

STRUCTURAL INTERPRETATION IN THE  
MOUNT WOODS INLIER



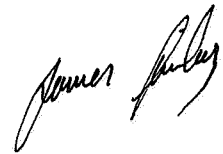
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This thesis is submitted in part fulfilment of the Bachelor of Science  
(Hons.) Degree, Department of Earth Sciences, Monash University.

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## DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma at any other University. To the best of my knowledge and belief, this thesis does not contain any material previously published or written by any other person except where it is duly acknowledged and referenced in the text.



James Finlay

November 1993

## ABSTRACT

The Mount Woods Inlier (MWI) is an Early to Mid-Proterozoic terrane represented by numerous small scattered outcrops of metasediments and granitoids, located approximately 100 km southeast of Coober Pedy, north-central South Australia.

Field mapping of three outcrops reveal the following deformation history:

1. D<sub>1</sub>/M<sub>1</sub> was a high T, low P event that produced an S<sub>1</sub> foliation defined by sillimanite, cordierite ± almandine garnet (Flint and Benbow, 1977).

2. D<sub>2</sub> produced folding on scales from microscopic crenulations of S<sub>1</sub> to macroscopic folding of metasedimentary units over tens of km. Steep fold axes and variations in fold orientations throughout the MWI appeal to fold interference (ie re-folding), which probably occurred during the subsequent D<sub>3</sub> shearing event.

3. D<sub>3</sub> was a shearing (+ folding) event that produced discrete zones (100's m long) and a large scale shear zone (≥ 7 km) in the Spire Hills-Skylark Hills area. Kinematic indicators such as Type I S-C mylonite fabrics suggest movement was predominantly strike-slip. The discrete shear zones appear to be the result of strain caused by dextral movement on the large scale shear zone.

Dating of a foliated granitoid interpreted as syn-D<sub>1</sub>/M<sub>1</sub> at ~1700 Ma and a granite interpreted as post-D<sub>2</sub> and pre- to early syn-D<sub>3</sub> at ~1580 Ma has constrained the timing of tectonism to within these dates. This deformation is synchronous with D<sub>3</sub> of the Kimban Orogeny, the Olarian Orogeny, the Ernabellan deformation of the Musgrave Block, D<sub>1</sub> of the Peake-Denison Inlier and deformation and metamorphism in the Karari Fault Zone.

The early high T, low P metamorphism, syn-D<sub>1</sub> intrusion of I-type granitoid and subsequent folding show many similarities with the tectonic model of Etheridge et al (1987), in which this sequence of events is produced by rifting-resulting from small scale mantle convection and magmatic underplating-followed by compression due to thermal subsidence and crustal delamination.

Large scale geophysical analysis infers the early granitoid is more widespread than indicated from outcrop and has locally affected F<sub>2</sub> fold geometry. Fold interference patterns have been interpreted as the result of D<sub>3</sub> shear and refolding. Two broad anomalies have been interpreted as late (1580 Ma) plutons at 1 - 3 km depth. A large east-west shear zone along the northern boundary of the MWI appears related to the ~1700 Ma Karari Fault Zone, however the D<sub>3</sub> shear event (1580 Ma) suggests subsequent movement on the shear zone.

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# 1. INTRODUCTION

## 1.1 PREAMBLE

The Mount Woods Inlier (MWI) represents one of the largest areas of the sparsely outcropping Proterozoic geology in the northern half of the Gawler Craton. This makes the study of the Inlier not only important for its own sake but also for its implications for the regional tectonics. Remote sensing data on a regional scale shows that beneath much of the Late Precambrian and Phanerozoic cover there is a complex pattern of older rocks which indicates a history of substantial tectonism. The Mount Woods Inlier is a small piece of this jigsaw.

An Honours project by nature must be focussed on specific problems and thus cannot incorporate all aspects of an area such as the MWI. In this project it is my goal to present a source of reliable data, observations and interpretations of the Inlier. From these some inferences will be made with respect to the regional tectonics of the area

## 1.2 Aims

The aims of this project are to:

1. Map the structural relationships in three areas:
  - (a) Spire Hills-Skylark Hills,
  - (b) Mirage Hills,
  - (c) Mount Woodsand determine their deformation histories.
2. Use geochronological dating of two samples to constrain the timing of deformation.
3. Relate the structure and timing of deformation to regional tectonic events.

### 1.3 Methods

Data was collected and interpreted with support from BHP Minerals using three methods :

1. Field mapping and sampling conducted over nine weeks. Subsequent thin section analysis.
2. Ion microprobe U Pb zircon dating by C.M.Fanning, Research School of Earth Sciences, The Australian National University.
3. Analysis of geophysical data (aeromagnetics and bouguer gravity).

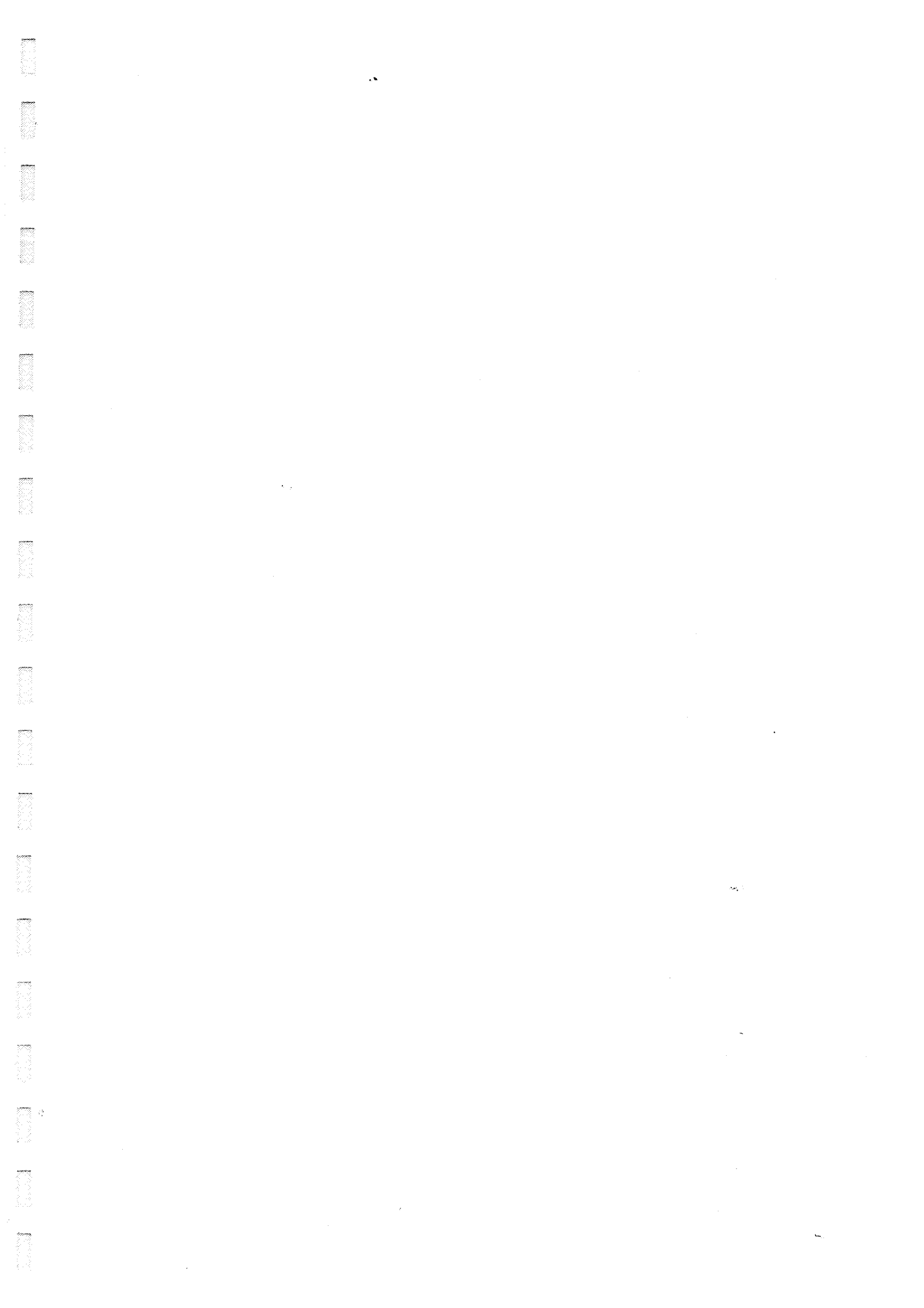
### 1.4 Location

The Mt Woods Inlier is a zone of Early to Mid-Proterozoic rocks covering about 800 km<sup>2</sup> located approximately 100 km south-east of Coober Pedy, in the north-east of the Gawler Craton (see figure 1.1). It comprises part of a belt of high bouguer gravity and magnetism which extends west and east along the northern edge of the craton. The scattered outcrop within the inlier is limited to about 60 km<sup>2</sup>.

The three areas mapped during the field season were Spire Hills-Skylark Hills, Mirage Hills and Mount Woods (see fig 1.2). The Spire Hills-Skylark Hills area covers ~32 km<sup>2</sup>, although only 30% of this is outcrop. Mirage Hills covers ~2 km<sup>2</sup> with 50% outcropping. Mount Woods is a 0.5 km<sup>2</sup> hill with patchy outcrop. To the east and southeast of Mount Woods are two small outcrops of the same rock type. The areas were chosen for the availability of aerial photos, the quality of the outcrop and the variety of structure.

### 1.5 Geology of South Australia

South Australian geology is dominated by the central Gawler Craton. To the East is the Adelaide Geosyncline and the Willyama Orogenic Domain. To the north, northeast and west of the craton are, respectively, the Phanerozoic Officer, Warburton and Eucla basins. To the north-west lies the Musgrave Block. Within these broad geological terrains are numerous Proterozoic inliers such as the Mt Painter - Mt Babbage Inlier, the Peake-Denison Block, the Ammooradinna Inlier and the Mt Woods Inlier (see figure 1.1).



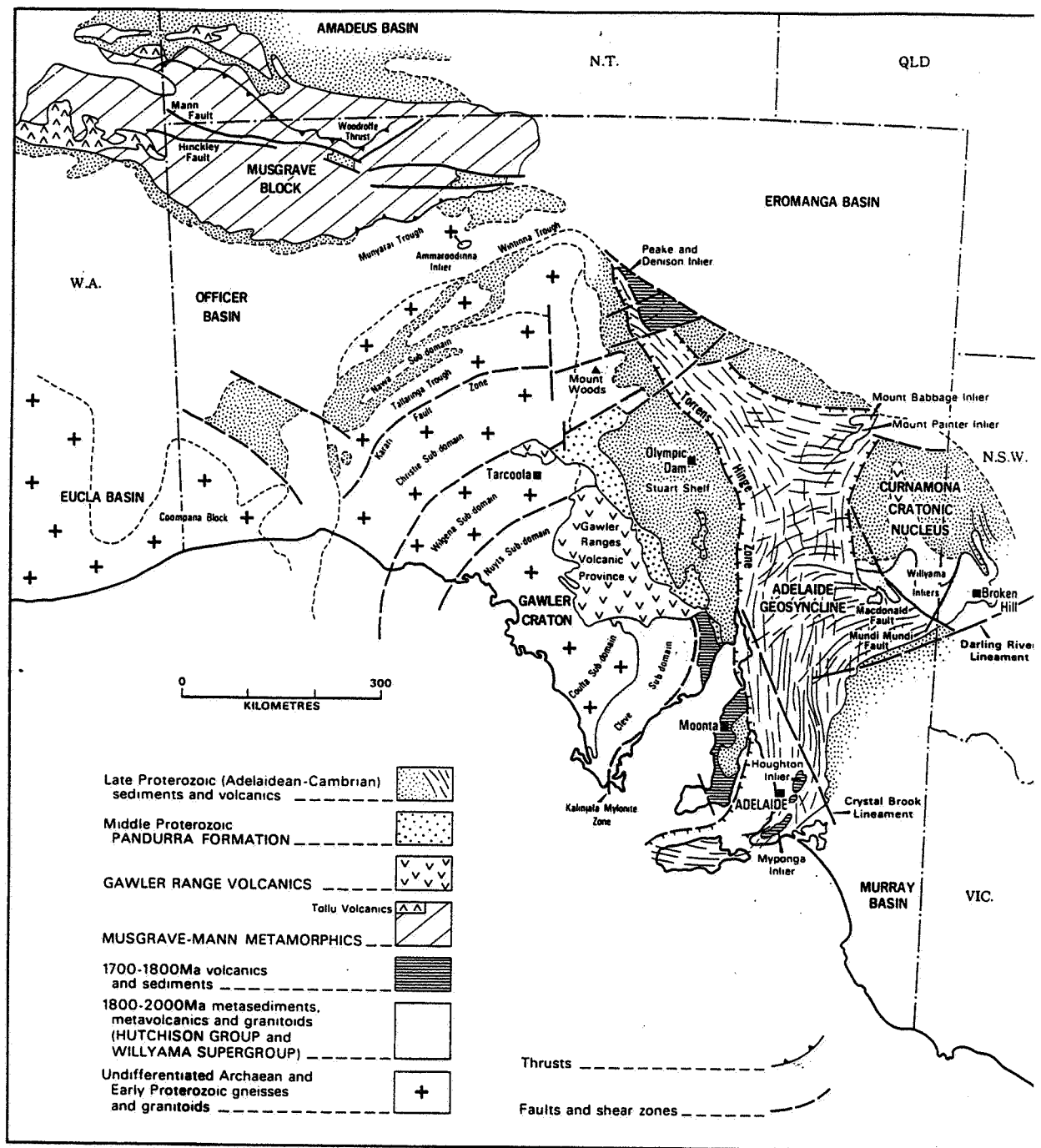


Figure 1.1 The Precambrian provinces of South Australia, dominated by the Gawler Craton. The Mount Woods Inlier is in the central north. Note the northeast structural trend of the Karari Fault Zone west of the MWI. From Parker, 1990.

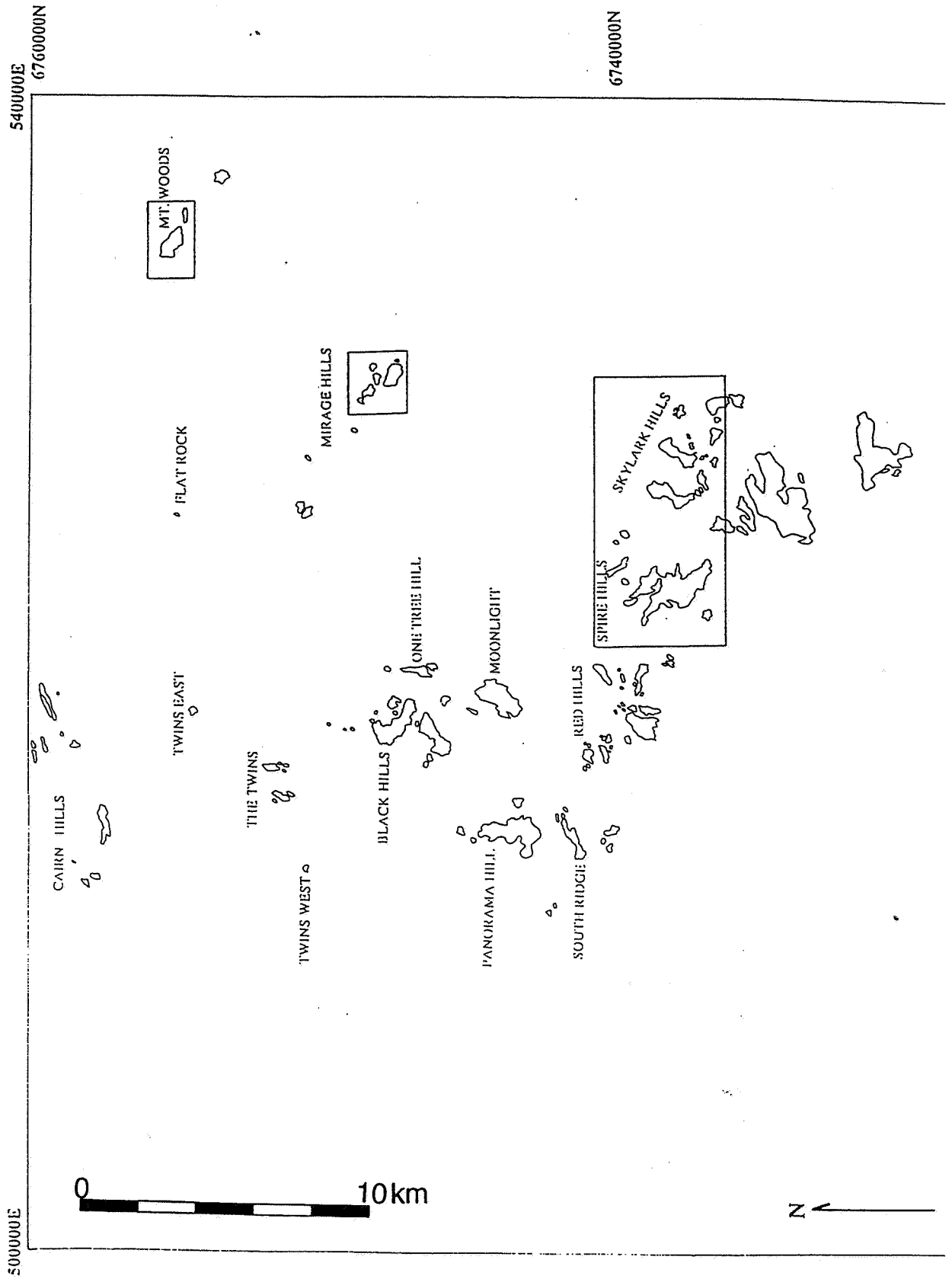


Figure 1.2 Outcrop map of the Mount Woods Inlier. The three field areas marked are:

- (a) Spire Hills - Skylark Hills
- (b) Mirage Hills
- (c) Mount Woods

## **1.6 Local History**

Before European settlement the area was occupied by the Kokata, Kujani and Arabana Aboriginal tribes (Ambrose and Flint, 1981). The outcrops in the MWI are scattered with spear heads and knives made in the Australian small tool tradition from silicified Tertiary sandstone.

The first Europeans in the area were the explorers Stuart, Warburton and Babbage in 1858 and Ross in 1874. The discovery of opal in the Cretaceous Bulldog Shale during the early 1920's initiated the settlement of Coober Pedy, a name derived from the local word for hole-dweller (Ambrose and Flint, 1981).

## **1.7 Brief Description of Rock Types**

The dominant rock types are metamorphics: banded iron formation, metapelites, migmatites, paragneisses (including some calc-silicate assemblages) and orthogneiss. These have been intruded by an early porphyritic, foliated (Engenina) adamellite and a later non-foliated, often porphyritic (Balta) granite (Flint and Benbow, 1977). The stratigraphy of the metamorphics is unknown.

The widespread occurrence of cordierite and sillimanite,  $\pm$  almandine garnet and the lack of primary muscovite, indicate that the rocks of the MWI reached granulite conditions and with temperatures of 650°-700°C at 3-4 kb pressure (Flint and Benbow, 1977). This temperature range is supported by the presence of migmatites indicating the onset of anatexis.

## **1.8 Previous Work**

The earliest geological observations were made by Brown (1905) and Lockhart Jack (1915, 1931) and mineral exploration was carried out during the 1950s, '60's and '70's. More recently, structural investigations have been carried out by Flint and Benbow (1977) and Betts (1992). Flint and Benbow (1977) mapped the dominant foliation of most outcrops and recognised three tectonic fabrics and deformations. However, no association was made between specific deformations and the mapped foliation. They recognized an early layer parallel foliation (schistosity and gneissity defined by biotite, quartz and feldspar) which has been overprinted by at least two deformations, one of which is an overprinting crenulation.

Flint and Benbow (1977) interpreted the foliated Engenina Adamellite as postdating the formation of the schistosity, gneissosity and granulite facies metamorphism in the neighbouring metamorphics. The foliation of the Engenina Adamellite has a similar orientation to fold axes and lineations in the metamorphics. Thus, Flint and Benbow (1977) imply the Adamellite intrusion to be synchronous with folding. This in turn implies that the foliation of the Engenina Adamellite is a tectonic feature (ie. resulting from deformation) rather than due to magmatic flow effects.

Betts (1992) structurally mapped two outcrops (Moonlight Hills and Mt Woods) and interpreted an aeromagnetic image of the Inlier at 1: 100 000 scale. Betts (1992) recognized five deformations:

D<sub>1</sub> produced a layer parallel foliation and D<sub>2</sub> produced tight folds. This corresponds with the D<sub>1</sub> and subsequent folding event of Flint and Benbow (1977). D<sub>3</sub> has been identified by Betts (1992) as a period of folding, NE trending faulting and shearing, which probably correlates with D<sub>3</sub> of Flint and Benbow (1977).

D<sub>4</sub> was a local (Moonlight Hills), north-west trending kinking and gentle warping of earlier foliations. D<sub>5</sub> is a set of small, north-west trending, sinistral strike-slip faults and joints that have been tentatively correlated with Late Proterozoic graben structures associated with the Pandurra Formation of the Stuart Shelf.

## 1.9 Previous Geochronology

Three rocks have been previously dated:

1. The Engenina Adamellite has been dated by Webb (1977) using Rb/Sr ratios at  $1641 \pm 38$  Ma, although it is not clear if this is a date of intrusion or deformation or both.

2. The unfoliated Balta Granite has been dated at 1450-1550 Ma using Sr/Sr ratios from six samples. Unfortunately the ratios yielded a non-linear distribution, resulting in the poor precision (Webb, 1977; Benbow and Flint, 1979).

3. The third rock type dated was a migmatitic, quartz-feldspar-magnetite rich metasediment of granulite facies, located 21 km south-west of Mt Woods in the north of the Spire Hills. Fanning et al (1988) have used conventional and ion microprobe U-Pb zircon analyses to produce a date of  $1742 \pm 27$  Ma. However, the data shows significant scatter due to a heterogeneous zircon population and the true meaning of the date is not clear. The source of



melt in the migmatite was possibly the Engenina Adamellite, so that the date may represent the timing of intrusion and migmatisation. Alternatively the date may be the timing of granulite facies metamorphism. Regardless, it sets a probable minimum time of deposition of the metasediments.

Geochronology for the Mount Woods Inlier has been fairly unsuccessful for two reasons.

Firstly, Rb/Sr dating of felsic igneous rocks throughout the Gawler Craton does not record the time of crystallisation, although a unique solution is indicated (Fanning et al, 1988; Fanning, 1993). Most rocks that have been re-analysed using U-Pb zircon techniques (ie ion microprobe and conventional analyses) have yielded dates 50-100 Ma older than the Rb/Sr dates (see Fanning et al, 1988).

Second, the widespread granulite-facies metamorphism in the MWI has resulted in mixed zircon populations in migmatitic rocks. This leaves a particular isochron open to interpretation.

### **1.10 Thesis Layout**

The thesis is organized into seven chapters, an appendix, two field maps and a regional map.

Chapter one introduces the Mount Woods Inlier (MWI), presents the aims, methods, previous work and brief descriptions of the local rock types and regional geology.

Chapter two describes the rock units in detail and discusses aspects relevant to structural interpretation, such as sedimentary origins and pluton types.

Chapter three presents the field data and describes the three deformations, high temperature - low pressure metamorphism, plutonism and relationships. A subsequent discussion relates a tectonic model developed by Etheridge et al (1987) to the MWI as a possible explanation for the deformation history.

Chapter four presents the results of ion microprobe U-Pb zircon dating of the early and late intrusions. The choice of rock types is justified and regional correlates noted.

Chapter five presents a large scale interpretation (1: 100 000 scale) based on outcrop geology and aeromagnetic images. Mesoscopic and macroscopic structure and geometric correlations are discussed.

(Thesis layout cont.)

Chapter six puts the MWI in regional context. The surrounding Proterozoic regions are summarised and the implied tectonic correlations are discussed in terms of geometry and synchronicity

Chapter seven states the conclusions and interpretations in point form.

The appendix lists the samples presented in photographs and text with their field locations.

## 2. ROCK TYPES

### 2.1 INTRODUCTION

The outcropping Precambrian rocks of the Inlier are meta-sediments and intrusives. No volcanics have been positively identified in outcrop or from drilling, and there are no obvious meta-volcanics. The meta-sediments are commonly high in magnetite and this is evident on aeromagnetic images (see fig.5.3, chapter 5).

The aim of this chapter is to define the rocks as much as necessary for the study of deformation, metamorphism and geophysical interpretation. Thus foliations are only briefly mentioned here, as they are an integral part of deformation and metamorphism and discussed fully in the next chapter.

### 2.2 META-SEDIMENTS

#### 2.2.1 Banded Iron Formation

In this study the term banded iron formation (BIF) is used for magnetite and haematite rich meta-sediments, as have Betts (1992) and Flint and Benbow (1977). The term "iron formation" is used here in the lithological sense and does not imply specific genesis.

BIF crop out at the Spire Hills, Mount Woods, South Ridge, The Twins, Panorama Hills and One Tree Hill. Iron formation xenoliths occur in migmatite at Moonlight Hills (Betts, 1992).

The BIF is the main metasediment at Spire Hills and Mount Woods. The main mineralogy consists of quartz, microcline, plagioclase, magnetite and biotite. The magnetite is disseminated throughout the rock although some layers are richer than others. Biotite is more layer specific and alternates with K-feldspar-rich layers causing the banded appearance. These bands are typically one to four cm thick and occur within a broader layering ten to 100 cm thick (see fig. 2.1). Texture is granoblastic. At Spire Hills minor minerals are sillimanite, cordierite and secondary muscovite (Flint and Benbow, 1977). At Mount Woods the iron formation differs by increased biotite, sillimanite and the presence of garnet in some areas. At the western end of Mount Woods the rocks are more pelitic with abundant large garnet porphyroblasts and sillimanite clots, and only minor magnetite. These

rocks structurally underlie the more magnetite-rich units. In the southeast of Mount Woods the BIF has quartz-biotite schist interbeds.



Figure 2.1 Banded Iron Formation (BIF), Cental Mt. Woods. Banding 1-2 cm thick is due to alternating layers of biotite ( $\pm$  magnetite) rich and quartz+feldspar layers.(photo D.Moore

The origins of the magnetite in the BIF open to question. A combination of sedimentary and metamorphic origins is favoured because of the lateral extent of individual BIF units - aeromagnetic data show units extending for tens of kilometers - and the readiness of biotite to break down to magnetite at granulite facies conditions (Yardley, 1989). The BIF of the MWI contrasts with Pilbara - style BIF in that the magnetite is much more disseminated.

The disseminated nature of the magnetite in the BIF of the MWI contrasts with Pilbara-style BIF, where the iron-rich minerals interbed with chert (Clark and Cook, 1986). This raises the question as to the origin of the magnetite in the BIF at MWI. The continuity of the BIF units over tens of km (clear from magnetic data), together with the mineralogy and regular layering indicate almost certainly the sedimentary origin of the unit. However, at granulite conditions biotite readily progrades to magnetite (Yardley, 1989), so that the magnetite may be a metamorphic phenomenon. This means that lateral magnetic variations within individual units could be the result of metamorphism or lateral facies change. No BIF of

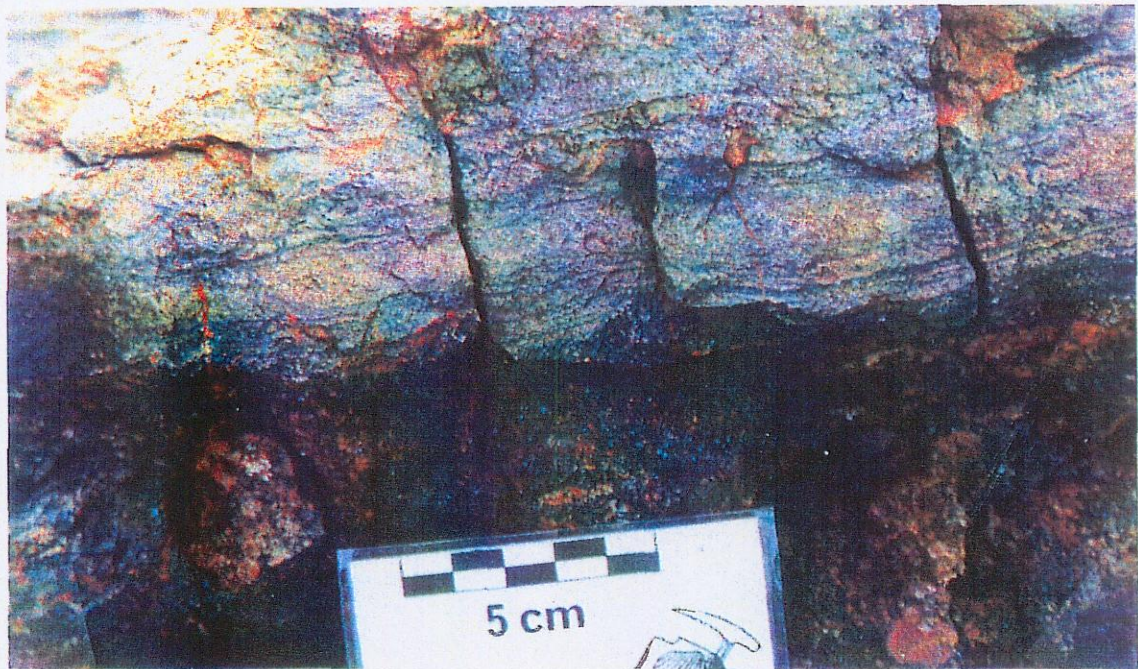
lower metamorphic grade has been found in the MWI, so the origins of the magnetite are obscure.

The nearest outcropping BIF occurs 300 km south at Tarcoola. This granulite-facies BIF is apparently more mafic than the MWI BIF as it contains quartz, magnetite, diopside, *hypersthene* and *amphibole*. It has a minimum metamorphic age greater than 2400 Ma determined from Rb-Sr analyses (Daly et al, 1978). Other BIFs of the Gawler Craton belong to the Hutchison Group and were deposited from ~1950--1860 Ma. Affinities between the BIFs at MWI and Tarcoola have been recognized by Fanning et al (1988).

### 2.2.2 Meta-conglomerate

This minor unit occurs in only three small outcrops, all at Spire Hills. Mapping suggests it may conformable with the underlying iron formation. It consists of rounded to sub-rounded quartzite clasts (5-65mm) with sub-angular to tabular clasts of haematite-rich rock resembling BIF. The matrix is aggregate quartz with hematite, tourmaline, ilmenite, clinozoisite, tremolite and rare monazite (Gilbert, 1991).

The meta-conglomerate at the Spire has several medium to coarse grained quartz meta-sandstone interbeds, 0.5 m thick. The graded conglomerate-sandstone contact rules out the possibility of an unconformity between them (see fig. 2.2).



2.2 Meta-conglomerate overlain by sandstone interbeds. Note the graded contact. The dark matrix and layering is hematite (Gilbert, 1991). Loc: The Spire, Spire Hills. Photo D.Moore

In the field the iron formation / meta-conglomerate contact is obscured. The Spire is a 4 m high, 30 x 60 m conglomerate outcrop located in the west of the Spire Hills. Here, bedding is gently folded into an open synform, with an axial plane orientation consistent with other folds in the area. Two other outcrops 500m south of The Spire have bedding parallel to the iron formation layering, although there is no gradational contact.

The origin of the meta-conglomerate is not simple. Titaniferous hematite with ex-solution rods of ilmenite suggest a high temperature origin ( $\geq 600^{\circ}\text{C}$ ), possibly associated with the nearby intrusives (Gilbert, 1991). However, the sandstone interbeds indicate a sedimentary origin, which would require a high energy depositional environment. This contrasts with the probable low energy environment of the (structurally) underlying BIF.

A Phanerozoic-Precambrian unconformity (ie meta-conglomerate unconformably overlying Precambrian BIF) is discounted because of the high temperature minerals in the meta-conglomerate (there is no known Phanerozoic metamorphism of the area). The best scenario is that the two units are separated by an Early to Mid Proterozoic non-conformity (ie layer parallel), with the high temperature mineralogy due to the regional metamorphism and/or hornfelsing.

#### **2.2.4 Other Meta-sediments**

A meta-pelite unit outcrops on the east side of Moonlight Hills and the northeast half of South Ridge. The main mineralogy is quartz, feldspar, garnet, biotite, sillimanite, cordierite and opaques (Betts, 1992). Layering is defined by alternating quartz-rich and garnet-rich layers 1-10 cm thick (Betts, 1992) with sillimanite porphyroblasts ( $\leq 1$  cm) between layers.

At South Ridge the rocks change from BIF in the southwest to meta-pelite in the northeast. Folding, migmatites and patchy outcrop obscure the contact but it is probable the meta-pelite either structurally overlies the BIF or is a facies change along strike.

Other meta-sediments include calc-silicates and marbles which have been intersected by drilling in the east of the Inlier.

## 2.3 INTRUSIVES

There are two generations of intrusives occur in the MWI and comprise approximately 60% of the outcrop.

### 2.3.1 Engenina Adamellite

The earliest intrusive is the Engenina Adamellite, which occurs at Spire Hills, Skylark Hills, Panorama Hills and South Ridge. It is foliated and porphyritic. Tabular microcline, orthoclase and plagioclase phenocrysts up to 4 cm long are mostly parallel and sub-parallel to the green-brown biotite defined foliation, which varies from strong to weak. At Spire Hills the phenocrysts are generally smaller yet more abundant than at Skylark Hills. The groundmass consists of quartz, microcline and plagioclase grains up to 5 mm wide. Lenticular aggregates of quartz and feldspar parallel to the foliation have metamorphic textures with very undulose extinction and serrated grain boundaries.

Composition varies from granitic to granodioritic, with green-brown ( $\text{Fe}^{3+}$ -rich) biotite comprising 10-15%. Accessory minerals are hornblende, sphene, epidote, zircon and opaques (mostly magnetite)(Whitehead, 1977; Betts, 1992). The intrusive character of the adamellite is shown by the abundant metasedimentary xenoliths up to one metre long and parallel to the foliation (see fig. 2.3). As well there are rounded mafic enclaves of similar size.

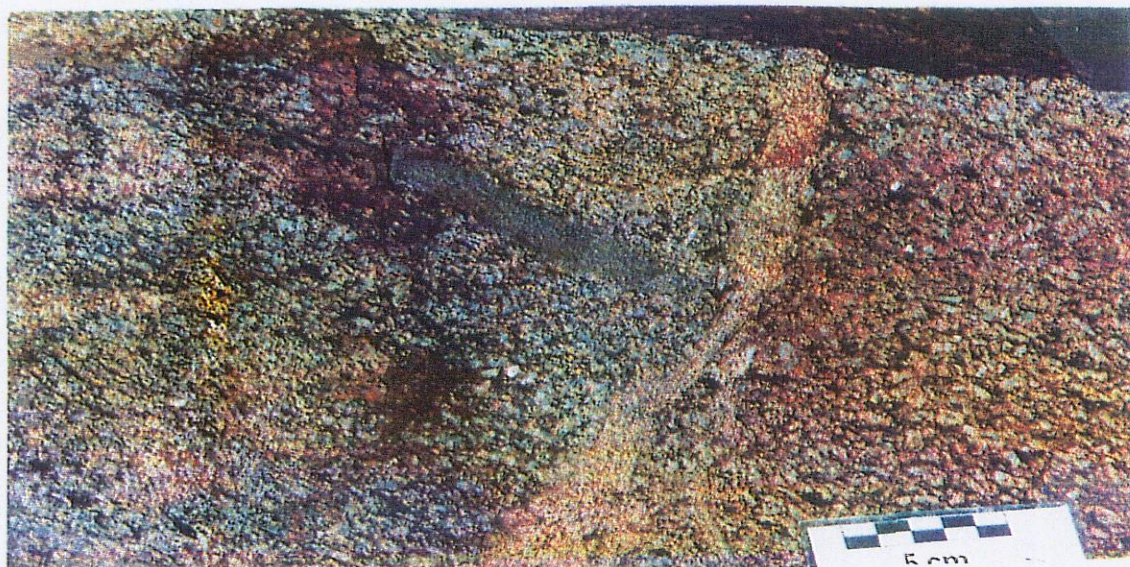


Photo: D. Moore

Figure 2.3 Engenina Adamellite, Central Spire Hills. Note the grey sedimentary xenolith just above centre is oriented parallel to the biotite foliation. Feldspar phenocrysts are parallel and sub-parallel to this foliation. A late aplite vein (pink) cuts down just right of the xenolith.

### 2.3.2 Mirage Gneiss

The Mirage Gneiss is a granitoid intrusive very similar in mineralogy and appearance to the Engenina Adamellite. It crops out only in the Mirage Hills. It consists of large phenocrysts of feldspar (microcline, orthoclase and plagioclase up to 4 cm long) and dark red to brown garnet in a quartz, feldspar, biotite matrix up to 5 mm in grainsize. The foliation varies from a weak biotite alignment to a strong gneissosity (see figure 2.4).

The porphyritic texture, adamellitic mineralogy, foliation and relatively unmetamorphosed character of the Mirage Gneiss is so similar to the Engenina Adamellite that the two units are assumed to be equivalent.



Figure 2.4 Mirage Gneiss, west outcrop, Mirage Hills. The foliation and mineral assemblage is very similar to the Engenina Adamellite, with the notable addition of garnet.



### 2.3.2 Balta Granite Suite

The Balta Granite Suite can be sub-divided into four units. (Benbow and Flint, 1979 and Betts, 1992):

- (a) Red Brick Granite
- (b) Granodiorite
- (c) Porphyritic granite
- (d) Hybrid granites

Only the Red Brick Granite outcrops in the field area at Spire Hills. This unit consists of microcline (60%-causing the distinctive red colour), plagioclase, quartz, green-brown biotite and hornblende. Grainsize varies between outcrops from fine to coarse. The feldspars range from 0.5 cm to 3 mm, with quartz slightly smaller. Texture is generally equigranular but also porphyritic in the west of the Spire Hills. Euhedral to anhedral blocky feldspars are characteristic of the unit (see fig. 2.5).

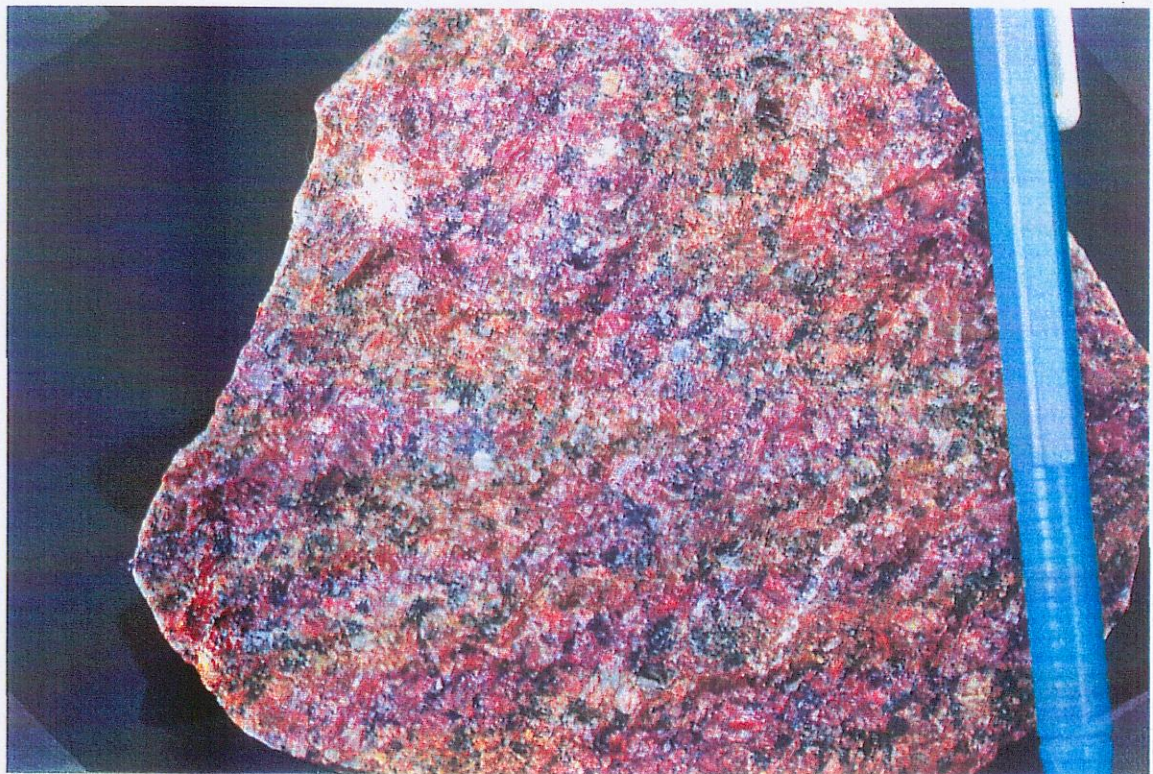


Figure 2.5 Red Brick Granite of the Balta Granitoid Suite, south central Spire Hills. Red colour due to the high microcline content (~60% - Flint and Benbow, 1977). Mafics are hornblende and biotite. (Sample No. SP12)

### 2.3.3 Dykes

Pink K-feldspar rich pegmatite dykes intrude all three field areas. At Spire Hills unfoliated dykes intrude the Engenina Adamellite and the Adamellite / iron formation contact. At the other areas the dykes are foliated, indicating that there are at least two generations of pegmatite dykes.

The main mineralogy consists of K-feldspar (orthoclase, microcline), plagioclase, quartz. Minor minerals are muscovite, garnet, tourmaline.

At the west end of Mount Woods quartz-tourmaline float suggests a large quartz vein trending north-south. Although the float shows no foliation, a nearby outcrop of BIF shows layering folding around a quartz-tourmaline vein, suggesting early formation (ie pre-folding) of the vein. It is likely the dyke has similar timing to this vein, however lack of outcrop of the vein means it is impossible to tell if it is folded.

## 2.4 MIGMATITES

Migmatite occur in the BIF in several areas of the Spire Hills, as well as at South Ridge, Moonlight Hills and One Tree Hill (Betts, 1992). At Spire Hills the origins of the melt are the Engenina Adamellite, the Balta Granite and BIF. Migmatitic melt that probably comes from the intrusives is important for determining the relationships of the intrusives to the host rocks.

The general mineralogy of all the migmatites is quartz, microcline, plagioclase and biotite. Variations on this mineralogy reflect the different melt sources. Migmatitic BIF is magnetite-rich. At Moonlight Hills and South Ridge sillimanite suggests a sedimentary source of some of the migmatites.

At Spire Hills the source of some of the migmatite can only be inferred to be adamellite because there are no adamellite pods (ie sources of melt) within the migmatite. However at South Ridge, 10 km west of Spire Hills, outcrop is better and the relationships more clear. This outcrop of BIF, migmatitic BIF, magnetite-rich pelite and Engenina Adamellite is one km long, 100 m wide and oriented northeast. At the southwest end the BIF/ migmatite/ adamellite transition shows :

- adamellite has intruded the BIF, indicated by BIF clasts in adamellite;
- adamellite was the source of at least some of the melt in the migmatite because some melt veins were large enough for the formation of the characteristic tabular feldspar phenocrysts.

The mineralogy of this migmatite is similar to the BIF and the adamellite

### **BIF-Balta migmatite**

This unit is observed in four small outcrops in the MWI, all at the south end of the Spire Hills. It is important for understanding the relationship of the Balta granite suite to the host rocks. The largest outcrop has several blobs of granitic material with large ( 0.5-1.5 cm) euhedral pink K-feldspar phenocrysts characteristic of the Red Brick Granite (see fig. 2.6).

The mineralogy of the migmatite is quartz, feldspar (orthoclase, microcline, plagioclase), sillimanite, magnetite, biotite.

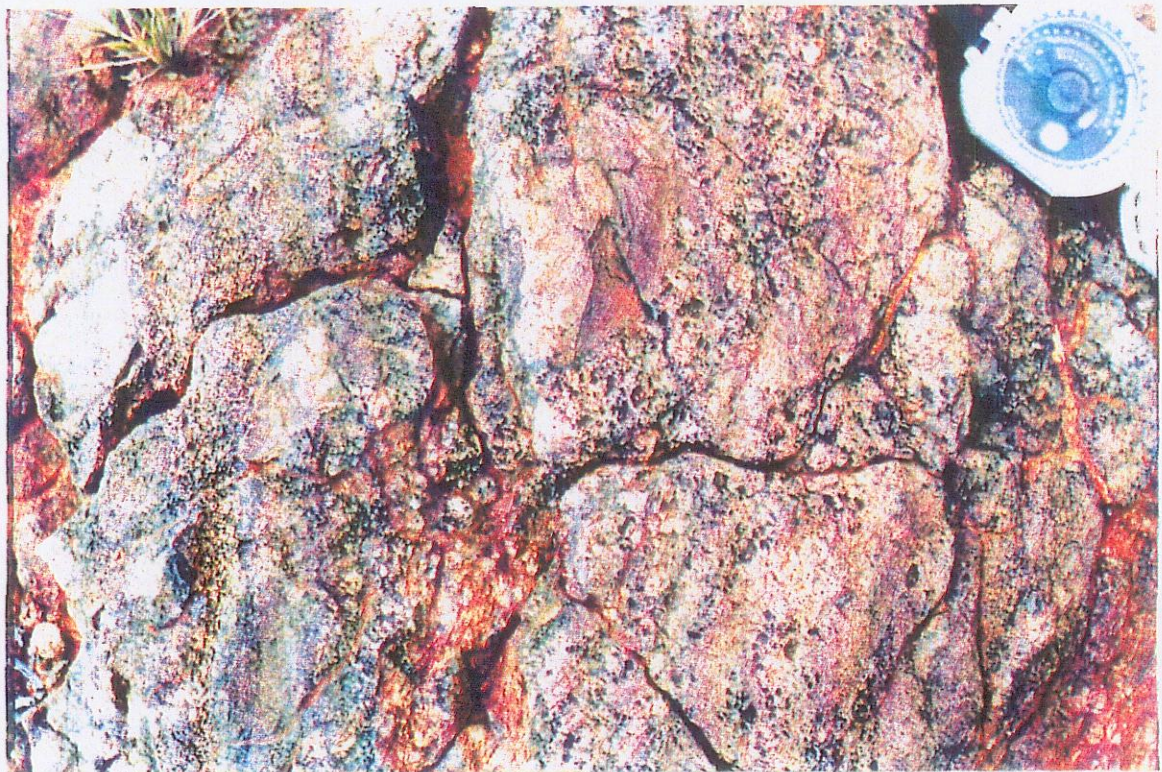


Figure 2.6 Migmatite with pink microcline phenocrysts. The adjacent Red Brick Granite pluton is the probable source of the leucosome. Very weak foliation trends east (inclined to the right up the page). Location: south central Spire Hills.

## 2.5 COMMENTS

It is perhaps simplistic to assign granitoids as S- or I-type based on mineralogy alone, as rare-earth element signatures allow a more precise insight into the crustal origins of granites. However, the mineral assemblages of the Engenina and the Balta Granitoid Suite are diagnostic enough to postulate the origins of the intrusives of the MWI, where S-type refers to S(upracrustal) and I-type I(nfracrustal), from Chappell and White (1974, 1984, 1992).

Based on the assemblage of Fe<sup>3+</sup>-rich biotite (green, green-brown), magnetite and accessory hornblende and sphene (Flint and Benbow, 1977; Betts, 1992) the Engenina Adamellite is an I-type granitoid based on criteria of Chappell and White (1992). This means a lower crustal origin is implied.

Applying the same mineralogical criteria to the Mirage Gneiss, which is similarly porphyritic, foliated and deformed like the Engenina Adamellite, suggests an S-type affinity based on the presence of garnet and therefore implies a shallow crustal magma source.

The problem created by the apparent similarities between the Engenina Adamellite and the Mirage Gneiss and the implied difference in origins must be viewed with caution. Possibly this says as much about the mineralogical basis (without geochemistry) for S- and I- type categorization as it does for magma source. However, the ?lower crustal origins of the adamellite has implications for the models for D<sub>1</sub> metamorphism discussed in chapter three.

The Balta Granitoid Suite can be classified as I-type with reasonable surety on the basis of hornblende, green-brown biotite and magnetite. This classification is common for "post-orogenic" (ie unfoliated) granites throughout the Proterozoic of Australia (Wyborn et al., 1992).

## 3. DEFORMATION, METAMORPHISM AND RELATIONSHIPS

### 3.1 SUMMARY

Figure 3.1 summarises the deformation history of the Spire Hills-Skylark Hills, Mirage Hills and Mount Woods. The summary includes dates of the Engenina Adamellite and the Red Brick unit of the Balta Granitoid Suite presented in chapter 4.

Three deformations ( $D_1/M_1$ ,  $D_2$ ,  $D_3$ ) have affected the Mount Woods Inlier.

1.  $D_1/M_1$  was a high T, low P event that produced an  $S_1$  foliation defined by sillimanite, cordierite  $\pm$  almandine garnet (Flint and Benbow, 1977).
2.  $D_2$  produced folding on scales from microscopic crenulations of  $S_1$  to macroscopic folding of metasedimentary units over tens of km. Steep fold axes and variations in fold orientations throughout the MWI appeal to fold interference (ie re-folding), which probably occurred during the subsequent  $D_3$  shearing event.
3.  $D_3$  was a shearing (+ folding) event that produced discrete zones (100's m long) and a large scale shear zone in the Spire Hills-Skylark Hills area. Kinematic indicators such as Type I S-C mylonite fabrics suggest movement was predominantly strike-slip. The discrete shear zones appear to be the result of strain caused by dextral movement on the large scale shear zone.

The Engenina Adamellite has been interpreted as intruding syn- $D_1/M_1$ , based on:

- (i) parallelism of  $S_1$  in pluton and host rocks
- (ii) identification of both a magmatic and a tectonic component of the pluton foliation, suggesting magma was subject to deformation, which continued in the adamellite sub-solidus.
- (iii) elongate pluton shapes, determined from field mapping of limited outcrop and magnetic data (presented in chapter 5).
- (iv) folding of syn-adamellite migmatite indicates the intrusion is at least pre- $D_2$ .

The Balta Granitoid Suite has been interpreted as probably preceding the D<sub>3</sub> shear deformation by a maximum of ~1 Ma. This is based on:

- (i) shear zone geometry around an irregular pluton boundary;
- (ii) folded leucocratic melt veins of granitic derivation within this shear zone show relatively mild deformation, suggesting intrusion at time of shear;
- (iii) shear zone schistosity is defined by fibrolite, indicating high T during deformation, possibly due to heat from the adjacent pluton;
- (iv) deformed granodiorite (Betts, 1992)
- (v) rate of cooling for a pluton moderate crustal levels is of the order of 0.1 - 1 Ma.  
(Paterson and Tobisch, 1992)

Preliminary Ion-microprobe U-Pb zircon dating by Fanning (1993) has given dates of crystallisation for both intrusive suites:

The Engenina Adamellite has been dated at  $1691 \pm 25$  Ma.

The Red brick Granite of the Balta Granitoid Suite has been dated at  $1584 \pm 18$  Ma.

(see also chapter 4)

From the interpretations summarised above and presented below in chapter 3, these dates constrain the three deformations of the MWI to the period between ~1700 and ~1580 Ma. Regional correlations are presented in chapter 6.

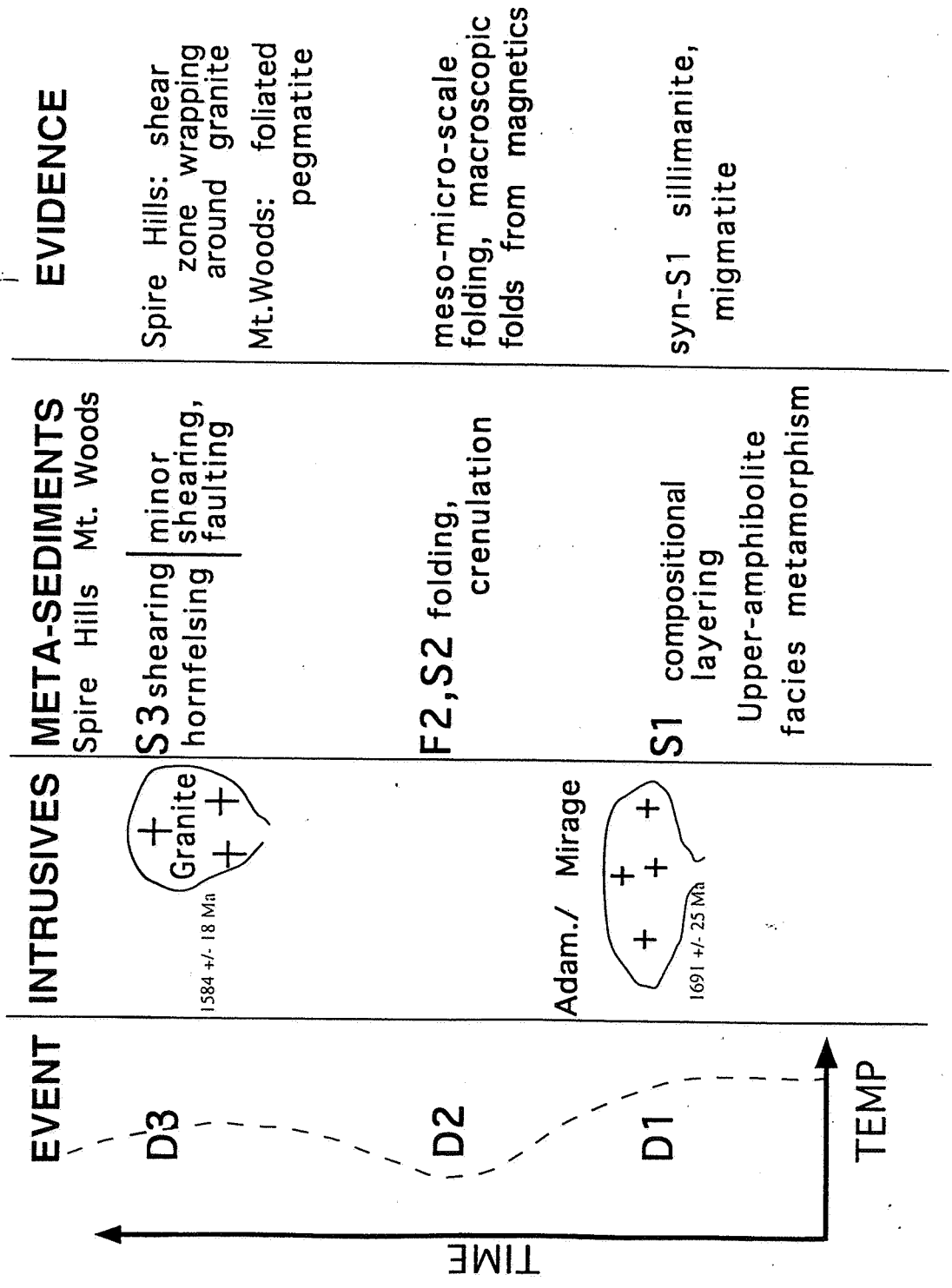


Figure 3.1 Summary of events of the Mount Woods Inlier

## 3.2 Introduction

This chapter presents data, observations and interpretations of the three field mapping areas. It forms the basis for the subsequent geochronology, timing of deformation, large scale geophysical interpretation and regional tectonic synthesis.

Three clear deformations are apparent from structures in the metasediments. D1/M1 (fabric formation and granulite facies metamorphism) and D2 (folding) are best seen at Mount Woods. The Spire Hills - Skylark Hills and Mirage Hills best show D3 (shear) and the intrusive-host rock relationships. The chapter is divided into three sections:

Section 3.3 presents the structural elements and evidence for each deformation

Section 3.4 examines the pluton - host rock relationships and relative timing of intrusion with respect to deformation.

Section 3.5 discusses the implications of the relationships between deformation and plutonism.

Previous work has shown at least three deformations occurred throughout the MWI. Benbow and Flint (1977) defined the early fabric and granulite-facies metamorphism and two subsequent deformations, one of which was an overprinting crenulation. Betts (1992) mapped the Moonlight Hills and defined three major deformations, a fourth local crenulation and a fifth minor faulting and jointing. The evidence presented below generally agrees with the previous authors.



### 3.3 STRUCTURAL ELEMENTS

#### 3.3.1 Evidence For Bedding (S<sub>0</sub>)

The meta-sediments at both Spire Hills and Mount Woods shows evidence of bedding. At Spire Hills the patchy outcrop often occurs in massive, parallel layers (10 - 100 cm thick) that are up to five metres apart suggesting a sedimentary layering. Some outcrops show banded layers (10-20 cm thick) interbedded with untextured layers (see figure 3.2). However, no sedimentary structures such as cross bedding have been found. The best evidence for bedding at Spire Hills are sandstone interbeds in the meta-conglomerate (see fig.2.2).

At Mount Woods outcrop is more continuous. There is a broad layering (0.5-1 m thick) separated by interbeds higher in biotite, sillimanite and cordierite than the more massive layers. This compositional variation is probably a depositional feature. Slight refraction of F<sub>2</sub> crenulation planes across bed/interbed boundaries reflect the compositional and competency differences.



Figure 3.2 BIF, northwest Spire Hills. Spaced layering 10-20 cm thick suggests sedimentary origins. Some textural variation between layers is evident, although granoblastic textures seen in thin section imply granulite facies metamorphism has altered original sedimentary structures.

### 3.3.2 D1/M1

An upper-amphibolite to granulite grade metamorphic event is indicated by the mineral assemblage of sillimanite, garnet and cordierite at Mount Woods and sillimanite at Spire Hills. Thin sections of iron formation from Mount Woods show layers of

quartz, K-feldspar and minor plagioclase

and

quartz, K-feldspar, biotite, sillimanite and cordierite.

Texture is granoblastic. The biotite and sillimanite occur in aggregates that are crenulated, indicating the early timing (ie pre-D<sub>2</sub> folding) of the high grade metamorphism (see fig. 3.3). This mineralogical layering, S<sub>1</sub>, is parallel to the large scale S<sub>0</sub> layering. More pelitic assemblages at the west end of Mount Woods have garnetiferous S<sub>1</sub> layers.

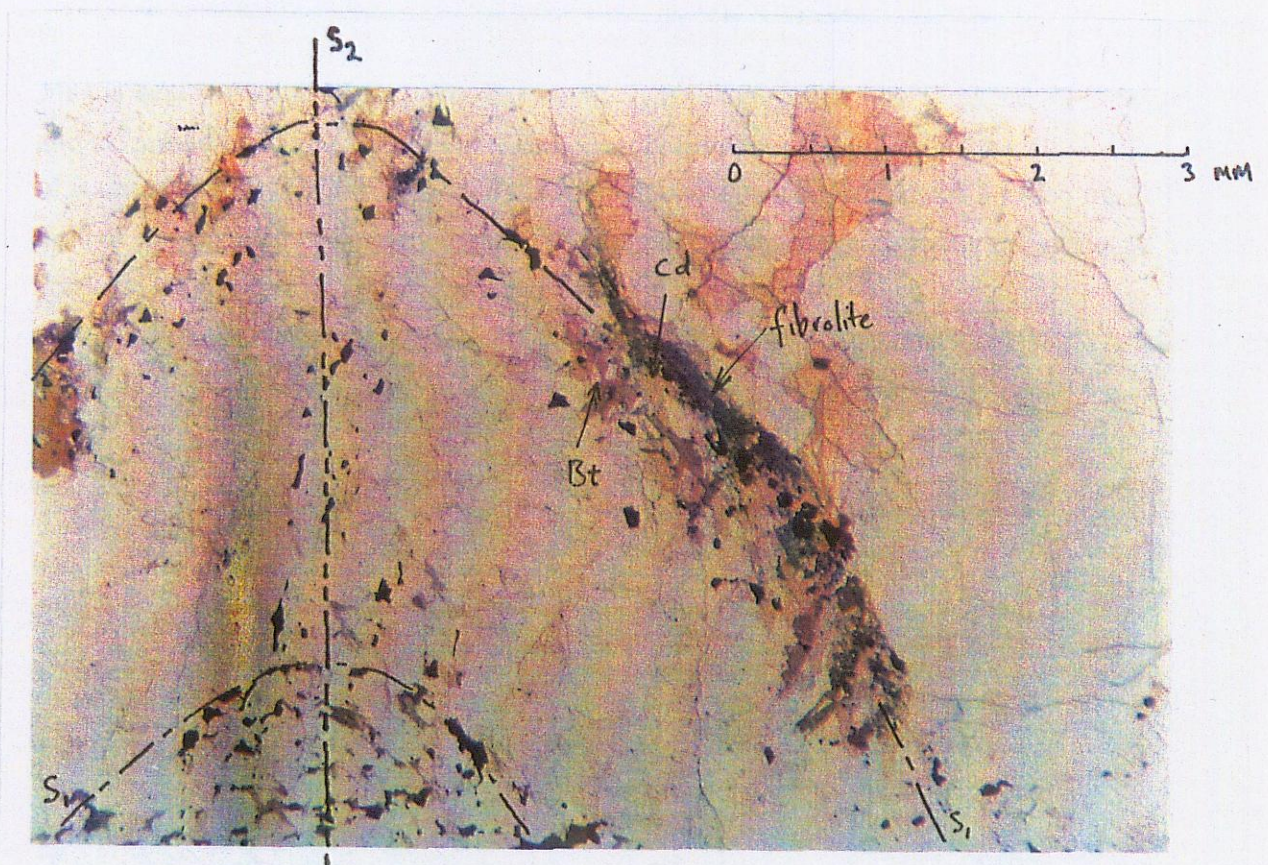


Figure 3.3 Photomicrograph (PPL) BIF, northwest Mount Woods. Aggregates of fibrolite cordierite and biotite define S<sub>1</sub>, which has been crenulated by S<sub>2</sub>. Note the biotite-rich layer (bottom left) and the quartz-feldspar layer above. Magnetite (black) trail is sub-parallel to S<sub>2</sub> suggesting syn-D<sub>2</sub> mineral growth. (Sample No. MW7)

At Spire Hills the iron formation differs from Mount Woods by increased magnetite and less biotite, sillimanite and cordierite. In hand specimen  $S_1$  occurs as light and dark layers. Thin sections show an  $S_1$  layering defined by coarse grained layers of

quartz, K-feldspar, magnetite and plagioclase  
and fine grained layers of

quartz, K-feldspar, magnetite, biotite,  $\pm$  sillimanite and cordierite.

No  $F_1$  folds are observed in thin section or at outcrop scale at Mount Woods or Spire Hills. Meta-pelites at Moonlight Hills and South Ridge exhibit a folded, sillimanite layering indicating the widespread occurrence of high grade metamorphism throughout the MWI.

### 3.3.3 D2

D2 was a major folding event throughout the MWI. Folding of meta-sediments at mesoscopic scale are inferred to be minor folds on larger folds seen in magnetic data.

This is best shown at Mount Woods, where  $S_1/0$  is overprinted by a spaced  $S_2$  cleavage and deformed into tight, steeply inclined, steeply plunging ( $F_2$ ) folds (Class 1C to Class 2 of Ramsay, 1967) (see fig. 3.4). On the microscopic scale  $S_2$  crenulates  $S_1$  (see fig. 3.3). Fold axes generally plunge southeast, but also east, south and southwest all within  $20^\circ$  of vertical (see figures 3.5 (map) and 3.6 (schematic 3D view)).



Figure 3.4 Inclined  $F_2$  folds in BIF, Mt. Woods. Asymmetric fold style at Mt Woods indicates larger folds, which are seen in magnetic data.

# Mount Woods

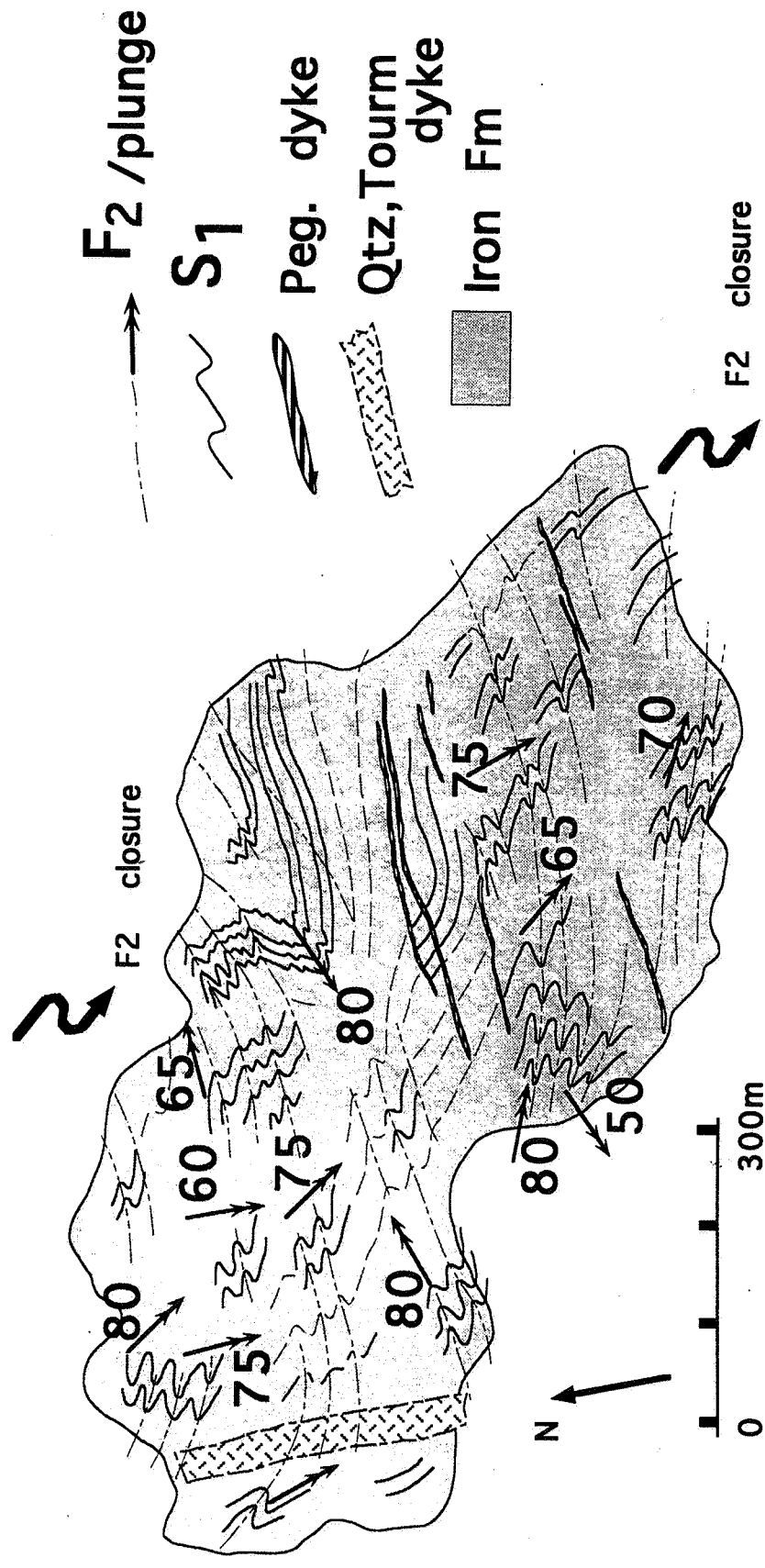


Figure 3.5 Outcrop map of Mt Woods. F<sub>2</sub> fold axial planes trend south-west, S<sub>0</sub>/1

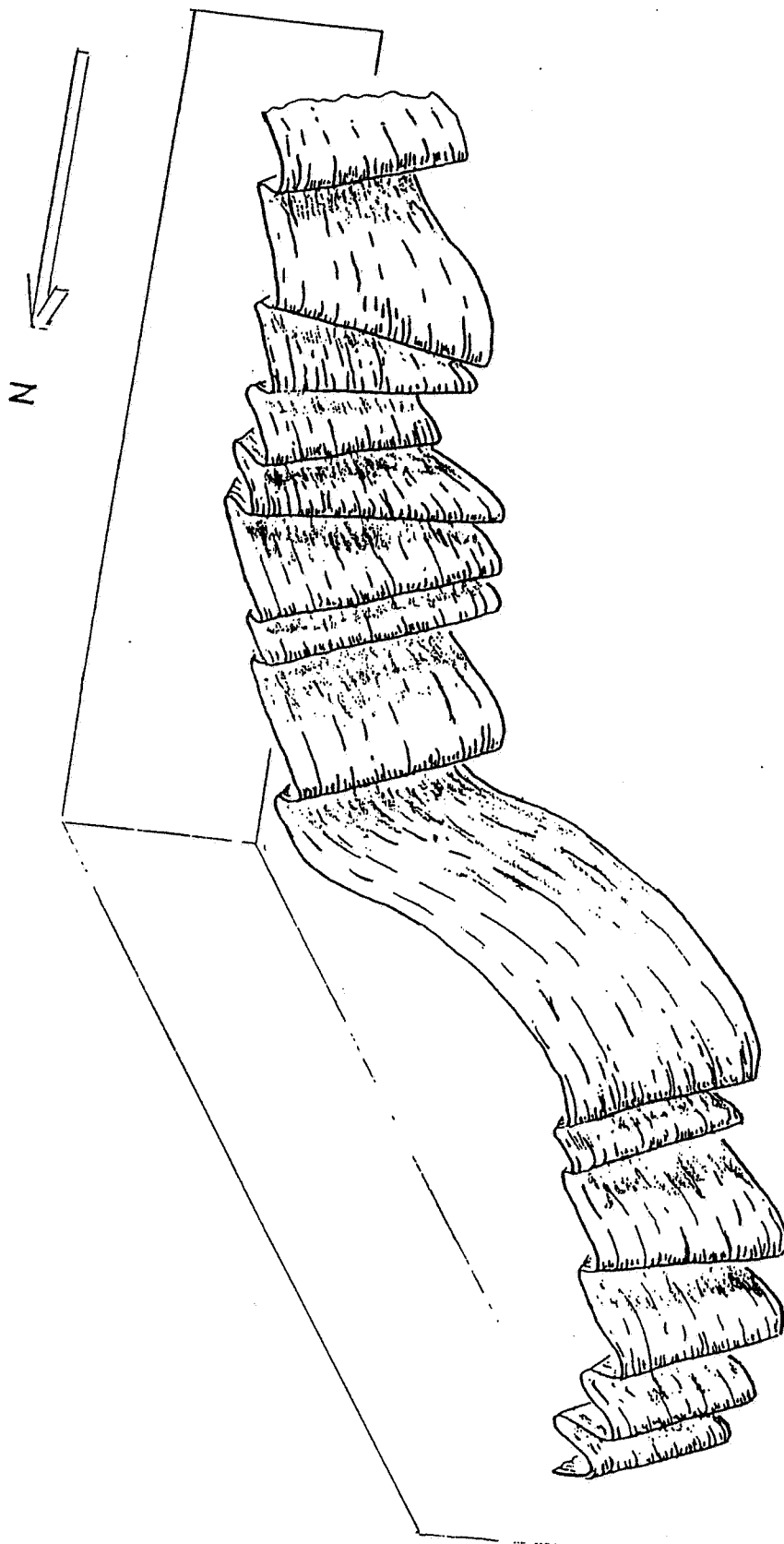
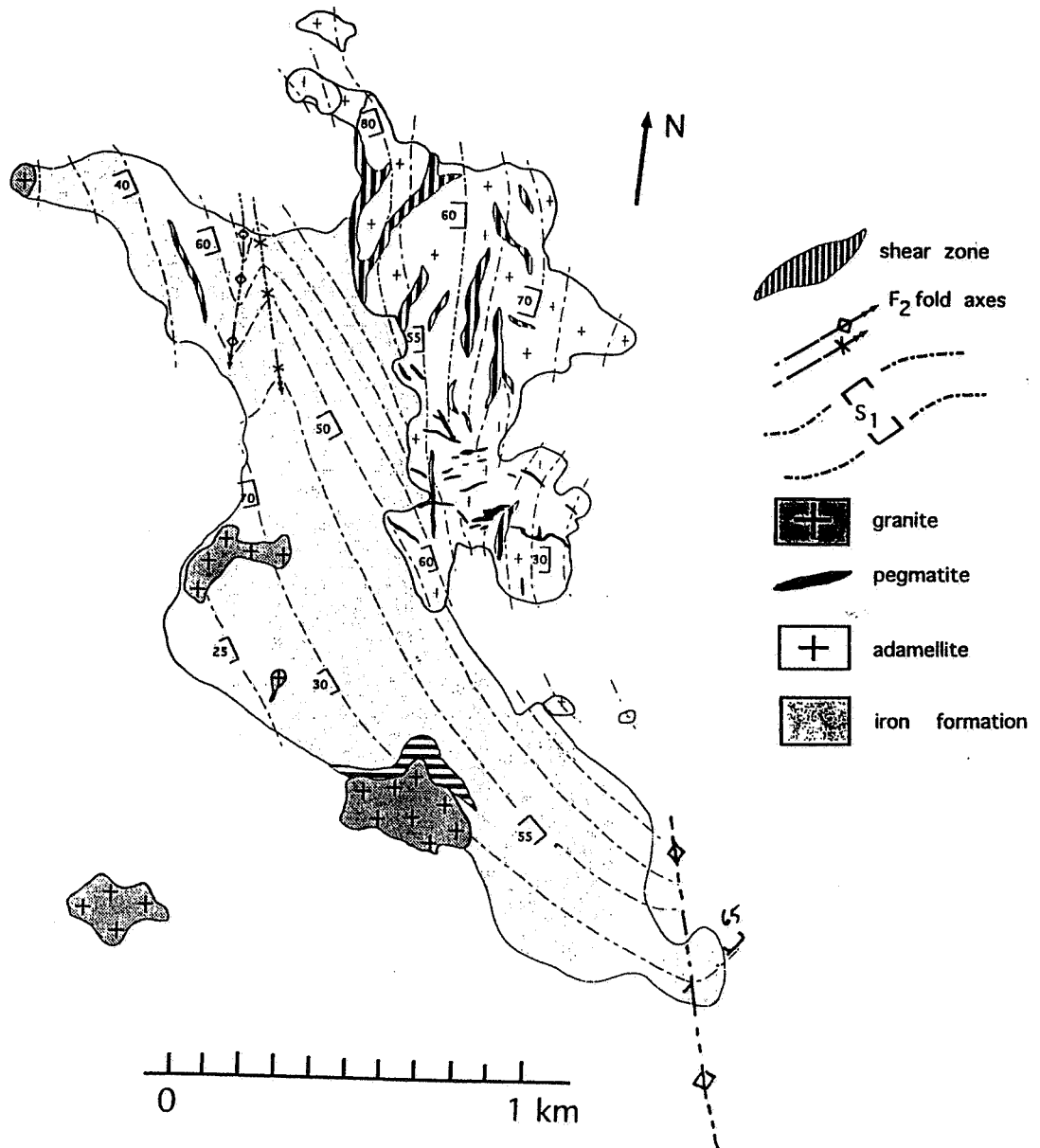


Figure 3.6: Three dimensional representation of a single layer (S<sub>1</sub>) of the Mount Woods outcrop.

The poorly outcropping BIF, migmatites and conglomerate in the northwest of Spire Hills have small scale folds ( $\leq 20$  m wide) from which larger folds ( $\sim 50$ - $100$  m wide) are inferred. Fold style is generally open to tight (class 1B to 1C of Ramsay, 1967), upright and steeply inclined to the west, with gently plunging fold axes trending north and northwest. A poorly defined  $S_2$  foliation was only occasionally seen in the field, although its rarity is probably due to poor outcrop.

In the southeast of Spire Hills the orientation  $S_1$  changes from southeast to northeast implying a broad, open anticline approximately one km wide (see fig.3.8). The interpretation of this structure is supported by vergence from the smaller folds in the northwest of Spire Hills and from magnetic data. Although no axial planar fabric was found in the very sparse outcrop the axial plane defined by limited  $S_1$  measurements is north trending and steeply dipping to the west (fold axis plunging  $53^\circ$  towards  $252^\circ$ ).

Figure 3.7 Map of the Spire Hills.



Small, rootless, isoclinal folds occur in the migmatite also at Spire Hills (see fig.3.9). It is difficult to tell whether folding occurred during D<sub>1</sub> or D<sub>2</sub> because although the compositional banding (S<sub>1</sub>) is folded, the wide variation in axial plane orientation suggest high temperature during the deformation. This implies that either D<sub>2</sub> was at high temperatures, or that an earlier folding event occurred late in D<sub>1</sub> during the high grade metamorphism.

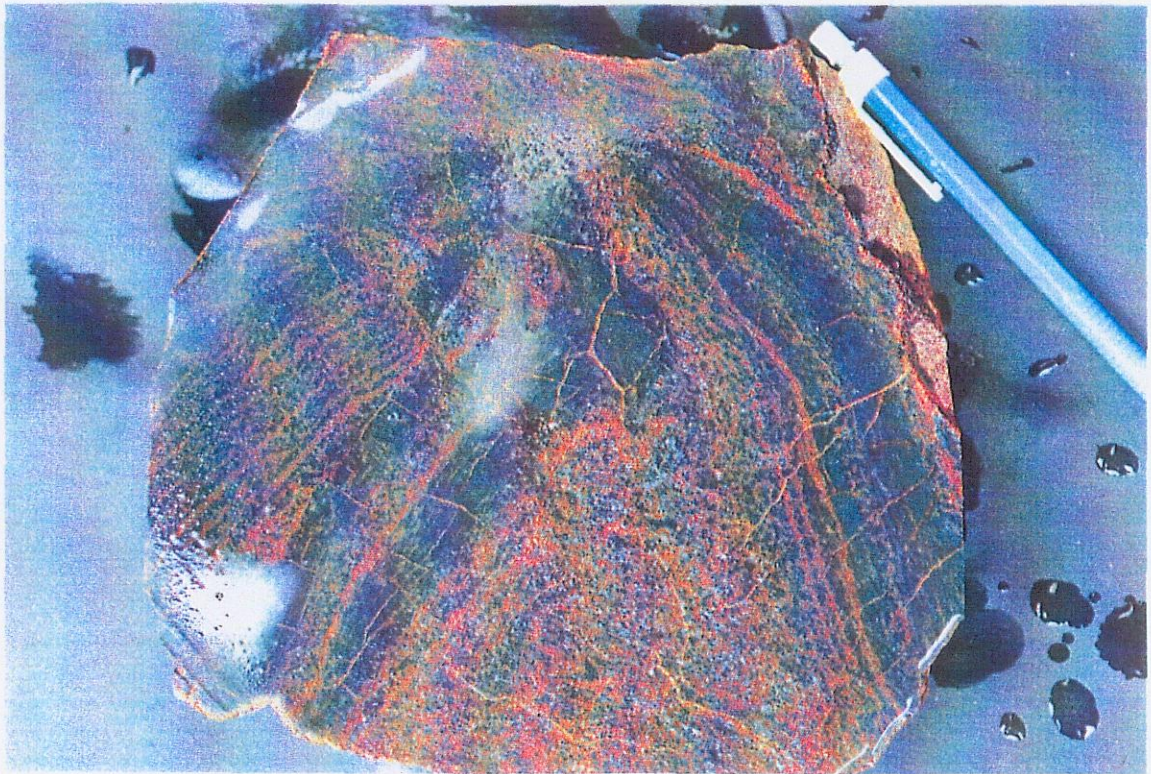


Figure 3.8 Isoclinal rootless folds in migmatite, northwest Spire Hills. (Sample No. SP24)

### 3.3 D3

D<sub>3</sub> was an event of shear zone formation that affected all three mapping areas. At Spire Hills, Skylark Hills and Mirage Hills there is significant deformation.. At Mount Woods D<sub>3</sub> is represented only by moderately foliated pegmatite dykes.

There are two types of shear zones: (1) discrete zones up to 30 m wide and 300 m long (see fig. 3.8), and (2) a single large, continuous E-W shear zone at the northern edge of the Spire Hills and Skylark Hills.

The zones are more common in the adamellite than the BIF possibly due to outcrop continuity rather than distribution of strain.

In the adamellite the shear zones generally exhibit fabrics typical of the Type I S-C mylonites of Berthé et al. (1979). Two foliations develop: (i) S-planes related to the accumulation of finite strain and (ii) C-planes related to localised high strain (Lister and Snoke, 1984). The S-planes anastomose into the more continuous C-planes. Movement sense is determined from the S- and C-plane geometry. The relative movement is determined from the angle between the S- and C-planes (see fig. 3.9)(Berthé et al., 1979). Generally the C-planes were found to be parallel to the shear zone boundaries.

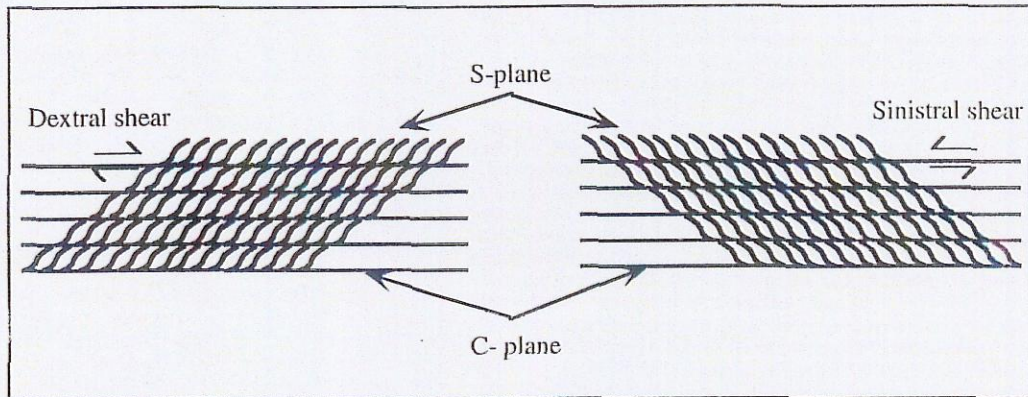


Figure 3.9 Movement sense determined from S-C plane geometry (from Lister and Snoke, 1984 and Streets, 1993)



Figure 3.10 Type I S-C mylonite fabric in Engenina Adamellite, large shear zone, northeast Spire Hills. The original S<sub>1</sub> foliation defined by biotite has formed the S-plane. Feldspar phenocrysts are generally parallel to the S-plane, but some are parallel to the C-plane striking east-west and across the page. Shear sense is dextral.



### 3.3.1 Discrete Shear Zones

The discrete shear zones are most evident in the adamellite at Spire Hills, where numerous north-south trending zones occur parallel and sub-parallel to the early, biotite-defined foliation. Shear sense varies between zones and occasionally within a single zone. Strike slip movement is prevalent over thrusting or dip-slip movement. This has been determined from rare stretching lineations and the cross-cutting relationships of the S-C fabrics. That is, for strike-slip movement, the S-C planes are clear on a horizontal surface whereas on vertical surfaces they both appear as anastomosing foliations without a clearly defined C-plane truncating an S-plane.

The amount of movement is interpreted to be relatively small because:

- (i) the included angle between S-C planes are usually high ( $> 20^\circ$ );
- (ii) there is no juxtaposition of rock types or the  $S_1$  foliation;
- (iii) the zones are discontinuous;
- (iv) shear sense varies both within a single shear zone and between adjacent zones.

In turn this implies that the discrete shear zones are a result of strain of the Spire Hills adamellite pluton, and have accommodated an overall distortion. This internal strain is probably caused by the dextral movement of the large scale shear zone (see section 3.3.2 below).

It must be noted that two narrow ( $\leq 20$  m) shear zones occur in the BIF and migmatite at Spire Hills. A strong schistosity has developed although kinematic indicators are not clear due to recrystallisation. In the southern shear zone adjacent to Red Brick Granite, the schistosity is defined by fibrolite which overprints biotite porphyroblasts. This shear zone is further discussed in section 3.4.2.

### 3.3.2 THE LARGE SCALE SHEAR ZONE

A large scale shear zone, trending east-southeast, has been interpreted from the northern adamellite outcrops along in the Spire Hills-Skylark Hills area. It is at least seven km long and 500 m wide. Essentially the shear fabrics are the same as those of the discrete zones previously described in section 3.3.1. All the northern outcrops show a dextral sense of shear with C planes striking between  $085^\circ$  and  $115^\circ$  and S planes between  $065^\circ$  and  $100^\circ$ . Small areas ( $\leq 2500$  m<sup>2</sup>) of unsheared adamellite occur within the larger areas of shear

show that strain was heterogeneously distributed. The relatively high included S-C angles indicate a moderate amount of movement. Within the SZ, highly strained pegmatite dykes, striking parallel to the C-plane cleavage, show that greater movement occurred along the dykes.



Figure 3.11 High angle S-C cleavage planes in Engenina Adamellite, large shear zone, northwest Skylark Hills. Shear sense is dextral.

It is difficult to say whether the moderately sheared rocks represent the intermediate zone between the unstrained wallrocks and more highly sheared, mylonite-type rocks that do not crop out, or that the overall structure is a shear zone of only moderate strain. Aeromagnetic data suggest that a BIF unit is present parallel to the shear zone about one km to the north of the area. It is likely that a more developed mylonite zone occurs at the adamellite / BIF contact. This will be discussed further in chapter 5 (large scale interpretation).

### **3.4 INTRUSIVE RELATIONSHIPS**

The widespread occurrence of plutonism throughout the MWI makes pluton - host rock relationships vital to the understanding of tectonics of the region.

#### **3.4.1 The Engenina Adamellite**

The adamellite has an early, biotite defined foliation and later S-C shear foliations. Evidence that the adamellite intruded the meta-sediments are sedimentary xenoliths in the adamellite and migmatite with adamellite as a melt source. The migmatite is folded so the timing of intrusion is pre-D2 (competent folding). At both Spire Hills and South Ridge the metasedimentary S1 and the early adamellite foliation are parallel. However, no folding of the adamellite foliation is evident, apart from subtle strike and dip variations (ie 20°-30° over 100 m).

#### **Timing of Intrusion and Mode of Emplacement**

What is the timing of intrusion with respect to D1/M1 (S1 foliation and granulite facies metamorphism) ? The origin of the early adamellite foliation - tectonic versus magmatic - provides implications for the timing of intrusion. If the foliation is magmatic (ie due to the flow of melt), it means the formation of the foliation may be independent of D1, and so could be pre-, syn- or post-D1. However, since D1/M1 involved granulite facies conditions, adamellite that intruded pre-D1/M1 would be re-heated to near solidus conditions which would probably destroy a pre-existing magmatic foliation. A magmatic foliation is more likely if the intrusion is syn or post D1.

#### **Evidence for both in adamellite**

The Engenina Adamellite shows evidence for both magmatic and tectonic foliation-forming processes, based on criteria reviewed by Paterson et al, (1989). To compensate for the effects of D2 folding, D3 shear and hornfelsing from the Balta granite, the samples studied were taken from adamellite away from shear zones, the pluton margins and the Balta Granite.

Indicators of a magmatic component are:

- (i) the foliation partially wraps around xenoliths and also runs into them, but the lack of strain shadows suggests magmatic origins (see figure 3.12).
- (ii) the BIF / adamellite contact and their foliations are parallel (see fig 3.7).

where a magmatic foliation is a result of magmatic flow. A definition of magmatic flow is "deformation by displacement of melt, with consequent rigid-body rotation of crystals, without sufficient interference between crystals to cause plastic deformation". The minimum amount of melt is ~30% of volume (Paterson et al., 1989).

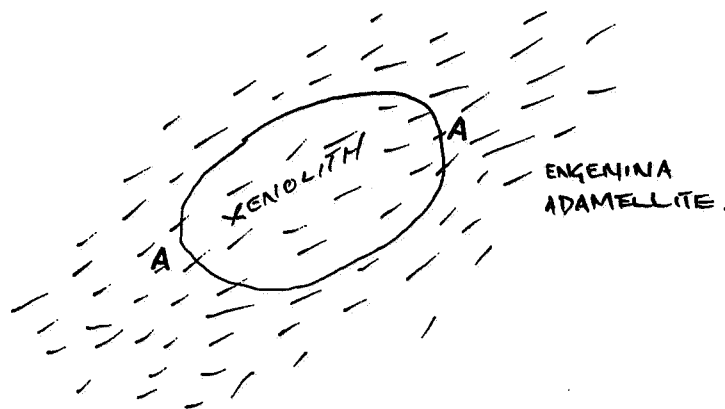


Figure 3.12 Representation of S<sub>1</sub> foliation in adamellite. Lack of strain shadows at the "A" region implies a magmatic component to the foliation.

Indicators of a tectonic component of the early foliation are:

- (i) foliation is defined by biotite rather than primary igneous minerals (ie feldspar phenocrysts), which are often sub-parallel (see fig 3.13).
- (ii) quartz and feldspar groundmass occur in lenticular undulose aggregates.
- (iii) biotite crystals wrapping around feldspar phenocrysts with strain shadows and fractures with biotite infilling cracks ( see fig.3.14).
- (iv) heterogeneous distribution of strain indicated by the variation in the intensity of the phenocryst alignment (cf figs 3.15 and 3.16, p. 36).

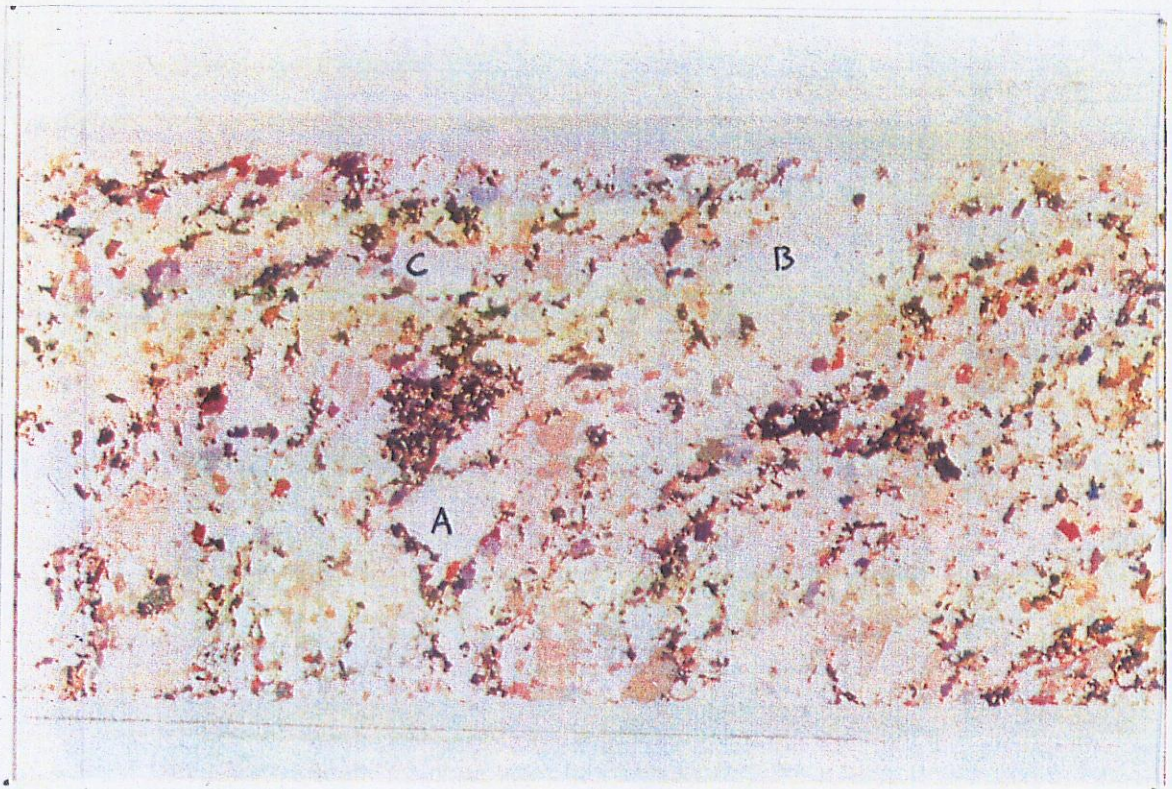


Figure 3.13 Photomicrograph (PPL) Engenina Adamellite, central Spire Hills. Biotite defines the foliation. The two large microcline phenocrysts (A and B) are fairly parallel to the foliation, however, other phenocrysts (eg C) is unaligned. Width of thin section is 2 cm (Sample No. SP8).

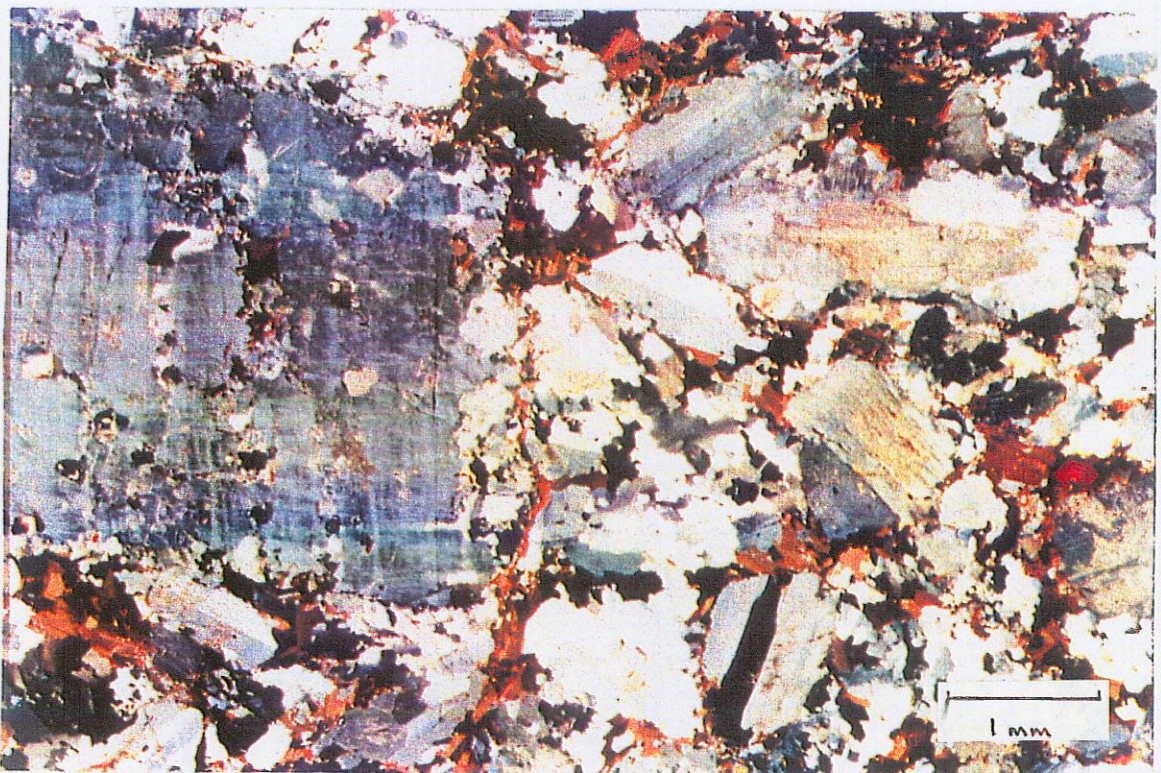


Figure 3.14 Photomicrograph (XPL) Engenina Adamellite, west Skylark Hills. Biotite wrapping around feldspar and infilling fractures in the microcline phenocryst (see top left). (Sample No. SK1)

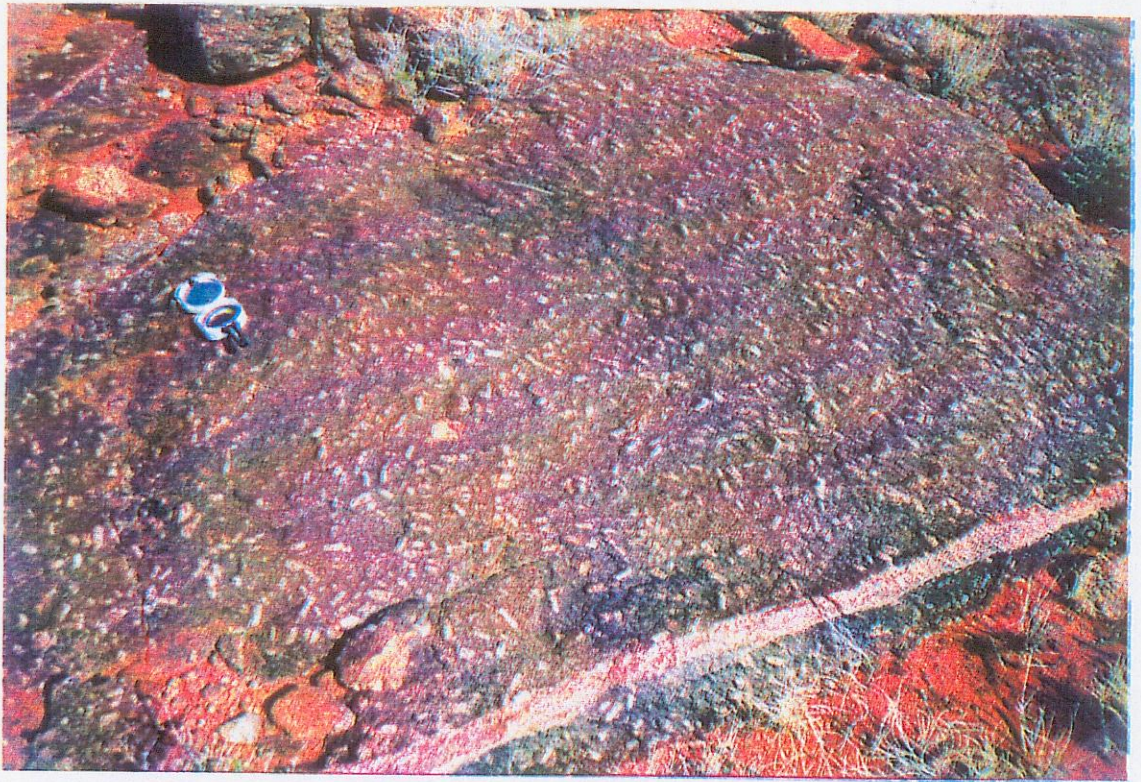


Figure 3.15 Engenina Adamellite, west Skylark Hills. Random orientation of phenocrysts.



Figure 3.16 Engenina Adamellite, south Skylark Hills. Well aligned phenocrysts.

Heterogeneous distribution of strain indicates a tectonic component to the adamellite foliation.

On this evidence it appears the foliation is the result of deformation of adamellite above and below the solidus, with the solid state component of the foliation more substantial. That is, there has been some displacement of melt, followed by solid state deformation.

This implies that the Engenina Adamellite intruded syn-D1, and that the foliations in the host rocks and the adamellite are the same generation.

Further evidence supporting the syn-D1 intrusion model is the elongate pluton shape inferred from the large scale magnetic image. This is discussed further in chapter five.

Other pluton emplacement mechanisms that produce magmatic foliations are flow during ascent and diapirism followed by expansion (ballooning) (Paterson et al., 1989). Both these mechanisms are plausible for the adamellite. However their criteria requires evaluation of the relative timing of effects such as foliation development, porphyroblast growth and macroscopic foliation trends without the complications of regional deformation (ie D1) and the lack of outcrop.

### **3.4.2 The Balta Granitoid Suite (Red Brick Granite)**

The Red Brick Granite crops out in the south, southeast and west of the Spire Hills (fig.3.7). The equigranular texture and lack of foliation suggest a non-tectonic mode of intrusion but deformed migmatites and shear zone relationships suggest the intrusion occurred around the time of the D3 shearing episode.

Undulose quartz grains in the granite indicate subsequent deformation. The surrounding migmatites have characteristic pink K-feldspar phenocrysts suggesting granite-derived melt (fig.2.6). They show increasing deformation away from the granite outcrops. Granitic pods within the migmatite are unfoliated. Granitic veins are pygmatically folded.

The southeast granite outcrop (fig.3.map) is bounded to the north by a curved, east-west trending D3 shear zone. The curved shape of the shear zone is due to the shape of the pluton and indicates deformation occurred syn or post the timing of intrusion.

The main foliation of this shear zone is a schistosity defined by layers of fibrolite (see fig.3.17), which indicates temperatures of at least 500°C during deformation (Yardley, 1989). A possible heat source was the adjacent Red Brick Granite pluton. Isoclinal folding of melt veins, with axial planes parallel to the schistosity of the shear zone imply the intrusion is late in the shear zone deformation (see fig. 3. 18).

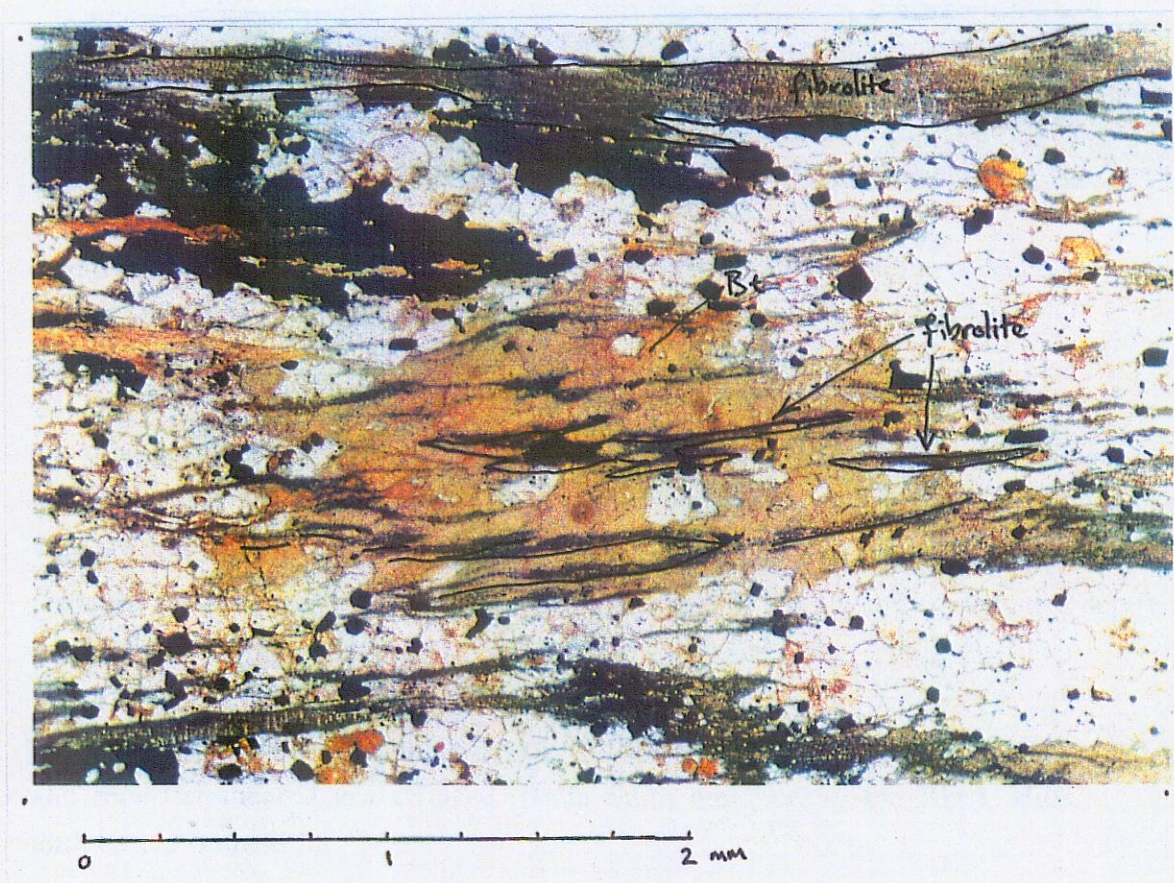


Figure 3.17 Photomicrograph (PPL) Sheared migmatite, southeast Spire Hills. Fibrolite schistosity overprinting biotite porphyroblast indicates high temperature at the time of deformation. (Sample No. SP16)





Figure 3.18 Sheared migmatite, southeast Spire Hills. Isoclinal folding of leucocratic melt vein. Axial plane is parallel to the fibrolite *schistosity* seen in figure 3.17. (Sample No. SP16)

The assemblage of this migmatite and the surrounding BIF contains the critical minerals of sillimanite and cordierite which infers high T ( $\geq 500^{\circ}\text{C}$ ), low P (4-5 kb) conditions (Yardley, 1989). It is therefore likely that the Red Brick Granite intruded at a crustal level where the pressure was  $\leq 5$  kb. A lithostatic pressure of five kb corresponds to a depth of approximately 17 km, ie mid-crustal level (from Clark and Cook, 1986).

Further evidence for the pre- to early syn-D3 timing of intrusion comes from Betts (1992), who reported sheared granodiorite (Balta Suite member) in the Black Hills, 15 km northwest of Spire Hills.

Given a cooling rate for a pluton at moderate to shallow crustal level is in the range of 0.1 - 1 Ma (Paterson and Tobisch, 1992), the timing of Red Brick Granite intrusion probably precedes the D3 shearing by a maximum of the order of one Ma.

### 3.5 DISCUSSION: IMPLICATIONS OF PLUTON - DEFORMATION RELATIONSHIPS

#### 3.5.1 D<sub>1</sub>/M<sub>1</sub> Fabric Formation, High Temperature Metamorphism and Syn-Deformation Adamellite Intrusion

The origin of the S<sub>1</sub> fabric and associated high temperature (650°-700°C) - low pressure (3-4 kb) metamorphism indicated by the mineral assemblage of cordierite, sillimanite ± almandine garnet (Flint and Benbow, 1977) poses a distinct problem: the T-P conditions can not be explained by burial at modern geothermal gradients because the depths corresponding to the temperature of metamorphism require a much higher pressure (> 10 kb) (see fig 3.20).

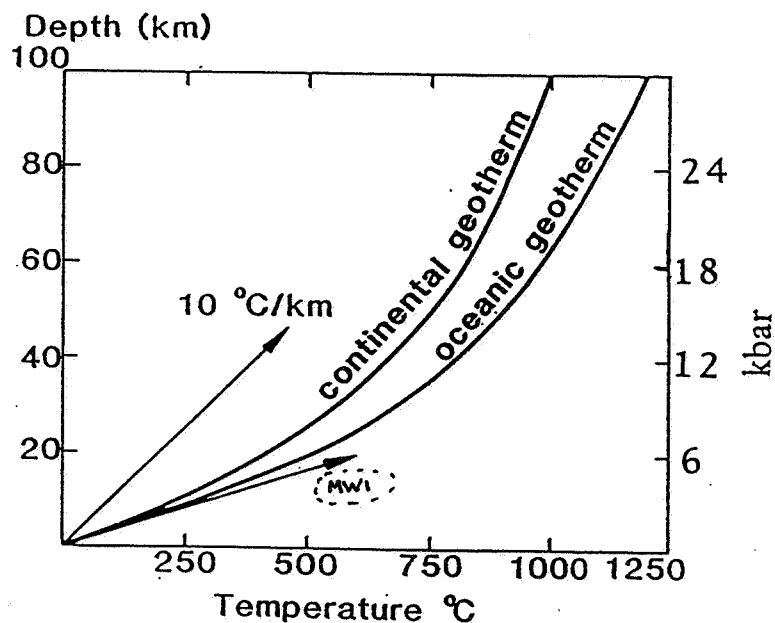


Figure 3.20 Modern geotherms for stable continental and oceanic regions. Note the T-P relative to the position of the MWI assemblage. In this case the "raised" geotherm needed to provide the elevated temperatures at low pressures would be a curve closer to the abscissa (ie raised relative to the crustal depth) (from Yardley, 1989).

Etheridge et al.(1987) have proposed a model to relate high T, low P metamorphism with tectonics.

The Etheridge model (fig. 3.21), based on the Barramundi Orogeny (~1880-1850 Ma) in the Arunta Block, is that the high T, low P conditions are a result of continental extension above upwelling zones of mantle driven by small mantle convection cells. The upwelling mantle produces underplating of the crust and high crustal level magma emplacement. The extension results in rift basins that cease prior to the formation of oceanic crust.

Underplating of the crust, together with the mantle convection and crustal heat transfer away from the upper mantle, may be sufficient to cool the upper mantle to a point where convection ceases, preventing rifting to progress to oceanic crust formation.

The mantle, now thickened by underplating, detaches from the crust (ie delaminates) resulting in subduction. This allows the intrusion of hot asthenosphere into upper crustal regions which produces crustal melting and low pressure metamorphism. In the case of the Barramundi Orogeny, compression is associated with this last stage of the model.

In terms of the geology that corresponds to this model, the sequence of events are:

- (i) initial sedimentation and volcanism associated with basin formation due to rifting, which is induced by small scale convection of the upper mantle;
- (ii) further sedimentation associated with a sag phase during thermal subsidence and initial delamination. Extension is still occurring;
- (iii) high temperature, low pressure metamorphism, intrusion of I-type granites and deformation during final delamination and detachment. Movement sense changes from extension to compression causing subsequent deformation (ie orogeny) of the high T, low P facies.

This model has much in common with the MWI in that early sedimentation (represented by the metasediments) has been regionally metamorphosed at high T, low P conditions and intruded by a syn-deformation I-type granite (ie Engenina Adamellite). The subsequent deformation (D<sub>2</sub>, ± D<sub>3</sub>) also agrees with the Etheridge model. That is, the D<sub>2</sub> (± D<sub>3</sub>) of the MWI represents the "Barramundi" stage of the model, although it may have been on a smaller scale. Note that these similarities between the Arunta and the MWI are a correlation in deformation style and not the ages of the deformations - the Barramundi Orogeny was concluded by ~1850 Ma (Etheridge et al, 1987).

Another feature of the model is the lack of MORBs and ophiolite sequences. This aspect corresponds with the MWI, but it must be noted that less than 10% of the MWI is outcrop and may not be statistically representative. Magnetic data is an important aid in this problem and is discussed in chapter five.

It is worth noting that Mortimer et al (1988) appeal to crustal growth by magmatic underplating for the south of the Gawler Craton in the Port Lincoln area near the Kalinjala Mylonite Zone.

# Mount Woods Inlier

# Arunta Block

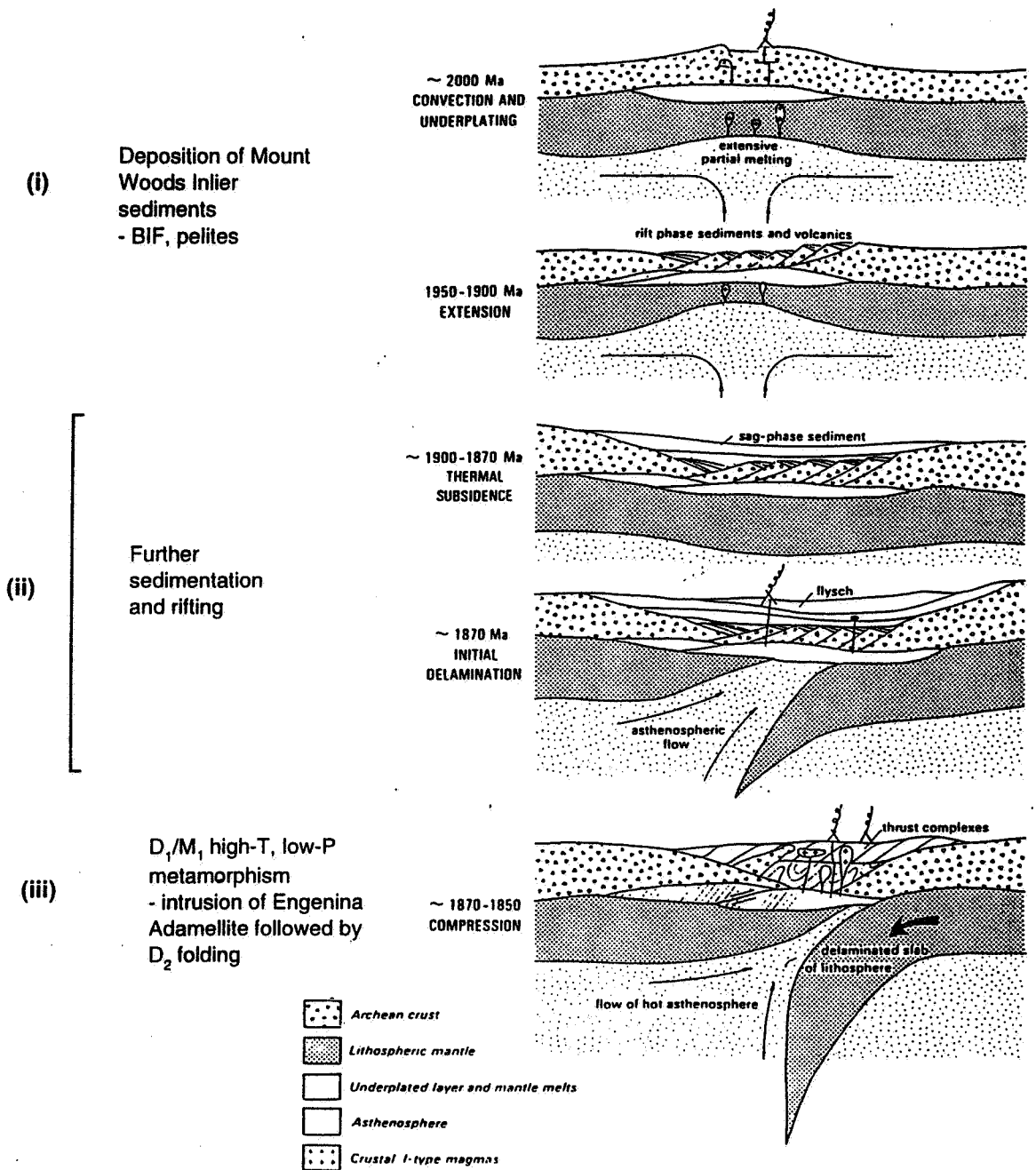


Figure 3.21 (adapted from Etheridge et al, 1987) The right side of the diagram shows a tectonic model for the evolution of Australian Early Proterozoic orogeny, based on the Barramundi Orogeny of the Arunta Block, Central Australia.

On the left is the geological history (sedimentation, metamorphism and deformation) of the MWI correlated with the tectonic model. Note that the dates in the centre relate to the Arunta Block only.

### 3.5.2 Origins of D<sub>2</sub> Fold Geometry

The D<sub>2</sub> folds throughout the MWI show a large variation in orientation and plunge (see table 3.1). D<sub>2</sub> folding alone does not explain the F<sub>2</sub> fold orientations seen at Mount Woods, Moonlight Hills and inferred in the south of Spire Hills

OUTCROP	AXIAL PLANE AZ./ DIP	PLUNGE—>PLUNGE AZ.
Spire Hills	N, NW / 90°-50°W	20°-50° S, SW,W,NW
Mt. Woods	E, SE / 90°-70° S, SW	70°-90° E, SE, S, SW, W
Sth Ridge	NE / 90° - 60° NW	60°-70° NE
Moonlight Hills*	NE / 60° - 90° NW	20°-70° SW, NW

\*Data from Betts (1992).

Table 3.1 Variations in F<sub>2</sub> axial planes and axes from the exposed geology of the MWI.

The variations in fold geometry between outcrops and often within a single outcrop (ie Spire Hills) suggest more than one folding event. Magnetic data (presented in chapter 5) show variable fold orientations on macroscopic scale and Betts (1992) reported mesoscopic and macroscopic F<sub>3</sub> folds in the Moonlight Hills.

The orientation of the Mount Woods folds could also be produced by a regional tilting of the S<sub>1/0</sub> foliation followed by D<sub>2</sub> folding.

At Spire Hills and South Ridge the folding is parallel to the adamellite contact so that it appears that the pluton has affected F<sub>2</sub> fold orientation.

On this evidence it seems likely that fold interference (ie refolding of F<sub>2</sub> folds by a later event), probably complicated by various adamellite plutons (Spire Hills and South Ridge) is the best solution to the present fold geometry.

## 4. GEOCHRONOLOGY

### 4.1 Summary

All three date samples are from the Spire Hills.

The ?syn-D1/M1 Engenina Adamellite has been dated at  $1691 \pm 25$  Ma. This correlates with a series of granitoids throughout the northwest Gawler Craton and adjacent areas, however they are relatively poorly constrained by the Rb-Sr method (Webb et al, 1986).

The early syn-D3 Balta Granite has been dated at  $1584 \pm 18$  Ma. Regional correlates are the Hiltaba Suite Granites and the Gawler Range Volcanics (Fanning et al., 1988).

A felsic granulite gneiss (host rock) has been dated at  $1736 \pm 14$  Ma

### 4.2 Introduction

This chapter presents the preliminary results of U-Pb ion microprobe zircon dating of the Engenina Adamellite and the Balta Granite by Fanning (1993). As part of this work, zircons have also been analysed from a sample of "host felsic gneiss" (SADME sample 5939 RS94, possibly migmatitic iron formation).

This dating represents a "commercial collaborative" between Mike Raetz of BHP Minerals Exploration Department, Mark Fanning of the Research School of Earth Sciences (Aust.Nat.Univ.) and Jim Finlay of Monash University.

### 4.3 Location of Samples

The location of the sample sites is shown on the field map in the back pocket.

A moderately foliated sample of Engenina Adamellite was taken from the centre of the Spire Hills outcrop (AMG co-ordinates 523320E, 6738390N).

A Balta Granitoid Suite sample was taken from the Red Brick Granite that crops out in the southeast of the Spire Hills (AMG co-ordinates 523260E, 6736790N).

The felsic gneiss sample site is located in the northwest of the Spire Hills (Parker ,1993 pers.comm).



#### 4.4 Results

The Engenina Adamellite sample has produced a crystallisation date of  $1691 \pm 25$  Ma (95% confidence limit from  $1\sigma_{\text{obs}}$ ) from preliminary analyses of seven areas in seven zircon grains (Fanning, 1993).

The Red Brick Granite sample from the Balta Granitoid Suite has given a date of crystallisation at  $1584 \pm 18$  Ma (95% confidence limit from  $1\sigma_{\text{obs}}$ ) from preliminary analyses of thirteen areas in twelve zircon grains (Fanning, 1993).

Eight areas in eight zircon grains from the felsic gneiss previously dated by Fanning et al (1988) were analysed. They have produced a date of  $1736 \pm 14$  Ma (95% confidence limit from  $1\sigma_{\text{obs}}$ ) (Fanning, 1993). The complex structure of the zircons indicates there may be two or more zircon crystallisation events (Fanning et al, 1988) and the  $\sim 1740$  Ma date may be the date of D1 metamorphism (Fanning 1993)

#### 4.5 Sample Selection

The two granitoids were chosen because they were most likely to give an accurate date of crystallization. Other rocks are perhaps more suitable structurally, such as a pegmatite dyke or aplite vein cutting across a shear zone or fold. The risk associated with these rocks is that zircons may have crystallised at any time from its origin (parent magma or country rock) to the place of intrusion.

The meta-sediments were considered less suitable than the granitoids because of the uncertainties associated with the previous ion microprobe U-Pb zircon dating of migmatitic felsic gneiss. These uncertainties are due to the indefinite timing of deposition, D1 granulite facies metamorphism and hornfelsing.

#### 4.6 Correlates

Intrusive correlates of the Engenina Adamellite from the north Gawler Craton and related areas are:

Pegmatite, Kalinjala Mylonite Zone	<i>ca</i> 1710 Ma
Augen gneiss, Ifould Lake (60 km SE Karari Fault Zone)	1667 ± 115 Ma
Burkitt Granite	1655 ± 61 Ma
Ammooradinna Inlier granitoid	<i>ca</i> 1700 Ma
Gneissic granite (Wynbring, Mulgathing and Malbooma)	1701 ± 30

by Rb-Sr method (Webb et al, 1986)

Correlates of the Balta Granitoid Suite are:

Hiltaba Suite Granites	1575 Ma
Gawler Range Volcanics	1592 ± 2 Ma

by Ion microprobe zircon analysis (Fanning et al, 1988)

## **5. LARGE SCALE COMBINED GEOLOGY & GEOPHYSICAL INTERPRETATION**

### **5.1 INTRODUCTION**

The structural geology determined from outcrop of the MWI is best put in context by geophysical analysis. Since outcrop covers less than eight percent (60 km<sup>2</sup> out of 800 km<sup>2</sup>) of the MWI, geophysical analysis and magnetics in particular is essential to understanding large scale structure. This large scale interpretation at 1:100 000 scale (see map pocket) combines the field mapping of this study, Betts (1992), Flint and Benbow (1977), the magnetic stratigraphy of Betts (1992) and geophysical data provided by BHP Minerals. Although Betts (1992) also produced a regional magnetic interpretation, it was considered necessary to re-interpret the data with the addition of more field mapping.

### **5.2 GEOPHYSICAL DATA**

The data presented below consists of a summary of the magnetic stratigraphy of Betts (1992) and the main magnetic image (combined TMI and high pass filter) used for the interpretation. The limited number of magnetic susceptibility measurements taken in the course of field work concur with the far more extensive data of Betts. Not included is the TMI image for the sake of brevity (the combined magnetic image shows similar features) or the bouguer gravity data because it essentially reflects the large scale features of the magnetic data (ie the Coober Pedy Ridge and inferred large intrusive bodies).

#### **5.2.1 Magnetic Stratigraphy**

The rocks of the MWI can be divided into high, medium and low magnetic susceptibility (see fig.5.1). The BIF with 2.3% magnetite is the most magnetic unit in the MWI. The units with medium susceptibilities consist of the Balta Granitoid Suite, the Engenina Adamellite and migmatite. With the exception of the BIF the metasediments are of low susceptibility (Betts, 1992). The magnetic response of all units corresponds to the amount of magnetite and opaque minerals in general. The exceptions to this are the meta-conglomerate and meta-pelite, in which most of the magnetite has altered to secondary hematite (Betts, 1992).

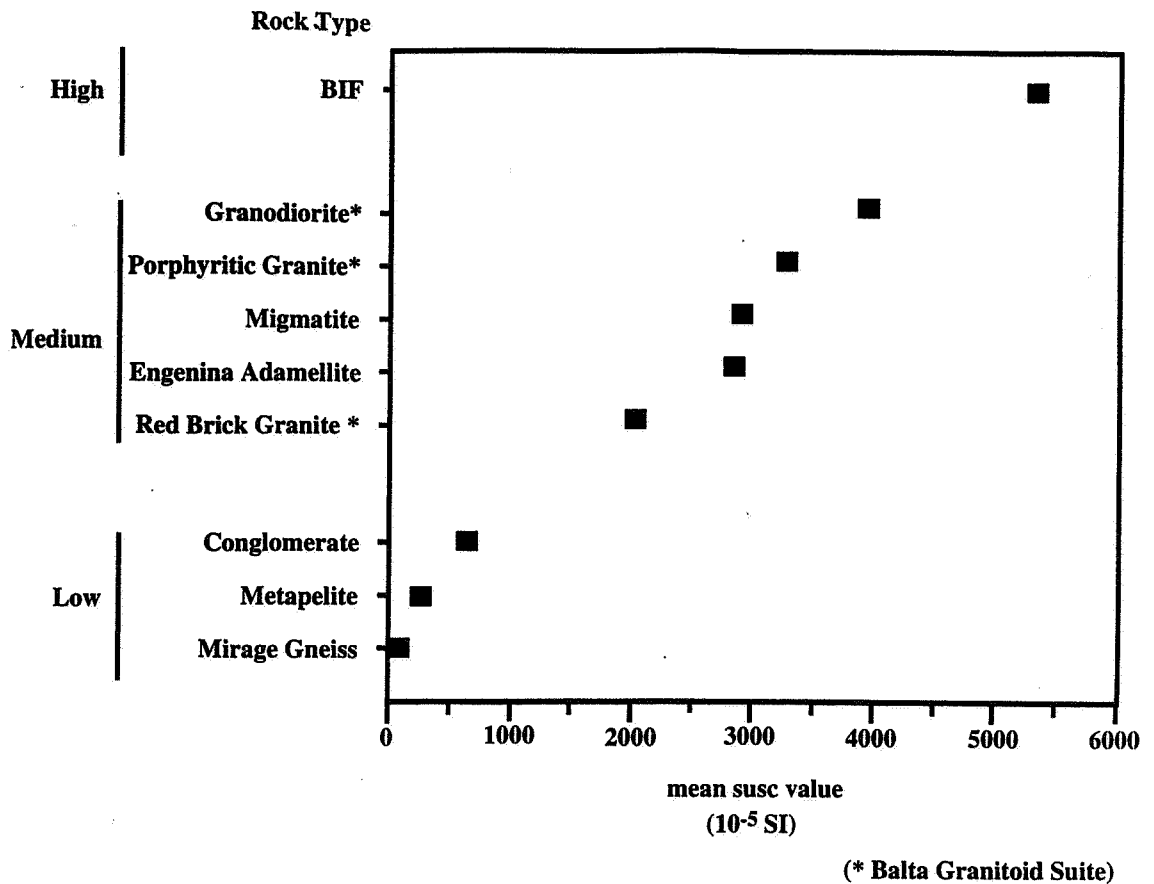


Figure 5.1 Magnetic stratigraphy showing the variation between the main rock types of the Mt. Woods Inlier. The BIF is clearly anomalous relative to other metasediments and to a lesser degree, the intrusives. Modified from Betts (1992).

### 5.2.2 Magnetic Image

The main magnetic image used for the interpretation is a combination of TMI (Total Magnetic Intensity) and high pass filter images (see fig. 5.3). The total magnetic intensity image is unfiltered data that allows interpretation of the depth of magnetic bodies (eg. plutons) from their sharpness and intensity (see fig.5.4). However, a problem with this type of image is that near surface features and structural details are missed due to high anomalies. A high pass filter image emphasizes near surface features and linear elements (see fig.5.2). The main problem with this type of image is that "noise" is enhanced, producing spurious linear features, ie "pseudo-structure". The combined image is a compromise that allows resolution of both structural detail and anomalies at depth.



TMI profile



High pass filter

Figure 5.2 The affect of a high pass filter on a magnetic profile. Note that small peaks and troughs are accentuated regardless of their overall magnetic susceptibility, so that low and high susceptibility data is enhanced.

The combined TMI/high pass filter image (see fig.5.3) is in greyscale form, displaying a distribution of grey intensities from highest to lowest values. The image merges data from various sources, which is the reason for the poor resolution in the central south of the image.

## 5.3 INTERPRETATION

### 5.3.1 Preamble

The interpreted area covers the central part of the MWI and includes all the exposed geology. The interpretation will be discussed starting with the field areas (see fig.5.3), followed by the adjacent structure and the regional structure. Note that figure 5.3 is a reduced image at 1: 500 000 that shows the field areas, the large scale interpretation area and the regional bounding structures of the MWI - it is not the interpretation itself, which is included in the map pocket.

In general the magnetic data correlates with the field mapping. Structural complexity increases with scale. On regional scale the structures that define the MWI - the east-west trending shear zone to the north and the northwest trending basin (ie graben) to the south - are readily apparent from the image (see fig. 5.3). It is the geometry and relationships of the structures on scales in between that are most difficult to interpret.

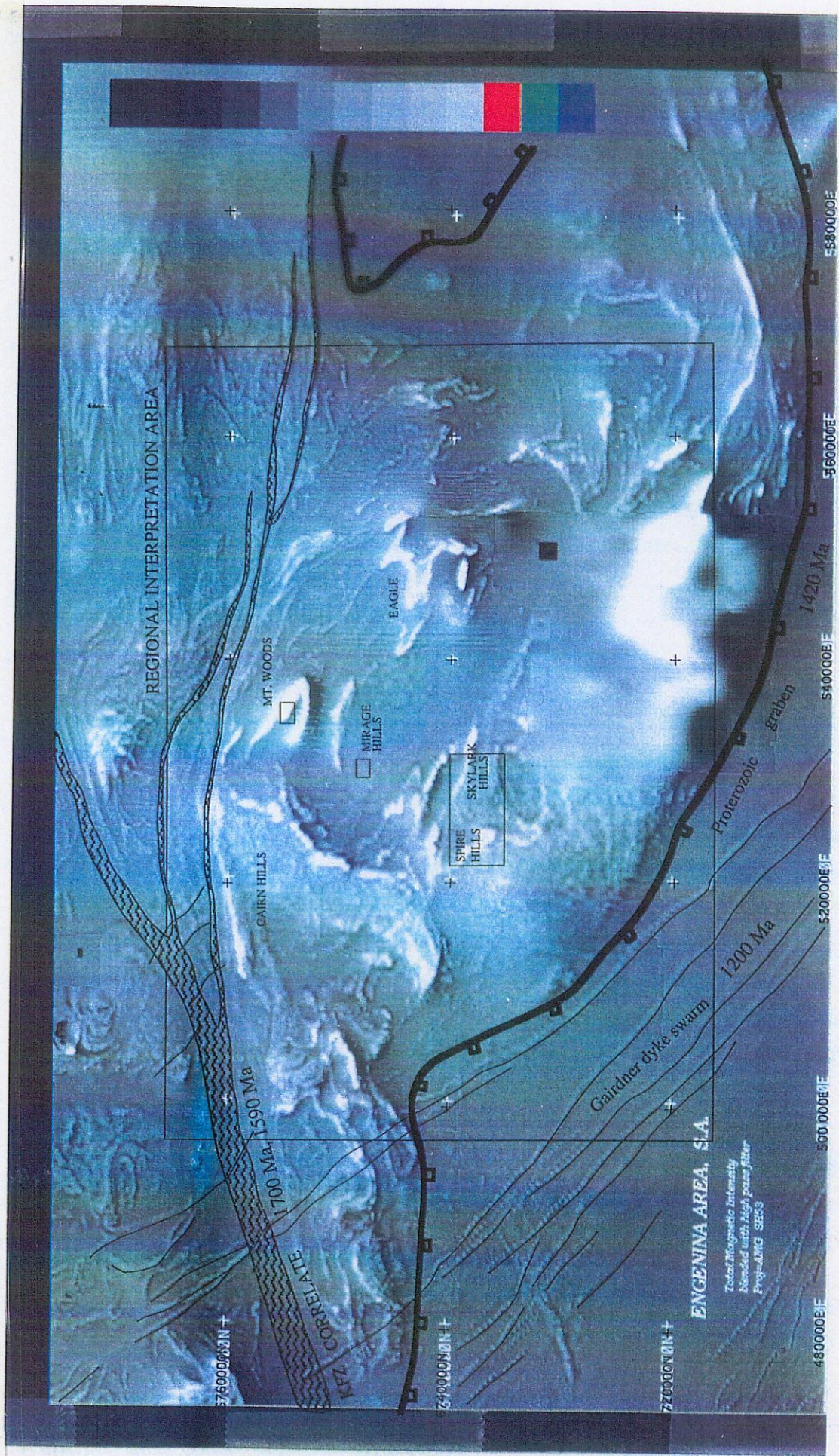


Figure 5.3 Aeromag. image showing the regional interpretation area and the 3 field areas. Note the large east-west shear zones (stippled) and post-MWI Proterozoic structures such as the graben and the overprinting Gairdner Dyke swarm (ca 1200 Ma-Parker, 1990).

### 5.3.2 The Spire Hills - Skylark Hills

The magnetic image shows the BIF units (white mag. high) folded around a series of Engenina Adamellite intrusions which dominate the area. This pattern suggests that adamellite plutons acted as stress guides during D<sub>2</sub> folding and that pluton shape affected the orientation of folding in adjacent host rocks, which in this area is the BIF. This pattern appears to be repeated throughout the MWI, particularly in the far west of the large scale interpretation. This suggests that adamellite/ BIF sequences are more common in the MWI than is indicated by outcrop.

In the southwest of the area the BIF unit trends there is north and northwest until an abrupt change to east-west trends. This change is due to the large east-west trending D<sub>3</sub> shear zone mapped in the field. North of the area folds trend east-southeast.

### 5.3.3 Mount Woods

The outcrop-to-image correlation of the area around Mount Woods highlights a recurring problem with magnetic interpretation of the MWI: this is that apparently conformable structures (such as a package of related folds) have been affected by a deformation that has re-oriented the structure in a discordant manner. The Mount Woods field map shows a BIF unit that is folded at both ends (ie north west and southeast) with a relatively straight limb section in the middle. Vergence (direction to next closure) indicates an antiform to the southeast. The magnetic image shows this closure to be several km away to the east-southeast, and so essentially agrees with the field data. However, the image also shows that several BIF units are involved, and in fact the Mount Woods unit is discontinuous. It is an adjacent BIF unit that "completes" the antiform.

This discontinuity requires shearing or perhaps a lateral facies change in the BIF to explain the abrupt loss of magnetic response. However, no straight, laterally continuous lineament is obvious from the data.

This type of problem also occurs 10 km southeast at the "Eagle" magnetic anomaly. Here a series of east-southeast trending D<sub>2</sub> folds in multiple BIF units change abruptly to strike north-south. Yet there is no consistent lineaments in this area to explain this D<sub>2</sub> fold re-orientation. Explanations must appeal to re-folding, folded shear zones and/or randomly oriented shear zones. A fourth possibility is more than one generation of shear. The most

likely solution is a combination of re-folding of D<sub>2</sub> folds combined with D<sub>3</sub> shearing. This is supported by the regional fold variations (see table 3.1, chapter 3) and by Betts (1992), who reported F<sub>3</sub> folds in addition to D<sub>3</sub> shear.

#### **5.3.4 The Mirage Hills**

The Mirage Hills are located in the centre of the MWI in a large zone of low to medium magnetism. Three small, low magnetic spots stand out from a background of lower magnetism. Immediately east are four slightly higher anomalies. The Mirage Hills consist entirely of Mirage Gneiss and are the only rocks to crop out in this huge central low magnetic zone.

It is difficult to say if the Mirage Hills represent the surrounding geology or merely intrude magnetically quiet metamorphics. On the magnetic image faint lineaments trend east-southeast conform to structural trends (fold axes, rock units) at Mount Woods, west Eagle and north of the Spire Hills-Skylark Hills area. This suggests the country rock around the Mirage Hills is metasediments. However, southwest of the MWI, dolerite dykes of the Late Proterozoic Gairdner Dyke Swarm also trend southeast. The lineaments may be these late dykes, rather than metasedimentary layering. There is little conclusive evidence either way, however I favour the metasedimentary country rock form because 10 km northwest of the Mirage Hills some lineaments appear to trend in a more northerly direction and are perhaps folded. This would indicate the lineaments are pre-D<sub>2</sub> in age and therefore metasediments.

Weak supporting evidence for the meta-sedimentary origins of the quiet region is the S-type affinity of the Mirage Gneiss (see section 2.4). The small Mirage Gneiss plutons could be the result of a shallow crustal melt forming early D<sub>1</sub> - the melt being derived from the (proposed) surrounding metasediments.

#### **5.3.5 Adjacent Areas- Plutons At Depth**

On the magnetic image the areas southwest and northwest of the Spire Hills are marked by broad highs with gradational boundaries. This style of anomaly is characteristic of deep magnetic intrusions and outcrop supports the interpretation of large Balta Granitoid plutons at depth. Two km west of the Spire Hills are the Red Hills (see fig.1.2, chapter 1), which consist of Red Brick Granite and porphyritic granite. Eight km northwest of the



Spire Hills are the granodioritic Black Hills. Although both these outcrops are small ( $\leq 4$  km<sup>2</sup> each) they are probably the surface expression of larger bodies.

This interpretation is supported by bouguer gravity data (not shown), which shows two anomalies that approximate the Red Hills and the Black Hills.

From the TMI magnetic image (not shown), the proposed depth to centre for the Red Hills pluton is about 2-3 km, and the Black Hills pluton about 1-1.5 km. This is based on the approximation of the depth of an anomaly is equal to twice the linear magnetic anomaly profile width (see fig 5.4 below)(Valenta, 1992).

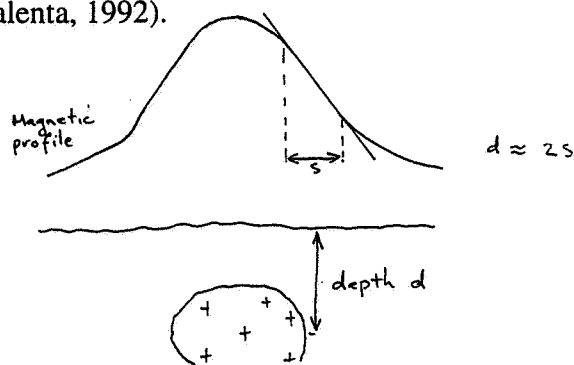


Figure 5.4 Estimation of depth of a circular magnetic body (from Valenta, 1992).

### 5.3.6 Large Scale Structural Geometry

The largest structural features (see figure 5.3) in the MWI area are:

- (i) the east-west trending regional shear zone that divides into several narrower zones to the east;
- (ii) the curved, east and southeast trending boundary in the bottom half of the combined magnetic image that separates the magnetic (and gravity) high of the MWI and magnetic low area to the southwest.

#### The Regional Shear Zone

The shear zone is defined by continuous (~20 km) medium magnetic high units and the truncation of folded magnetic units (BIF). Shear sense is not clearly defined but appears to be sinistral immediately north of Mount Woods. The northeast orientation of the zone in the northwest correlates with regional structures such as the Karari Fault Zone and related northeast trending shear zones (see also fig. 1.1).

### Southwest Boundary

The regional magnetic high of the MWI is bounded by a fairly uniform, low magnetic region. The boundary is abrupt for most of its length (> 100 km) and appears to cut off MWI units. In the west it is interpreted to overprint the regional shear zone. The whole southwest region, including the MWI is overprinted by the northwest trending (Late Proterozoic) Gairdner Dyke Swarm. The boundary is interpreted to be a graben or graben associated with the deposition of the (~1420 Ma) Pandurra Formation, which has been mapped to the southeast of the MWI (Parker, 1990).

## 6 REGIONAL TECTONIC SYNTHESIS

### 6.1 INTRODUCTION

The aim of this chapter is to put the MWI in context of the regional tectonic history and structures. It is necessary to briefly examine the various Archean and Proterozoic provinces that surround the MWI, such as the Gawler Craton, the Willyama Domain, the Musgrave Block, the Karari Fault Zone the Peake-Denison Inlier and the Ammooradinna Inlier (see fig. 1.1). A time-event diagram (fig. 6.1) is presented last in this chapter.

### 6.2 The Gawler Craton

The Gawler Craton is oval-shaped, approximately 600 x 900 km<sup>2</sup> and consists of Archean to Mid-Proterozoic rocks. Three orogenic megacycles have been recognized (figure 3) (Fanning et al, 1988).

- (i) Late Archean - Early Proterozoic sedimentation was deformed in a high grade gneiss - forming event (Sleafordian Orogeny) which concluded with granite intrusions at ~2300 Ma.
- (ii) Early Proterozoic sediments, volcanic and intrusives, together with the underlying Archean gneisses, were deformed by the Kimban Orogeny. This consisted of three deformations with D<sub>1</sub> (~1840 Ma to ~1750 Ma) and D<sub>2</sub> (≥ ~1750 Ma to ~1740 Ma) as prograde events and D<sub>3</sub> (~1740 Ma to ~1590 Ma) as a retrograde event. Only F<sub>2</sub> and F<sub>3</sub> folds are evident.
- (iii) Mid Proterozoic anorogenic magmatism and basin development. The main event was the extrusion of the Gawler Range Volcanics (~1590 Ma) followed by widespread granite intrusions at ~1570 Ma. Probably post-dating these intrusions was a mild folding event, D<sub>4</sub>, which reactivated D<sub>3</sub> folds and formed F<sub>4</sub> crenulations, probably around ~1500 Ma.

### 6.3 Willyama Domain

The Willyama Domain straddles the S.A. - NSW border and is separated from the Gawler Craton by the Adelaide Geosyncline and the Stuart Shelf. It has been informally divided into the Olary Block to the west in South Australia and the Broken Hill Block in New

South Wales (Clarke et al., 1986). For the purposes of this discussion the two blocks are considered to be the same and the term Willyama Domain includes both.

The Willyama Supergroup is characterised by high-grade metamorphic basement rocks of mainly sedimentary origin. They range from lower amphibolite to granulite facies (Glen et al, 1977). Within the lower and middle part of the sequence are considerable quantities of meta-volcanics (rhyolites, dacites, basalts) and subvolcanic intrusives (Stevens et al, 1988).

A pre-tectonic thermal event, M<sub>1</sub>, has been recognized in the low and medium grade rocks of the Olary Sub-domain by the presence of andalusite that is pre-sillimanite (D<sub>1</sub>) in age (Glen et al, 1977).

There appears to have been five deformations throughout the Willyama Domain. The first three have been assigned to the Early to Mid Proterozoic Olarian Orogeny, while D<sub>4</sub> and D<sub>5</sub> occurred during the Paleozoic Delamarian Orogeny (Clarke et al, 1986; Glen et al, 1977).

D<sub>1</sub> and D<sub>2</sub> are associated with a prograde metamorphic event, which occurred at 1660± 10 Ma (Rb/Sr date) (Stevens et al, 1988). D<sub>1</sub> is characterised by a schistosity defined by sillimanite and biotite in high grade rocks and muscovite in lower grade rocks. Isochinal, recumbent F<sub>1</sub> folds (nappes) have been inferred from various upward and downward facing beds. Mesoscopic F<sub>1</sub> folds axes trend east to north-east (Glen et al, 1977; Clarke et al, 1986).

D<sub>2</sub> produced open to tight upright folds and an axial planar schistosity S<sub>2</sub>, defined by sillimanite and biotite in higher grade rocks. Lower grade areas record only a weak F<sub>2</sub> crenulations. D<sub>2</sub> is inferred to have closely followed the D<sub>1</sub> event (Clarke et al, 1986). In the higher grade areas the conditions associated with the 1660± 10 Ma metamorphism were 650-720°C and 2-4 kb (Berry et al, 1978, in the Olary Block).

The D<sub>3</sub> event produced gentle, upright, open folds trending north-east to east-north-east with steep north-east plunges. The accompanying S<sub>3</sub> is formed by crenulating of the earlier fabrics. Retrograde shear zones are syn-D<sub>3</sub> as well as intrusion by Mundi Mundi - type granitoids, dated at 1490± 20 Ma (Rb/Sr and conventional U-Pb dating) (Glen et al, 1977; Clarke et al, 1987; Stevens et al, 1988). This retrograde deformation marks the end of the Olarian Orogeny. Further deformation, D<sub>4</sub>, occurred as mild crenulations and kinks throughout the Willyama Domain, as well as late stage shear zones on varying orientations in the Broken Hill Block (Glen et al, 1977).

## 6.4 The Karari Fault Zone

The west and north-western margins of the Gawler Craton are obscured by the Phanerozoic Eucla Basin and Tallaringa Trough. Aeromagnetic and drill core reveal several major north-east trending lineaments in magnetite-rich, upper-amphibolite meta-sediments that are the source of a 300 km long north-east trending magnetic anomaly (Rankin et al., 1989). The western most lineament is the Karari Fault Zone (see fig.6.1).

Metamorphic assemblages within mylonites suggest P-T conditions were in the range of 2-4 kb at 400-600°C, which infers crustal depths of 10-15 km (Rankin et al., 1989).

A long and varied movement history of the Karari Fault Zone is shown by kinematic indicators in mylonites, contrasting metamorphic grade and fault zone-parallel structure in overlying Palaeozoic sediments (ie the Tallaringa Trough).

Quartz-sapphirine bearing granulites on the northwestern side are juxtaposed with the upper-amphibolite gneisses (meta-sediments) imply an early (pre Kimban D<sub>3</sub>, perhaps Archaean) upthrusting of the northwest side of the fault zone (Rankin et al., 1989).

Small outcrops of deformed Early Proterozoic (Lincoln Complex) granitoid fifty km southeast of the fault zone have been dated at 1667± 67 Ma (Rb-Sr). The date has been interpreted as the time of deformation (Webb et al, 1986).

Rankin et al (1989) have interpreted the Karari Fault Zone as an intra-cratonic shear zone with downthrow of the north-west block and a sinistral strike-slip component. Although later movement of the zone is evident they have inferred that main displacement has occurred at ~1700 Ma. This correlates with D<sub>1</sub> and the Engenina Adamellite of the MWI and D<sub>3</sub> of the Kimban Orogeny.

## 6.5 The Musgrave Block

The Musgrave Block emerges from the Phanerozoic Officer Basin 400 km northwest of the MWI (see fig. 6.1). Amphibolite to granulite facies rocks are overprinted by a series of wide and very long east-west trending shear zones (eg. Mann and Hinkley Faults, Woodroffe Thrust). The granulites have an inferred minimum metamorphic Rb-Sr age of 1700 to 1600 Ma, and the overprinting fault/shear zones are dated at 1620-1600 Ma (Rb-Sr) (Parker, 1990).

(Musgrave Block continued)

In the southeast of the Musgrave the (pre-shear) gneissic fabrics of the metamorphics trend northeast, which is perhaps significant to the northeast trending Karari Fault Zone. It must be restated, however, that the northeast orientation prevales over a wide area and involves many phases of tectonism throughout the Proterozoic and the Early Phanerozoic.

### **6.6 The Ammooradinna Inlier**

About 300 km north-west of Coober Pedy lies a small, oval shaped outcrop of foliated granitoid approximately 50 km<sup>2</sup>. Magnetic data indicates the outcrop is part of a larger anomaly of about 500 km<sup>2</sup>. The outcrop, anomaly and foliation all trend northeast. The exact relationships between it and the Musgrave Block are unknown. It is believed to be ~1700 Ma old (Parker, 1990).

### **6.6 The Peake-Denison Inlier**

The ?Early Proterozoic Peake-Denison Inlier is located about 250 km northeast of the MWI. The rocks (meta-volcanics and arenaceous meta-sediments) have reached greenschist to amphibolite facies during the first of six periods of tectonism. This is represented by a schistosity and gneissosity. The schistose Wirriecurrie Granite, interpreted as syn-tectonic, has been dated at 1650 Ma using Rb-Sr (Ambrose et al, 1981).

## 6.7 Integration of Tectonic History and Structural Geometry

The three deformations of the MWI occurred between ~1720 Ma and ~1580 Ma. This coincides with (from Fanning et al, 1988; Parker, 1990):

D<sub>3</sub> (retrograde) of the Kimban Orogeny of the Gawler Province,

the Olarian Orogeny of the Willyama Domain, although direct correlation between specific deformations is unrealistic due to poor constraints on the three Olarian deformations,

major thrusting and high grade metamorphism of the Karari Fault Zone,

D<sub>1</sub>/M<sub>1</sub> amphibolite facies metamorphism of the Peake-Denison Inlier,

the poorly constrained Ernabellan Orogeny in the Musgrave Block.

Clearly this was a period of substantial tectonism over a huge regional area. It is notable that during the amphibolite-granulite facies metamorphism of the MWI, the Karari Fault Zone, the Musgrave Block, the Peake-Denison Inlier and the Willyama Block -the Gawler Craton was undergoing greenschist facies metamorphism as part of the declining stages of the Kimban Orogeny. This implies a progression of tectonism nucleating in the south and advancing north and east.

The large scale magnetic data strongly implies an association between the major shear zone north of the MWI and the Karari Fault Zone. The common dates of ~1700 for high grade metamorphism also show correlation. The interpreted thrust of the Karari Fault Zone (Rankin et al, 1989) is compatible with the compression stage of the model of Etheridge et al (1987) for high T-low P metamorphism associated with magmatic underplating, rifting and subsequent compression. As previously discussed in section 3.5, D<sub>1</sub>/M<sub>1</sub> and D<sub>2</sub> ( $\pm$  D<sub>3</sub>) of the MWI have strong similarities to this model, in particular the association of the high T, low P metamorphism, S<sub>1</sub> foliation and the syn-deformation, layer parallel intrusion of the I-type Engenina Adamellite.

The subsequent intrusion of the I-type Balta Granitoids and D<sub>3</sub> shear suggests that movement on the major shear zone occurred ~1580 Ma. This in turn implies further movement on the Karari Fault Zone after the major thrusting at ~1700 Ma.

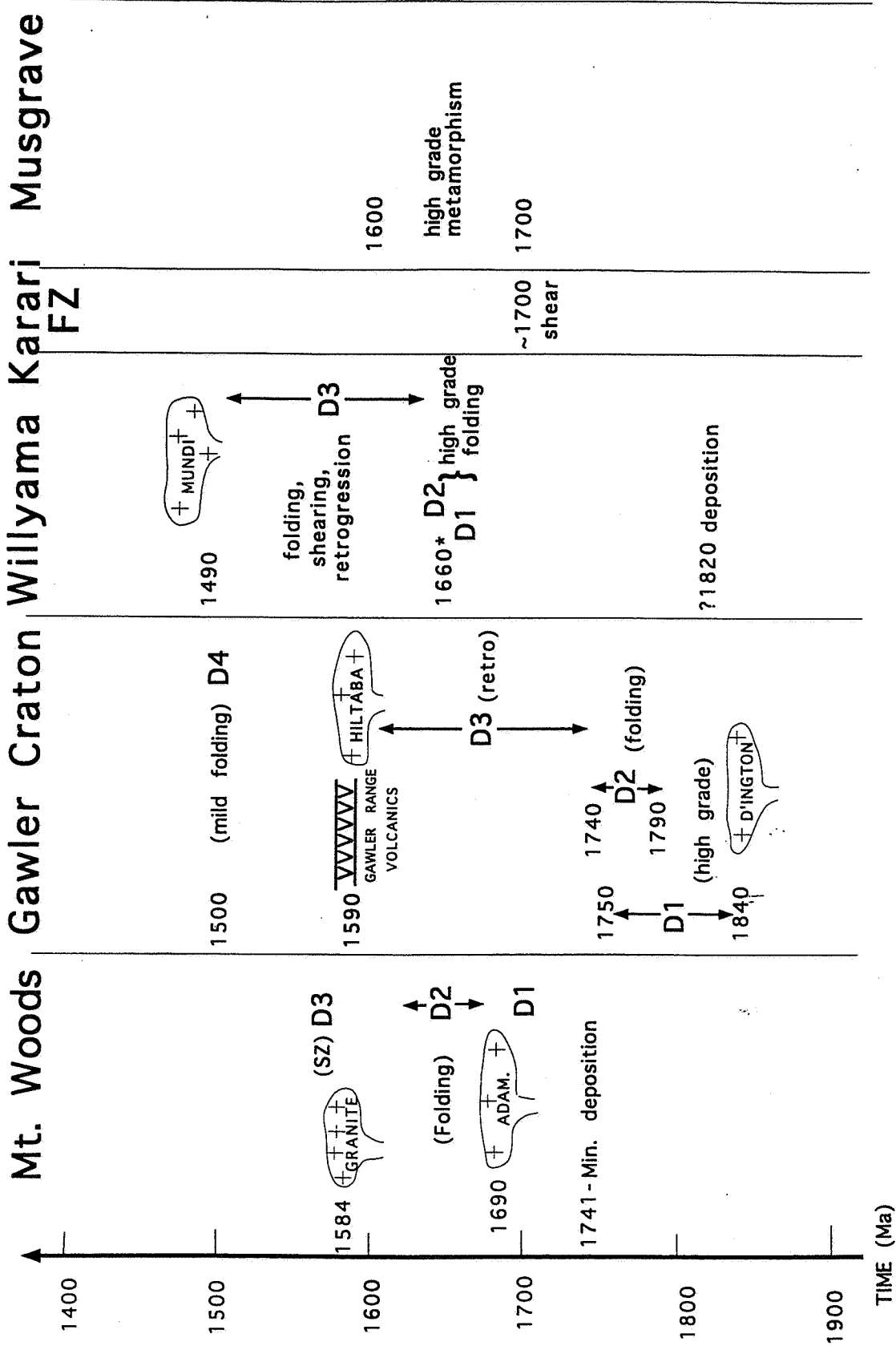


Figure 6.2 Summary of regional tectonics (from Fanning *et al.*, 1988,

Fanning 1003 and Darker 1000)



## 7. CONCLUSIONS

Field mapping has revealed structures resulting from three episodes of deformation D<sub>1</sub>/M<sub>1</sub>, D<sub>2</sub> and D<sub>3</sub>, where

D<sub>1</sub> resulted in foliation formation (S<sub>1</sub>) and Upper amphibolite - granulite facies metamorphism represented by the high temperature, low pressure assemblage of sillimanite, cordierite ± almandine garnet (Flint and Benbow, 1977).

Probably syn-D<sub>1</sub>, and definitely pre-D<sub>2</sub>, was the intrusion of the Engenina Adamellite. The parallelism of S<sub>1</sub> in the adamellite, S<sub>1</sub> of the host metasediments and the pluton / host rock contact suggest the adamellite to be intimately related to and possibly causing the high grade metamorphism.

The Engenina Adamellite has been dated by ion-microprobe U-Pb zircon analysis at 1691 ± 25 Ma (Fanning, 1993). This is a minimum age on the metamorphism of the sediments and a maximum age on the D<sub>2</sub> folding event.

D<sub>2</sub> produced folding on scales from microscopic crenulations of S<sub>1</sub> to macroscopic folding of metasedimentary units over tens of km. Steep fold axes and variations in fold orientations throughout the MWI appeal to fold interference (ie re-folding), which probably occurred during the subsequent D<sub>3</sub> shearing event.

D<sub>3</sub> resulted in shear zone formation throughout the Spire Hills, Skylark Hills and the Mirage Hills. Discrete shear zones in the Engenina Adamellite indicate internal compensation of strain due to a large dextral shear zone trending east-west in the north of the Spire Hills-SKylark Hills area.

Sheared migmatite related to the Balta Granite indicate the timing of intrusion was pre- to early syn-D<sub>3</sub>. The S<sub>3</sub> schistosity defined by sillimanite in this migmatite indicates high temperature at the time of D<sub>3</sub> was probably related to hornfelsing from the Balta Granite. This implies D<sub>3</sub> occurred within one Ma of the time of intrusion.

The Red Brick Granite member of the Balta Granitoid Suite has been dated by ion-microprobe U-Pb zircon analysis at 1584 ± 18 Ma. This date correlates with Hiltaba Granites and the Gawler Range Volcanics (Fanning, 1993). This is a minimum date on the D<sub>2</sub> folding event and probably the D<sub>3</sub> shearing event.

The three deformations of the MWI therefore occurred between ~1720 Ma and ~1680 Ma.  
This coincides with:

D<sub>3</sub> of the Kimban Orogeny of the Gawler Province,

the Olarian Orogeny of the Willyama Domain, although direct correlation between specific deformations is unrealistic due to poor constraints on the three Olarian deformations,

the Karari Fault Zone,

D<sub>1</sub>/M<sub>1</sub> amphibolite facies metamorphism of the Peake-Denison Inlier,

the poorly constrained Ernabellan Orogeny in the Musgrave Block.

Magnetic data show the MWI is truncated to the north by a strong, east-west trending lineament (ie fault/shear zone) that appears to be associated with the intracratonic, northeast-trending Karari Fault Zone. The principal movement (downthrow of northwest) and amphibolite facies metamorphism in this zone has been interpreted to be ~1700 Ma (Webb et al., 1986; Rankin et al., 1989), which correlates with the intrusion of the Engenina Adamellite and probably with the high grade D<sub>1</sub>/M<sub>1</sub> event of the MWI.

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**APPENDIX Sample location, mineralogy, method.**

Sample No.	Rock type	Location	Mineralogy	Thin section	AMG east/north
Spire Hills (SP)					
SP1	Adamellite	NE Sp.H	K/f.spar,plag,bi	Y	
SP2	meta-SS	W.Sp.H	qtz,hem,kspar	N	522830/6737820
SP3	meta-conglom.	W.Sp.H	qtz,hem,kspar,silli	N	" /"
SP4	migmatite	NW Sp.H	qtz,fspar,sill,bi,mag	N	523260/6736790
SP5	Adam/xeno	E.Sp.H	K/f.spar,plag,bi	N	
SP6	pegmatite	" " "	Kspar, plag,qtz,bi	N	523320/6738390
SP7	adamellite. (date sample)	" " "	K/f.spar,plag,bi	N	523320/6738390
SP8	adamellite	" " "	K/f.spar,plag,bi	Y	523320/6738390
SP9	adamellite	" " "	K/f.spar,plag,bi	Y	523320/6738390
SP10	pegmatite	" " "	Kspar, plag,qtz,bi	N	523320/6738390
SP11	Red B. granite (date sample)	SE Sp.H	Kspar, plag,qtz,bi,hbl	N	523260/6736790
SP12	Red B. granite	SE Sp.H	Kspar, plag,qtz,bi,hbl	Y	523260/6736790
SP13	migmatite	" " "	qtz,kspar,sill,bi,mag	N	523260/6736790
SP14	migmatite	" " "	qtz,kspar,sill,bi,mag	N	523260/6736790
SP15	migmatite	" " "	qtz,kspar,sill,bi,mag	N	523260/6736790
SP16	migmatite	" " "	qtz,kspar,sill,bi,mag±cd	Y	523260/6736790
SP17	Adamellite	N.Sp.H	K/f.spar,plag,bi	Y	
SP18	Adamellite	N.Sp.H	K/f.spar,plag,bi	N	
SP19	Adamellite	N.Sp.H	K/f.spar,plag,bi	Y	523000/6737860
SP20	Adamellite	N.Sp.H	K/f.spar,plag,bi	Y	523100/6737820
SP21	Hbl.adam	N.Sp.H	K/f.spar,plag,bi,hbl	N	523100/6737820
SP22	BIF	NW Sp.H	qtz,kspar,bi,mag	Y	
SP23	BIF	NW Sp.H	qtz,kspar,bi,mag	N	
SP24	Migmatite	NW Sp.H	qtz,kspar,bi,mag	N	
SP25	Meta-SS	W.Sp.H	qtz,kspar, Mu	N	522830/6737820
SP26	Migmatite	SW Sp.H	qtz,plag,kspar	N	
SP27	R.Br.Granite	SW Sp.H	kspar,qtz,bi,±hbl	Y	



### Skylark Hills (Sk.H)

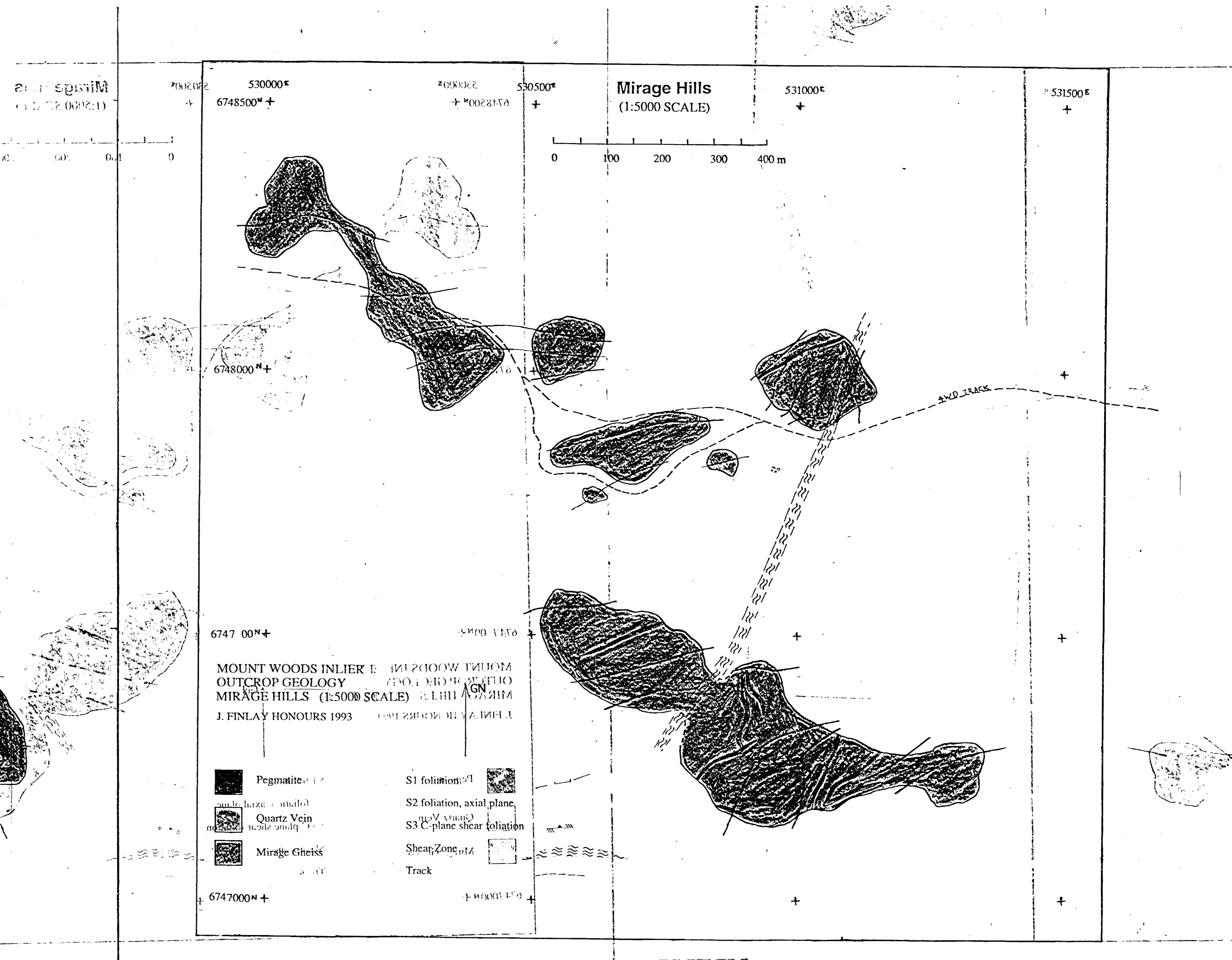
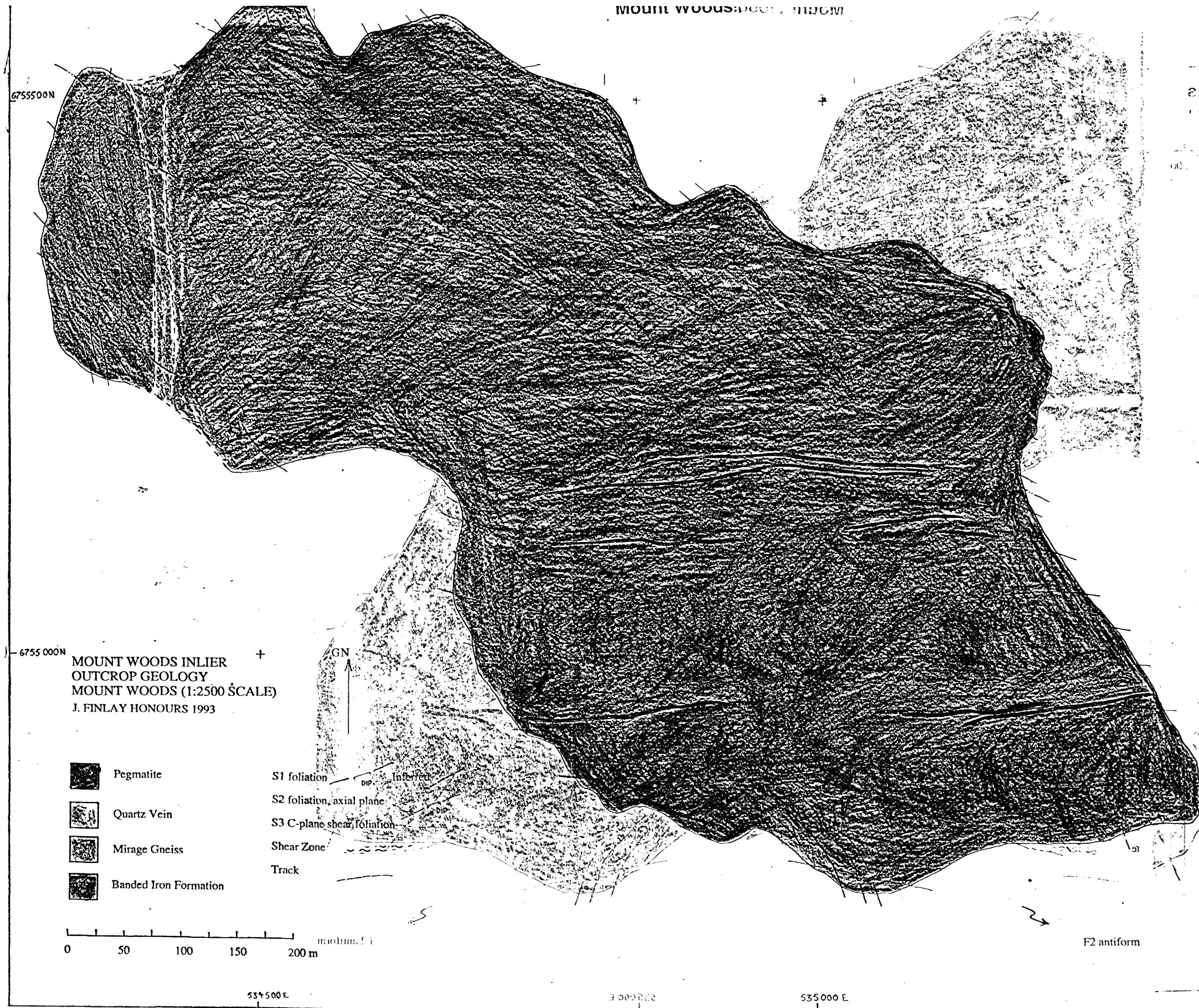
SK1	Adamellite	NW Sk.H	K/f.spar,plag,bi	Y
SK2	Adamellite	NW Sk.H	K/f.spar,plag,bi	Y
SK3	Adamellite	NW Sk.H	K/f.spar,plag,bi	Y
SK4	Adamellite	E Sk.H	K/f.spar,plag,bi	Y
SK5	Adamellite	E Sk.H	K/f.spar,plag,bi	N
SK6	Adamellite	N Sk.H	K/f.spar,plag,bi	N
SK7	Adamellite	NW Sk.H	K/f.spar,plag,bi	N
SK8	Adamellite	NW Sk.H	K/f.spar,plag,bi	N
SK9	Adamellite	NE Sk.H	K/f.spar,plag,bi	Y
SK10	Adamellite	NE Sk.H	K/f.spar,plag,bi	Y

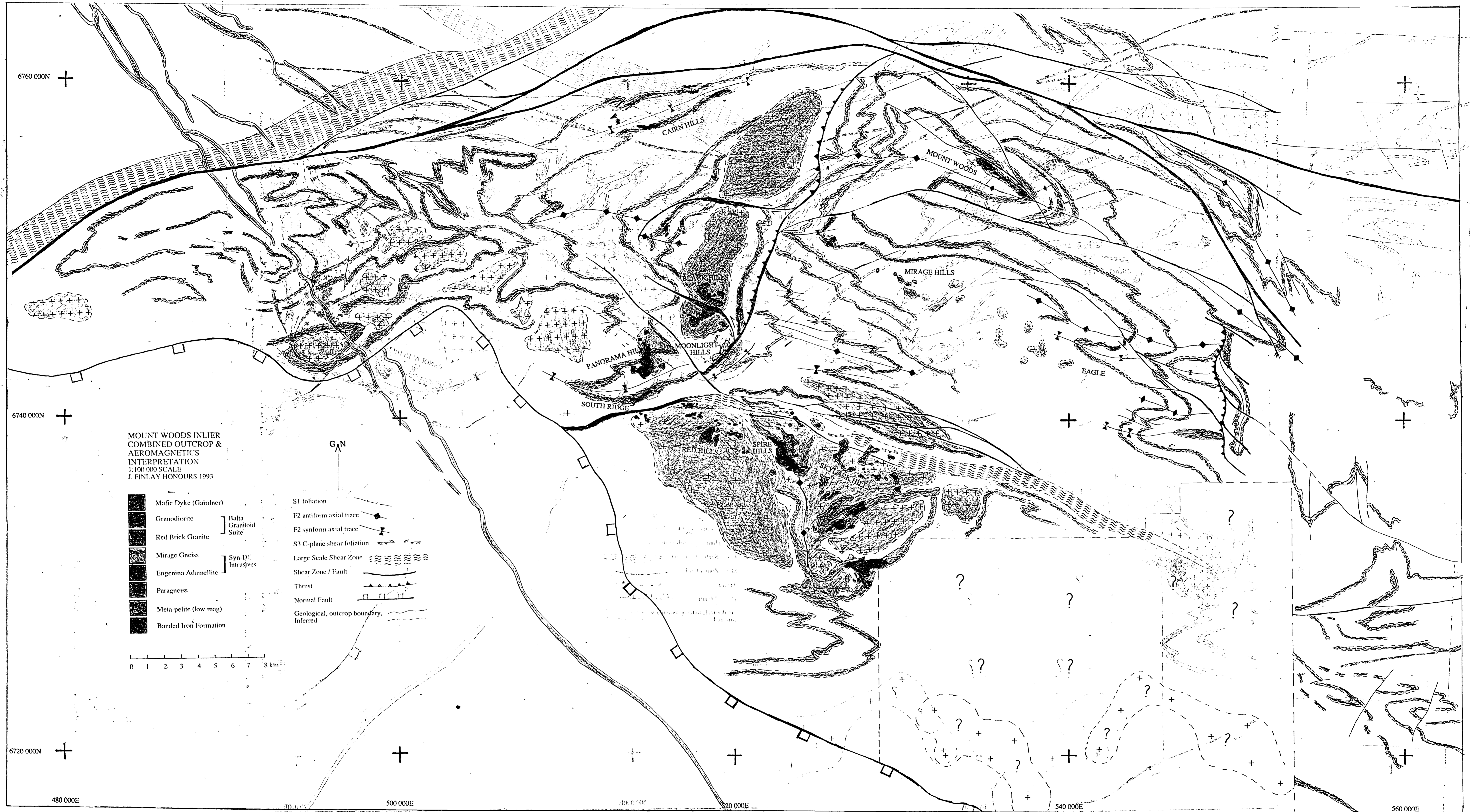
### Mount Woods (MW)

MW1	BIF	NE	qtz,kf,sil,bi,cd,mag	Y	534940/6755300N
MW2	BIF	W	qtz,kf,bi,cd,mag	Y	
MW3	BIF	N	qtz,kf,sil,bi,cd,mag	Y	535090/6755300
MW4	Garnet pelite	central	qtz,kf,sil,bi,gt,tourm		534840/6755100N
MW5	pegmatite	central	kf,qtz,tourm	N	534840/6755100N
MW6	pegmatite	central	kf,qtz,tourm	N	534840/6755100N
MW7	BIF	NW	qtz,kf,sil,bi,cd,mag	Y	534440/6755520
MW8	Metapelite	NW	qtz,kf,sil,bi,cd	Y	534440/6755520
MW9	BIF	N	qtz,kf,sil,bi,cd,mag	N	
MW10	Meta-pelite	NW	qtz,kf,sil,bi,cd	Y	534440/6755520

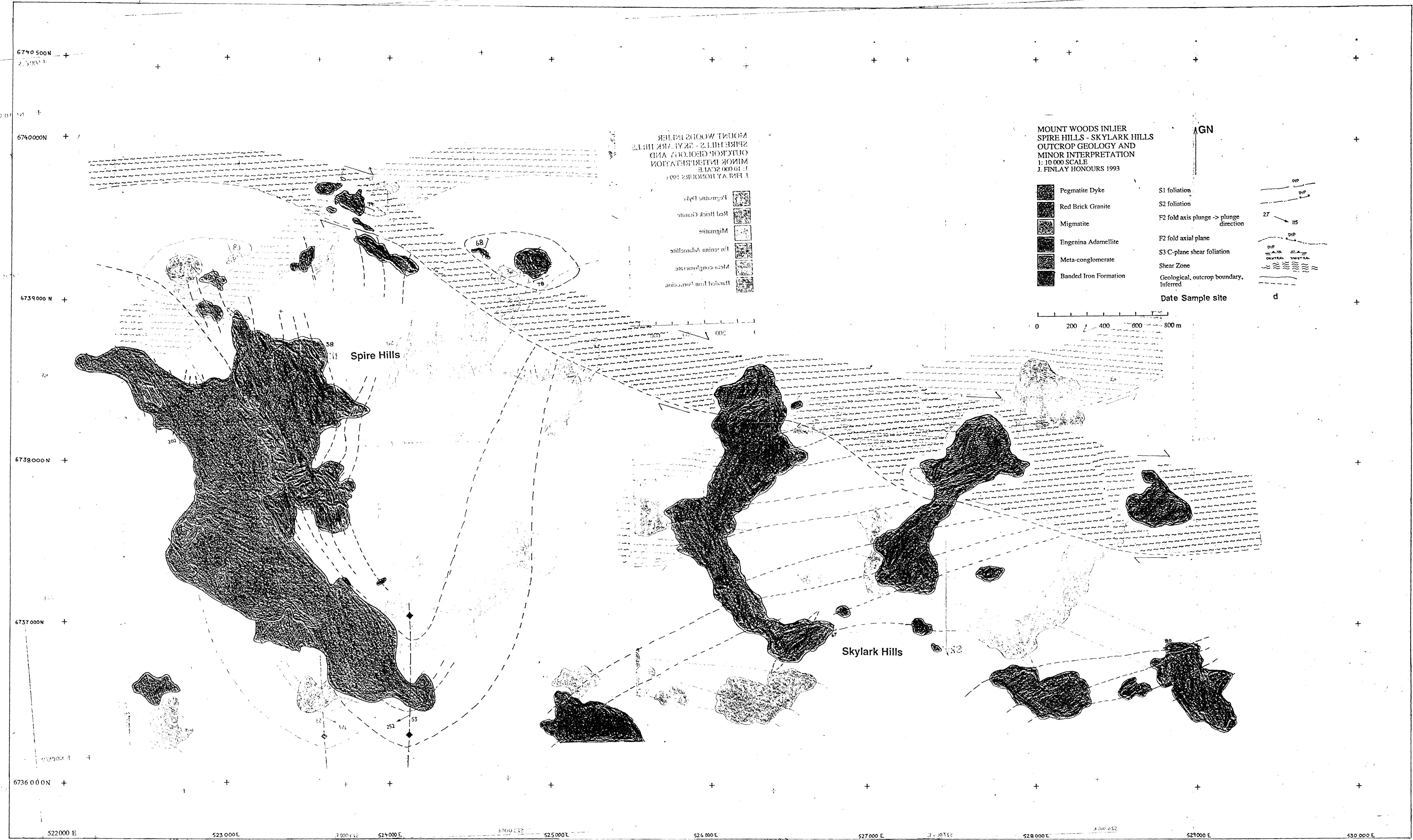
### Mirage Hills (MH)

MH1	Orthogneiss	Central	qtz,bi,kf,plag,gt	Y
MH2	pegmatite	"	kf,plag.,qtz,mu	N
MH3	O.gneiss	"	qtz,kf,plag,bi	Y
MH4	P.gneiss	S	qtz,bi,kf,plag,gt	Y





Plan 2



MOUNT WOODS INLIER  
SPIRE HILLS - SKYLARK HILLS  
OUTCROP GEOLOGY AND  
MINOR INTERPRETATION  
1:10 000 SCALE  
J. FINLAY HONOURS 1993

- Pegmatite Dyke
- Red Brick Granite
- Migmatite
- Engenina Adamellite
- Meta-conglomerate
- Banded Iron Formation

MOUNT WOODS INLIER  
SPIRE HILLS - SKYLARK HILLS  
OUTCROP GEOLOGY AND  
MINOR INTERPRETATION  
1:10 000 SCALE  
J. FINLAY HONOURS 1993

- Pegmatite Dyke
- Red Brick Granite
- Migmatite
- Engenina Adamellite
- Meta-conglomerate
- Banded Iron Formation

- S1 foliation
- S2 foliation
- F2 fold axis plunge -> plunge direction
- F2 fold axial plane
- S3 C-plane shear foliation
- Shear Zone
- Geological, outcrop boundary, Inferred
- Date Sample site

