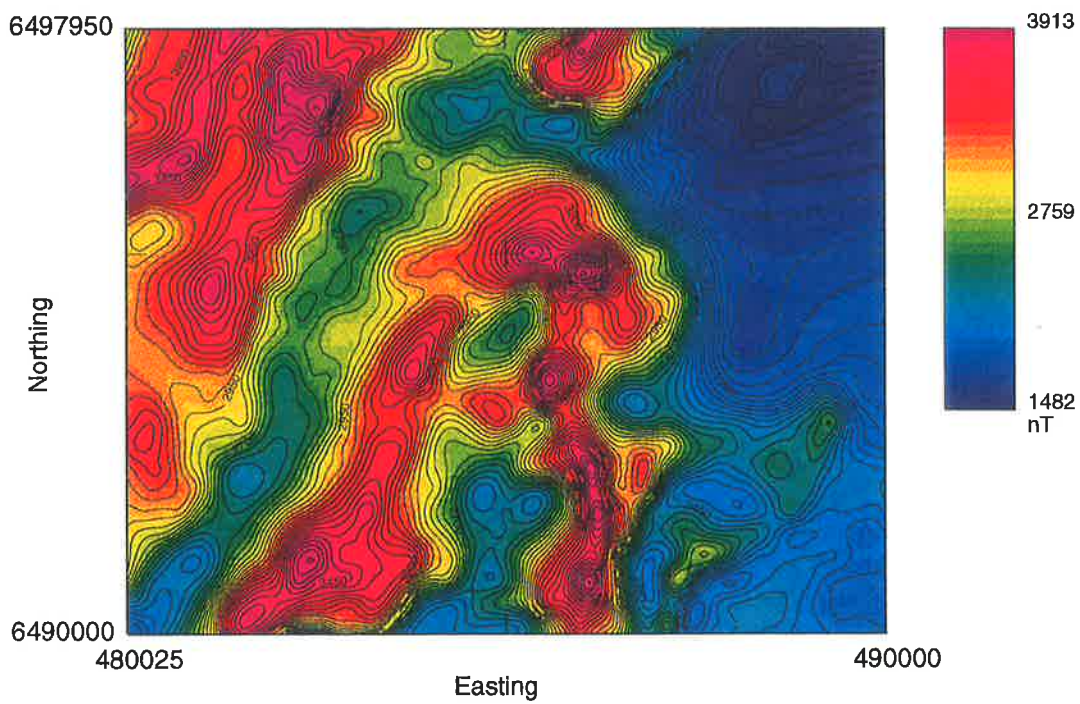


Fig. 6.34 TMI contour map of the north east Mulyongari area  
Contour interval 50 nT  
Map scale 1:100,000

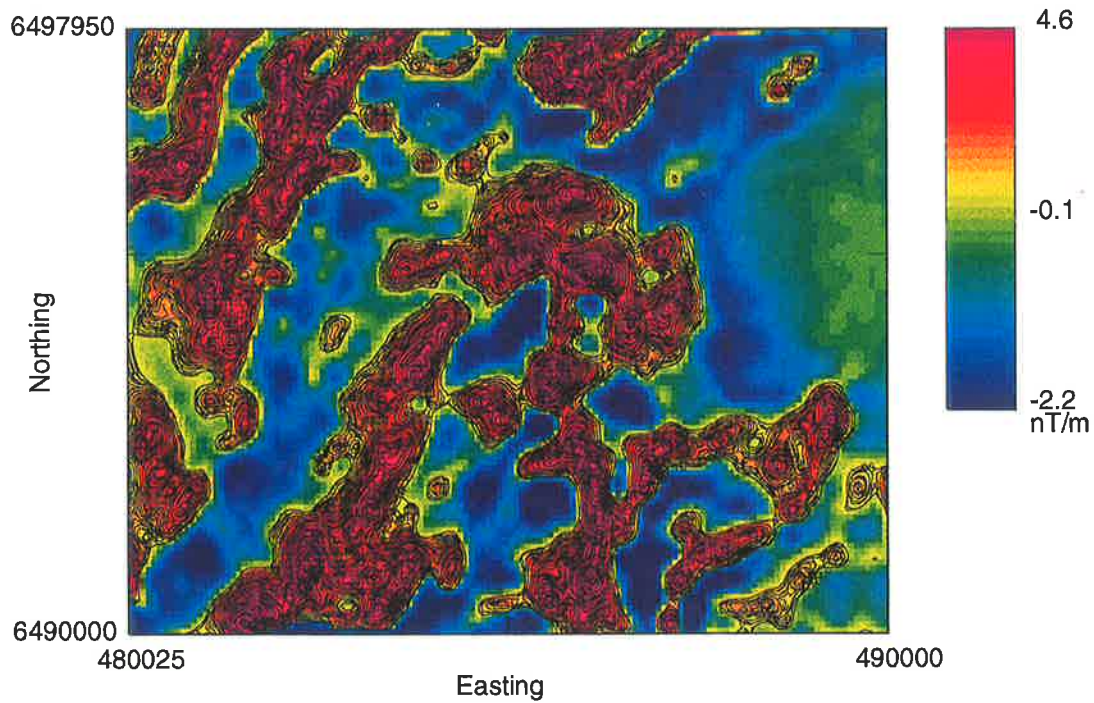


Fig. 6.35 VG contour map of the north east Mulyongari area  
 Contour interval 0.1 nT/m  
 Map scale 1:100,000

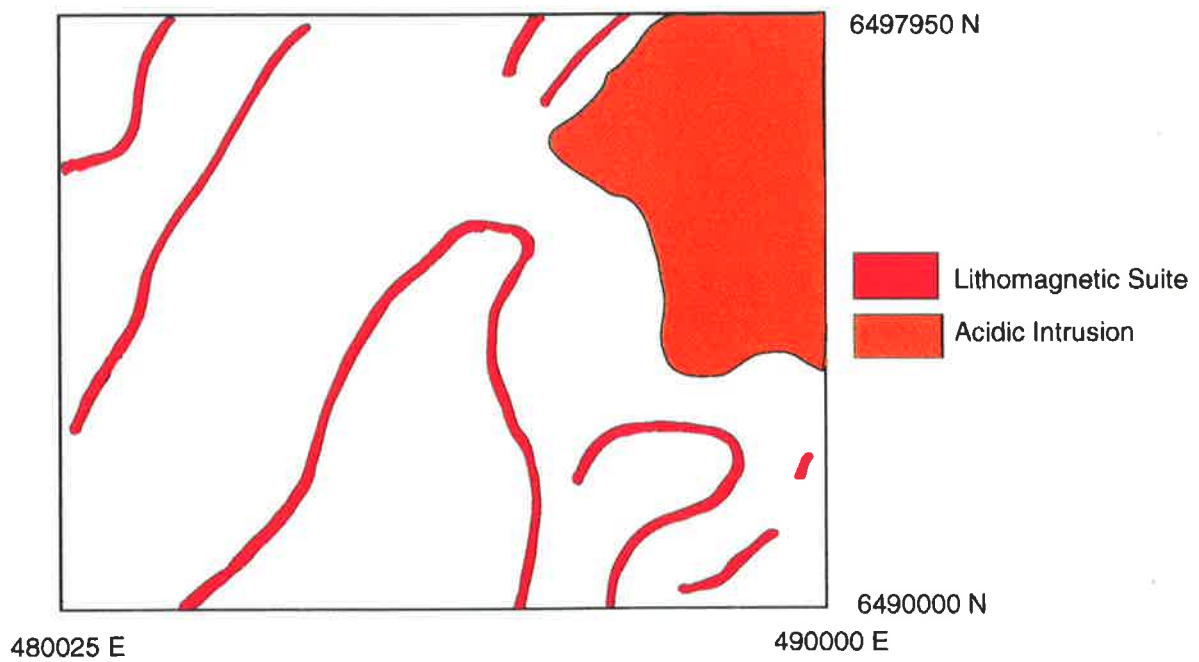


fig. 6.36 interpreted fold and intrusion in north east mulyongari

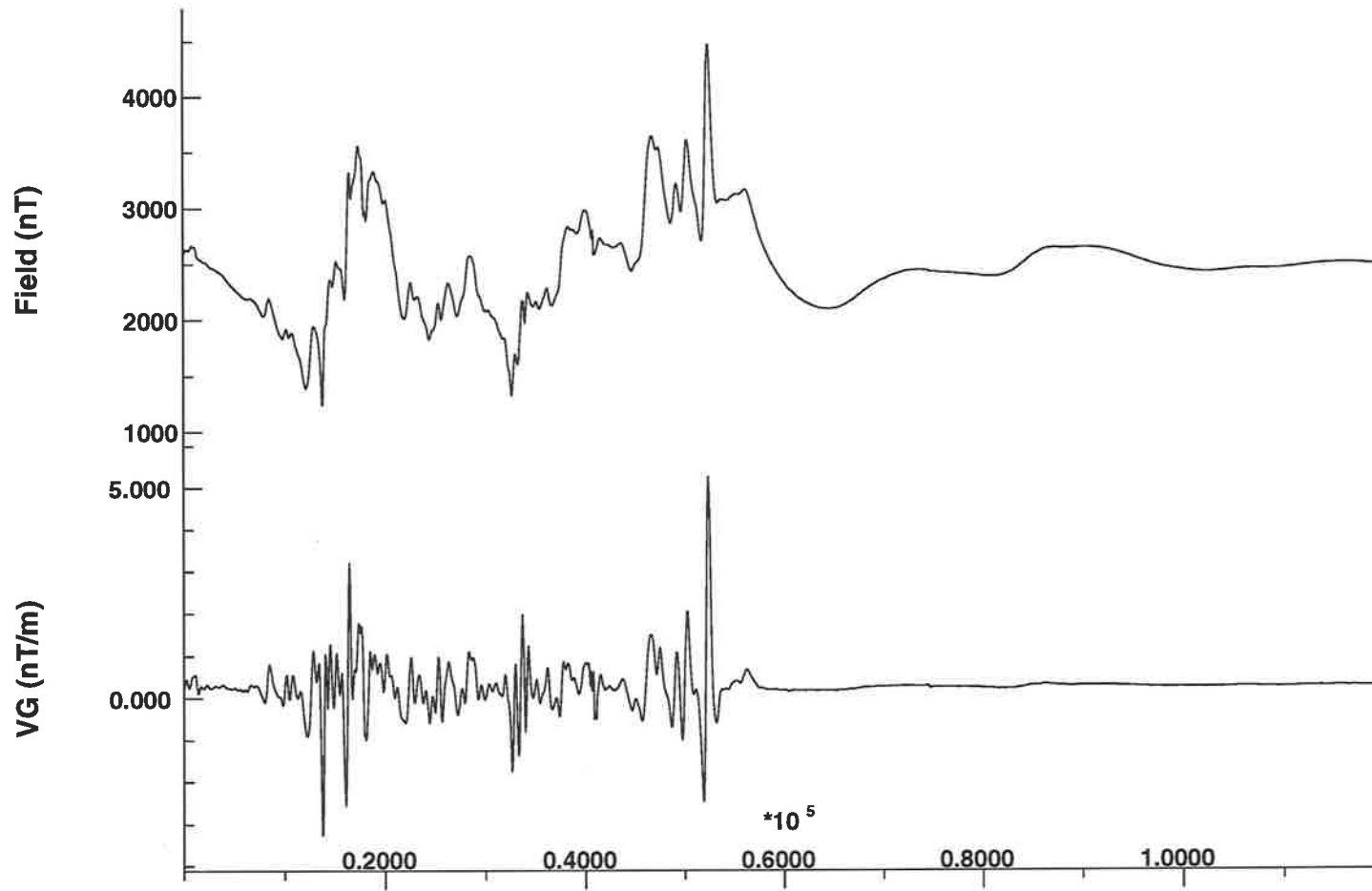


Fig. 6.37 North South profile on the eastern most part of the Curnamona 1:250,000 sheet

at a steep angle to it. It appears that this faulted boundary continues to the south west and is terminated by the MacDonald shear (see section 7.2.2) (fig 6.33).

The intersection of the Bimba Suite with the best assay of mineralisation at Hunters Dam (Yates, 1993) (hole 6 in fig. 6.1) is located very close to the western boundary of this interpreted Lithomagnetic suite and confirms this interpretation. This is another example of the association of the Lithomagnetic suite with an intrusion and shear zone showing anomalous mineralisation as speculated in section 6.4. The south eastern part of the Mulyongari North sheet looks magnetically very similar to the response of the regional granitoids and migmatite in the Kalabity South region.

A major east-west basement structural boundary at a distance of about 38 km from the south eastern corner of the Curnamona map sheet was interpreted from the colour image of TMI of the Curnamona 1:250,000 sheet (fig. 6.2). This change in magnetic pattern is illustrated by the north south magnetic profile (fig 6.37) along the extreme eastern boundary of the data which is 75 m from the border of New South Wales.

The southern region of this east west feature has shallow magnetic sources less than 200 m deep, while to the north, broader anomalies implying greater depth to the basement, are located. This east-west basement structure terminates to the west with the circular granitic intrusive and appears to continue eastward. The gravity stations of the gravity map of the Curnamona 1:250,000 sheet are probably too far apart to show this east west structure and the extended north south gravity low probably reflects the granitic intrusion interpreted in this area.

A funnel shape low magnetic area is located in the north eastern part of the Mulyongari 1:100,000 sheet and extends through the Lake Charles sheet to the north (fig. 6.2). This area is bounded to the east, west and south by the Willyama Supergroup rocks and constitutes the AMZ (fig 6.1). To the east, drill hole information from MU2 drilled by Western Nuclear Australia Ltd indicated Adelaidean underlain by metasilstone at a depth of 547 m (fig. 6.1). The Adelaidean has also been drilled to the west of MU2 as is shown on the interpolated cross section of the geological map of the Curnamona 1:250,000 sheet.

The presence of the Adelaidean from drill hole information to the north of this low magnetic area and the consistency of the low magnetic character towards the south suggests that the Adelaidean is the source of this magnetic low and the Willyama Supergroup rocks are not present here. The Adelaidean here is possibly continuing further north east through the Yalkalpo sub basin. MacIntyre and Watt (1978); and Isles (1986) inferred the presence of Adelaidean in the north western corner of the Broken Hill Block.

This low magnetic area is bounded to the west by wide north south magnetic anomalies which are interpreted as the continuation of the Willyama Supergroup rocks to the north. These rocks were intersected at a depth of 542 m by Marathon Petroleum Australia Ltd on EL 957 (hole 7 in fig. 6.1). It is suggested that the source of these north south positive anomalies, forming the western boundary of the low magnetic area, is low grade metasediments of the upper part of the Willyama Supergroup rocks (Pelite suite).

Modelling results showed that the depth to the top of these metasediments varies between 450 m to 1200 m. It is deeper to the south and gradually gets shallower towards the north. Drill holes information (Yates, 1993) indicates that shallow magnetic anomalies at a depth of around 30 m are superimposed on the relatively deeper metasediments to the north. The shallow sources are the volcanics overlaying the Willyama Supergroup rocks. In this area the Adelaidean overlie the volcanic rocks which in turn overlie the Willyama Supergroup rocks.

This interpretation correlates with the interpolated geological cross section of the Curnamona 1:250,000 sheet and drill hole information (Yates, 1993). Magnetically these shallow sources look like the volcanics in the Benageri 1:100,000 sheet which will be discussed in the next section. Altered basalt has been drilled 1500 m west of these shallow anomalies by Newmont Australia Ltd on EL 1684 with an average depth of about 38 m (holes 8 and 9 in fig. 6.1).

#### **6.4. The Benageri 1:100,000 sheet**

The Benageri 1:100,000 sheet is dominated by three wide arcuate anomalies in the central area and a less pronounced smaller anomaly in the north. Three deep holes were drilled by MESA into these anomalies targeting Olympic Dam type deposits but all of them showed volcanics (compare figs. 6.1 and 6.2).

This volcanic area is called the VMZ and is differentiable from the WSMZ in which the anomalies are circular or equidimensional in the former and elongated with north to north

east trend in the latter. Another important difference between these two magnetic domains is the curvilinear deformed anomalies of the WSMZ which reflect the tectonic and genetic history of these rocks and the undeformed non linear circular shape of the VMZ.

Drill hole LNM10 (fig. 6.1) in the north intersected bi-modal volcanics at a depth of 231 m and continued up to 742 m. BWM1 hole (fig. 6.1) was drilled into the west central anomaly and intersected tuff, breccia and acid volcanics at depths of 391.4 m up to 600 m. Hole ETM5 (fig. 6.1) was drilled into the southern anomaly and indicated trachytes and rhyolites from 444.6 m to 742 m.

The east central anomaly has not been drilled yet but the magnetic response over this anomaly is similar to the west central one and it is interpreted in this study as volcanic. The anomalies are narrower and more elongated in the south eastern portion of the Benageri 1:100,000 sheet than to the west. Drill hole information indicates metapelites (Yates, 1993) which correlate with the western extension of the interpreted Willyama Supergroup rocks (fig. 6.1).

The interpreted Willyama Supergroup rocks in the southeastern part of the Benageri 1:100,000 sheet extend to the north while volcanics are overlain on them. Small amplitude shallow anomalies which are superimposed on the deeper sources are evident both on the contour map and the images (fig. 6.2) and are interpreted as volcanics over the metasediments. Altered basalt overlying the metapelites has been intersected at an average depth of 38 m (holes 8 and 9 in fig 6.1) (Yates, 1993).

A north south lineament on the western portion of the Benageri 1:100,000 sheet is running through the entire sheet. This feature is recognisable on the colour image of TMI (fig. 6.2) and contour maps; and it terminates over the interpreted Lithomagnetic suite on the northern part of the Kalabity 1:100,000 sheet. Because this trend lies over the volcanics on hole LNM10 and BWM1 and it terminates over the interpreted Willyama Supergroup rocks it suggests a volcanic flow as a source.

## **7. View of the geology of the Curnamona 1:250,000 sheet in the light of new geophysical information**

### **7.1. Introduction**

Limitations of the magnetic information regarding mapping geological units (discussed in chapters 5 and 6) lead to a simplified geological map. However in the absence of any outcrop geology and limited drilling information a simplified magnetic interpretation map is the most cost effective approach and will provide a foundation on which future refinement will be established.

The simplified interpreted geology maps (figs 6.1, 6.7 and 6.33) were prepared on the basis of constraints between rock outcrops and magnetic information; and susceptibility measurements on representative outcrop of the rock units. Where the rock units have similar or no magnetic response differentiation is difficult, if not impossible, and the result will be the presentation of single magnetic units, that is, a simplified interpreted geology map.

The aim of this chapter is to evaluate the contribution of the geological information provided through this study. The simplified interpreted geology maps (figs 6.1, 6.7 and 6.33) were compared with the previous published map (fig 7.1). The geological

information in these interpreted maps will be presented in three sections. Section one will be the overall comparison of the interpreted map of the Willyama Supergroup rocks with the previous published map to show the extent of these rocks spatially. The interpreted lineaments and faults are presented in the second section. Mapped intrusions and granitoids; and their subdivisions will be discussed in section three. Current issues in relation to the depositional environment of the Willyama Supergroup rocks and their mineralisation potential will be summarised and will be considered in the context of new geophysical information in the last two sections of this chapter respectively.

## **7.2. The improved geological interpretation of the Curnamona 1:250,000 sheet**

The Lithomagnetic suite (discussed in chapter 5) consists of : (i) the Quartzofeldspathic suite, (ii) the calcalbitite rocks and (iii) the Calcsilicate suite. Comparison of mapped outcrops and field susceptibility measurements with magnetic information indicated that wherever the Lithomagnetic suite is mapped it shows a recognisable magnetic character in comparison to the upper and lower units in the sequence. This magnetic character made it possible to trace the Lithomagnetic suite from the outcrop areas which are very limited to the covered areas where very few exploration drill holes (fig. 6.1) give information about the geology.

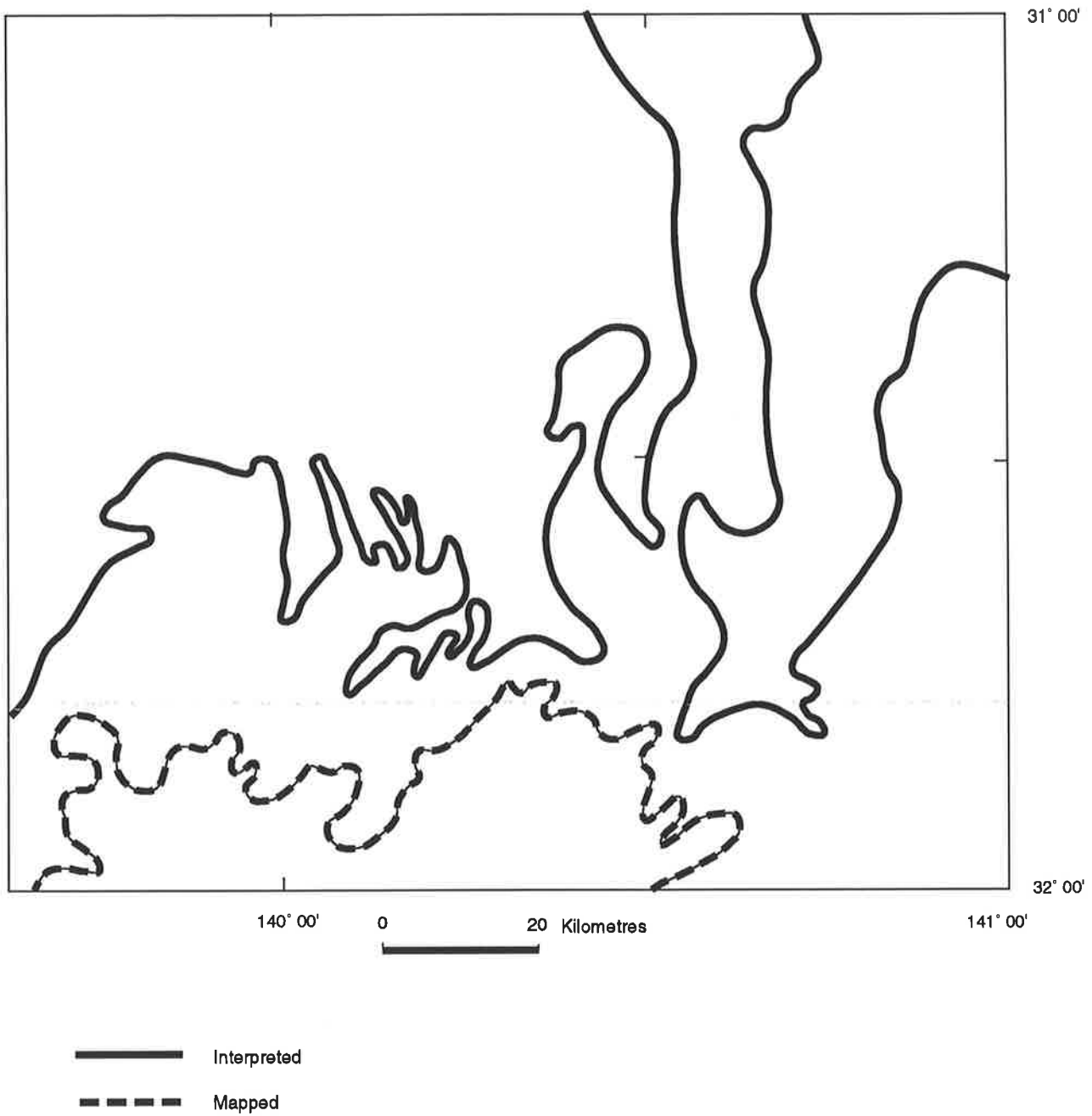


Fig. 7.1 Comparison of previous mapped Willyama Supergroup rocks and the interpreted one in Curnamona 1:250,000 sheet

The Composite Gneiss and Migmatite suite is less magnetic than the Lithomagnetic suite (discussed in chapter 5) in the stratigraphic section (fig. 2.2). Beside their moderately magnetic character they appear as rounded, polygonal and nonlinear on the colour image of TMI (fig. 6.2) which make them distinct from the other units in the sequence. The Bimba suite and the Pelite suite above it have no distinct magnetic response and correspond with low magnetic anomalies in the outcrop areas (see chapter 5).

This made it difficult to distinguish the Bimba suite from the Pelite suite magnetically. The overall result is a simplified interpreted geology map indicating the location of the Lithomagnetic suite; faults, lineaments and folds; and granitic intrusions. The location of the Bimba suite which is sulphidic and an exploration target in the area can be deduced from the position of the Lithomagnetic suite in the WSMZ (figs 6.1, 6.7 and 6.33).

### **7.2.1. The Interpreted Willyama Supergroup rocks**

The distribution of interpreted Willyama Supergroup rocks in the Curnamona 1:250,000 sheet is indicated in figures 6.1, 6.7 and 6.33. Comparison of the previous published geological map of the Curnamona 1:250,000 sheet with the detailed interpreted maps (figs 6.7 and 6.33) and the regional interpreted map (fig. 6.1) shows a considerable improvement of geological information (fig. 7.1). Most of the interpreted extension of the Willyama Supergroup rocks to the west, north east and north of the Curnamona sheet (1:250,000) were made by tracing the Lithomagnetic marker horizon under cover. Limited exploration drill holes were used to verify the accuracy of this extension.

Examples are the drilled Bimba suite at Hunters Dam north east of the Mulyongari 1:100,000 sheet, metapelites around Benageri Homestead and further north to the south west of Bileroo Tank (fig. 6.1). The interpreted Willyama Supergroup rocks extend north and north east though getting deeper; the former along the Benageri Ridge towards the central part of the Curnamona Craton and the latter towards the Mundi Mundi Fault in the Broken Hill Block in New South Wales.

The Lithomagnetic suite shows persistent folded structures to the south west and east central area in the Mulyongari 1:100,000 sheet (fig. 6.33) (see the detail in chapter 6). There are also well defined folded structures of the Lithomagnetic suite to the north east of this sheet. The continuation of the Lithomagnetic suite is evident on the colour image (fig. 6.2) while getting deeper north of the east west interpreted basement structure (discussed in section 6.3.5) and north of the interpreted acidic intrusion (fig. 6.33).

The Bimba suite was intersected at a depth of 80-120 m (Yates, 1993) at Hunters Dam (fig. 6.1) which is very close to the western margin of the interpreted folded structures of the Lithomagnetic suite in this study. Further north east along the western edge of these folds the Willyama Supergroup rocks were intersected at a depth of 614.5 m in drill hole MU2 (fig. 6.1) by Western Nuclear Australia Limited on EL 679.

The above drill hole data (Yates, 1993) shows that Mesozoic and Adelaidean are underlain by the Willyama Supergroup rocks, confirming the interpreted continuation of these rocks towards the Broken Hill Block in New South Wales. Although change in the

depth of the Willyama Supergroup rocks is evident on the colour image of TMI at a latitude of 31°30' (discussed in 6.3.7) these rocks are intersected at a depth of about 100 metres at Hunters Dam while they are 614.5 metres deep 32 km away at MU2 hole indicating a gradual increase in depth (less than 0.01°/km).

Although to the north they do not show as intense folding and deformation as in the southern part, the interpreted Willyama Supergroup rocks extend as far north as latitude 31°30' to the north west of the Kalabity 1:100,000 sheet (fig. 6.7). This is a large improvement in terms of spatial distribution of these rocks over the Kalabity region (see fig. 7.1). The Willyama Supergroup rocks terminate in the western part of the Kalabity 1:100,000 sheet (fig. 6.7) at the above latitude with a sinusoidal pattern in a direction parallel to the Strathearn Fault (will be discussed in the next section) while continuing to the north towards the Benageri Ridge on the eastern part of this sheet.

The continuation of the Willyama Supergroup rocks to the north is along a wide NW-SE anomaly (fig. 6.2) which is oriented parallel to the Strathearn fault (fig. 7.5) on its north east margin. North of the Strathearn Fault the Willyama Supergroup rocks extend to the north in two branches which are separated by non-magnetic Adelaidean and overlying rocks (fig. 6.1).

The eastern branch persists to the north towards the Frome 1:250,000 sheet and probably to the central area of the Curnamona Craton (fig. 6.1) while it is thinned by a NW-SE lineament (fig. 7.5) (Benageri fault). The Strathearn fault also thins and

truncates the extension of these rocks to the north. Similar thinning and displacement of the Willyama Supergroup rocks is evident on the colour image of TMI of the Curnamona 1:250,000 sheet (fig. 6.2) over the north eastern extension of these rocks towards the Broken Hill Block.

The western branch, the shorter extension of the Willyama Supergroup rocks, terminates at latitude  $31^{\circ}18'$  where it is bounded to the north by the non-magnetic Adelaidean. The northernmost anomaly of this branch was drilled by Marathon Petroleum Australia, LTD in EL 957. Holes BD001 and BD002 (fig. 6.1) intersected sediments of early Mesoproterozoic (at a depth of 302.5 m and 276.45 m respectively) unconformably overlying the Willyama Supergroup rocks (Yates, 1993). Hole BD003 (fig. 6.1) was drilled by the same company on the eastern branch but reached the same rocks as the other two at a depth of 542.7 m. This drilling information confirms the interpretation of the extension of the Willyama Supergroup rocks.

The Willyama Supergroup rocks were intersected at a depth of 10 to 20 metres at Johnny Hill area (fig. 6.1) by BHP Minerals LTD on EL 970. The magnetic data over this area was selected for upward continuation to be compared with the magnetic information over the drilled meta-sediments to the north on the eastern extension of the interpreted Willyama Supergroup rocks. The magnetic data over this selected area was upward continued to 540 metres which is the depth of meta-sediments drilled in the north in Hole BD003 by Marathon Petroleum Australia LTD on EL 957.

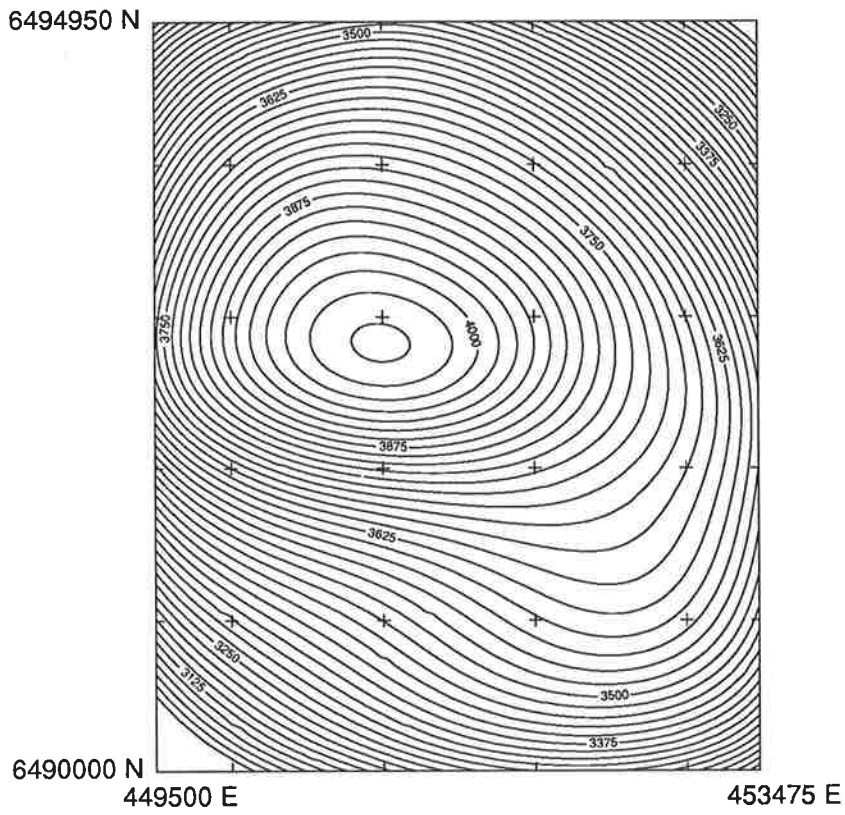


Fig. 7.2 Willyama Supergroup upward continued to 540 metres  
Contour interval 25 nT. Map scale 1:100,000

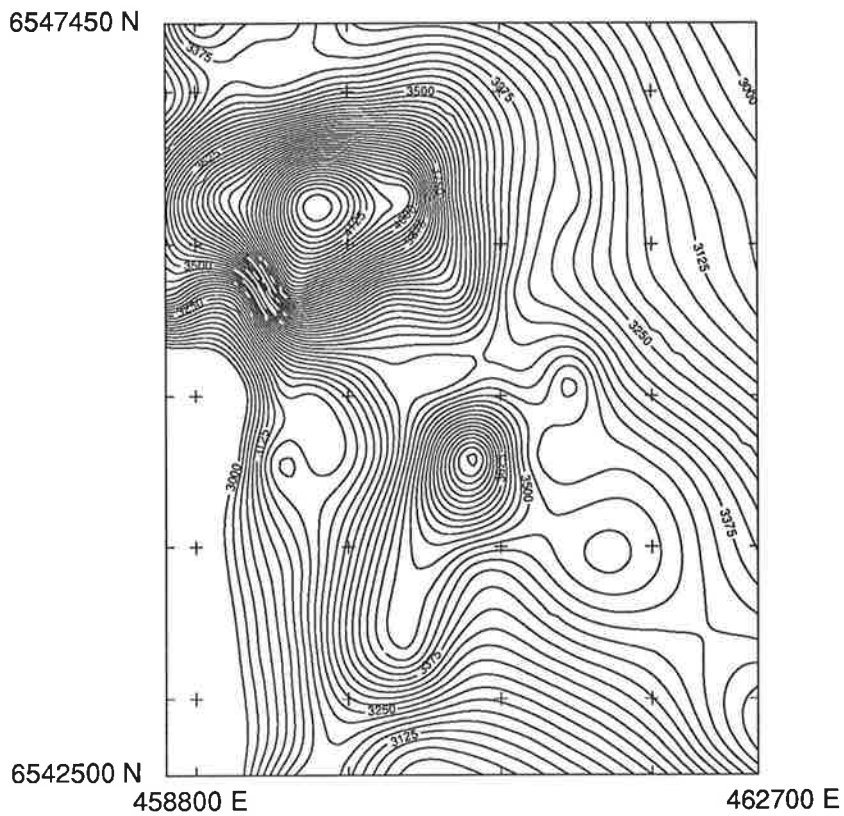


Fig. 7.3 Drilled metasediments at a depth of 540 meters  
Contour interval 25 nT. Map scale 1:100,000

The upward continued magnetic contour map of TMI (fig 7.2) and the magnetic contour map over the meta-sediments (fig 7.3) does not look similar. The difference is possibly related to the shallow sources superimposed on the deeper meta-sediments. The upward continued TMI data over the Willyama Supergroup rocks was compared with the magnetic contour map further south than the BD003 hole (fig 7.4).

There is considerable similarity between these two and the difference may be related to a smaller depth than 540 metres assumed for the north south anomaly. On this basis and the apparent continuation of anomalies on the colour image of TMI (fig. 6.2) it seems that Willyama Supergroup rocks continue through the eastern branch over the Benageri area towards the Frome 1:250,000 sheet.

The intersected metasediments over the Hole BD003, Bumbarlow on Frome area and Mt Painter are thought to be Willyama Supergroup equivalents, that is, low grade meta-sediments of the upper part of the Willyama Supergroup rocks (Pelite suite) (Preiss pers. communication). The width of the anomalies of the Willyama Supergroup rocks over each branch is not more than 12 km, although the eastern one is getting wider on the border to the Frome 1:250,000 sheet.(fig. 6.1)

### **7.2.2. Lineaments and Interpreted Faults**

A system of regional cross cutting faults are interpreted from the magnetic data (fig. 7.5). These all have common tectonic origin with the deformation of the Willyama

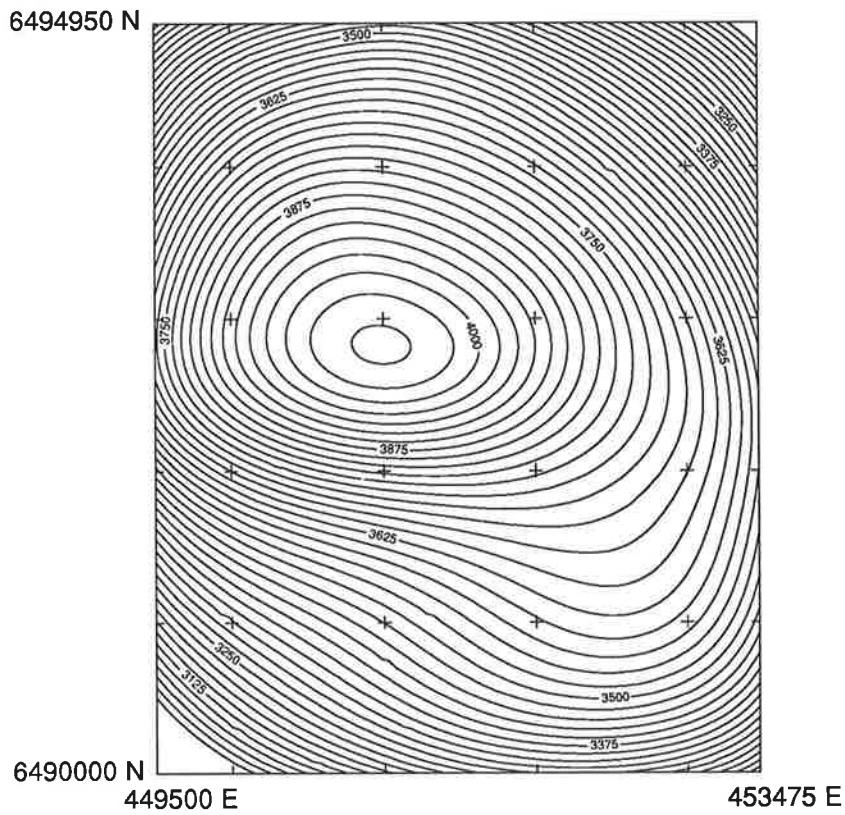


Fig. 7.2 Willyama Supergroup upward continued to 540 metres  
Contour interval 25 nT. Map scale 1:100,000

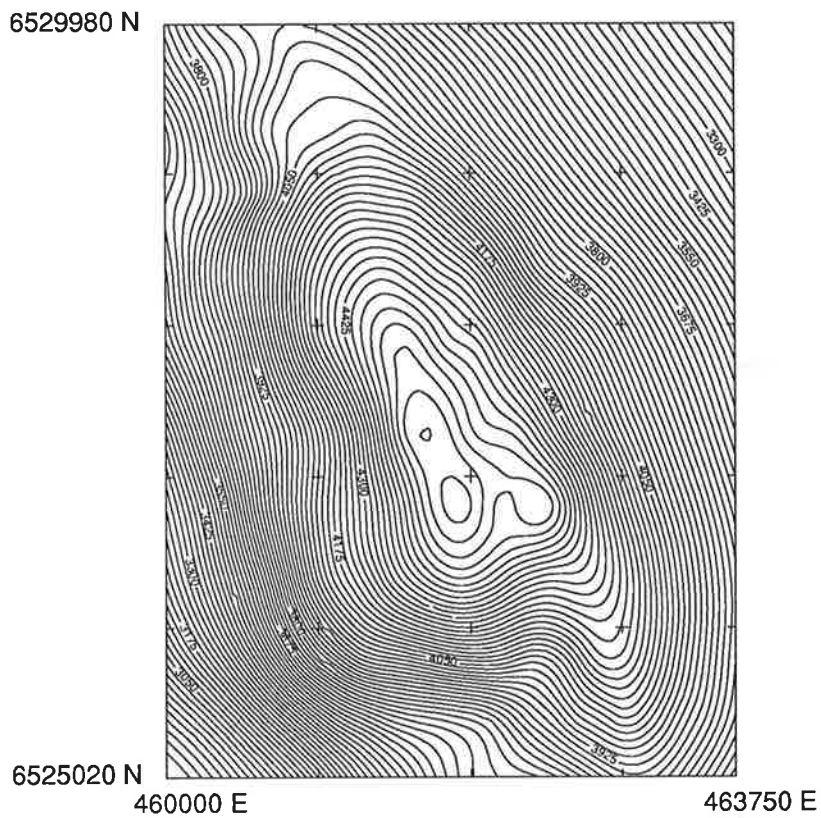


Fig. 7.4 Interpreted extension of the Willyama Supergroup rocks  
Contour interval 25 nT. Map scale 1:100,000

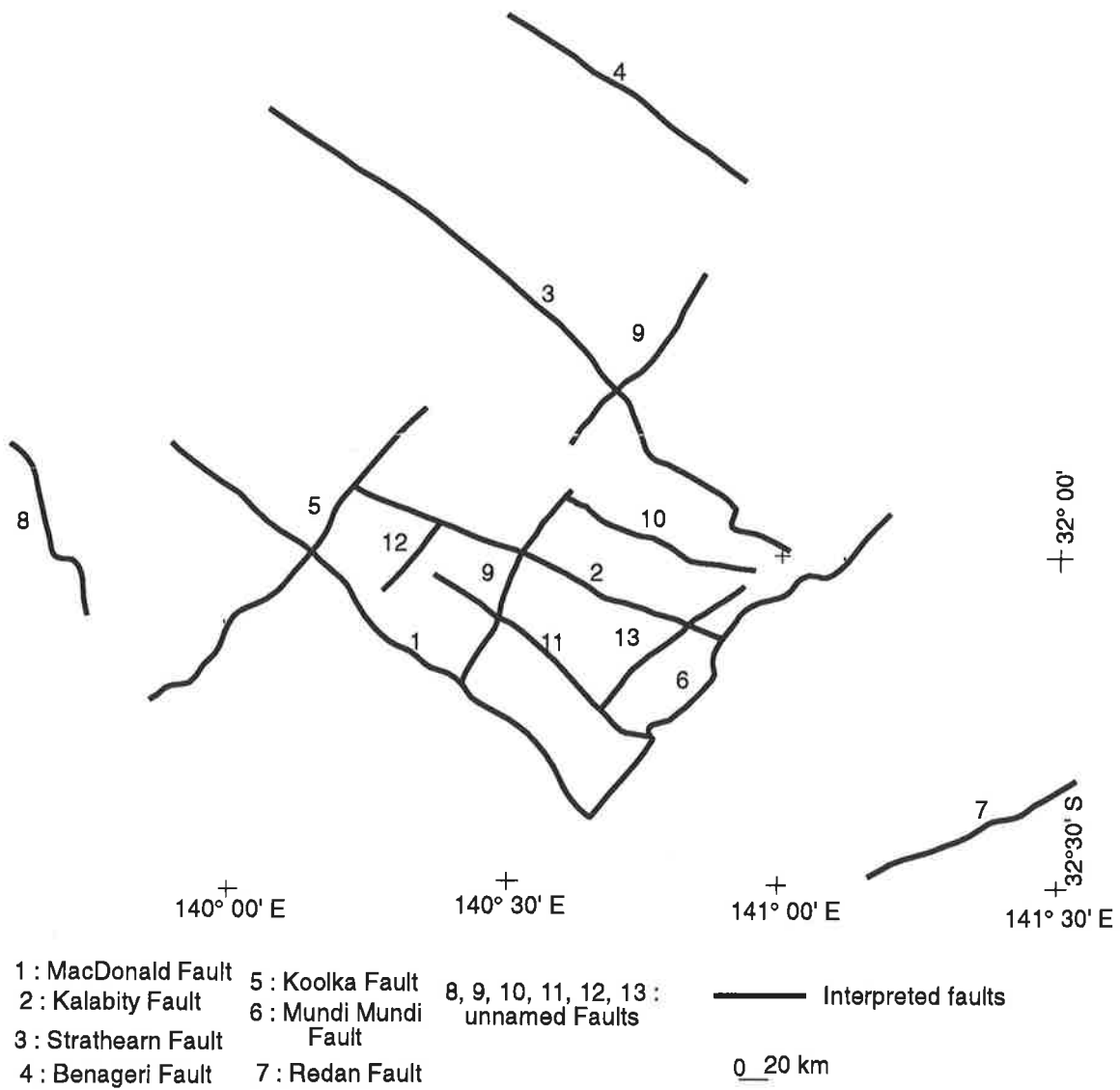


Fig. 7.5 Interpreted faults and regional lineaments

Supergroup rocks. The Benageri, Strathearn and MacDonald faults (4, 3, and 1 respectively in fig. 7.5) are roughly NW-SE while the Mundi Mundi and the two interpreted ones (6, 9 and 5 respectively in fig. 7.5) are NE-SW. These two trends of major faults are similar to the thrust belt of the central province of the Broken Hill area (White et al., 1995).

Thinning and displacement of the wide N-S anomalies on the colour image of TMI (fig. 6.2) occur along the WNW-ESE lineament (4 in fig. 7.5) which coincides with the inferred Benageri Fault of the tectonic sketch map of the Curnamona sheet (the Geological map of the Curnamona 1:250,000) interpreted by Mills (1986). However this fault does not converge with his interpreted Strathearn Fault at the north western corner of the Curnamona sheet as he indicated.

Interpreted folded structures on the eastern area of the colour image of TMI of the Curnamona map sheet (fig. 6.2) are terminated abruptly by a regional WNW-ESE lineament (3 in fig. 7.5). Part of this lineament coincides with the NNW-SSE diagonal line of different depth to the basement (fig. 6.4) calculated on the Benageri 1:100,000 sheet and predicted as a fault (discussed in section 6.4). The Strathearn lineament (3 in fig. 7.5) continues southeastward to the Thackaringa shear zone on the northwestern corner of the Minindee 1:250,000 geological map sheet.

This lineament shows orientation parallel to the wide anomalies of the Willyama Supergroup rocks as well as the acid volcanics of the Benageri. It is terminated to the

View of the geology of the Curnamona 1:250,000 sheet in the light of new 120  
geophysical information

south east by the Mundi Mundi Fault in the Broken Hill Block (first vertical gradient grey image of the Olary and Broken Hill Blocks provided by CRA) which implies a common tectonic origin. This lineament coincides with the inferred Strathearn Fault of the tectonic sketch of the geological map of the Curnamona 1:250,000 sheet (Mills, op. s.).

These two regional faults, the Benageri and Strathearn faults (fig. 7.5), are parallel with the MacDonald Fault and all have a common relationship with the deformation of the Willyama Supergroup rocks. The Strathearn and MacDonald faults have been terminated by the Mundi Mundi Fault. Two parallel interpreted faults (5 and 9 in fig. 7.5) over the south and east central part of the Curnamona 1:250,000 sheet have been cross cut by the MacDonald fault (fig. 7.5).

The first vertical gradient grey image of CRA on the Olary and Broken Hill Blocks shows these regional faults and their cross cutting relationship. Interpreted lava flows of the younger Benageri volcanics have not been displaced by the Strathearn lineament (fig. 7.5) which indicates that it is an older and deeper structure than the volcanics and has a relationship with the tectonic history of the Willyama Supergroup rocks.

A NNW-SSE linear trend, similar and subparallel with the interpreted fault (2 in fig. 7.5) of the Kalabity South sheet, is delineated in the south western part of the Boolcomata South sheet (11 in fig 7.5). These two linear features are interpreted as faults because of either truncation or alignment of anomalies.

The eastern boundary of the longer extension of the Willyama Supergroup rocks (fig. 6.1) shows a north south alignment with a small sinusoidal curvature. This may be a faulted boundary between non-magnetic Adelaidean to the east and the Willyama Supergroup rocks to the west.

A north south trend runs through the smaller anomaly of the mixed volcanics (hole LNM 10 in fig. 6.1) and to the east of the larger anomaly of acid volcanics (hole BWM1 in fig. 6.1) (fig. 6.2). This trend coincides to the south with the interpreted thin elongated lava flows. It may be either a previous topographic low due to faulting which later accommodated the lava flows or the location of a volcanic extrusion. Modelling parameters for this N-S linear feature are depth 290 m, susceptibility 0.00036 SI units, dip  $90^\circ$  and width 445m. The susceptibility of the required model is in the range of the logged susceptibility of the volcanics on hole LNM10 drilled by Mines Administration Pty Ltd and the depth to the top of the magnetic body is consistent with the interpretation depth map on the Benageri 1:100,000 sheet.

### **7.2.3. Interpreted Intrusions and Granitoids**

Several suites of granitoids and intrusives are recognised and were mapped from the magnetic information (figs 6.7 and 6.33) (see the detail in chapter 6):

# (i) Exclusively intrusive with sharp contact, associated with magnetic lows, gravity lows and circular in shape. These are located in the north east of the Kalabity and Mulyongari 1:100,000 sheets (figs. 6.7 and 6.33) and they are less than 10 km across.

# (ii) Not obvious as intrusive compared with type # (i), polygonal in shape, not coincident gravity low but normally associated with a region of low gravity with higher magnetic intensity than group #(i) and less magnetic than the Lithomagnetic suite. These are mapped to the south east and western corner of the Kalabity sheet; and the east central and western corner of the Mulyongari 1:100,000 sheet (figs. 6.7 and 6.33).

This group occupies large areas forming dome structures which were also mapped in the south and south east of the Kalabity 1:100,000 sheet, and in the south central part of the Mulyongari 1:100,000 sheet (figs. 6.7 and 6.33).

# (iii) The highest magnetic amplitude found over this group on the Tonga Hill granitoids and east of it over the Poodla Hill.

Between the various types of granitoids group #(i) and #(iii) show distinctive magnetic characteristics, the former being low and interpreted as acidic intrusion and the latter being high and interpreted as more mafic. Type #(ii) are probably more related to migmatization and regional granitoids (Ashley et al., 1995). His subdivision of intrusions is based on mapping and age determination in the Olary 1:250,000 sheet and to the mapped outcrop in the southern part of the Curnamona 1:250,000 sheet. A far larger area and variety of granitic intrusions were mapped in this study (figs. 6.7 and 6.33).

The interpreted type (ii) intrusion also coincides with the regional granitoids of Ashley et al. (1995) in the Triangle Hill area. Age determination of the Triangle Hill granitoids (Cook, 1993 and Cook et al., 1994) revealed an age of 1590 Ma which is a major event of partial melting and granitoid formation in the Olary Block. This age is reported to be consistent with the timing of high grade metamorphism in the Broken Hill Block (Page and Laing, 1992) and an age of  $1580 \pm 32$  Ma from a gneiss near Binberrie Hill (Olary 1:250,000 sheet) (Compston et al., 1966).

This event is equated with the high grade metamorphic and deformation episodes in the Olary Block. On a wider scale it is also coeval with the emplacement of the Hiltaba suite granitoids (compositionally generally similar to the most widespread Olary Block granitoids) (Ashley et al., 1995), the Gawler Range volcanics and the Olympic Dam Cu-U-Au deposits in the Gawler Craton (Flint, 1993b and Cross et al., 1993).

A broad domal shape migmatite and composite gneiss (group #(ii)) is interpreted in the south central part of the Mulyongari 1:100,000 sheet (fig. 6.33). Although there is some intermixing, the folded Lithomagnetic suite aligns with the eastern and western boundary of this interpreted migmatite. This is structurally and magnetically similar to the interpreted composite gneiss and regional granitoids in the south eastern part of the Kalabity 1:100,000 sheet (fig. 6.7).

### **7.3. Volcanics**

Certainly there is no indication of the presence of the Willyama Supergroup rocks at relatively shallow depth in the western half of the Benageri 1:100,000 sheet (see fig. 6.3 index map sheet). Three semi circular anomalies are located in this sheet (see VMZ in fig 6.1). The western and southern were drilled by Mines Administration Pty Ltd (see fig 6.1 for the location of drill holes). The former (BWM1) intersected massive rhyolite at 444.6 metres and the latter (ETM5) reached metamorphosed acid volcanics at 391.4 metres and without variation up to 600 metres. Both were defined as Benageri volcanics (Yates, 1993). The third, the eastern anomaly, has not been drilled yet and is interpreted here to be compositionally the same rocks at a depth of 380 metres.

All these three volcanics (fig. 6.2) are surrounded by the non-magnetic Adelaidean but the two eastern ones appear to be connected to each other (fig. 6.1). Some thin elongate anomalies which are interpreted as due to volcanic flow extend south from these volcanics

Further north of these acid volcanics a smaller anomaly was drilled (LNM10 in fig. 6.1) by Mines Administration Pty Ltd. This intersected bi-modal volcanics at a depth of 231.5 metres. Magnetic characteristics show that the basaltic volcanics appear to continue towards the north and east south east (fig. 6.2). Altered basalt was intersected by Newmont Australia Limited in EL 1684 at a relatively shallow depth (average 38 m).

These holes are located over the shallow anomalies to the north of the shorter extension of the Willyama Supergroup rocks and west of the longer one (holes 8 and 9 in fig. 6.1).

The anomalies over the Benageri 1:100,000 sheet were interpreted as either volcanics to the west and north or Willyama Supergroup rocks to the east. All are overlain by the Adelaidean and recent sediments.

#### **7.4. Environment of Deposition**

Depositional environment and post depositional history of the Willyama Supergroup rocks were discussed by Cook and Ashley (1992); and Stevens et al. (1990) respectively. Crystalline basement sedimentation history of these rocks was also presented by Callen (1990) and Flint and Parker (1993). The information here is summarised from the above sources and will be evaluated in the context of geophysical information.

Callen (1990) indicates that the entire sequence of the Willyama Supergroup rocks in the Curnamona 1:250,000 sheet is consistent with deposition in a shelf environment, either open marine or in a large lake. He deduced similarity of age, composition and regional magnetic characteristics between acid volcanics of the Curnamona 1:250,000 sheet and intercontinental events of the Gawler Ranges volcanics. An eastwards extension of the Gawler Ranges province or separation of a portion by rifting is speculated by him.

The history of the Broken Hill Block events was described by Stevens (1986) in four tectonic stages : Pre-cratonic, transition, epicratonic and cratonic. These dates were correlated between the whole Willyama rocks (the Broken Hill Block, the Olary Block and the Euriowie Block) (Stevens et al., 1990).

The pre-cratonic stage commenced with separation of crustal material from the mantle at 2100-2300 Ma. Deposition of the Willyama Supergroup rocks occurred at about 1820 Ma. These rocks were metamorphosed and deformed twice at about 1660 Ma, in the Olarian orogeny and a third deformation occurred soon after.

The transitional tectonic stage commenced at  $1490 \pm 20$  Ma. Between 1490 Ma and about 1100 Ma, the presently exposed Willyama Supergroup rocks were elevated from between 13 to 20 km below the surface, to surface and near surface levels.

During the epicratonic stage (1100-500 Ma), continental and shallow marine sediments of the Adelaide System plus minor basalt were deposited in grabens or half grabens on the Willyama basement. A thermal pulse at  $520 \pm 20$  Ma marks the Delamarian orogeny.

The Cratonic stage began from 500 Ma to the present. Although Stevens (1986); Stevens et al. (1990) documented the sequence of events for the development of the Willyama Supergroup rocks and the depositional environment of each stratigraphic group in the Broken Hill Block, no correlation was made with the Olary Block in terms of environmental setting.

The Willyama Supergroup has been interpreted as deposited in a failed paleo to Meso-Proterozoic rift which has been deformed and cratonised (Willis et al., 1983). The western margin of the rift, between Mt Robe and Olary, corresponds with the western limit of significant volumes of basic magma (Laing and Barnes, 1986). The eastern margin may have been near Broken Hill, the eastern limit of Hornes Gneiss acid volcanics and the mantle-tapping metal feeder zone for the Broken Hill-lead-zinc orebody (Flint and Parker, 1993).

However as a result of subsequent deformation, including formation of regional nappes with overturned limbs, the Broken Hill orebody has been folded into its present position and is not now on top of the original crustal fracture that controlled ascent of metalliferous fluids (Flint and Parker *op. s.*).

Detailed paleo-environmental analysis for the Olary Block is not complete and for some units is made by comparison with the Broken Hill Block. Nevertheless, most studies have recognised the depositional environment as predominantly shallow marine interspersed with non-marine playa lakes (i.e. shelf or intracratonic basin) (Thomson, 1975b; Glen et al., 1977; Rutland, 1976; Cook and Ashley, 1992; and Flint and Parker, 1993.) but deepening upward.

Laing and Barnes (1986) proposed a model similar to Cook and Ashley (1992) in which the Willyama Supergroup rocks were formed in a rift environment, but major rifting took place only in the Broken Hill Group time (1700-1690 Ma). The Broken Hill Group,

unlike the underlying and overlying sequences, shows strong differentiation into rift and shelf facies. These are the Broken Hill rift facies and the Olary shelf facies (Laing *op. s.*). The Broken Hill rift was an asymmetric regional half graben.

The eastern margin of the rift was a focus of hydrothermal activity and base metal effusion, without significant volcanism. The western margin was the site of paired acid and basic volcanism. The volcanics were extruded into the rift but not significantly onto the shelf to the west. The Olary shelf featured minor volcanics, and carbonate/evaporite lithologies in an oxidising saline environment (Laing *op. s.*).

The origin of the giant Broken Hill Pb-Zn-Ag deposit and the enclosing early to middle Proterozoic supracrustal succession of the Willyama Supergroup is still under debate and probably will be for the coming years. Epigenetic and syngenetic models have been proposed by Wright *et al.* (1987). Submarine exhalation of volcanogenic metal-bearing fluids responsible for the mineral deposits were suggested in studies in the 1970s to early 1980s (eg. Stanton, 1972, 1976; Plimer, 1985). A model involving subsurface metal-bearing fluids migrating into and along permeable sandstone units has been recently developed by Wright *et al.* (1987).

Slack *et al.* (1989) discussed the possibility that the sedimentary sequence contained non-marine evaporite rocks which formed part of the mineralised strata. Other deposit types in the Broken Hill Block, for example the Thackaringa cobaltian Pyrite and tungsten occurrences associated with calcilicite rocks have also been considered as having been

deposited as chemical precipitate from hot spring sources (eg. Plimer, 1977; Barnes, 1988). Evidence of evaporitic conditions operative in the formation of parts of the Willyama Supergroup rocks on the Olary Block was presented by Cook and Ashley (1992).

Cook and Ashley (1992) believe that the alkali-rich Quartzofeldspathic rocks have chemical compositions unlike any known primary volcanic rocks and they have been interpreted by them as representing felsic volcanoclastic material (subaerial) enriched in alkalis due to saline fluid interaction during diagenesis or at deposition resulting in the crystallisation of analcime and other zeolites. Magnetite is the most common opaque mineral within the albitites, locally comprising up to 9 weight percent (Cook, 1993). It defines the laminations in the finest-grained rocks and occurs in the coarser rocks as disseminated grains.

Haematite has been described from rocks near Burdens Dam in the Quartzofeldspathic suite by Ashley (1984b), Rolfe (1990), and Cook (1993). The textures in the haematite-bearing rocks was virtually identical to those of the magnetite-bearing samples. Cook (1993) indicated that haematite from the Burdens Dam area is a prograde metamorphic phase and locally coexists with Piedmontite, garnet and tremolite (in addition to albite and quartz), reflecting the relatively oxidised nature of the rocks compared to the magnetite-bearing samples.

Cook (1993) indicated that magnetite is an important constituent of the calcalbitite rocks, comprising between 1 and 10 modal percent. As in the quartzofeldspathic rocks, haematite is also present in the calcsilicate-bearing varieties, with a form very similar to that of the magnetite grains.

The above evidence (production of haematite in both quartzofeldspathic rocks and calcalbitite rocks during prograde metamorphism) indicates that magnetite in the Quartzofeldspathic suite has been deposited with the original sediments. However in Cook's study (1993) it was not indicated whether his samples had been collected from below the weathering zone and whether haematite was only produced through metamorphism). The changes in magnetic character over a metamorphic boundary could possibly indicate the effect of metamorphism on magnetite development or the decay of it.

The map of the variation of metamorphic grade within the Willyama inliers (Clarke et al., 1987, and Phillips, 1980) was compared with the interpreted map of the Willyama Supergroup rocks (fig. 6.7). A broad relationship between the stratigraphy and prograde metamorphism was indicated so that upper parts of the succession are of lower grade than the basal succession. However it is difficult to distinguish the metamorphic grade boundary from the magnetic data. The Lithomagnetic suite continues from the region of high grade to the areas of low grade without any change in the magnetic character. This suggests that magnetite development in the Lithomagnetic suite was not extensive during metamorphism and that magnetite may be inherited from primary deposition.

The occurrence in the Olary Block of relatively reduced strata (the Bimba suite and the calcsilicate suite) overlying more oxidised strata (the quartzofeldspathic suite) (Cook, 1993) is the reason for the absence of magnetic minerals in the former and the presence of them in the latter. Recalling the discussion of 4.6 concerning the geological influence on the distribution of magnetic minerals It seems that the difference in magnetite concentration between the Quartzofeldspathic suite and the Bimba suite is related to the condition of deposition of these two suites.

Cook and Ashley (1992) noted "we have developed an interpretive "tectonic cartoon" (fig. 8) for the Broken Hill and Olary Blocks of the Willyama Supergroup at the time of Broken Hill Pb-Zn mineralisation. A rift setting is envisaged, possibly many hundreds of kilometres wide, analogous to the Salton Sea trough. We infer that the present boundary between the Broken Hill and Olary Blocks (Mundi Mundi Fault) is a reactivated major crustal feature, possibly a normal fault.

At the time of Broken Hill Pb-Zn-Ag mineralisation, the Broken Hill Group was situated in deeper water, while in the Olary region evaporitic conditions may have prevailed. Underlying the Upper Broken Hill Group are older evaporite rocks (Thackaringa Group and the calcsilicates of the Ettlewood Calcsilicate Member) formed in a similar setting to the Olary rocks. Heat flow towards the centre of the rift was probably greatest, initiating large hydrothermal systems capable of providing the quantities of fluid required to form the Broken Hill lode, with smaller hydrothermal systems existing locally throughout the remainder of the Olary and Broken Hill Blocks".

Bierlein et al. (1995) indicated that metalogenesis in the Olary Block is the result of a complex interplay between fluid-assisted, brittle and ductile processes. They argue that sulphides were deposited during sedimentation and diagenesis, as well as during metamorphism and multiphase tectonic episodes. Bierlein et al. (1995) also argue that a classic red bed-style Cu deposit in the Bimba suite proposed by Cook and Ashley (1992) is improbable. Ongoing research about the origin of the mineralisation and the environment of deposition of the Willyama Supergroup rocks will change the current issues summarised above, just as the detailed study of Bierlein et al (1995) has already changed the previous regional interpretation of Redox boundary mineralisation of Cook and Ashley (1992).

Investigation of the regional first vertical gradient grey image of CRA on the Olary and Broken Hill Blocks indicates a system of parallel ENE-WSW clear magnetic boundaries. The eastern two of these coincide with the Redan Fault and the Mundi Mundi Fault (7 and 6 in fig. 7.5). The Redan Fault was interpreted as a steep dipping normal fault by Isles (1983) and the Mundi Mundi Fault by MacIntyre (1991); and Isles (op. cit.) also as normal fault.

Two other parallel faults are interpreted in this study (5 and 9 in fig. 7.5) over the south and east central parts of the Curnamona 1:250,000 sheet, the former extending across the MacDonald shear to the Olary sheet up to the north west of the Weekeroo Inliers and the latter forming the eastern boundary of a funnel shaped low magnetic Adelaidean.

The NE-SW interpreted fault (5 in fig. 7.5) in the south western area of the Curnamona (1:250,000) sheet is cross cut by the MacDonald and possibly by the Strathearn faults. The interpreted fault to the east central area (9 in fig. 7.5) of the Curnamona (1:250,000) sheet is cut by the Strathearn fault. The first vertical gradient grey image of CRA on the Olary and Broken Hill Blocks shows that both the MacDonald and Strathearn faults are cross cut by the Mundi Mundi fault. These patterns of parallel cross cutting faults on a regional scale indicate a common tectonic origin for the deformation of the Willyama Supergroup rocks. This is similar to the pattern of cross cutting faults in the central part of the Broken Hill Block (White et al., 1995). Further investigation is necessary to determine the proposed rift models and the complex structural setting of the Willyama Supergroup rocks.

## **7.5. Mineralisation Potential**

The geology of the Broken Hill Block and its mineralisation has been intensively studied because of the presence of the giant Broken Hill lead-zinc-silver orebodies. Far less is known about the Olary Block. The rock types in each structural block are very similar (Stevens, 1990). The whole Willyama Block is intensely mineralised and each structural block shows distinctive metal associations (table 3 of Stevens et al., 1990).

In the Olary Block copper and uranium deposits are the most significant, with lesser iron, barium, cobalt, tungsten, gold and fluorite. The Broken Hill Block is dominated by

View of the geology of the Curnamona 1:250,000 sheet in the light of new 134  
geophysical information

deposits of lead, zinc, and silver with lesser tungsten, copper, iron, cobalt, gold, nickel, platinum, tin, beryllium and fluorite.

Exploration targets in the Olary Block were summarised by Yates (1993) and mineral deposits of this Block have been classified by Ashley et al., 1994. A "rift model" for the formation of Broken Hill type mineralisation has been proposed by Laing, 1986. The mineralisation potential over the Curnamona 1:250,000 sheet will be improved in the light of the new geophysical information in this thesis. Stratiform and strata bound mineral deposits in the Olary Block are restricted to the Quartzofeldespathic suite, Calcsilicate suite and Bimba suite (Ashley, *op. s.*).

Much of the stratiform and stratabound mineralisation in the Olary Block has been interpreted as resulting from syngenetic and diagenetic processes, including chemical sedimentation from hot spring exhalations and from redox boundary-related precipitation (Cook and Ashley, 1992). It is clearly evident though that deformation and metamorphic processes have caused complete recrystallisation and local syntectonic mobilisation into transgressive structures (Bierlein et al., 1995).

Bierlein et al. (1995) argue that there is not much evidence for a well-defined redox boundary or any pronounced lateral and/or vertical zonation in sulphide minerals in the Olary Block. They infer the uniform chemical composition of stratiform/stratabound sulphides represent a primary feature, reflecting similarities in source area and fluid compositions.

Although the Bimba suite is non-magnetic, the other two suites, as defined by the Lithomagnetic marker (discussed in chapter 5), were traced accurately under cover (see chapter 6) (maps 6.7 and 6.33). These maps will provide an exploration guide in the search for stratiform and stratabound lead-zinc-silver deposits in the covered areas of the Willyama Supergroup rocks in the Curnamona 1:250,000 sheet. The validity of this interpretation map has been tested by either mapped outcrop or drilling information.

Epigenetic deposits possess no significant stratigraphic control and are found in all suites of the Willyama Supergroup rocks and in granitic intrusives (Ashley et al., 1995). The position of the Bimba suite may be deduced from the mapped location of the Lithomagnetic suite (Quartzofeldespathic suite, calcalbitite rocks and Calcsilicate suite) due to its non-magnetic nature. The location of granitoids under cover are also mapped along with the Lithomagnetic marker suite as discussed in section 7.2.3 (figs. 6.7 and 6.33). This leaves the Pelite suite from the whole succession of the Willyama Supergroup rocks which occupies the space between the Lithomagnetic marker and intrusives.

Epigenetic mineralisation occurs in the form of replacement of favourable horizons (Black Maria), cross-cutting veins (Centralia, Mt Preservance), stockworks or within brecciated fracture systems (Ashley et al. op. cit.) (eg., Waulkaloo, Walparuta, Woman-in-White, Ram Dam, Hunters Dam). These deposits do not show stratigraphic control and are commonly not spatially associated with pre-metamorphic occurrences.

Epigenetic deposits are, in places, associated with retrograde schist zones or zones of pervasive retrogression (eg., Cathedral rock area), which suggests that mineralisation in these occurrences resulted from fluid movement during retrograde metamorphism. Unlike the occurrence of Fe-dominated sulphides at various stratigraphic levels over more than 250 km of strike length, Cu-dominated deposits are commonly structure-controlled and closely related to several generations of epigenetic veins within shear zones and faults (Bierlein et al., 1995).

Vein and shear zone hosted epigenetic deposits are relatively widespread in the Olary Block and occur in all suites and in granitoids as indicated above. The location of granitoids as well as shears in the unexposed rocks and poorly mapped outcrops are interpreted from the magnetic information and have been mapped here (figs 7.5, 6.7 and 6.33). Many regional and local shears have been mapped from aeromagnetic interpretation in this study. These may be the location of fluid circulation and zone-hosted epigenetic deposits.

Because of the continuation of the Willyama Supergroup rocks to the north base metal and gold exploration in the Olary Block is necessarily becoming directed towards areas in the northern parts of the Block where either the direct geological information is very limited or there is none at all. Exploration in such terrain requires an appreciation of the interpreted map provided in this study to facilitate the proper location for future geochemical prospecting for base metals and gold deposits.

A detailed contour map of depth to the magnetic sources (volcanics and Willyama Supergroup rocks) for the northern part of the Curnamona 1:250,000 sheet (the Benageri 1:100,000 sheet) is provided in this study (fig 6.4) (discussed in chapter 6). This map shows that at least 45 percent of the anomaly sources are less than 200 metres deep. This interpreted map of depth to the basement along with new gravity (1 km versus old 7 km spacing) and magnetic data which MESA were collecting during this study will demonstrate other feasible locations in the search for Olympic Dam type model deposits over the Benageri area which is similar in age and composition to the Olympic Dam area.

## 8. Summary and conclusion

From the magnetic view point, three main rock types with distinctive magnetic character are present in the sequence of the Willyama Supergroup rocks in the Curnamona section of the Olary Block in eastern South Australia. These rocks have been mapped over the limited area where they outcrop but the magnetic map shows them to occur over a much greater area to the north where they are obscured by a thick cover of Adelaidean and recent sediments. In this thesis the distribution and structure of these rocks have been determined from the magnetic map.

The first rock type is the composite gneiss and migmatite which is the basal unit in the sequence. This is easily identified magnetically from the moderate amplitude of its magnetic signature and the pattern of circular to semi-circular anomalies seen on the total magnetic intensity colour image which make it distinct from the other units in the sequence. The boundary of the composite gneiss and migmatite may be traced from the frequent disruption of linear to curvilinear anomalies which arise from the quartzofeldspathic rocks. The composite gneiss and migmatite, along with granitic intrusions, produce anomalies which are normally equidimensional in shape and show subdued magnetic character.

The second main rock type and the important one which lies in the middle of the sequence, and hosts the Broken Hill orebody in the adjacent Broken Hill Block, is the

quartzofeldspathic rocks. These rocks constitute the dominant magnetic pattern of multiple, linear to curvilinear anomalies whose sources are essentially stratiform. The quartzofeldspathic rocks constitute the magnetic marker horizon in the Willyama Supergroup rocks and are subdivided into three sections according to their magnetic response.

The lower section which is the Quartzofeldspathic Suite is the most magnetic unit in the stratigraphic sequence of the Willyama Supergroup rocks. This high magnetic response is related to the presence of disseminated magnetite, local concentration of iron formations and reconstitution of massive magnetite after brecciation. Surface and drill hole susceptibility measurements show that the Quartzofeldspathic Suite has a bi-modal distribution of susceptibilities with a lower peak of  $6 \times 10^{-5}$  SI units and a higher peak of  $5000 \times 10^{-5}$  SI units. The Quartzofeldspathic Suite produces strong linear and curvilinear anomalies which indicate bedding trends.

The middle section of the quartzofeldspathic rocks is made up of the calcalbitite rocks. This is the gradation between the lower Quartzofeldspathic Suite and the upper Calcsilicate Suite. Magnetite is reported to be an important constituent of the calcalbitite rocks comprising between 1 and 10 modal percent. These rocks have magnetic pattern similar to the Quartzofeldspathic Suite and both produce a single curvilinear magnetic anomaly along strike. This magnetic character led the author to the recognition of problems in previous mapped geology in the Mt Howden Mine area in the Koolka South 1:25,000 geological map sheet.

The third section, the upper one, is the Calcsilicate Suite which has susceptibilities similar to the lower value of the Quartzofeldespathic Suite. Therefore it is not possible to distinguish the Calcsilicate Suite from the Quartzofeldespathic Suite from the magnetic information and the previous definition of the Calcsilicate Suite as the magnetic marker is called into question. Thus the combined Quartzofeldespathic Suite, the calcalbitite rocks and the Calcsilicate Suite together represent the magnetic marker horizon, a distinctive feature in the magnetic maps of the Willyama Supergroup rocks.

The third main rock type and the upper unit in the sequence of the Willyama Supergroup rocks is the Pelite Suite. This suite is non-magnetic relative to the quartzofeldespathic rocks and the composite gneiss and migmatite. It correlates with the areas of low amplitude anomalies in the magnetic map. The thin sulphidic Bimba Suite which lies stratigraphically above the Quartzofeldespathic rocks and below the Pelite Suite cannot be distinguished from the non-magnetic Pelite Suite magnetically. However the position of this economic target may be deduced from the location of the interpreted quartzofeldespathic rocks and the dip as determined from magnetic modelling.

In addition to the above three main rock types three suites of granitoids and intrusives are recognised from the magnetic information:

The first of these are made up of exclusively intrusive bodies with sharp contact. They are associated with magnetic lows, gravity lows and are circular in shape. These are located in the north east of the Kalabity and Mulyongari 1:100,000 sheets and are less than 10 km across.

The members of the second suite are not obvious as intrusive bodies when compared with the first suite. They are polygonal in shape and are not coincident with a gravity low. However they are normally associated with a region of low gravity and with higher magnetic intensity than members of the first suite, but they are less magnetic than the quartzofeldspathic rocks. This suite occupies large areas and is mapped in the south east and western part of the Kalabity 1:100,000 sheet. It is also mapped in the south west and eastern part of the Mulyongari 1:100,000 sheet.

The third suite gives anomalies with the highest amplitude. They have been mapped geologically in the Koolka South 1:25,000 sheet as the Tonga Hill granitoids and east of it as the Poodla Hill granitoids.

Among the three suites of granitoids, the first and third suites show distinctive magnetic characteristics. The former have low amplitude anomalies and are interpreted as acidic intrusions whilst the latter have high amplitude anomalies and are interpreted as more mafic. It has been suggested that the second suite is probably more related to migmatization and regional granitoids.

With the recognition of the distinct magnetic character of the rock types and the identification of the magnetic marker, that is the quartzofeldspathic rocks, the magnetic map provides a great deal of information about the geology of the areas where little was known. The results of the interpretation depend on how much is already known about the geology. In areas where there is a significant amount of outcrop, the magnetic map

indicates boundaries, the strike of the units in the rock groups and the presence of major breaks in the outcrop pattern due to faults and shear zones.

In the areas where outcrops are sparse and separated by extensive areas of cover such as on the Koolka South, the Kalabity South and the Kalabity North sheets, the magnetic interpretation establishes with very much greater certainty the relationship between the outcrops. The magnetic interpretation also provides much more continuous geology; and provides a very important assistance in following stratigraphy; and understanding structures.

In the poor outcrop areas, the southern part of the Kalabity 1:100,000 sheet, a more continuous pattern of folded quartzofeldspathic rocks; a much bigger body of mafic intrusion which has been dissected by the MacDonald fault; and large bodies of regional granitoids which are intermixed with the quartzofeldspathic rocks and are cut by major faults were mapped. Because of sparse outcrop this geological information cannot be seen by field mapping alone.

In the areas where there is virtually no outcrop and most of what can be observed about the geology comes from the rocks seen in the drill holes, the magnetic map is essential for starting to understand the geology of the area. The effectiveness of the magnetic map to provide information about the geology in these areas depends on the interpretation which has already come from the areas of outcrop where the geology is known.

In the almost totally covered areas the quartzofeldspathic rocks were traced from latitude 32°S to 31°30'S and longitude 140°E to 141°E on the Kalabity; and Mulyongari

1:100,000 sheets (7200 km<sup>2</sup>). The interpreted map of the Kalabity 1:100,000 sheet, in the covered areas to the north of the outcrops, show clearly less complex fold structures of the quartzofeldspathic rocks; a minimal distribution of migmatite and granitoids; and relatively few faults. The interpreted map of the Mulyongari 1:100,000 sheet, where the Willyama rocks are totally covered, shows the longest trend of the quartzofeldspathic rocks which are cut by various granitoid bodies and regional faults.

Detailed magnetic maps of the Willyama rocks contain a considerable amount of significant geological information, and if carefully integrated with other available geological data and rock property measurements, are a cost effective means of resolving structural and stratigraphic problems in many areas. The magnetic maps allow mapping the quartzofeldspathic rocks as the magnetic marker as well as the stratigraphic marker; the granitic intrusions and migmatites; and faults. The interpreted maps show fold structures whose axes trend NE-SW and major faults which strike NW-SE and NNE-SSW.

The regional interpretation map indicates that the Willyama Supergroup rocks extend under cover further north of latitude 31°30'S to the Frome 1:250,000 sheet (latitude 31°S) along the eastern part of the Benageri 1:100,000 sheet, that is the Benageri ridge. There is an indication suggesting that they probably extend to the central area of the Curnamona craton (latitude 30°30'S and longitude 139°30'E). The regional interpretation map also shows that the Willyama Supergroup rocks are not present at

relatively shallow depth in the western half of the Benageri 1:100,000 sheet. This is consistent with the drill hole information.

The magnetic map provides very important information about another aspect of the geology of the area, the thickness of overburden, but this information is of interest only if the rocks are not too deep to be explored by drilling. The depth interpretation map, which provides knowledge of the thickness of cover to the magnetic sources for the Benageri 1:100,000 sheet, shows the areas where the magnetic basement rocks are shallow. This is useful for further geological investigation or selection of exploration targets. The eastern three quarters of the Benageri 1:100,000 sheet has magnetic sources less than 350 metres deep and almost half of them are less than 200 metres deep.

As well as providing detailed information about the geology, the magnetic map also shows major structures of regional significance. The map of interpreted lineaments of the Curnamona 1:250,000 sheet shows a pattern of cross cutting faults similar to the pattern of cross cutting faults in the central province of the Broken Hill Block. The Mundi Mundi Fault and the Thackaringa Fault in the Broken Hill Block clearly extend to the Olary Block. The Thackaringa Fault can be followed in the Curnamona section of the Olary Block.

Additional information regarding the type of faults may be obtained from modelling. This is only appropriate when the anomaly of the fault is not influenced by neighbouring sources and remanent magnetisation. The MacDonald Fault, which strikes NW-SE, meets this condition. Modelling results for this fault shows a dip of  $20^{\circ}$  to the north east.

Considering the dip direction (assuming no remanence) and knowing the relative age of the Willyama Supergroup and the Adelaidean rocks on each side, the fault is seen to be a thrust fault. However the offset of the two interpreted mafic granitoids in the Tonga Hill area suggests that there has been a right lateral slip component of motion along the strike of the MacDonald Fault. This may indicate that the MacDonald Fault is not a pure thrust fault as modelled above.

The interpreted geology maps of the Curnamona section of the Olary Block provide a better understanding to the geology of the Curnamona 1:250,000 sheet. These maps show the distribution of the quartzofeldspathic rocks, granitic intrusions and faults under cover. Previous geochemical investigations in the outcrop areas and limited exploration drill holes in the covered areas have shown that the quartzofeldspathic rocks are prospective for base metal mineralisation. Since this is the case, the interpreted maps of this study provide a direct exploration guide for further geochemical prospecting on the totally covered areas.

The interpreted lineaments map shows the location of major faults in the covered and poorly mapped areas. Epigenetic mineralisation, particularly Cu-dominated deposits, are previously reported to be structurally controlled and closely related to faults and shear zones. Therefore the interpreted lineaments map also directly guides further investigation to the proposed location of fluid circulation and zone-hosted epigenetic deposits in the covered areas.

The interpretation of aeromagnetic data over the Willyama rocks is an on-going process. With the collection of recent higher resolution aeromagnetic data and smaller station

spacing gravity measurements over the Broken Hill and Olary Blocks of the Willyama Inliers, previous interpretation will be updated, tested and improved. Basic rock property data, the results of magnetic modelling and the information on the interpreted maps included in this thesis should provide more lasting factual information. It is hoped that the maps and interpretation presented in this study will provide a basis for future research.

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## Appendix 1: Susceptibility measurements

Outcrop Susceptibility measurements. The units are taken downwards; Abbreviations are as follows; PS : Pelite Suite; BS : Bimba Suite; CS : Calcsilicate Suite; QFS : Quartzofeldspathic Suite; CGS : Composite Gneiss Suite; Mag. Susc. : Magnetic Susceptibility

Formation	Mag. Susc.×10 <sup>-5</sup> SI Units	Locality
PS	2000	Mooleulooloo area
	380	
	350	
	350	
	275	
	310	
	330	
BS	75	Brooks Dam area
	80	
	60	
	45	
	80	
	75	
	55	
CS	79	Bulloo area
	65	
	70	
	80	
	38	Cathedral rocks area
	42	
	57	
	106	
	61	
	674	
	15	Mt. Howden Mine area
	14	

Formation	Mag. Susc.×10 <sup>-5</sup> SI Units	Locality
	19	
	20	
	8	
	14	
	19	
	20	
QFS	210	Dome rock Copper Mine area
	200	
	80	
	100	
	40	Mt. Howden Mine area
	9	
	13	
	2710	
	1720	
	55	
	6	
	5200	
	1700	
	1200	Dome rock area
	5500	
	2500	
	5500	
	2000	
	1200	
	900	
	3200	
	215	Toramanga Hill area
	396	
	207	
	605	
	62.8	
	325	
	1870	Iron Stone Well area
	90	
	20	
	60	
CGS	450	Triangle Hill area
	250	
	750	
	150	
	2000	

Formation	Mag. Susc.×10 <sup>-5</sup> SI Units	Locality
	293	Tonga Hill area
	2	
	328	
	30	
	636	

Magnetic Susceptibility ( $\times 10^{-6}$  SI units) of the Quartzofeldspathic Suite intersected in a 327 m drill hole; logged four readings/m by CRA Exploration Pty LTD. in the Waulkaloo area; and weathered up to 45 m. Abbreviations are as follows; Mag. Sus : Magnetic Susceptibility; D. D. : Downhole Distance

D. D.(m)	Mag. Sus.	D. D (m)	Mag. Sus.	D. D (m)	Mag. Sus.
30	45	40	600	50	20000
	15		950		2000
	60		400		950
	25		200		6500
31	200	41	200	51	7500
	600		50		2500
	85		100		1500
	450		250		7000
32	550	42	100	52	8500
	150		100		7000
	100		30		4500
	350		50		2000
33	250		15	53	8500
	150	43	600		1500
	100		550		1500
	100		350		900
34	65		45	54	10000
	100	44	45		20000
	30		3000		5500
	200		100		8000
35	80		85	55	4000
	650	45	9000		3500
	85		8000		70
	05		3250		7000
36	10		7500	56	5750

D. D.(m)	Mag. Sus.	D. D (m)	Mag. Sus.	D. D (m)	Mag. Sus.
	55	46	4000		4500
	250		2500		9500
	55		550		2000
37	200		1000	57	3000
	150	47	200		4000
	100		2000		4500
	100		400		700
38	200		7000	58	30
	100	48	1500		10
	200		8000		500
	350		3500		400
39	472		2000	59	4000
	100	49	7000		500
	200		4000		850
	850		6000		2000
60	1000	70	7000	80	3000
	800		8000		3500
	15		9500		3000
	20		4000		3000
6i	200	71	2500	81	4000
	2000		8500		1500
	2000		8500		2000
	1000		7000		2250
62	4500	72	8500	82	2500
	1000		17500		2500
	8500		12500		2500
	300		10000		5000
63	4800	73	10000	83	3000
	1000		3000		2000
	150		6000		3000
	450		12500		1500
64	1000	74	25000	84	1000
	7000		9000		7000
	100000		8500		5000
	250		10000		500
65	600	75	7500	85	3000
	3000		9000		450
	650		4500		650
	450		6000		650
66	450	76	60	86	500
	4000		35		700
	10000		45		650

D. D.(m)	Mag. Sus.	D. D (m)	Mag. Sus.	D. D (m)	Mag. Sus.
	15000		100		600
67	15000	77	200	87	1000
	9500		150		1000
	10000		60		1000
	20000		300		1250
68	10000	78	10000	88	1500
	4000		1500		2000
	8000		2000		2000
	5500		2000		100
69	15000	79	3000	89	15
	20000		4000		300
	8500		4000		15
	8000		3000		700
90	500	100	2500	110	10,000
	5000		7500		9000
	15000		12500		12500
	800		15000		6000
91	5500	101	7000	11	10000
	3000		12500		20000
	1500		17500		12500
	450		15000		25000
92	4000	102	8000	112	10000
	7500		9000		25000
	9500		12500		20000
	7000		22500		50000
93	7000	103	12500	113	25000
	9500		15000		25000
	9000		20000		30000
	10000		12500		15000
94	10000	104	15000		20000
	9500		20000	114	10000
	10000		20000		10000
	2000		25000		20000
95	5500	105	10000		20000
	3500		2000	115	20000
	100,000		20000		10000
	80,000		100,000		20000
96	2000	106	100,000		20250
	2500		100,000	116	12500
	70,000		80,000		25000
	75,000		10000		17500
97	2500	107	3000		30000

D. D.(m)	Mag. Sus.	D. D (m)	Mag. Sus.	D. D (m)	Mag. Sus.
	8000		4500	117	17500
	60,000		6000		12500
	10,000		5000		10000
98	500	108	6500		15000
	3000		6000	118	30000
	600		8000		12500
	1000		15000		20000
99	100	109	10000		17500
	100		9000	119	17500
	150		9000		17500
	85		9500		15000
120	12500	130	20000		10000
	17500		17500	140	15000
	20000		15000		15000
	30000		17500		15000
121	40000	131	20000		20000
	35000		25000	141	15000
	10000		17500		15000
	15000		20000		15000
122	15000	132	15000		15000
	10000		20000	142	15000
	12500		15000		12500
	10000		17500		17500
123	8250	133	15000		15000
	10000		10000	143	12500
	10000		17500		15000
	17500		15000		20000
124	9500	134	12500		15000
	10000		15000	144	15000
	15000		15000		20000
	17500		12500		15000
125	15000	135	15000		20000
	15000		15000	145	15000
	15000		12500		20000
	15000		10000		15000
126	15000	136	12500		17500
	15000		3000	146	17500
	15000		6500		20000
	15000		3500		20000
127	15000	137	7000		15000
	20000		9500	147	15000
	12500		15000		10000

D. D.(m)	Mag. Sus.	D. D (m)	Mag. Sus.	D. D (m)	Mag. Sus.
	25000		6000		15000
128	15000	138	17500		10000
	15000		15000	148	9000
	15000		17500		8000
	15000		20000		10000
129	15000	139	15000		30000
	17500		18000	149	8500
	15000		15000		10000
	15000		15000		10000
150	15000	160	15000		12500
	10000		17500	170	17500
	12500		15000		15000
	15000		15000		17500
151	6500	161	10000		20000
	4000		15000	171	15000
	10000		8000		15000
	10000		8000		10000
152	12500	162	8000		22500
	12500		8000	172	20000
	15000		8000		15000
	15000		8000		20000
153	15000	163	8000		20000
	15000		10000	173	12500
	12500		4000		15000
	25000		10000		15000
154	17500	164	8500		15000
	20000		10000	174	12500
	20000		500		12500
	4000		450		400
155	15000	165	400		12500
	15000		15000	175	17500
	20000		10000		10000
	12500		10000		15000
156	15000	166	10000		15000
	17500		10000	176	15000
	20000		10000		12500
	8000		15000		20000
157	8000	167	15000		10000
	10000		15000	177	10000
	10000		15000		9000
	10000		15000		9000
158	9500	168	2000		10000

D. D.(m)	Mag. Sus.	D. D (m)	Mag. Sus.	D. D (m)	Mag. Sus.
	20000		2000	178	10000
	10000		15000		9000
	10000		20000		9000
159	12500	169	20000		10000
	15000		10000	179	10000
	15000		20000		10000
	15000		17500		10000
180	9750	190	20000		10000
	8000		10000	200	15000
	5000		10000		10000
	5000		10000		20000
181	5000	191	10000		17500
	5000		400	201	15000
	5000		3500		15000
	6000		17500		15000
182	7500	192	9000		20000
	10000		10000	202	15000
	10000		12500		15000
	6000		12500		15000
183	6000	193	17500		10000
	6000		12500	203	10000
	6000		17500		10000
	5500		12500		10000
184	5000	194	15000		2500
	10000		15000	204	2500
	10000		9500		15000
	9500		10000		12500
185	9500	195	9500		15000
	6500		7500	205	6500
	10000		9000		10000
	10000		9000		10000
186	15000	196	6500		17500
	30000		6500	206	15000
	35000		15000		15000
	15000		15000		15000
187	12500	197	20000		20000
	15000		15000	207	17500
	20000		15000		10000
	20000		20000		10000
188	20000	198	20000		15000
	17500		17500	208	10000
	20000		17500		10000

D. D.(m)	Mag. Sus.	D. D (m)	Mag. Sus.	D. D (m)	Mag. Sus.
	20000		20000		17500
189	10000	199	20000		15000
	20000		30000	209	10000
	20000		15000		12800
	15000		17500		15000
210	10000	220	12500		8000
	7000		17500	230	12500
	10000		15000		125000
	9500		15000		15000
211	9500	221	12500		15000
	6000		15000	231	15000
	9000		2000		15000
	10000		6000		12500
212	9750	222	7000		15000
	10000		9500	232	15000
	15000		10000		15000
	10000		20000		15000
213	15000	223	12500		15000
	10000		20000	233	15000
	10000		10000		15000
	10000		15000		12500
214	10000	224	22500		15000
	2000		17500	234	15000
	3000		25000		15000
	2000		20000		15000
215	5500	225	17500		15000
	8000		15000	235	15000
	10000		15000		20000
	9000		20000		20000
216	9750	226	17500		17500
	9500		20000	236	20000
	10000		25000		20000
	10000		15000		15000
217	10000	227	15000		20000
	10000		15000	237	17500
	10000		22500		15000
	12500		20000		25000
218	8000	228	15000		15000
	8500		15000	238	17500
	9000		15000		17500
	20000		15000		15000
219	15000	229	15000		15000

D. D.(m)	Mag. Sus.	D. D (m)	Mag. Sus.	D. D (m)	Mag. Sus.
	15000		15000	239	15000
	15000		20000		30000
	40000		12500		15000
240	15000	250	10000		22500
	15000		10000	260	25000
	15000		12500		40000
	15000		9500		25000
241	22500	251	10000		30000
	20000		15000	261	20000
	15000		15000		20000
	20000		15000		15000
242	17500	252	10000		20000
	25000		10000	262	20000
	15000		15000		15000
	20000		10000		10000
243	20000	253	12500		15000
	15000		15000	263	10000
	17500		15000		9000
	15000		15000		15000
244	15000	254	15000		15000
	15000		15000	264	15000
	15000		20000		10000
	20000		20000		10000
245	20000	255	15000		10000
	10000		15000	265	10000
	15000		15000		10000
	12500		20000		10000
246	20000	256	15000		10000
	15000		10000	266	12500
	15000		3000		15000
	10000		15000		15000
247	10000	257	20000		10000
	10000		15000	267	9000
	10000		15000		15000
	15000		15000		15000
248	15000	258	20000		10000
	30000		20000	268	15000
	12500		10000		10000
	17500		10000		15000
249	10000	259	10000		10000
	12500		10000	269	12500
	10000		20000		10000

D. D.(m)	Mag. Sus.	D. D (m)	Mag. Sus.	D. D (m)	Mag. Sus.
	15000		10000		15000
270	9000	280	15000		10000
	12500		8000	290	12500
	15000		8000		10000
	15000		40000		15000
271	15000	281	35000		10000
	20000		30000	291	10000
	10000		10000		10000
	10000		30000		8000
272	10000	282	20000		600
	10000		30000	292	10000
	15000		100,000		15000
	15000		10000		12500
273	10000	283	30000		200
	20000		40000	293	9000
	15000		20000		15000
	10000		10000		20000
274	10000	284	20000		15000
	12500		15000	294	10000
	10000		10000		15000
	10000		15000		20000
275	10000	285	15000		15000
	12500		20000	295	10000
	10000		15000		15000
	8000		8000		15000
276	10000	286	15000		10000
	15000		100	296	10000
	10000		1000		30000
	15000		300		6000
277	15000	287	6500		8000
	10000		9000	297	3000
	10000		6000		10000
	10000		7000		10000
278	40000	288	9000		15000
	10000		10000	298	10000
	10000		10000		25000
	10000		6000		15000
279	10000	289	10000		30000
	9000		10000	299	100,000
	10000		12500		90000
	10000		10000		30000
300	12500	310	8500		50000

D. D.(m)	Mag. Sus.	D. D (m)	Mag. Sus.	D. D (m)	Mag. Sus.
	15000		7500	320	8000
	12500		10000		8000
	15000		8000		7500
301	10000	311	7000		6500
	25000		9000	321	7000
	12500		7000		6500
	10000		7000		7500
302	15000	312	5000		7000
	30000		9500	322	9000
	15000		1500		9500
	10000		4000		10000
303	20000	313	5000		15000
	15000		7000	323	3500
	10000		4000		10000
	15000		40000		15000
304	10000	314	5000		10000
	20000		5000	324	10000
	15000		4000		10000
	10000		5000		8000
305	10000	315	15000		15000
	12500		6000	325	20000
	15000		5000		10000
	10000		5000		15000
306	10000	316	6000		10000
	10000		15000	326	10000
	10000		10000		8000
	10000		10000		20000
307	10000	317	10000		10000
	10000		10000	327	20000
	15000		8000	E.O.H.	
	10000		10000		
308	10000	318	10000		
	15000		6000		
	15000		15000		
	12500		15000		
309	10000	319	9000		
	20000		8500		
	10000		9000		
	15000		10000		

## Appendix 2: Calculated depth parameter

Appendix (2) Calculated depth parameter on the Benageri 1:100,000 sheet. The 75×75 m gridded data over the Benageri 1:100,000 sheet consists of 760 rows and 640 columns. Rows are selected from this grid interval for modelling.

Numbers	Easting	Northing	Depth [m]	
1	422,900	6,517,500	440	Row 29
2	429,850	6,517,500	440	
3	436,760	6,517,500	400	
4	440,180	6,517,500	280	
5	440,790	6,517,500	280	
6	445,120	6,517,500	280	
7	445,590	6,517,500	280	
8	446,120	6,517,500	270	
9	419,660	6,520,000	340	Row 62
10	428,280	6,520,000	340	
11	436,349	6,520,000	600	
12	443,120	6,520,000	300	
13	443,800	6,520,000	300	
14	447,210	6,520,000	250	
15	413,700	6,523,500	660	Row 109
16	416,800	6,523,500	660	
17	427,610	6,523,500	660	
18	435,850	6,523,500	420	
19	445,880	6,523,500	360	
20	419,610	6,526,000	550	Row 142
21	427,520	6,526,000	480	
22	427,650	6,528,000	700	
23	419,460	6,528,000	600	
24	433,890	6,528,000	480	Row 169
25	435,200	6,528,000	480	
26	448,900	6,528,000	700	
27	447,000	6,528,000	700	

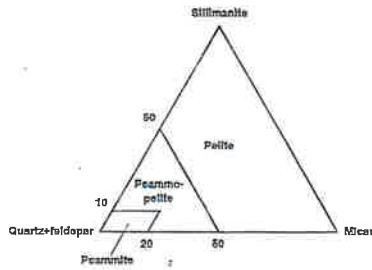
Numbers	Easting	Northing	Depth [m]	
28	418,780	6,529,000	500	Row 182
29	419,570	6,529,000	500	
30	423,850	6,529,000	400	
31	435,030	6,529,000	380	
32	446,900	6,529,000	700	
33	413,000	6,530,500	450	Row 203
34	415,350	6,530,500	450	
35	418,500	6,530,500	780	
36	424,100	6,530,500	480	
37	434,700	6,530,500	460	
38	440,010	6,530,500	180	
39	420,000	6,533,000	530	Row 236
40	417,720	6,533,000	530	
41	422,680	6,533,000	500	
42	421,620	6,533,000	500	
43	425,550	6,533,000	480	
44	430,720	6,533,000	480	
45	435,020	6,533,000	460	
46	439,310	6,533,000	200	
47	440,050	6,533,000	200	
48	440,060	6,533,000	200	Row 236
49	435,060	6,533,000	380	
50	444,000	6,533,000	250	
51	421,100	6,536,000	550	Row 276
52	431,200	6,536,000	380	
53	431,900	6,536,000	380	
54	438,680	6,536,000	220	
55	439,630	6,536,000	200	
56	445,225	6,536,000	280	
57	415,220	6,539,000	600	Row 316
58	430,870	6,539,000	750	
59	439,515	6,539,000	240	
60	446,780	6,539,000	160	
61	416,160	6,541,500	650	Row 349
62	416,740	6,541,500	650	
63	417,200	6,541,500	650	
64	431,650	6,541,500	600	
65	432,700	6,541,500	600	
66	437,350	6,541,500	320	
67	444,250	6,541,500	280	
68	447,650	6,541,500	280	
69	4,161,000	6,544,500	800	Row 389

Numbers	Easting	Northing	Depth [m]	
70	420,200	6,544,500	460	
71	426,800	6,544,500	380	
72	431,700	6,544,500	360	
73	438,200	6,544,500	330	
74	444,200	6,544,500	350	
75	448,800	6,544,500	300	
76	449,200	6,544,500	275	
77	426,760	6,548,000	300	Row 436
78	433,080	6,548,000	295	
79	442,980	6,548,000	160	
80	450,080	6,548,000	300	
81	411,540	6,551,000	550	Row 476
82	417,530	6,551,000	550	
83	427,309	6,551,000	480	
84	433,210	6,551,000	380	
85	433,970	6,551,000	380	
86	440,600	6,551,000	320	
87	449,400	6,551,000	300	
88	412,950	6,555,500	380	Row 536
89	418,730	6,555,500	310	
90	427,905	6,555,500	100	
92	443,560	6,555,500	380	
93	448,630	6,555,500	240	
94	421,050	6,558,500	340	Row 576
95	429,185	6,558,500	300	
96	438,835	6,558,500	360	
97	445,350	6,558,500	290	
98	412,000	6,561,000	460	Row 609
99	415,300	6,561,000	300	
100	423,080	6,561,000	300	
101	428,660	6,561,000	310	
102	438,655	6,561,000	290	
103	443,480	6,561,000	120	
104	420,575	6,563,000	300	Row 636
105	430,910	6,563,000	300	
106	434,550	6,563,000	180	
107	443,700	6,563,000	280	
108	449,500	6,563,000	220	
109	417,550	6,566,000	600	Row 676
110	421,400	6,566,000	380	
111	428,660	6,566,000	450	
112	439,880	6,566,000	300	

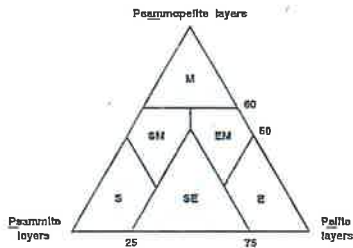
<b>Numbers</b>	<b>Easting</b>	<b>Northing</b>	<b>Depth [m]</b>	
113	449,380	6,566,000	300	
114	415,240	6,569,000	400	Row 716
115	420,770	6,569,000	400	
116	434,490	6,569,000	330	
117	439,890	6,569,000	335	
118	446,470	6,569,000	290	

**PELITIC METASEDIMENTS**  
(S,M,E,EM,SE,EMS,Q)

Three fundamental rock types are rearranged as defined in the diagram.



Mapped units of metasediments are composed of layers of psammite, psammopelite and pelite in various proportions, and are classified as in the following diagrams:



- S** Psammite-rich unit, with minor pelite and psammopelite; psammite typically a massive, fine to medium-grained, blue-gray quartz-rich rock with minor feldspar, biotite and garnet; also occurs as a buff-colored feldspar-rich rock with minor quartz and biotite; bedding not obvious.
- M** Psammopelite-rich unit, with minor psammite and pelite; psammopelite typically medium to coarse-grained quartz-feldspar-biotite-sillimanite-garnet schist and gneiss; bedding not obvious.
- E** Pelite-rich unit, with minor psammite and psammopelite; pelite is medium to coarse-grained micaceous or sillimanite-rich schist and gneiss; bedding indistinct to obvious.
- SM** Psammite and psammopelite-rich unit, with minor pelite; rock types as for units S and M; poorly to moderately bedded.
- EM** Psammopelite and pelite-rich unit, with minor psammite; medium to coarse-grained sillimanite-rich pelite and psammopelite; bedding indistinct to obvious.
- SE** Psammite and pelite-rich unit, with psammopelite minor to abundant; medium to coarse-grained pelite sillimanite schist and gneiss with well-defined beds of massive psammite quartz-feldspar-rich rock.
- EMS** Undifferentiated mixture of E,M,S lithologies: "schist"
- Q** Quartzite, with at least 90% quartz (+/-minor feldspar); compact, hard.

If graphite is present (i.e. carbonaceous material): c  
If minor tourmaline is present (<5%): t  
If minor epidote is present (<5%): e  
If minor chloritoid is present (<5%): ca (a = andalusite)

**COMPOSITE GNEISSES AND MIGMATITES**

These rocks units are interpreted as bedded metasediments (and/or bedded metavolcanics) containing a significant proportion of material melted during metamorphism.

The rock units consist of layered metamorphic rocks with various proportions of pegmatitic and granitic material. Classification of the rock units is based primarily on the proportions of "mobile" and "immobile" material, and on the nature of the "immobile" material.

"Mobile" material shows features attributable to melting or solution and includes pegmatitic and granitic rock.

"Immobile" material shows solid state features, and includes metasedimentary rock, and metamorphic-textured quartz-feldspathic gneiss and layered sodic plagioclase+quartz rock.

A composite gneiss is composed of from 50 to 90% "immobile" component and from 10 to 50% "mobile" component. The rock is generally a layered metasedimentary and/or quartz-feldspathic rock containing subordinate amounts of granitic/pegmatitic material. There is generally minor to moderate disruption of layering.

In a migmatite the "mobile" component comprises at least half the volume of the rock. The "immobile" component may comprise only a few percent, or up to 50%. Layering is generally extensively disrupted, and feldspar megacrysts may be common.

- F** Undifferentiated composite gneiss/migmatite.
- Fm** Undifferentiated migmatite.

**METASEDIMENTARY COMPOSITE GNEISS AND MIGMATITE**  
(FS, FM, FSM, Fms)

In these rock units the "immobile" component consists of metasedimentary material. The rocks consists of layers and/or lenses of metasediments intimately intermixed with pegmatitic to granitic material.

Letter symbols for metasedimentary composite gneisses are constructed by addition of an "F" prefix (from feldspathic), to the appropriate metasediment letter symbol. Metasedimentary migmatites are denoted as Fms.

- FS** Psammite-rich composite gneiss unit; massive fine to medium-grained, psammite quartz-feldspar-biotite-sillimanite-garnet-cordierite rock, with minor layers and lenses of feldspathic segregations; bedding thin, irregular, and discontinuous.
- FM** Psammopelite-rich composite gneiss unit; finely layered, psammopelite quartz-feldspar-biotite-sillimanite-garnet-cordierite schist and gneiss, with minor psammite and pelite layers, and abundant, thin quartz-feldspathic segregations; bedding poorly developed.
- FSM** Psammite and psammopelite-rich composite gneiss unit; interlayered psammite rock and psammopelite schist, both comprising quartz-feldspar-biotite-sillimanite-garnet-cordierite, with abundant quartz-feldspathic segregations; bedding poorly developed.

Leucocratic quartz-feldspathic rocks consist almost entirely of quartz and feldspar, with <10%, generally <=5%, mafic minerals (biotite, garnet, magnetite) and <5% calc-silicate minerals. They include deformed layered and/or gneissic rocks (Pl, Lf) which are interpreted as metavolcanics, and a include pegmatites (p), many of which are folded and are interpreted as products more or less in situ. Some pegmatites are clearly post-folding intrusives and may be post-Early Proterozoic. Granitic rocks with clear post-folding intrusive relationships are excluded.

**PEGMATITE**

(p)

These rock units comprise at least 80% pegmatite, and may contain up to finer grained leucocratic quartz-feldspathic rock.

- p** Simple type (quartz+feldspar+/-muscovite, tourmaline).
- pz** Zoned, complex, commonly quartz core, with feldspar-muscovite+/-biotite, beryl, tourmaline, sulphides, phosphates, oxides.

**FELDSPAR+QUARTZ-RICH ROCK WITH A GNEISSIC TO GRANITIC TEXTURE**  
(Lf)

- Lf** Medium to coarse grained, gneissic to granitic and massive textured leucocratic feldspar-quartz+/-biotite rock (sodic plagioclase commonly dominant).

**PLAGIOCLASE+QUARTZ+/-K-FELDSPAR-RICH ROCKS GENERALLY CONTAINING SACCHAROIDAL PLAGIOCLASE-RICH LAYERS**  
(Pl)

- Pl** Undifferentiated.
- Plm** Fine, medium and coarse grained, massive to thickly laminated quartz-feldspathic rock (sodic plagioclase generally dominant, but may grade to quartz-rich), with or without accessory K feldspar, biotite, muscovite, magnetite, haematite, pyrite, tourmaline; blocky, commonly weathers orange/pink.
- Plm<sub>1</sub>** With quartz "eyes", i.e. probable relict volcanic quartz phenocrysts.
- Plm<sub>2</sub>** With pyrite.
- Plm<sub>3</sub>** With accessory magnetite and/or haematite.
- Plf** Fine to medium grained, commonly well laminated but locally massive; sodic plagioclase-quartz dominant, but locally with abundant K feldspar, with or without accessory biotite, muscovite, magnetite, haematite, calc-silicates; white/grey; grades into ca pieces.
- Plf<sub>1</sub>** Quartz-K feldspar+/-plagioclase, biotite, muscovite, calc-silicates, magnetite (i.e. K feldspar-rich).
- Plf<sub>2</sub>** With accessory pyrite.
- Plf<sub>3</sub>** Quartz-plagioclase+magnetite+/-K feldspar, haematite, biotite, muscovite.
- Plf<sub>4</sub>** As above with <5% essential calc-silicates; grades into ca
- Plf<sub>5</sub>** Plagioclase+epidote-bearing (i.e. manganese type).
- Plf<sub>6</sub>** Brecciated equivalents.
- Plf<sub>7</sub>** Massive Pl, possibly intrusive.

**AMPHIBOLE AND/OR PYROXENE-BEARING ROCKS**

The three classes of amphibole and/or pyroxene-bearing rocks are for the most part markedly different from one another. However, rocks with characteristic intermediate between classes are not uncommon and hence the classes are together.

The amphibolites are interpreted as metamorphosed basic volcanics and/or subvolcanic intrusives. The calc-silicate rocks are interpreted as metamorphic carbonates and/or metabasaltic sediments. The basic and ultrabasic intrusives typically lack high-grade deformation structures and are interpreted as having been emplaced after high-grade metamorphism. Some may be post-Palaeoproterozoic.

**AMPHIBOLITE**

(a)

- a** Amphibolite, equigranular, massive to foliated, composed of hornblende-plagioclase+/-clinopyroxene+/-epidote ("protectonic").

**CALC-SILICATE ROCKS**

(c)

(>5% calc-silicate minerals)

- ca** "calc-silicate", fine to medium grained, commonly well laminated, but locally massive or "spotty" textured; composed of quartz-plagioclase+/-K feldspar, with >5% calc-silicates (<25% clinopyroxene, amphibole, garnet, epidote, titanite)+/-accessory magnetite.
- caX** Brecciated equivalent.
- cs** Calc-silicate-rich rock with >25% calc-silicate minerals (e.g. clinopyroxene, amphibole, garnet, epidote, titanite, vesuvianite, wollastonite, scapolite)+/-feldspar, quartz, magnetite, haematite, sulphides.
- cs<sub>1</sub>** As above with >5% sulphide minerals.
- cc** Carbonate-rich (>10% carbonate) with calc-silicates, quartz, feldspar, sulphides.

**BASIC AND ALKALINE INTRUSIVES**  
(bp, ba)

These rocks characteristically lack high-grade deformation structures, although some exhibit a retrograde schistosity.

- bp** Metadolerite, metabasalt; partial retention of relict igneous textures, generally low grade metamorphic assemblages (post-Willyama).
- ba** Alkaline intrusives of carbonate-feldspar-tranquillite-syenite affinity.
- ba0** Porphyrites.
- bav** Volcanics; layered.

**IRON, MANGANESE, BARIUM, BORON, AND SULPHIDE-RICH ROCKS**

These are generally granular and/or layered rocks, commonly associated with sulphide mineralization.

- gs** Garnet quartz+/-amphibole (garnet is spessartine-almendrin-grossular).
- qm** Quartz+magnetite+haematite+pyrite+barite iron formation (locally contains garnet, epidote, muscovite, biotite); haematite specular.
- qm<sub>1</sub>** Quartz+haematite+/-magnetite+/-barite (haematite+magnetite) iron formation; haematite specular.
- qm<sub>2</sub>** qm with >5% sulphides (pyrite, chalcopyrite, pyrrhotite).
- qmx** Brecciated equivalent.
- qb** Quartz+barite+/-magnetite, haematite, sulphides (barite>Fe oxides).
- su** Sulphide-rich rocks (>25% sulphides); only found in drill core; are generally sulphide-rich variants of ca, cs, ca, E, M, qm<sub>2</sub>.
- fe** Gossan or limonite; derived by weathering of iron sulphide-bearing ca, E, M, qm<sub>2</sub>.
- q** Vein quartz (quartz "blebs").