THE UNIVERSITY OF ADELAIDE

# The Structural Geology of an Area South of Kanmantoo, S.A.

by

L.E. Poole, B.Sc.

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# CONTENTS

## ABSTRACT

There have been at least two periods of deformation in this area. The (probable) first deformation is the most prominent and has an axial plane schistosity. The second deformation deforms this schistosity and is only generally manifest as crenulations. "Deformation zones" exist throughout the area and can be interpreted as either reverse faults or transposed limbs of folds. It is probable that the major metamorphic phase took place during the first deformation. The ore deposits in the region show a structural and stratigraphic control.

## INTRODUCTION

The aim of this study was to investigate the deformational history of the area shown on the map in Figure 1, and to relate this to the known mineral occurrences in the region.

Previous investigations in the general region include the study by Kleeman and Skinner (1959), Grasso and McNamus (1954), Mirams (1962), Linquist (1966), Askins (1968), and the work of geologists of Mines Exploration Pty Ltd, a subsidiary of Broken Hill South.

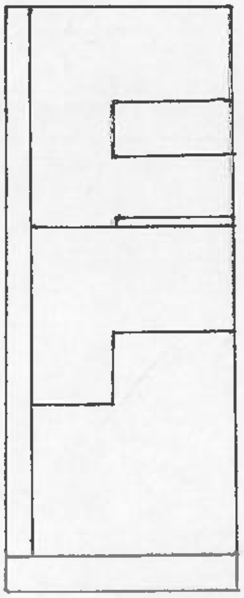
There is no mining being carried out at present in the area although Broken Hill South who hold the leases over the region have sunk an exploratory shaft into a copper deposit near the Old Kanmantoo mines, and it is probable that an open cut mine will be established in the future.

A total of eight weeks from March to May 1969 was spent in the field mapping and collecting data and samples.

# REGIONAL GEOLOGY

## STRATIGRAPHY

The rocks in the area studied belong to the Kanmantoo Group, a series of metasediments which overlie the Proterozoic rocks of the Adelaide System (fig. 1). On the eastern side of the Mount Lofty Ranges the Kanmantoo Group rocks are unfossiliferous but are regarded as being Cambrian (possibly extending into the Ordovician) in age. The nature of the boundary with the Proterozoic is uncertain. It is regarded as unconformable (Campana and Horwitz 1956), conformable (Kleeman and Skinner 1959), and thrust faulted (Rutland 1968). A summary of the regional stratigraphy is given below.

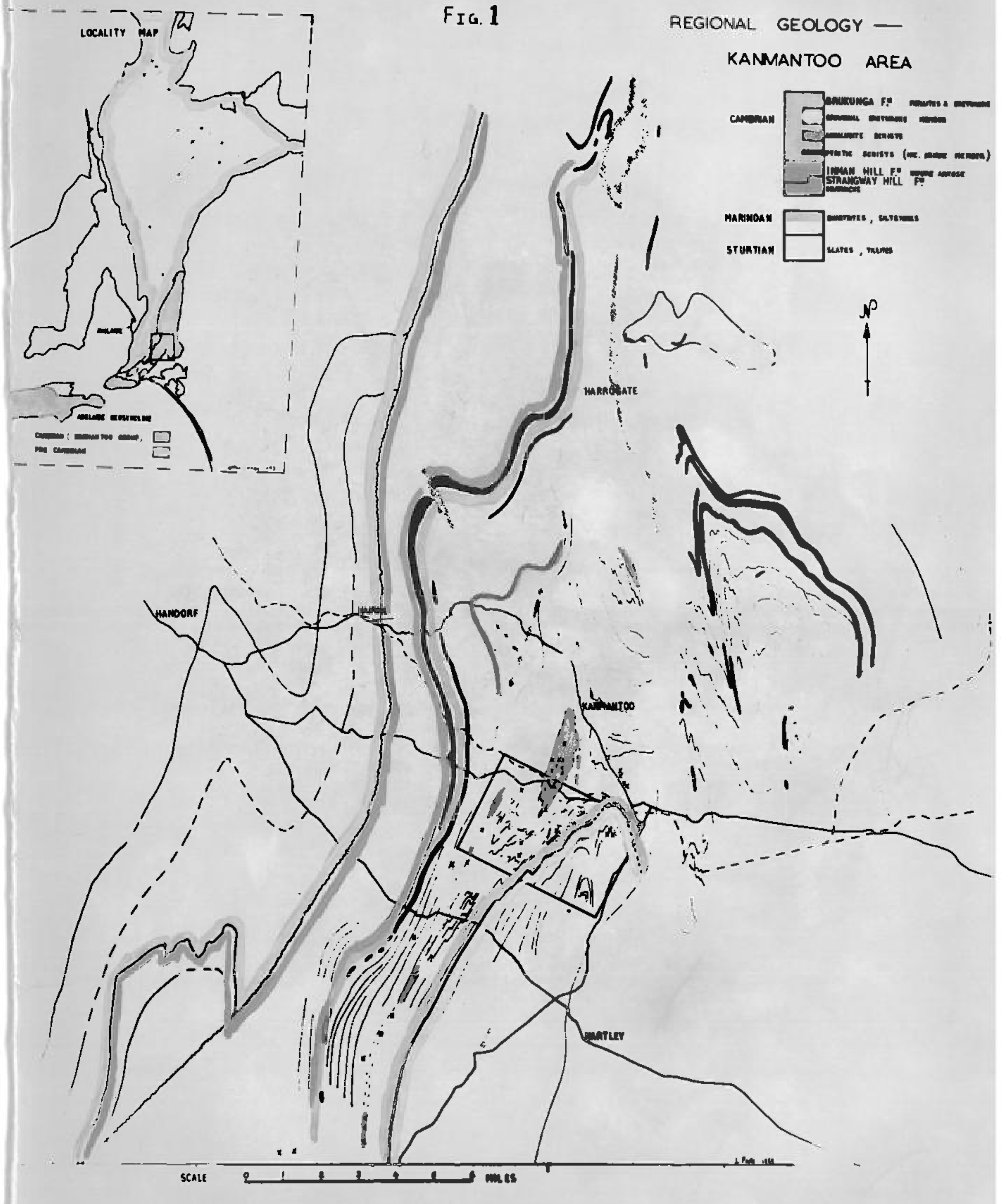


BRUKUNGA FORMATION: interbedded phyllites
and greywache with lenticular pyritic and
calc. silicate lenses.
BROWNHILL GREYWACKE MEMBER
Pyritic phyllite and low grade (?) schist,
in part carbonaceous including
NAIRNE PYRITE MEMBER
INMAN HILL FORMATION: coarse grained impure
arkose locally cross-bedded and with slump
structures.
STRANGWAY HILL FORMATION: greywacke with
siltstones and phyllitic shales, quartzites
Marble
Phyllitic shales and siltstones locally
pyritic, phosphatic or carbonaceous.
Marble
Quartzite
ADELAIDE SYSTEM ROCKS

Higher in the sequence the rocks are intruded by the Murray Bridge and Monato Granites. There is evidence that the Monato granite is a product of granitisation of the enclosing Kanmantoo Group rocks.

FIG. 1

REGIONAL GEOLOGY — KANMANTOO AREA



## METAMORPHISM

On a regional scale, the metamorphic grade generally increases from west to east across the Mount Lofty Ranges (Mills 1964). The mineralogy of the rocks in the area studied - hornblende, andalusite, staurolite, garnet, biotite and muscovite - suggests that the metamorphism has reached mid Amphilolite facies. There is also some evidence for a retrogressive metamorphism.

## STRUCTURE

The regional structure has been described by Offler and Fleming (1965). They suggest three deformations. The most prominent deformation present in the area studied is their F1 folding of bedding about a well developed axial plane schistosity trending Northerly and dipping to the East at high angles. The fold axes pitch southerly over most of the area except for occasional shallow northerly pitches in the mine areas.

On a regional scale the rocks are probably folded in a large scale drag fold, with fold axes plunging southerly in the south and (?) northerly in the north (Fleming 1969 pers.com.) figure (2). At the core of this structure is an andalusite schist which contains the Kanmantoo copper mines.

There are some large regional faults which trend North to North Easterly, e.g. the Bremer fault, and a lineament which disrupts the Nairne pyrite horizon (B.P. Thompson 1969 pers. com.). The possibility of a thrust fault passing through the Aclare and Kanmantoo mines is discussed later. There are also some smaller east west faults which are parallel to the main joint set.

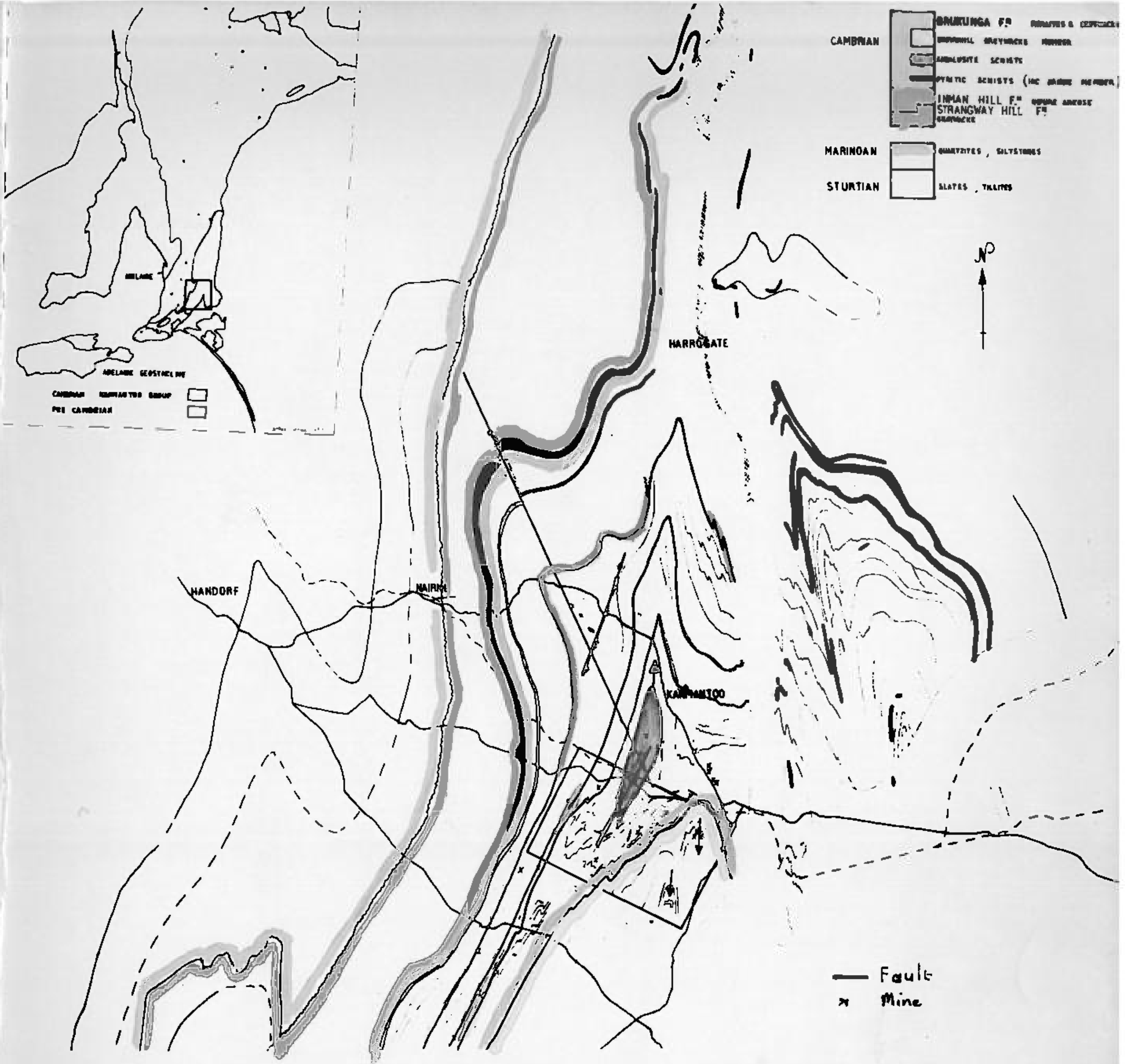


Fig. 2. Showing interpretation of regional geology.

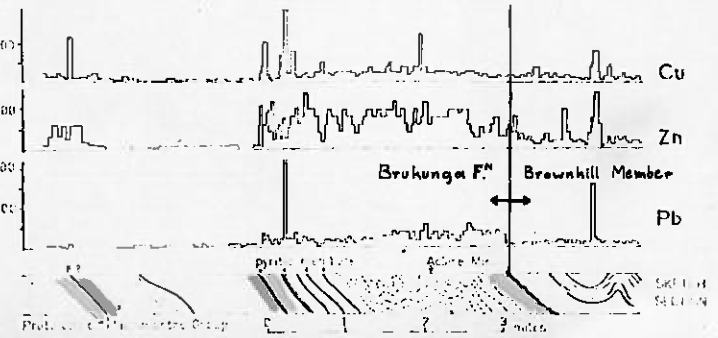


Fig. 3. Geochemical profile across Kanmantoo group
(along Barker Creek). (after Thompson)

## LOCAL GEOLOGY

The rocks of the area belong to the Brukunga Formation which contains the Brownhill Greywacke member. The latter is a distinct unit, being distinguished by its petrology and texture, good outcrop pattern on aerial photographs, and its background geochemical pattern (fig.3) from the underlying (un-named) member of the Brukunga.

### BRUKUNGA FORMATION - Petrology and Petrofabrics

The main rock type in the member of the Brukunga formation below the Brownhill Greywacke is a quartz (± feldspar) mica schist. Other rock types include andalusite schists and pyritic schists.

### QUARTZ (± Feldspar) - Mica Schists

hand Spec?

In band section these are light to dark grey coloured fine grained schists. They are rather even grained although mica grains are commonly larger than quartz and feldspar grains. There is a strong dimensional preferred orientation of mica and quartz in the plane of S2 (fig. 4 - N and P sections).

Quartz grains generally show no undulose extinction except in rocks which contain kinks. Quartz - Quartz boundaries are generally straight or gently curved and triple point junctions are common. (fig.6). Quartz - biotite boundaries are generally straight and where biotite trains enclose quartz bands one grain thick the quartz - quartz boundaries are at 90° to the quartz - biotite boundaries (fig.7). Quartz grains are generally free from inclusions.

Biotite is more common than muscovite and is pleochroic from pale yellow to reddish brown or dark brown. The 2v of biotite is generally 5° showing little variation over the area. Short mica trains of 3 - 4 grains are common but there is no tendency for the micas to diverge at high angles to S2 - they are all parallel to S2. (i.e. there is no "anastomosing"). Also there is a tendency for the micas and the quartz to be elongate in the direction of L1. (fig. 4 - S section). Pleochroic haloes are common in the biotite, and occasionally tiny inclusions of (presumably) zircon can be seen at the centre of these haloes (fig. 8). Most muscovite is intergrown with biotite parallel to S2 but occasionally it is observed to grow in S1. These are probably not original sedimentary muscovites because occasionally they can be seen to grow around quartz grains (fig. 9). These S1 muscovites are generally much coarser than the rest of the rock.

Some biotite has altered to chlorite which in the more quartz rich rocks is oriented parallel to S2 but in the more schistose rocks can form in any orientation, often cross cutting (fig. 10). Large platy chlorites have been seen in the "ac" plane and hence have an orientation parallel to most of the joints in the area. Chlorite also forms in veins of a cross cutting nature.

Plagioclase and orthoclase occurs in these rocks to a variable extent, but alteration to sericite is uncommon, suggesting that they are possibly not original sedimentary grains. Garnets are common, and are generally idioblastic, with few inclusions. They are coarser and more abundant than the garnets found in the Brownhill Greywacke. Hornblende is present and is generally pleochroic

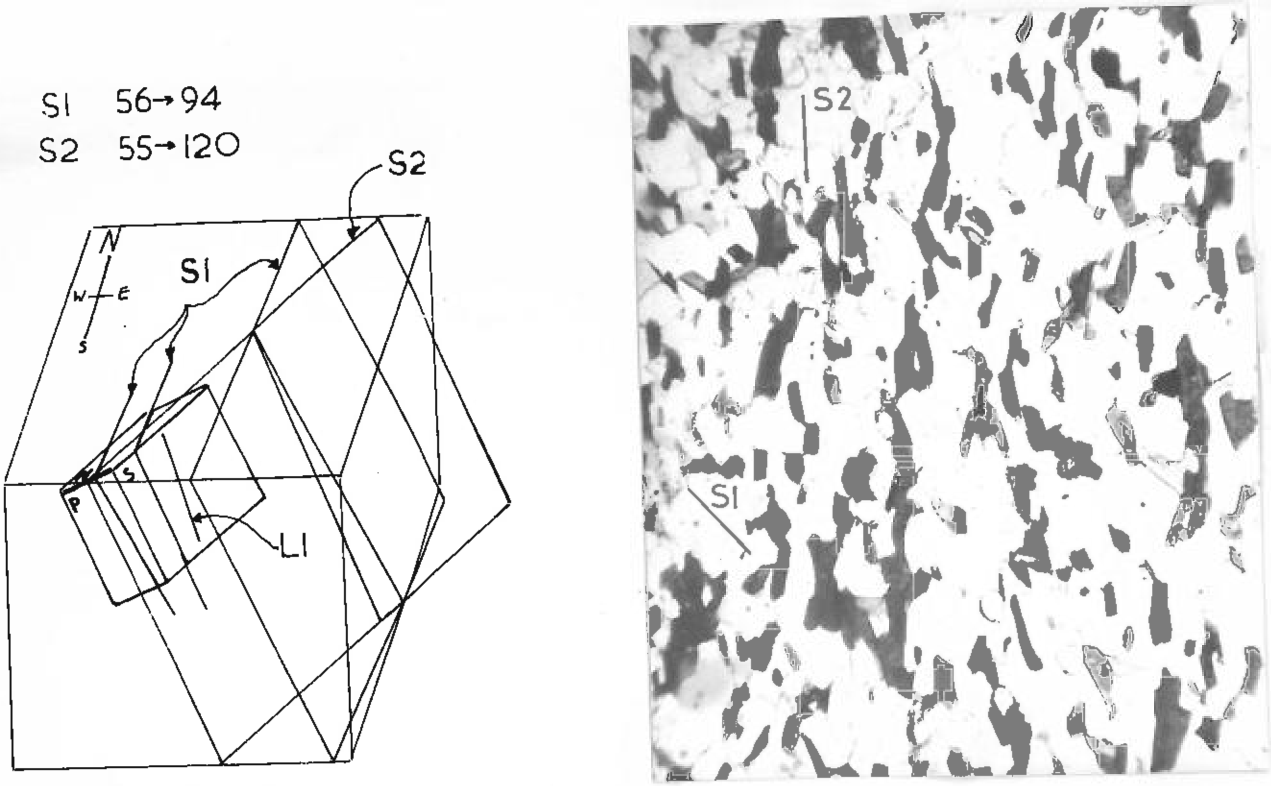


Fig. 4(a). Orientation diagram.

Fig. 4(b). N Section.

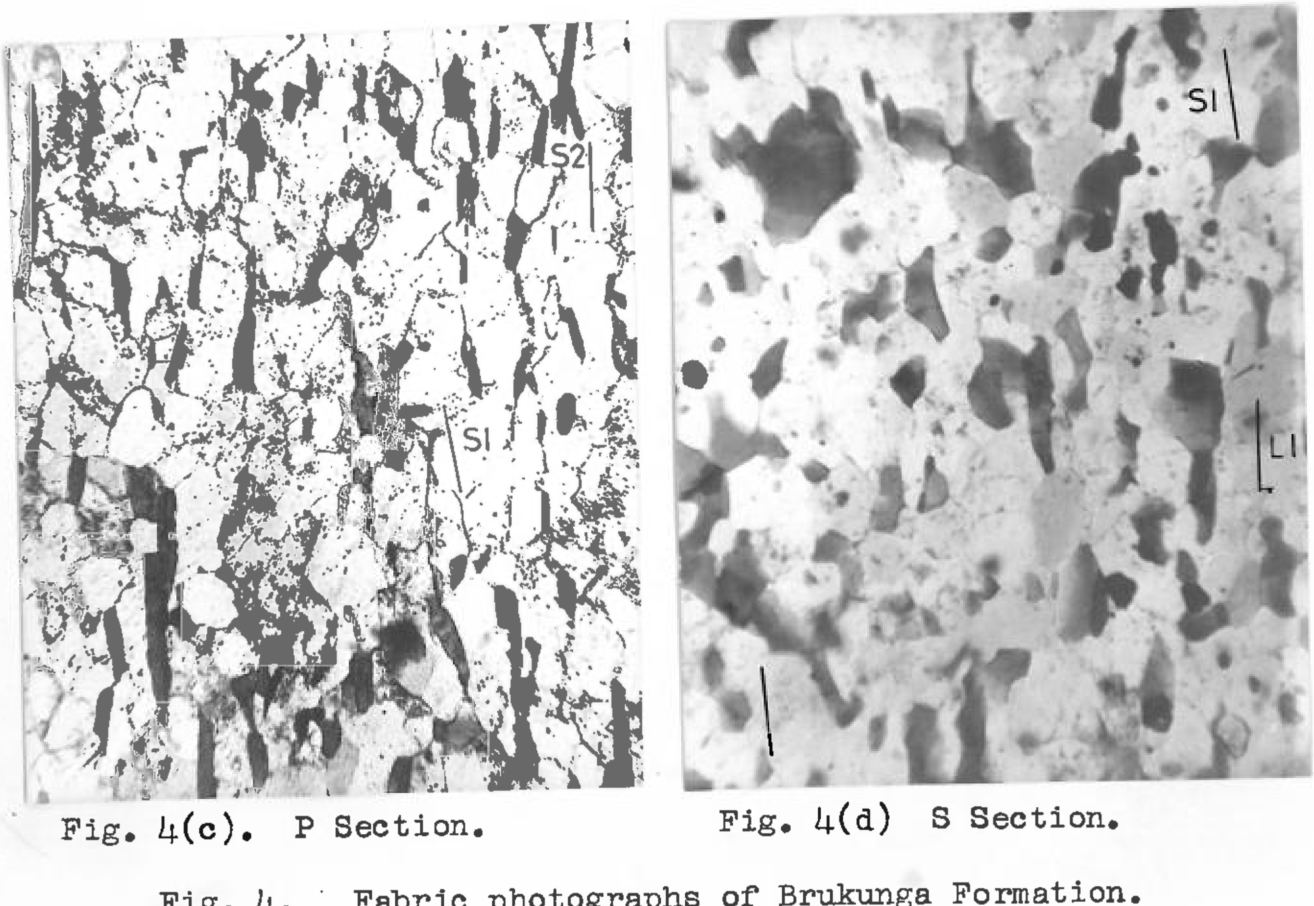


Fig. 4(c). P Section.

Fig. 4(d) S Section.

Fig. 4. Fabric photographs of Brukunga Formation.
Spec. K1. Transmitted light. x75.

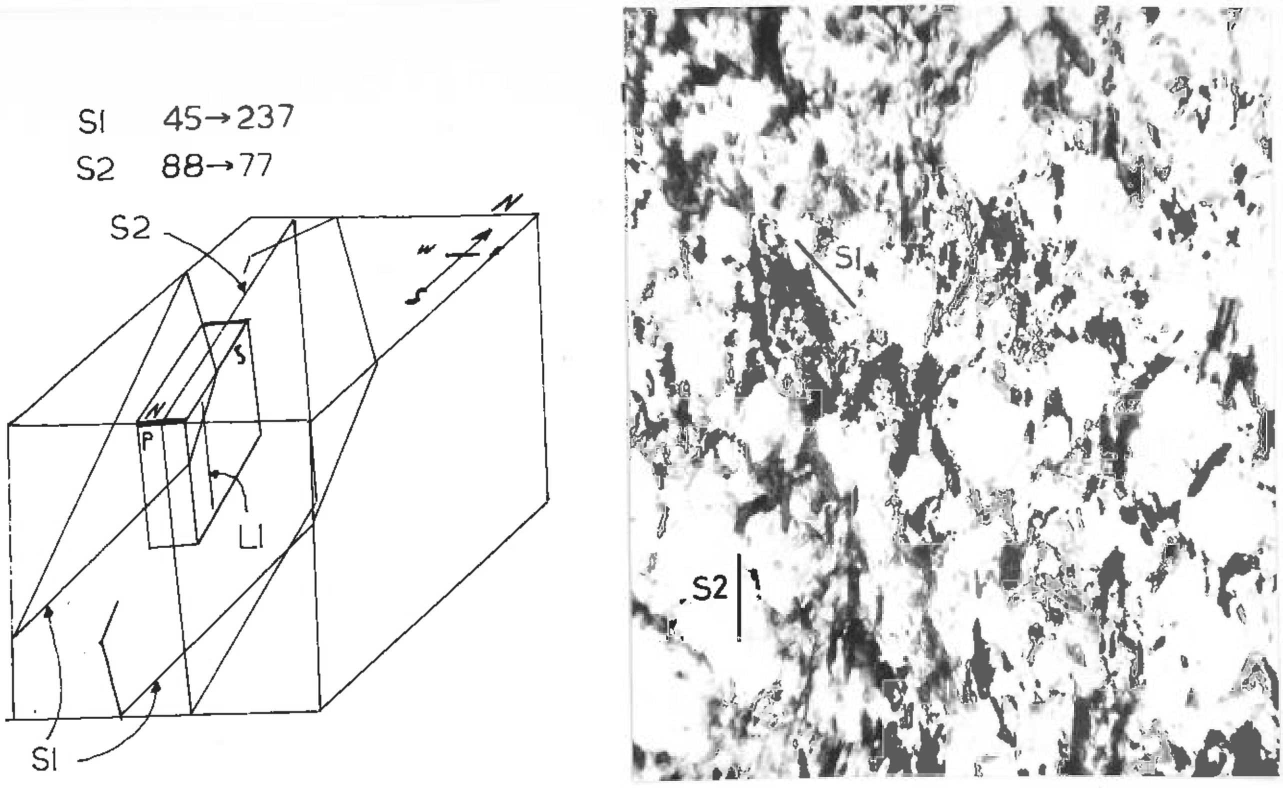


Fig. 5(a). Orientation diagram.

Fig. 5(b). N Section.

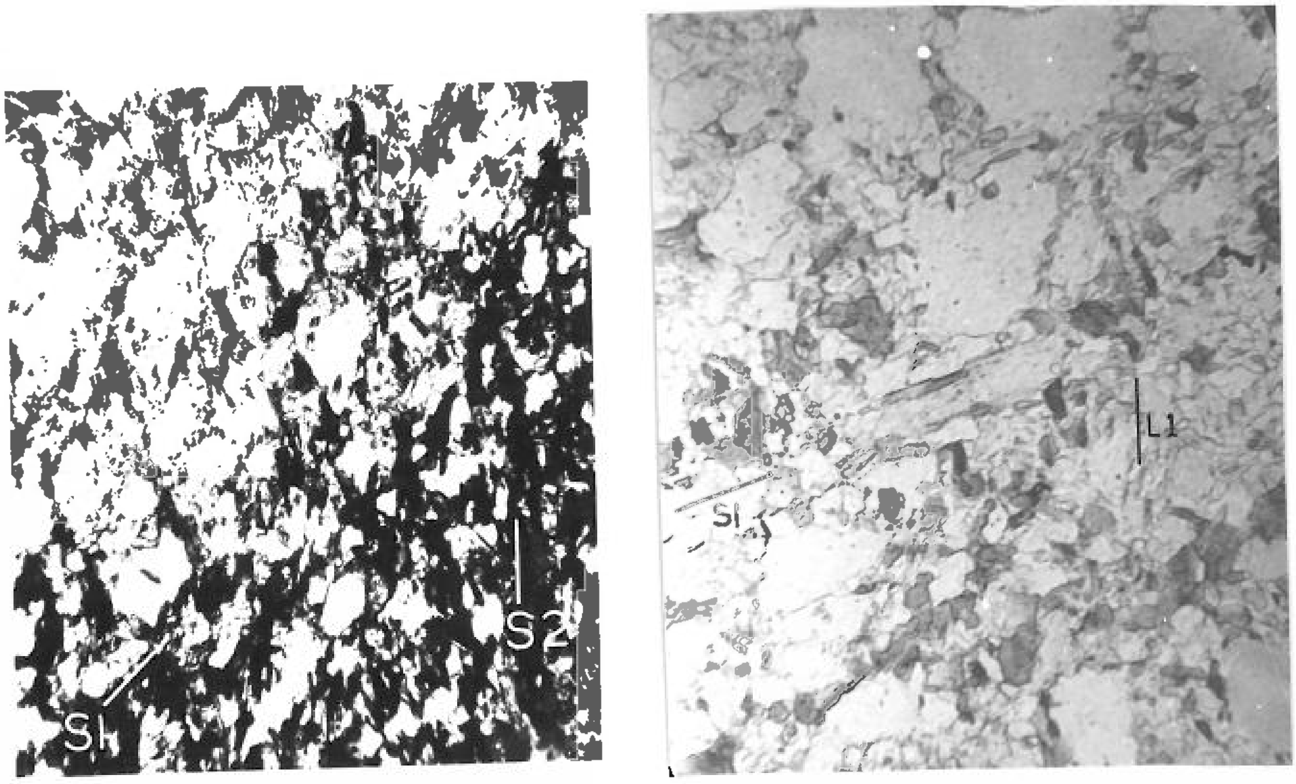


Fig. 5(c). P Section.

Fig. 5(d). S Section.

Fig. 5. Fabric photographs of Brownhill Greywacke.
Spec. CB. Transmitted light. x75.

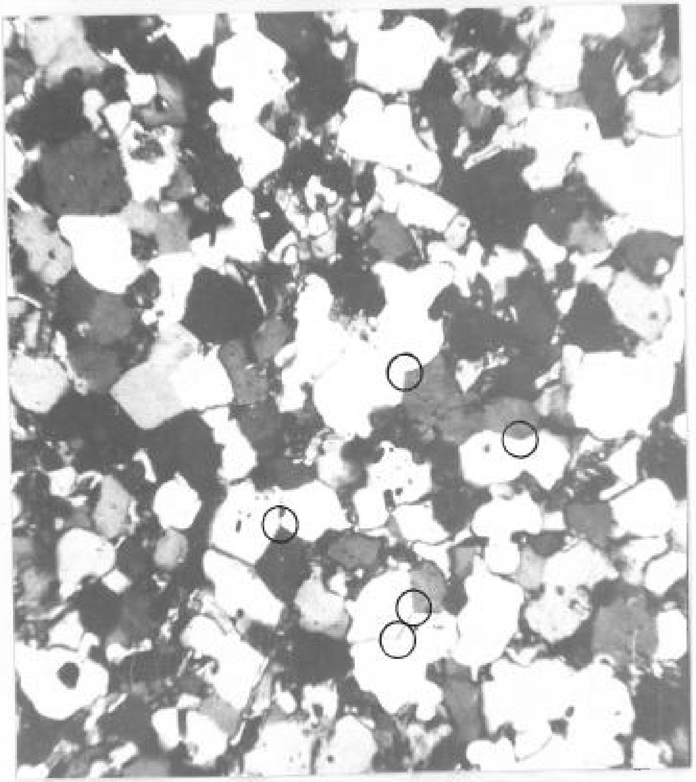


Fig. 6. Quartz triple point intersections. See also Fig.4. Spec. B73. Crossed Polars. x~~240~~.75

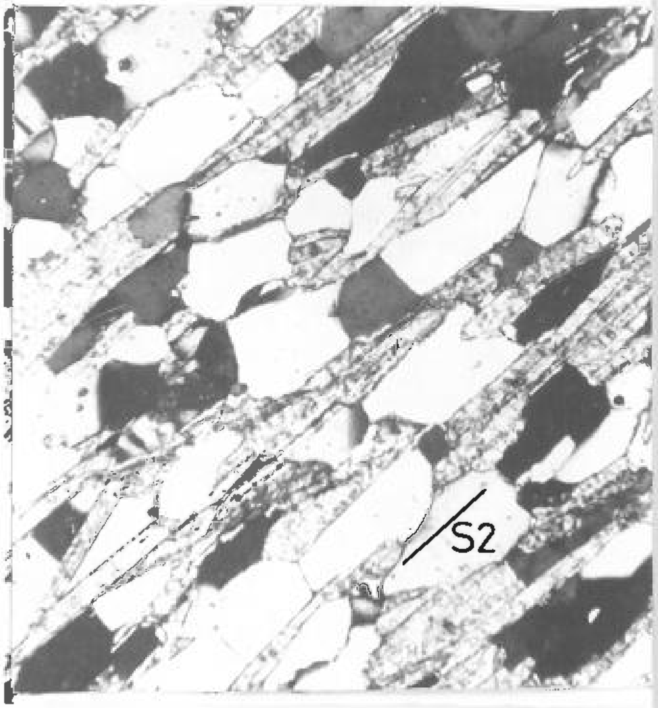


Fig. 7. Quartz-quartz boundaries between biotite grains. Spec. B73. Crossed Polars. x~~240~~.140

Fig. 8. Pleochroic halo around minute zircon in biotite grain. Spec. C1. Transmitted light. x450.

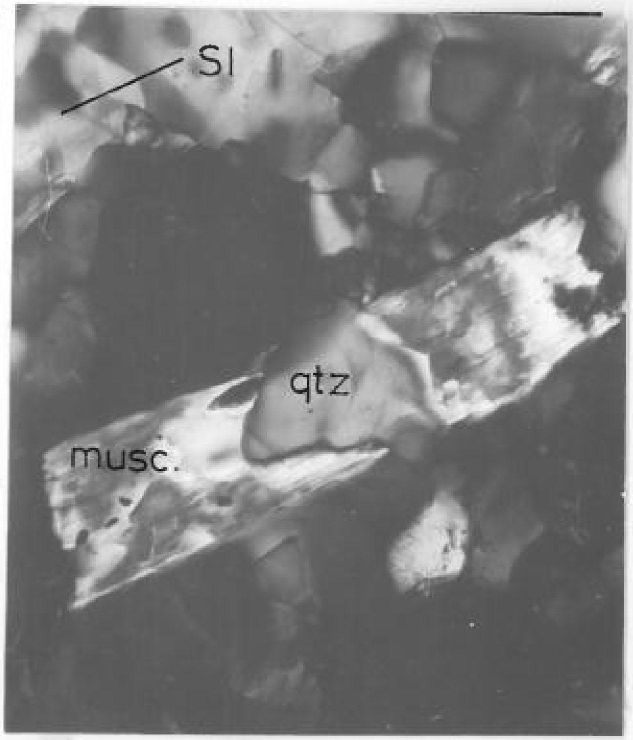


Fig. 9. S1 muscovite growing around quartz grain. Spec. B45. Transmitted light. x240.

green to green blue, with typical amphibole cleavage. Reaction rims are common.

Accessory minerals include sub-angular grains of apatite, occasional well rounded zircons, and occasional andalusite and staurolite grains. Opaques, dimensionally oriented parallel to S2, are present generally in bands parallel to S1, and probably represent small sedimentary heavy mineral bands. Occasionally knots of finer grained granular quartz and sericite occur, and may represent alteration products of former porphroblasts.

Analyses of these rocks imply they were probably originally arkoses or greywackes (fig. 11; specimen ②). These rocks show the attainment of textural equilibrium in contrast to the rocks of the Brownhill Greywacke Member.

## ANDALUSITE SCHISTS

There is a large andalusite schist unit in the Brukunga which has been known in the past as the Paringa andalusite lens. The Kanmantoo copper deposits occur in this unit and the petrology has been described by Linquist (1966). There are other finer grained andalusite schists in the area to the south and in these rocks the andalusites (relative to the host - quartz schist) occur in coarse grained bands parallel to compositional layering previously designated as S1. 100 grams of one of these bands (specimen ①) together with 10 grams of the host schist (specimen ②) was analysed by X-Ray Fluorescence and the results are tabulated below.

## X-Ray Fluorescence Analyses.

Note:P,Mg.and Na amounts were not determined.

| | Fe | Mn | Ti | Ca | K | Si | Al | Tot |
|---|---|---|---|---|---|---|---|---|
| ① Spec.B73-Andalusite band. | | | | | | | | |
| Oxide% | 10.8 | .4 | 1.1 | .1 | 5.1 | 46.4 | 27.2 | 91 |
| ② Spec.B73-Quartzo-Feldspar Mica Schist Host. | | | | | | | | |
| Oxide% | 7.0 | .1 | .6 | .3 | 3.3 | 70.6 | 12.1 | 94 |
| ③ Spec.B16-Quartzo-Feldspar Mica Schist. | | | | | | | | |
| Oxide% | 3.8 | .03 | .5 | 1.2 | 2.7 | 75.0 | 11.9 | 95 |
| +Average Greywacke. | | | | | | | | |
| Oxide% | 1.5±1 | .1±.1 | .6±.3 | 3.0±2 | 2.0±1 | 65±5 | 15±4 | |
| +Average Arkose. | | | | | | | | |
| Oxide% | 3.5±2 | .1±.1 | .4 | 1.5±1 | 4.0±2 | 74±6 | 9±2 | |
| +Average Shale. | | | | | | | | |
| Oxide% | 3.0±1 | .1±.1 | .6±.2 | 3.0±2 | 3.5±.5 | 58±5 | 14±3 | |
| +Average Residual Clay. | | | | | | | | |
| Oxide% | 5.0±3 | .03 | 1.0±1 | .2±.2 | .5±.4 | 47±7 | 30±10 | |

Fig.11

+Figures from Prettijohn;"Sedimentary Rocks".

From these figures it is possible that the andalusite band represents an original clay band derived from washed down residual clay from some exposed portion of the depositional area, or else metamorphic differentiation has occurred, with an influx of aluminium and iron and a reduction in the Silica. In view of the agreement between the analysis and that for an average residual clay, the former is more probably the case. It must be stated, however, that at Victor Harbour, metamorphic bands of andalusite not parallel to S1 do occur.

Petrologically, the andalusite schists show a variety of coarse - grained minerals such as andalusite, staurolite, muscovite, chlorite and garnet. Andalusite is commonly idioblastic , although often they have a "ragged" appearance. Andalusites invariably contain inclusions of quartz, opaques, biotite and muscovite. Where the inclusions could be seen to be oriented, they were in general oriented parallel to S2 (fig. 12 ~~(a) & (b)~~). In this figure, S2 has either been refracted or else some rotation has occurred after the formation of the schistosity. Biotite commonly tends to wrap around the andalusite crystals forming crenulations parallel to L1 in S2, and this is described in Ramsey ref(?) where he proposes a flattening mechanism (fig. 13). Biotite tends to form thick trains // S2 as the andalusite band is approached (fig. 11 ).

Whereas andalusite is poikiloblastic, staurolite rarely contains any inclusions. It is commonly idioblastic and smaller in size than andalusite. Coarse grained muscovite and chlorite are

Fig. 10. Chlorite replacing biotite. Spec. B82. Crossed Polars. x75.

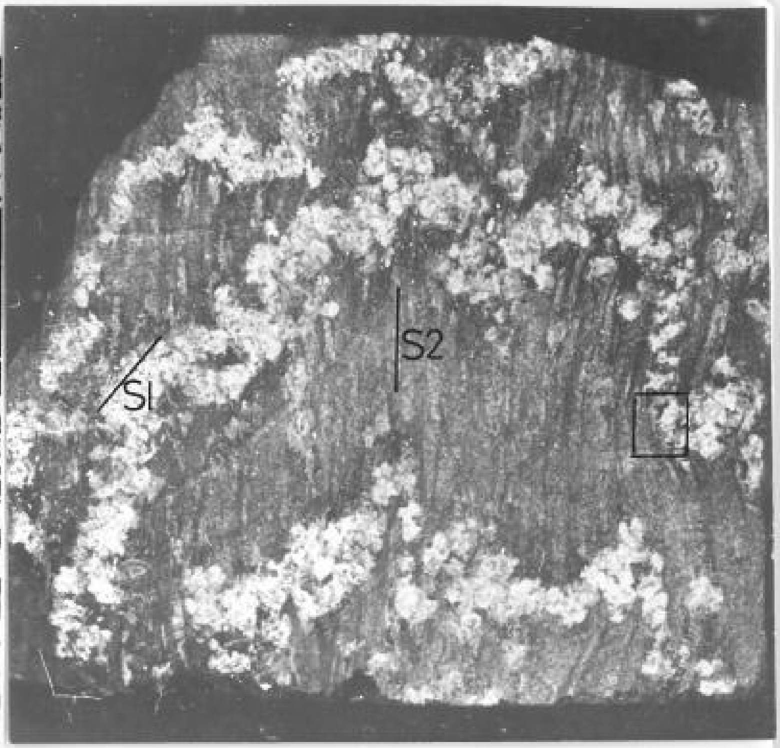


Fig. 11. Andalusite band in quartz-feldspar schists. Spec. B73. Natural scale.

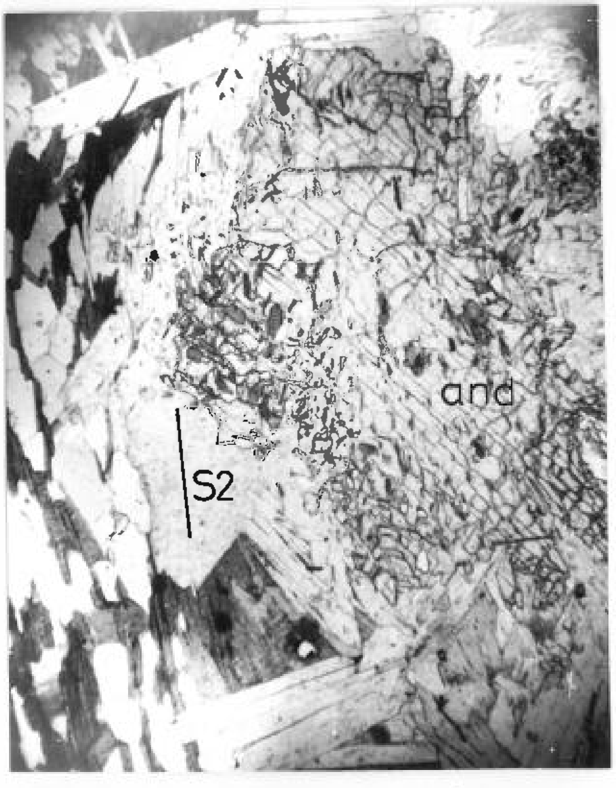


Fig. 12. Close up of Fig. 11 showing andalusite inclusions parallel to S2. Spec. B73. Transmitted light. x75.

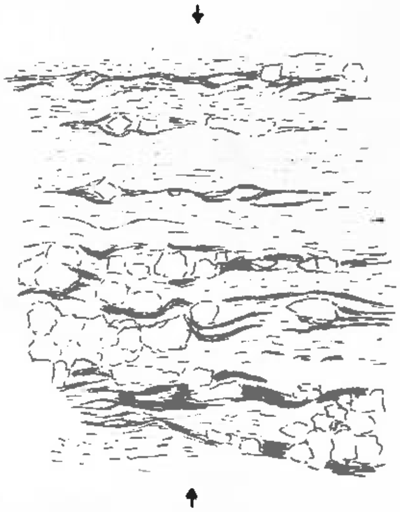


Fig. 13. Showing development of crenulations associated with andalusite grains. Natural scale. Spec. B73.

found in the andalusite rich band, and orthoclase, garnets, apatite and zircons are also present. Garnet crystals always truncate the micas which end abruptly without any deformation or alteration at the garnet margins, suggesting the garnets have probably grown later than the biotite.

Whether the Paringa andalusite lenses out stratigraphically to the south or it is folded out is still not definately known but the former is probably not likely. (fig. 2)

## PYRITIC SCHISTS

These appear in the field as leached white, yellow or red stained sericitic schists which stand out on air photos and have been described by Askins (1968). In one locality (C3) the transition from fresh pyritic quartzite to iron stained sericitic schist could be seen, and a photomicrograph of the unaltered quartzite is included (fig. 14). In some localities these schists are a peculiar blue colour and are simply mapped as "blue schists".

## CATACLASTIC ROCKS

The east west fracture zones (see map) consist of iron stained material varying from "sheared" quartz mica schist to typical breccias as indicated in figure 15. These have been described by Linquist (1966).

## THE BROWNHILL GREYWACKE MEMBER

The rocks of the Brownhill Greywacke Member outcrop in the eastern section of the area and consist of quartz feldspathic schists with minor fine shales and some pyritic schists. The

Fig. 14. Photomicrograph of pyritic schist showing pyrite cubes in quartz-sericite matrix. Spec. C12. Transmitted light. x75.

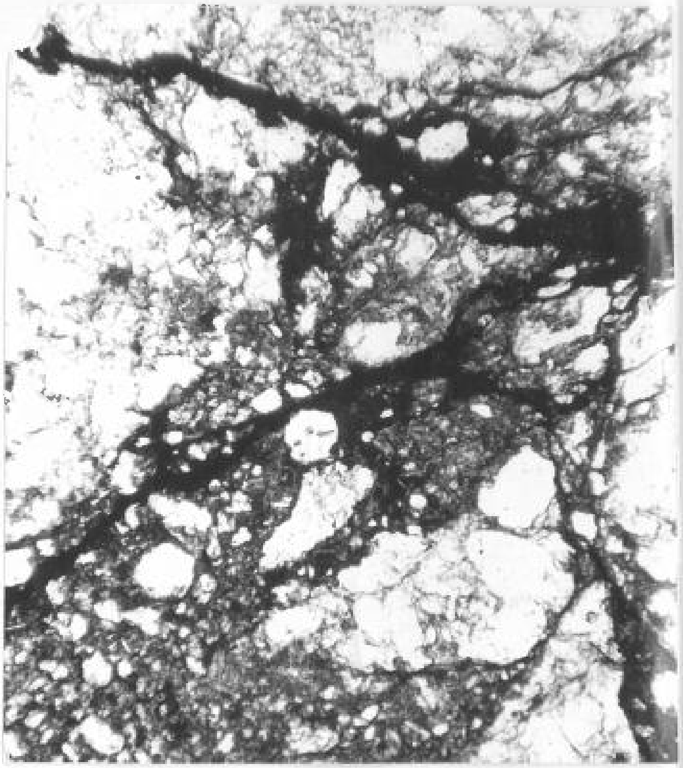


Fig. 15. Brecciated quartz-mica schist. Spec. B18. Transmitted light. x75.

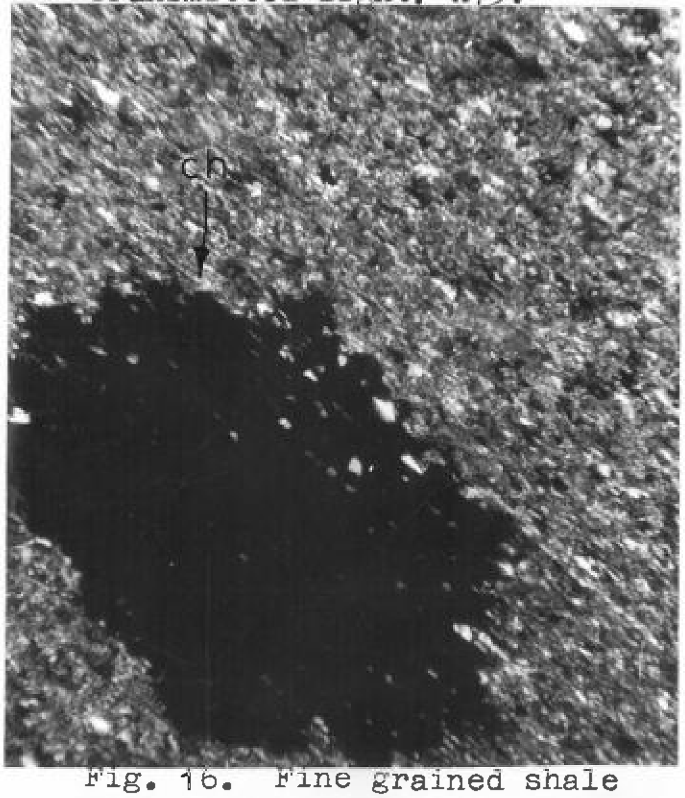


Fig. 16. Fine grained shale with large chlorites. Spec. B10. Crossed Polars. x75.

Fig. 17. Amphibolite showing radiating actinolite in feldspar-quartz matrix. Spec. B33. Transmitted light. x75.

shales consist mainly of very fine grained quartz and sericite with some chlorite present in large platy laths. (fig. 16). One sample of a calcareous silicate was found and consisted predominantly of radiating actinolite, quartz, and some feldspar.(fig.17)

## QUARTZ (± feldspar) SCHISTS

In band specimen these are light to dark coloured fine grained schists. They are very uneven grained (see mortar texture fig. 5), with larger grains of quartz and feldspar set in a fine granular matrix of quartz, feldspar, biotite and sericite. There is no dimensional preferred orientation of quartz in the plane of S2 but the mica, which tends to concentrate around the quartz grains, shows a tendency to align roughly parallel to S2. This "anastomising" of the biotite around quartz grains is particularly noticeable in the P sections (fig. 5).

Many quartz grains show undulose extinction, and quartz - quartz, quartz - feldspar, and quartz - biotite boundaries are generally Seriate? serate. Quartz commonly contains fine inclusions. Biotite is pleochroic from pale yellow to dark brown. Coarse muscovites occur parallel to S1. Both feldspars- orthoclase and albite show alteration to sericite. Garnet is sometimes present as small generally idioblastic grains, and apatite is a common accessory. Occasionally hornblende grains are also present.

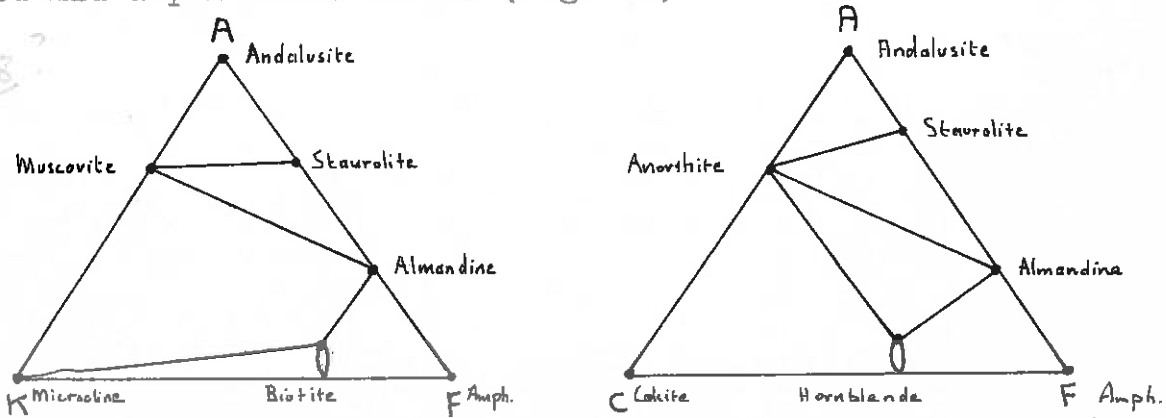
Many of the larger quartz and feldspar grains represent original detrital grains. Silicate analysis of specimen B26 is shown in figure 11. spec. ③

This shows a composition very similar to the quartz (± feldspar) schists from the underlying member of the Brukunga Formation, i.e. the rocks were probably originally greywaches or arkoses. (See also a summary of petrological descriptions in the appendix)

## METAMORPHISM

From mineralogical considerations the metamorphism has probably reached mid amphibolite facies (fig. 18).

Fig 18



From textural evidence the rocks of the Brownhill greywacke do not appear to have reached the equilibrium which the rest of the Brukunga Formation appears to have achieved. Some of the rocks in the north of the area which "stratigraphically" belong to the Brukunga actually show textures which are more similar to those of the Brownhill Greywacke which may imply that the difference between the two rock types is a metamorphic effect.

## S. SURFACES

Summary of Nomenclature for structural elements.

S1 - bedding

S2 - schistosity

S3 - axial plane to crenulation

S4 - kink planes

L1 - mineral streaking

F1 - $B^{s2}_{s1}$ fold axes

F2 - $B^{s3}_{s2}$ crenulation directions

### BEDDING - S1

Compositional layering varying from 1 mm or less to several metres thick is present throughout the area and is regarded as bedding in most cases (figures 19 & 20). The most common compositional layering consists of bands containing different portions of mica and quartz - e.g. pelitic bands within (generally thicker) psammitic layers (fig. 21). Other minerals which are concentrated in bands // S1 are iron oxides (presumably representing original detrital heavy minerals) and garnets. Andalusite and staurolite are also concentrated in bands (commonly ½ to 5 cm. wide) // S1 and no examples of andalusite bands crossing bedding are observed (although they do occur at Victor Harbour and in the Kanmantoo copper mines). The ore layers in the Aclare mine are also parallel to the compositional layering described above and hence probably reflect original bedding.

Probable cross bedding has also been observed (fig. 22), and the high angle between the topset and foreset beds implies strain has occurred (shortening in the c direction, fig. 31). This cross bedding is distinct from biotite anastomosing (see page 9 for explanation) which superficially resembles cross bedding. Figure 23.

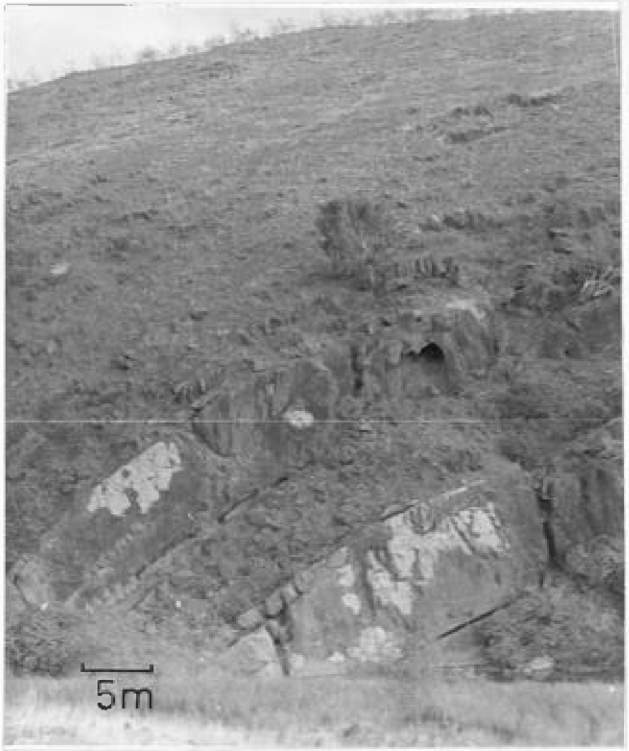


Fig. 19. Easterly dipping beds. Brownhill greywacke. Location B19.

Fig. 20. Folds in bedding. Location B96.

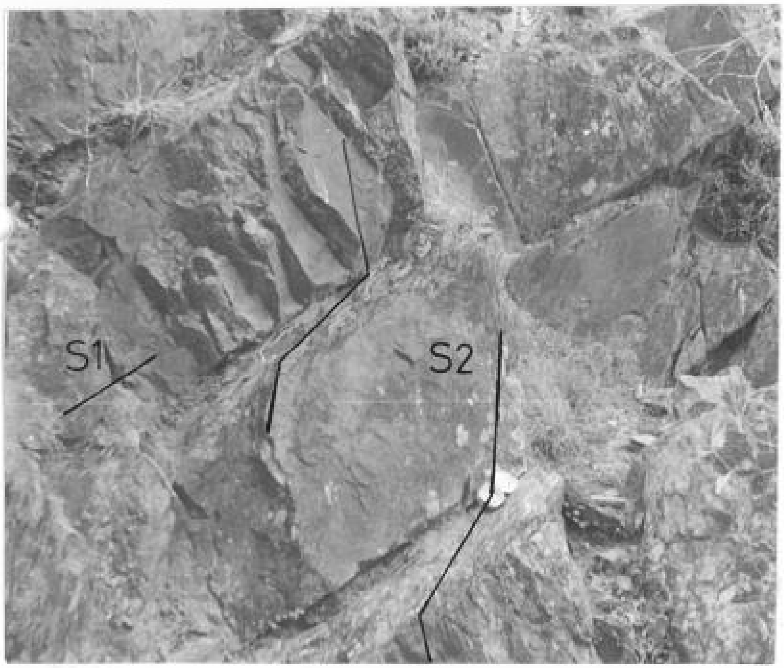


Fig. 21. Showing cleavage refracted almost parallel to bedding in the pelitic bands. Location B96.

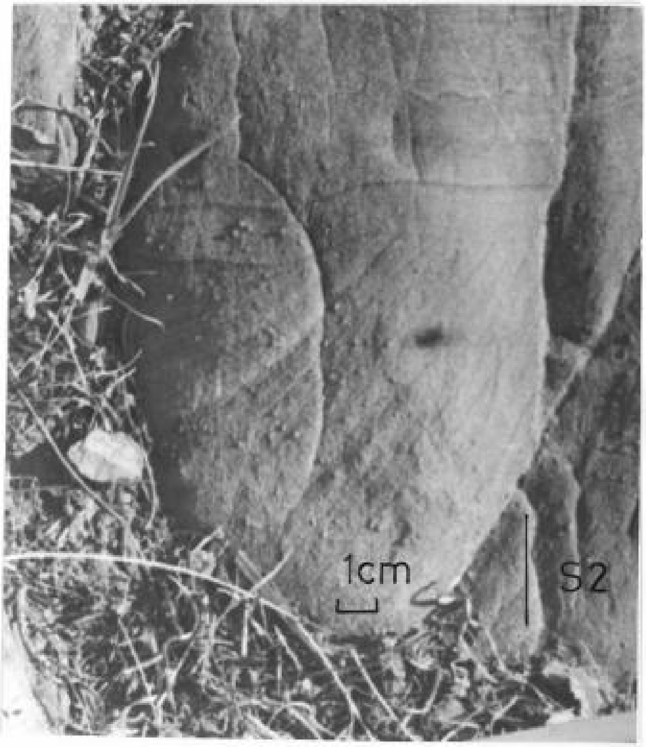


Fig. 22. Cross Bedding in quartz-feldspar mica schist. Location B57.

Large muscovite crystals can be found growing in the bedding. (Fig. 5).

## SCHISTOSITY S2

This surface is defined by minerals with a distinct dimensional preferred orientation, and is most obvious in biotite. S2 is axial plane to most folds in the area varying in scale from millimeters to Kilometers in wavelength. Some good examples of refracted cleavage are present; in the psammites the cleavage is axial plane whereas in the pelite interbeds it is almost parallel to the bedding. This is consistent with Ramseys concepts of refracted cleavage and the flexural slip type mechanism for the formation of the folds. See fig. 24. Refracted cleavage also occurs on a Thin section scale with biotite (fig. 25) - although this may also be taken as evidence for an original schistosity which was parallel to S1 implying an earlier deformation.

Inclusions in andalusite are parallel to S2 which shows refraction as it passes through a andalusite band (fig. 12). This indicates that the metamorphism was possibly contemporareous with the F1 folding.

There is both an orientational and fabric difference between S2 in the east and west portion of the area. In the east the schists ~~show~~ are more generally ~~to be~~ 88 to 90 cm and 56 to 90 as seen in the west (see plots and local geology).

## CRENULATION AXIAL PLANES - S3

S3 is the axial surface to crenulations of the schistosity in

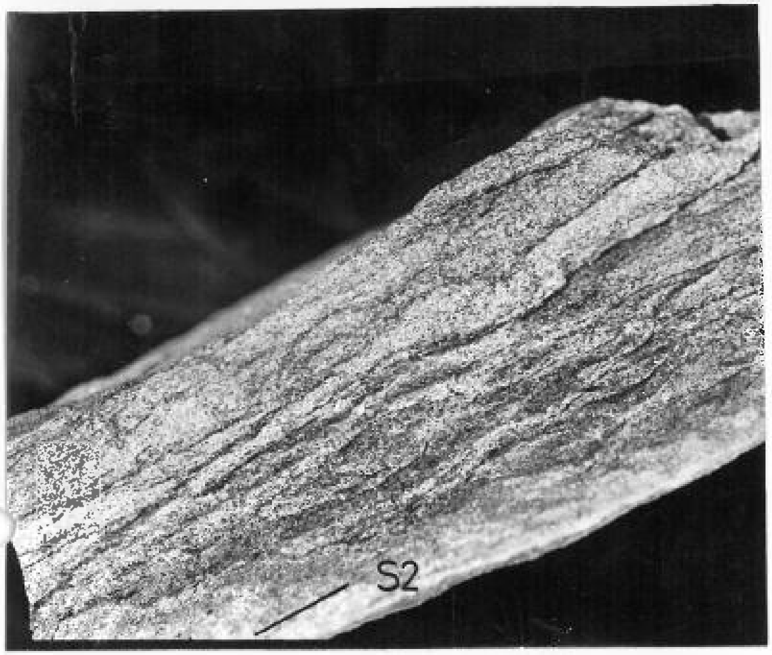


Fig. 23. Biotite anastomosing resembling cross bedding.

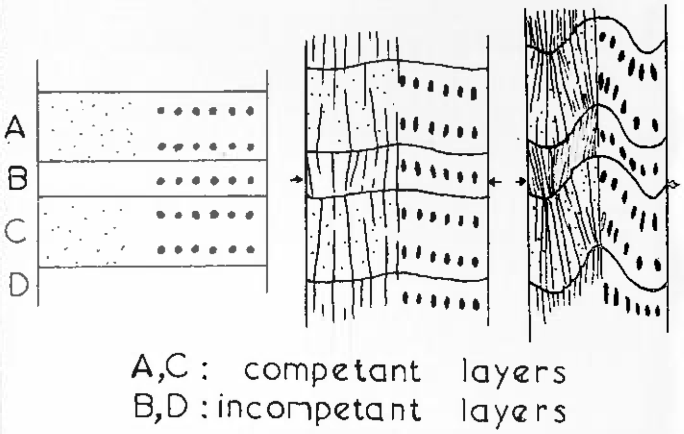


Fig. 24. Theoretical interpretation of refracted cleavage (after Ramsey).

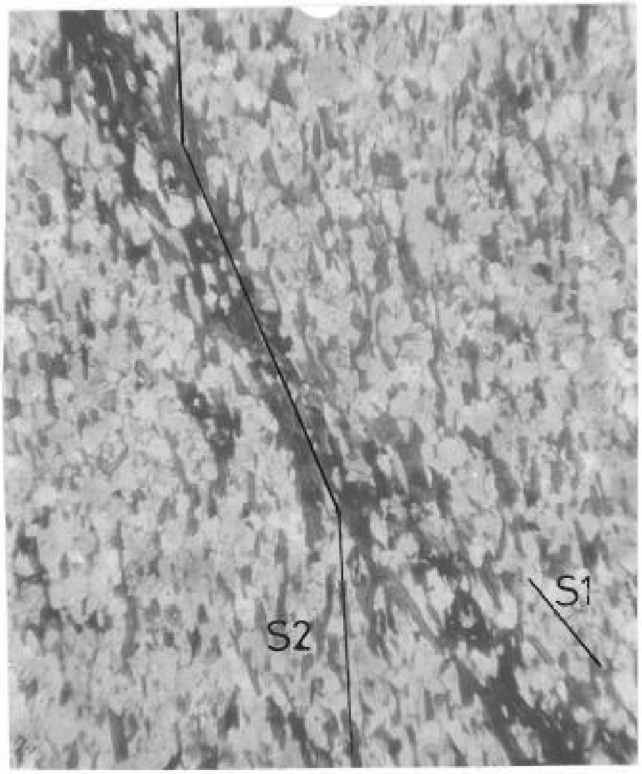


Fig. 25. Fine scale refraction of cleavage in biotite rich band. Spec. CB.
P Section.

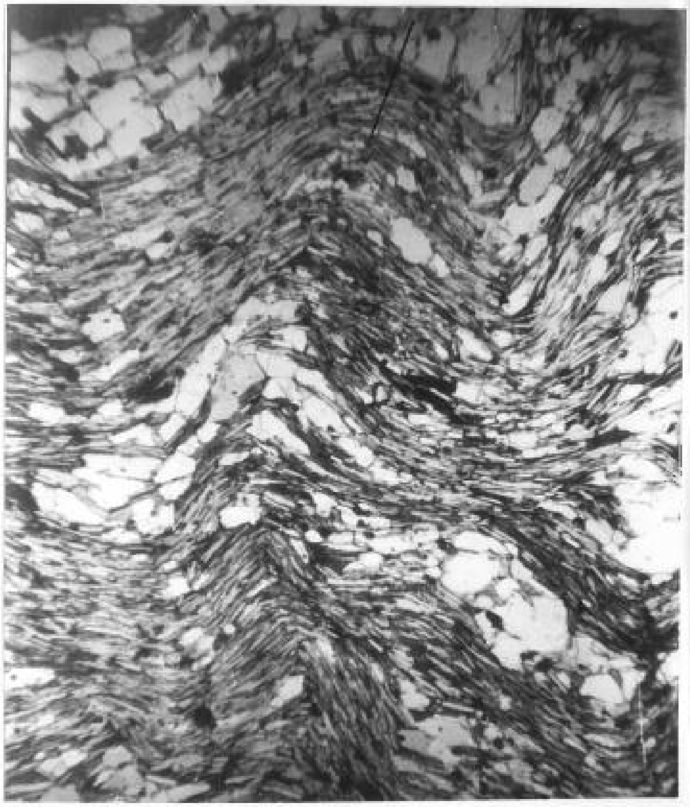


Fig. 26. Second generation folding of schistosity producing crenulations.
Spec. AC. Transmitted light. x75.

the area (fig. 26). The quartz shows a slight tendency to concentrate in the hinges of these crenulations, and the biotite and muscovite shows a slight tendency to concentrate in the limbs, but this is not developed suffiently to define a new compositional layering. Occasionally two conjugate sets of crenulations can be seen in the specimen, and when this is the case, the axial surfaces are designated S3 and S3$^1$. (fig. 27).

The geometry of S3 is discussed in the section on folding.

## KINK PLANES - S4

Kink surfaces are designated S4. They form sharp angular deflections of schistosity. They are only common in the more pelitic rocks and vary in amplitude from 1 to 5 cm. (fig.28). They are variable in orientation but are generally sub horizontal. See ~~map~~ appendix. Kinks commonly represent brittle fracture of a well foliated material subject to stress with the maximum stress lying in the foliation. (Paterson - Wiess 1962). They probably present the final deformation in the orogenic phase.

Biotite is commonly found altered to chlorite in the kink zones (see fig. 29) hence the retrogressive metamorphism which formed the chlorite was either after or during the kink deformation. The alteration in these zones probably was a result of the biotites being more highly strained than in the rest of the rock.

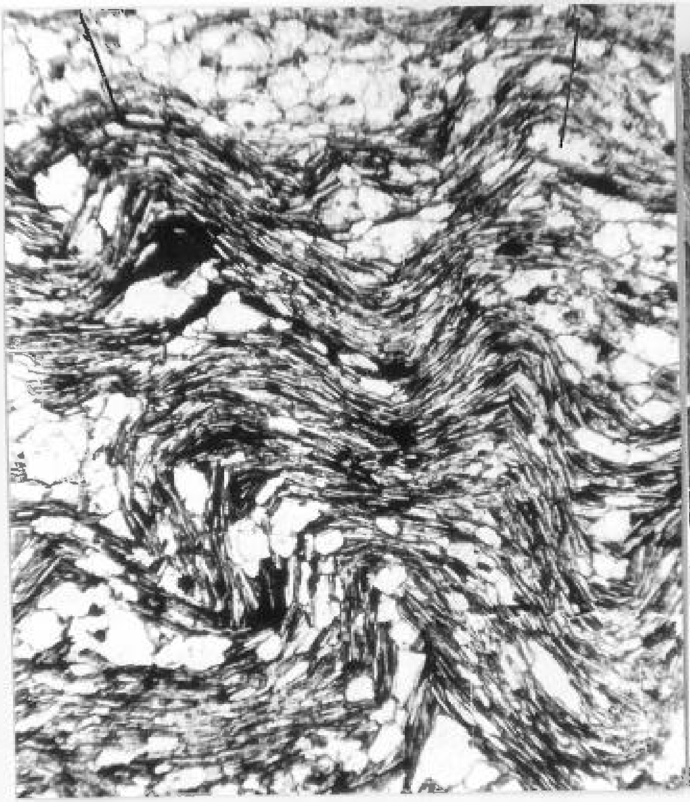


Fig. 27. Development of 2 conjugate sets of crenulations. Spec. AC. Transmitted light. x75.

Fig. 28(a). Sets of kink surfaces. Location C11.

Fig. 28(b). Conjugate set of fine kinks. Spec. C8. Transmitted light. x75.

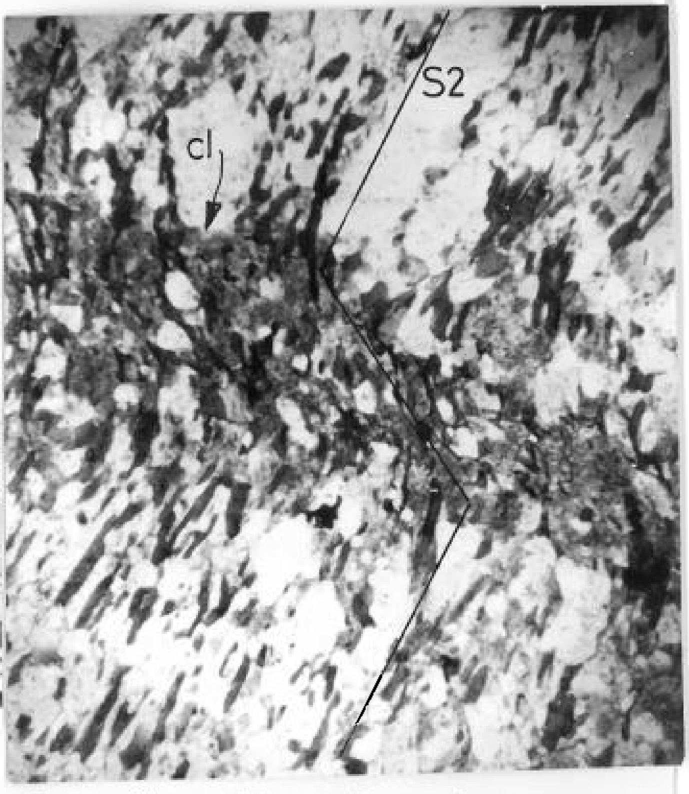


Fig. 29. Chlorite replacing biotite in kink zone only. Spec. C8. Transmitted light. x35.

## FOLDING

As mentioned before there is evidence of two periods of folding, and there is some indications of an earlier warping.

### ARGUEMENTS FOR A DEFORMATION PRIOR TO F1.

The F1 or $B_{s1}^{s2}$ folds are by far the most prominent throughout the whole area. These appear to be the first deformation structures although there are some facts which could indicate an earlier deformation (FO). These include:

(1) The variation in plunge of the F1 fold axes on the map scale.

(2) The variation in plunge of the F1 fold axes on the outcrop scale.

(3) The possible existence of FO mullions (?).

Point 1) is seen from the sub area plots (see ~~map~~ appendix.). In the folded region, variation in fold axes for a particular deformation may be due to one of three reasons.

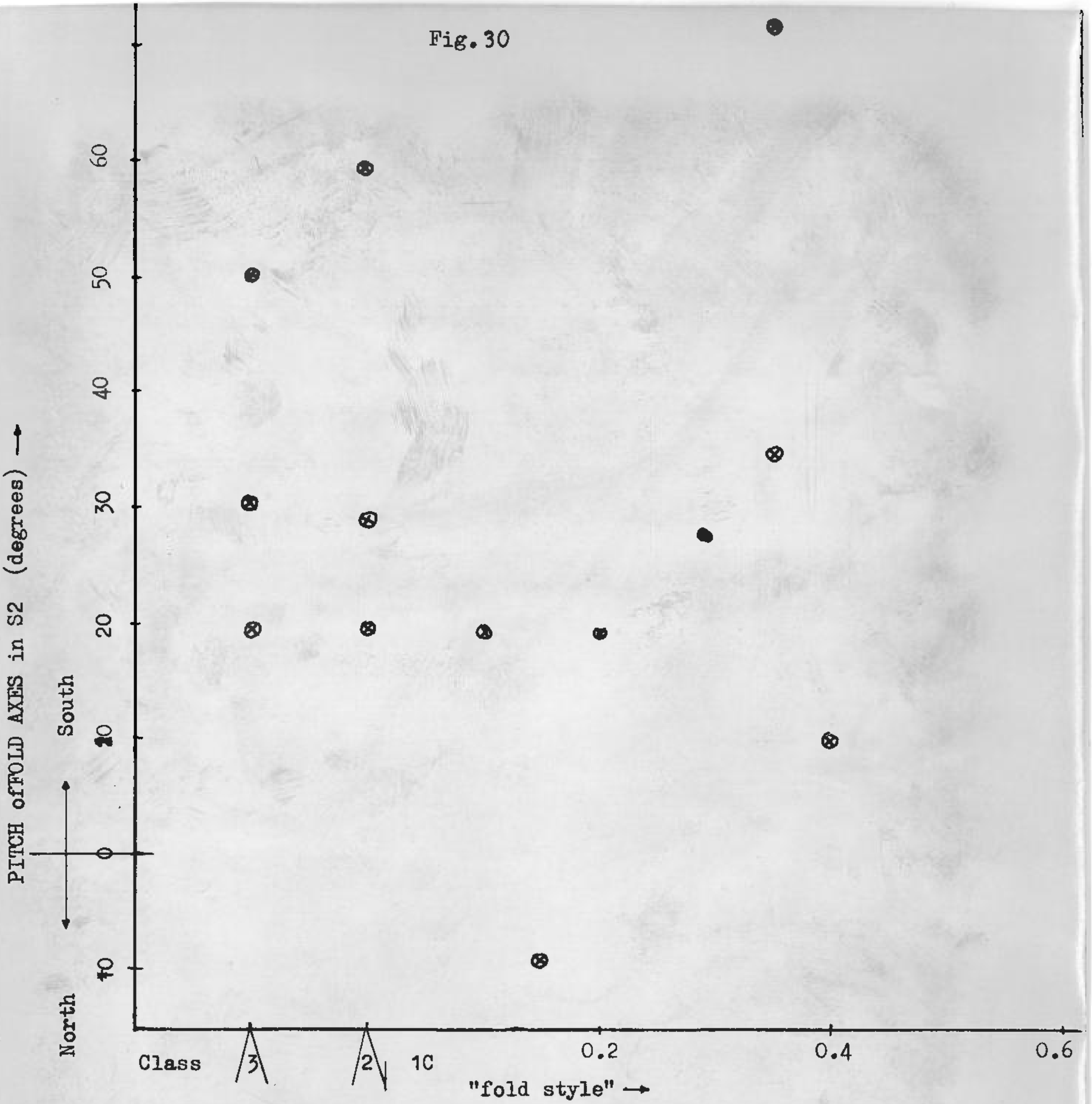
(a) Inhomogeneous deformation.

(b) Refolding by a later deformation.

(c) Folding of an initially inhomogeneous surface.

The first possibility (a) was investigated by classing the folds under Ramsey's classification and plotting the style against the pitch of the folds for the whole area (see fig. 30). If the inhomogeneity in the fold axes' pitches is a result of differential flattening then one may expect the graph to reflect this trend. (see fig.31). Since no trend is obvious it is possible that inhomogeneous strain cannot be invoked as the reason for pitch

Fig. 30



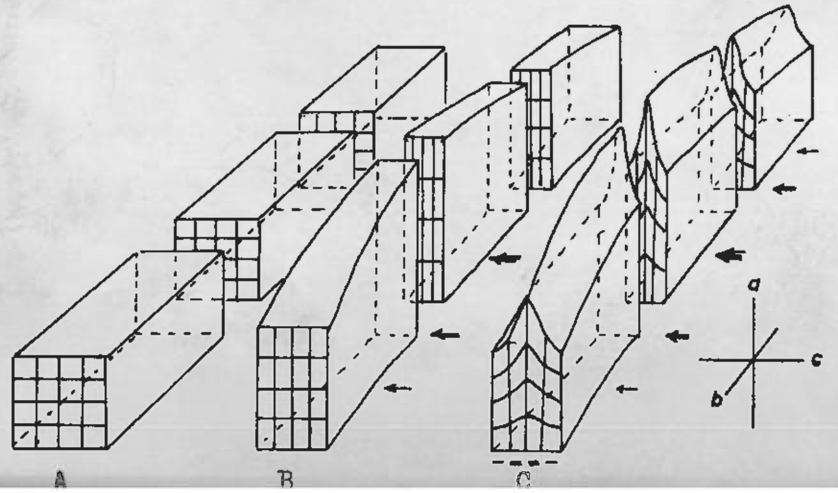


Fig.31 A) Rock prism.
B) Variable flattening iin bc plane.
C) Variable flattening in ac plane.

variation.

The second possibility (b) may apply but where refolding can be demonstrated it is associated with crenulations. Since crenulations are only present in a few areas, and also since the schistosity in the area (except subarea 5) is reasonably constant, it is more likely to be deformation of an inhomogeneous surface (c) which leads to the variation in pitch over the area.

Point 2) is illustrated in figure 32 which shows a specimen with a pitch variation of 30° in two feet. There is no inhomogeneous strain in the specimen because the fold wavelength remains constant along the length. Also there is no axial plane crenulations or folded schistosity in the sample implying that hypothesis (c) is more probable than (a) or (b).

Point 3) is illustrated in figure 33. These pods of material may represent original F0 mullions squashed in the ac plane of the F1 folding, but are more likely to be slivers of rock which have not responded to the folding in the same way as the rest of the rock.

Another factor which may indicate that refolding has not been responsible for the variation in pitch of the F1 fold axes in the area is the fact that the mineral streaking which is probably related to the F1 folding has such a constant orientation independent of the orientation of the F1 fold axes.

One final point which may be taken to indicate an earlier deformation is the existence of biotite and muscovite parallel or sub-parallel to S1 (figures 25 & 5). It is however, more likely that the muscovite has grown in the bedding and that the biotite represents refracted S2 cleavage.

End on view. Side view.

Fig. 32. Folded andalusite bands showing plunge variation along strike. Location B73.

Fig. 33. Fo Mullions (?) (see text). Location C18.

Fig. 34. Open F1 fold in quartz rich psammites. Plunge 10°N. Location B20.

### F1 Folding.

The F1 folds are folds in bedding with an axial plane schistosity, and are present on all scales from 1 cm to 1 Km in wavelength. The style of the folds varies considerably depending to some extent on the rock type.

### Folds in quartz rich rocks.

The folds in psammites are generally open with a poorly developed axial plane schistosity. They fall into class 1C (Ramsey) - (fig. 34 - 35). Fig. 36 shows a structure which plunges 10° North, has an axial plane cleavage, but which may represent slumped cross bedding which has an axial plane schistosity imposed on it, or it may be an F1 fold.

### Folded quartz rich bands in a mica schist host.

These folds are open on a large scale but tightly appressed on a smaller scale (fig. 37 - 39). This is also the case in some folded andalusite bands (fig. 40). This is probably a result of drag folding on the limbs. Throughout the whole area the sense of the drag folding is synstral predominantly (fig. 2).

"Pinching" of softer more ductile bands is common between bands of quartzite. Although only demonstrative on a small scale (fig. 41), this has probably occurred with the southerly portion of the andalusite unit containing the Kanmantoo copper mines (fig. 2). Ramsey has found a similar pinching between rocks of differing viscosity in particular the cover - basement rocks of the Alps.

Fig. 35. Fold profile of F1 fold in quartz rich psammite.

Fig. 36. North plunging structure either F1 fold or slumped cross bedding. Quartz rich psammite. Location C17.

Fig. 37. F1 folding of psammitic layers in pelitic host.

Fig. 38. F1 folding of interlayered psammite and pelite bands showing small scale transposition.

Fig. 39. F1 folding of interlayered psammite and pelite bands.

Fig. 40. F1 folding of andalusite bands in quartz-feldspar schist. Location C18.

typical interface between psammite and pelite bands.

Fig. 42. Isoclinal folding in andalusite schist.

## Folding in the Pelites and Transposition.

The more schistose rocks which generally lack well defined bedding show more appressed fold styles, and isoclinal folding is present in the andalusite schists (fig. 42). Transposition is very common in the pelites, and unless quartz rich bands occur it is impossible to trace the original stratigraphy (fig. 43). Much of the Brukunga formation shows S1 // S2 and thus transposition is possibly present over much of the area. This means that the true stratigraphic thicknesses will be considerably less than obtained by simple measurement normal to the strike.

There are features in the Brukunga formation which can either be explained by transposition of one limb of the folds or thrust faults. The latter will be dealt with under faults. Assuming the former is the case, the transposed limb is the western limb of anticlines. The Aclare mine shows this well (fig. 44). The transposed zone (or "deformation" zone which may be a better term) commonly shows complex irregular isoclinal folding, and the compositional layering (S1) is mostly parallel to S2 (fig. 45).

On a larger scale in the Brukunga formation, these transposed limbs tend to form zones striking parallel to the schistosity. It is possible that there is a tie up between the two major andalusite bands in the area (see Block diagram 1) and much of the band is in a transposed limb, but it is probably more likely that Block diagram 2 is the case. Mapping further to the North is necessary to resolve this problem.

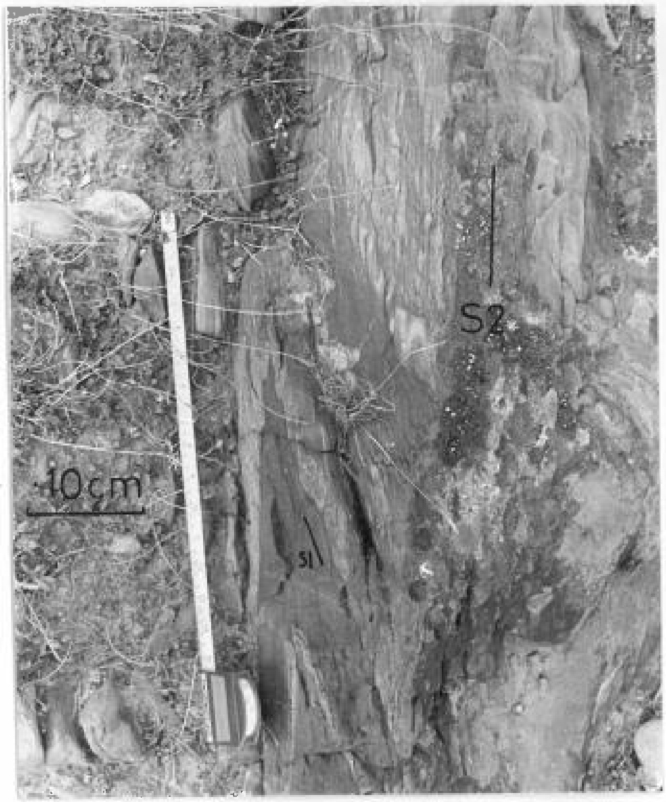


Fig. 43. Small scale transposition of compositional layering parallel to schistosity. See also Figs. 38, 39.

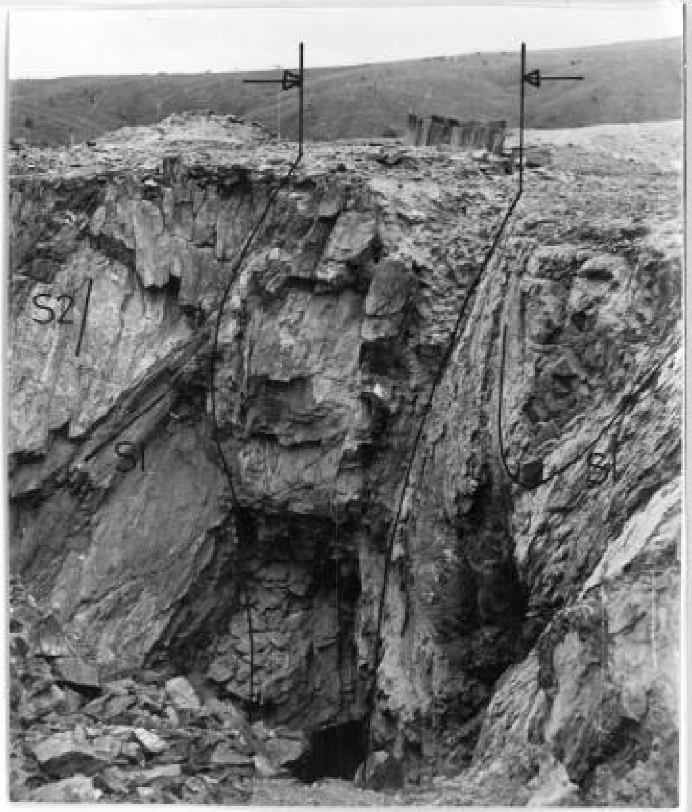


Fig. 44. Looking south at Aclare mine showing deformation zone.

Fig. 45. Showing compositional layering parallel to schistosity. Spec. B73.

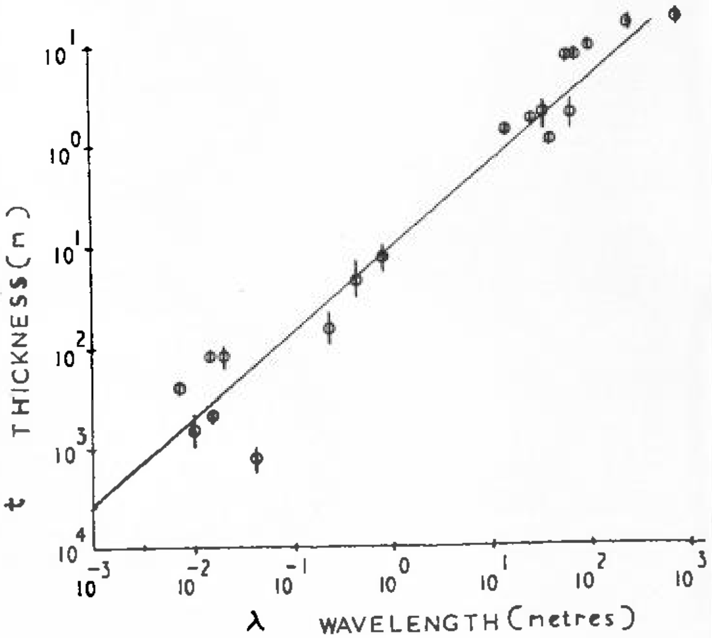


Fig. 46. Wavelength of folds (λ) versus thickness of units (t).

Additional points.

The preferred orientation of quartz c axes seems to be related to the F1 deformation (see petrofabrics).

A fold wavelength versus thickness of folded layers graph was plotted for folds of all scales and a general straight line plot was obtained (fig. 46). This is in general agreement with Ramsey's concepts.

Second Generation folding ($B^{s3}_{s2}$)

A deformation later than F1 has affected the area but only to a small extent. The deformation generally only manifests as small crenulations in the schistosity. (fig. 26) (not to be confused with fine crenulations parallel to a mineral streaking). It is only developed in the more schistose rocks. There is only one sub area (5) where large scale $B^{s3}_{s2}$ folds form. In this area the rocks have a high mica content and it is difficult to distinguish bedding.

It is probable that the crenulations have a geometry similar to those further north (see fig. 47). This is because there are normally two sets of crenulations visible in most places (fig. 27), and from the stereo plots these appear to fan about an axis of intersection which is steeper than the indivual $B^{s3}_{s2}$ and $B^{s3'}_{s2}$ axes. (fig. 48).

The nature of the folding (bent micas etc. and undulose extinction etc.) implies that no major recrystallisation has occurred during this deformation. Also there is not much tendency for forming an axial plane layering (fig. 26).

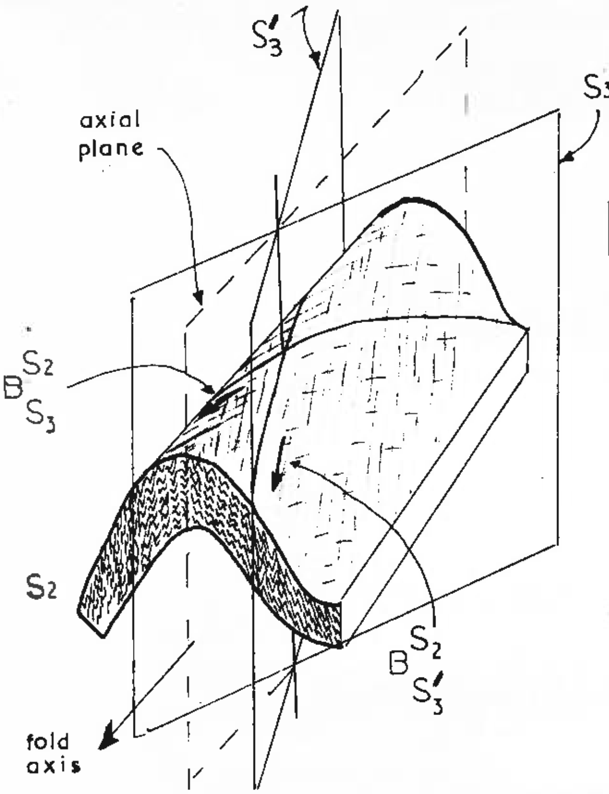


Fig. 47. Relationships of crenulation surfaces.

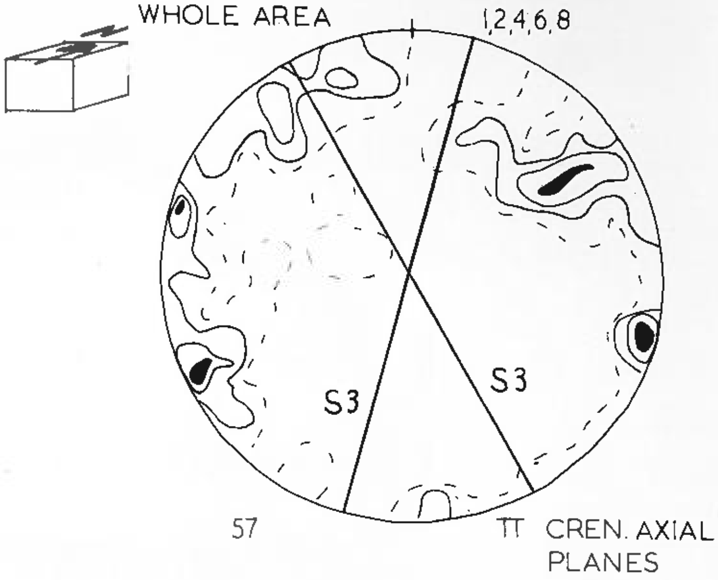


Fig. 48. Poles to $S_3$ and $S_3'$ with interpretation.

Fig. 49. Crenulations associated with boudinaged quartz vein. Location C1.

Crenulations are also associated with boudinaged quartz veins, e.g. in the Wheal copper mines (fig. 49). These crenulations are probably the result of initial inhomogeneities in the inherited fabric.

<u>KINKS</u> - $B_{s2}^{s4}$

Kinks are common throughout the more schistose rocks dying out when a quartz rich band is present. They have already been described in the section on S surfaces.

## LINEATION (L1)

There is a prominent lineation defined by a mineral streaking with a fine crenulation often paralleling throughout the area (fig.50). This lineation lies in the schistosity and shows a remarkably constant orientation (pitch 88 N or S) all over the area (fig. 51).

It is more obvious in the Brukunga than the Brownhill greywacke. L1 is actually a dimensional elongation of mineral grains particularly quartz and biotite (fig. 4). The lineation is deformed by later folding.

The lineation probably represents the "a lineation", i.e. it is parallel to the direction of movement of material (fig. 52). In this case the area is similar to the Scottish highlands except there is no evidence of the strong deformation which has occurred in the Highlands prior to the deformation in which the a lineation developed. Stretched pebbles elongate in this direction are found south of the area.

Two reasons for calling the lineation an "a" lineation are:

(1) remarkably constant orientation.

(2) non parallelism of fold axes - see fig. 51.

The geometry of L1 is shown in figures 51 and 52. The fact that $B^{s2}_{s1}$ is not at 90° to L1 is presumably means that the bedding was initially at some angle (not 90°) to the movement direction, possibly because of some of the earlier warping (deformation (?)) prior to the F1.

The fact that there is a fine crenulation parallel to L1 in most cases could mean that the mineral streaking is actually an older crenulation which has been recrystallized and transformed so that it resembles a mineral streaking.

Crenulations around andalusites are commonly parallel to L1. This is consistent with the idea that the andalusites formed during or prior to the F1 folding due to flattening in the c direction, the cleavage is wrapped around the andalusites (fig. 13). On one large outcrop the andalusites were observed to have their long dimensions in the S2 plane although there was no preferred direction of orientation in S2.

The Kanmantoo orebody is a tabular body generally parallel to the schistosity and elongate in the L1 direction. This relationship can be seen on a smaller scale also, where elongate blebs of ore occur parallel to L1.

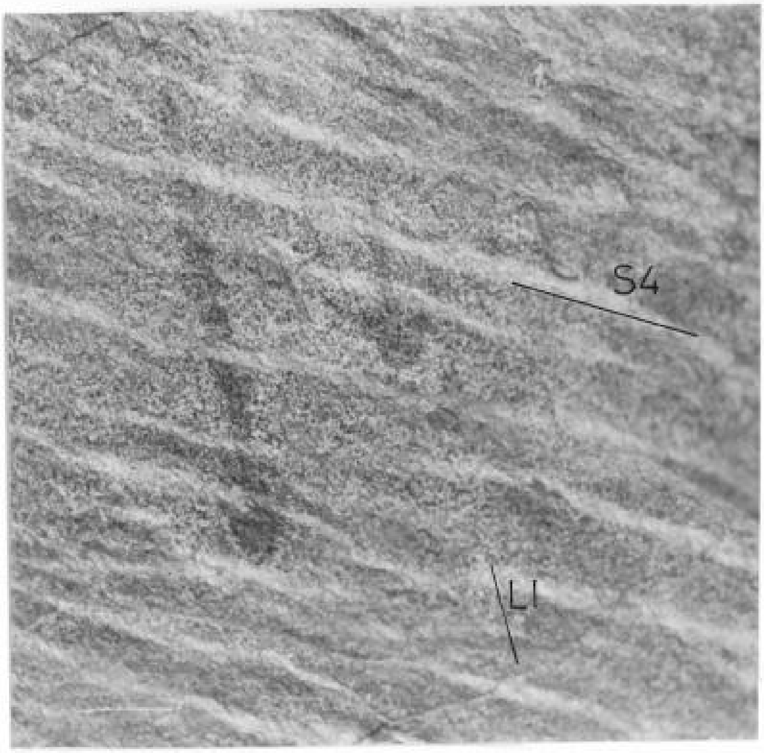


Fig. 50. Schistosity surface showing mineral streaking and kinks. Location B98.

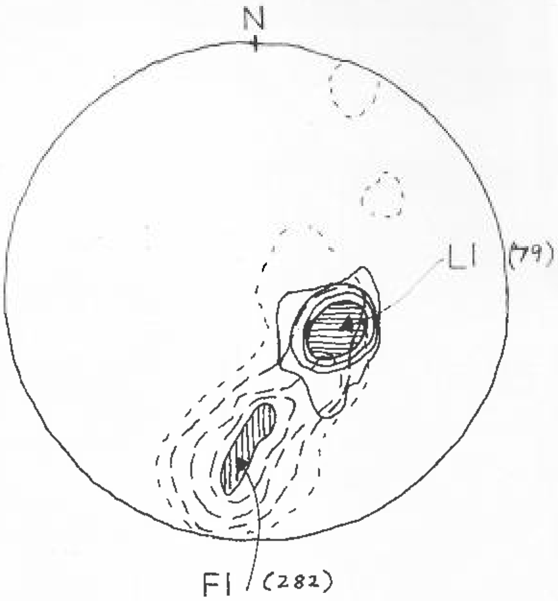


Fig. 51. Poles to mineral streaking (L1) and Fold axes (F1) showing non correspondance.

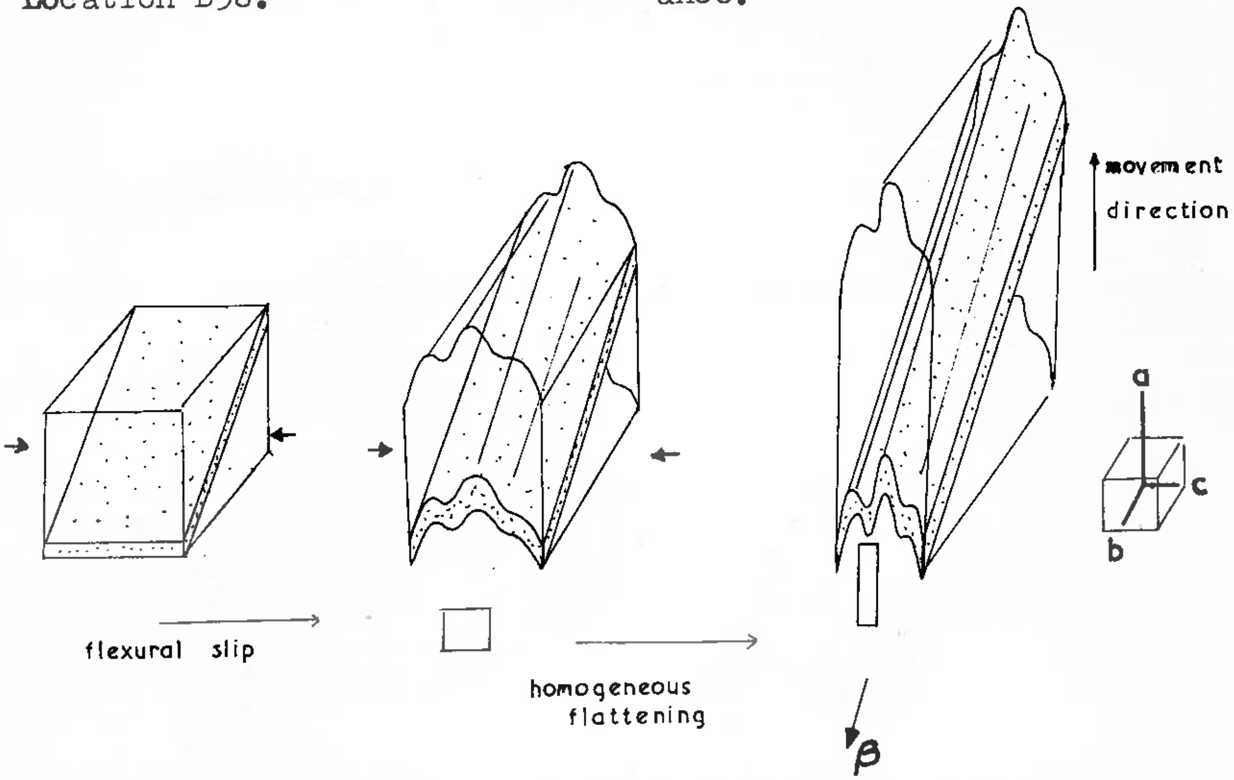


Fig. 52. Development of fold with folded surface initially inclined to kinematic axes. (after Ramsey).

## FAULTS

There are a number of north south and east west fracture zones in the area. These are commonly iron stained (see fig. 15) probably as a result of oxidation and solution of the iron oxides by ground-water moving through the zones. A displacement of 20 metres was noted on one of the E.W. faults - see road cutting exposure (fig. 53).

Earlier it was stated that there were features in the area which could be explained by transposition or thrust faults. If the deformation zone at the Aclare mine is a thrust, then, considering the structure of the whole region, it may consist of a large drag fold (fig. 2) with a central thrust along which horizontal movement has been right lateral and the easterly block has been uplifted. (fig. 44) The Bremer fault could be similar, as too could be the North South fracture zone running through Dawsley, and possibly, even the base of the Kanmantoo.

There is a NE lineament passing through Dawsley (B. Thompson unpublished report) the significance of which is discussed under ore deposits.

## JOINTS

There is one main joint set through the area which has an east west orientation (total $\pi$ joints, fig. 54) parallel to the EW faults. Joints are more often developed in the psammite rocks (fig. 55). Since the joints are in the ac plane they may represent "ac" joints, thought by many workers (Billings 1962) to indicate a slight extension in the b direction.

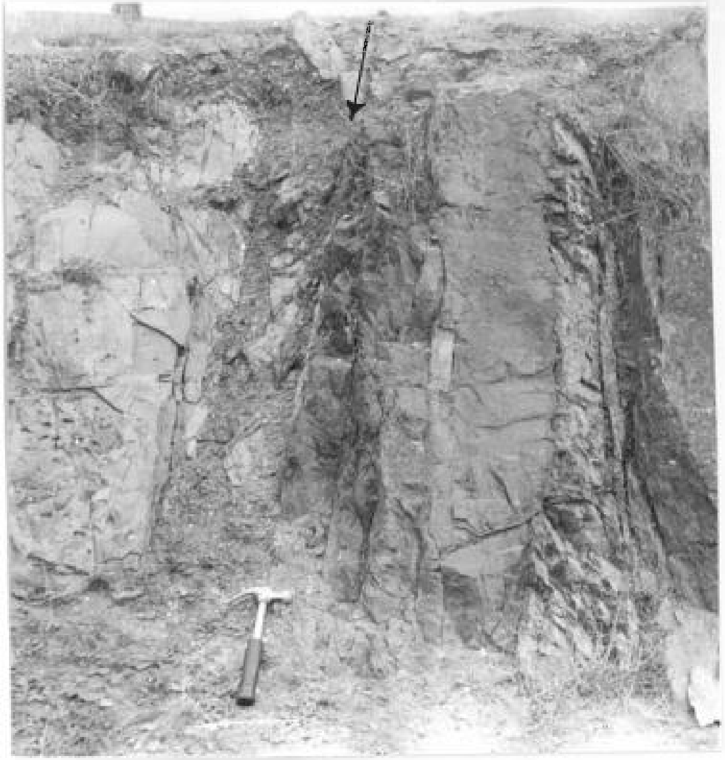


Fig. 53. Small E-W fault exposed in road cutting. Location C16. Looking west.

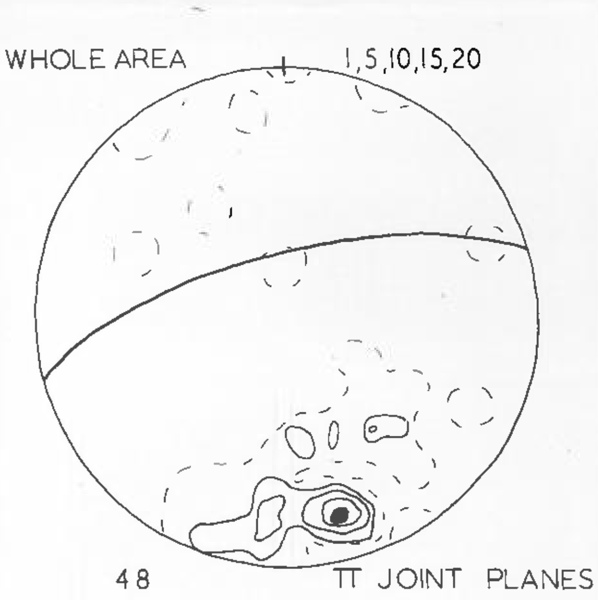


Fig. 54(a). Total poles to joint surfaces.

Fig. 54(b). Photographs of joints in the more quartz rich rocks. Location B75.

## PETROFABRICS

WDTM?

### QUARTZ

### c axes - Optical

A total of 1100 quartz (0001) axes were counted, and (if they were done properly) the three sections which were done showed that there is a weak preferred orientation related to the kinematic axes. The plots obtained were actually small circles in the N section slides (see K1, K5, B56, fig. 55 - 57).

The plots also show that there has been some effect of the inherited fabric on the preferred orientation (e.g. bedding). It is possible that, since the c axes are symmetrically related to the kinematic axes that the recrystallisation is related to the stress and/or strain field operating during or after the deformation.

It is difficult to interpret these plots except to say that symmetry remains the prime criterion for kinematic interpretation of the mineral orientation.

Other petrofabric descriptions are treated under "Local Geology".

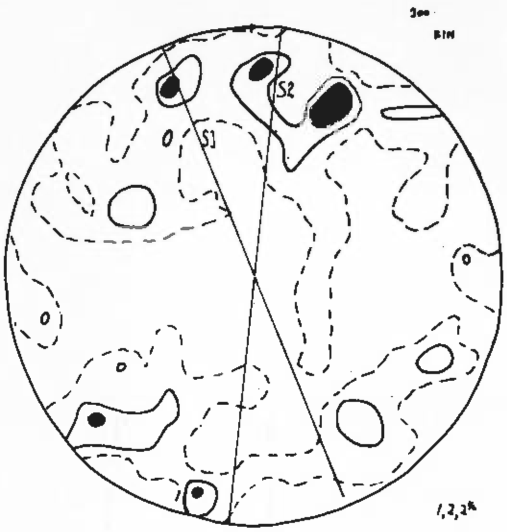


Fig. 55. Spec. K1.
300 quartz c-axes. N Section.

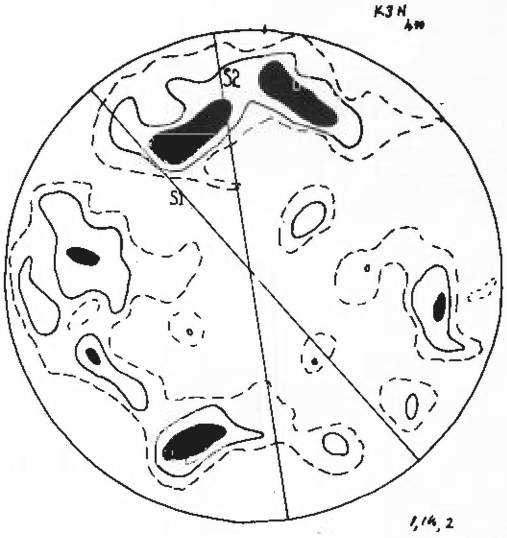


Fig. 56. Spec. K3.
400 quartz c-axes. N Section.

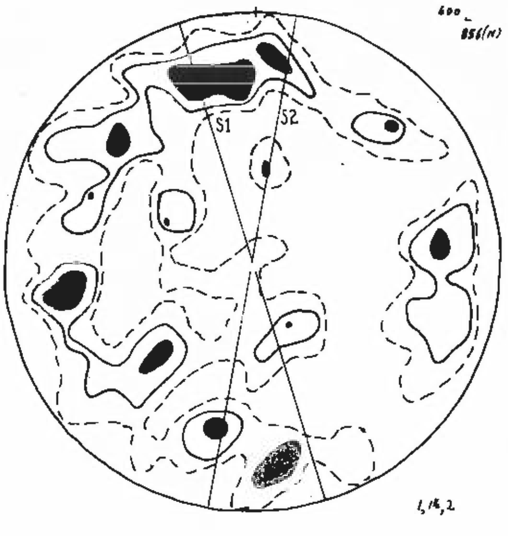


Fig. 57(a). Spec. B56.
400 quartz c-axes. N Section.

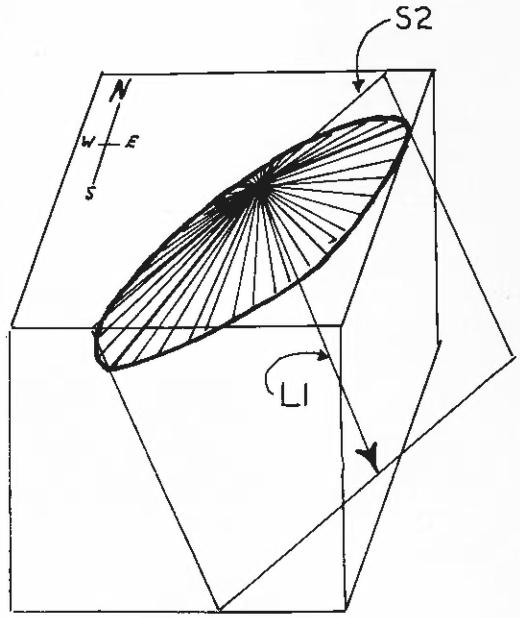


Fig. 57(b). Diagramatical representation of quartz c-axes data.

## ORE DEPOSITS

The ore deposits in the area include the various copper mines and two silver lead zinc mines (see map fig 2). A structural stratigraphic control is advocated for these ore deposits. Before launching into the structural considerations with respect to origin of the ore, a definition of terms is appropriate. Syngenetic is used in the sense that the ore was deposited at the same time as the enclosing sediments. Epigenetic is used in the sense that the ore was deposited at a later stage. Recent work indicates that this simple classification is not adequate in many cases, and this is probably the case in both the copper and silver lead zinc mines.

## ACLARE MINE

### 1) MESOSCOPIC SCALE

A description of the workings and mineragraphy can be found in P.W. Askins Honours thesis 1968. As explained before, the mineralisation occurs in a deformation zone (fig. 44) which either represents a reverse thrust or a transposed limb. In either case it is obvious that the stress in this zone has been exceedingly high. Since the zone crosses the bedding on either side, the ore cannot be designated as purely syngenetic. On the other hand the ore appears to lens out into a pyritic quartzite with traces of lead and zinc sulphides, (The same occurs in the Scotts creek mine), which weathers into a typical pyritic schist band, implying some stratigraphic control.

### 2) MACROSCOPIC SCALE

On a macroscopic scale the ore is folded in a variety of styles and with varying fold axes pitching south (see profiles fig. 59 - 63). As with the enclosing country rocks the most obvious deformation in the area is the F1. The folds in the ore consist of folded quartz lenses (originally S1?) deformed in a sulphide matrix (see fig. 60), and folded sulphide bands (parallel to possible S1) in the micaceous quartzite host (see figs. 62 - 63).

### 3) HAND SPEC - MICROSCOPIC SCALE

On a band specimen scale, the ore occurs in layers parallel to the compositional banding assumed to be bedding. The quartz grain size increases markedly next to these layers (fig. 58). The ore in these bands shows evidence that it has undergone deformation. For example in the section, fig. 58, the coarse muscovites which have possibly grown in the bedding appear to have formed into an axial plane breakaway in the hinge zone. This is consistant with the idea that the sulphides were present prior to ~~ordinary~~ deformation and, as the folds formed, the limbs were attenuated and the sulphides, being more ductile were squeezed into the hinges. This enrichment of sulphides in ~~large~~ hinge zones is common although it does not always occur (see fold profiles, figs. 59 - 63). It is possible that the sulphides have replaced favourable beds e.g. carbonates, but no carbonate layers were seen. Blebs of sulphides are commonly oriented parallel to S2.

### ORIGIN - SUMMARY

~~Since~~ The structural evidence implies the ore was present during the folding yet also implies that the ore is in a deformation zone which transgresses the enclosing bedding on either side.

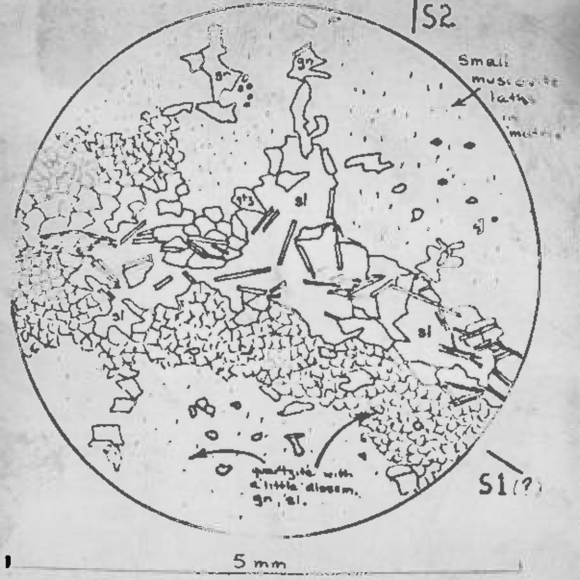


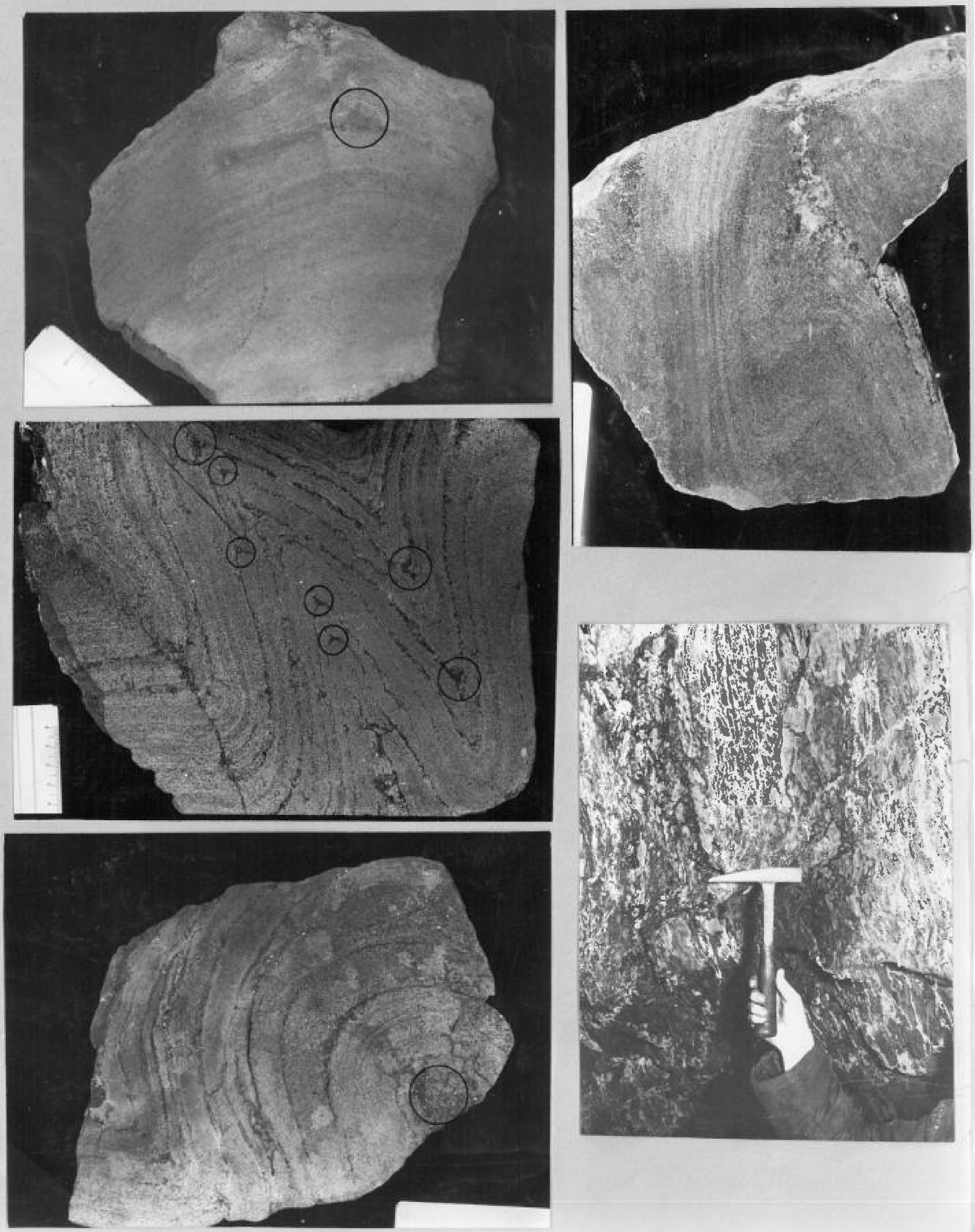
Fig. 58. Folded sulphide layer showing "flowage" of sulphides. Aclare mine. (After Askins).

Fig. 59. Folds in sulphide ore. Aclare mine.

Fig. 60. Fold in sulphide ore. Aclare mine.

Fig. 61. Fold in sulphide ore. Aclare mine.

Examples of fold profiles in Aclare Mine ore.



Petrofabrics imply that the metamorphism was either before or more likely during the folding (F1). Hence it is possible that the sulphides were originally present in the pyritic schist but have been concentrated into a favourable (high stress) structural site during the metamorphism and deformation.

## THE KANMANTOO COPPER DEPOSIT

Broken Hill South have recently discovered an ore deposit near the old Kanmantoo workings which contains at least 9 million tons of low grade copper, mainly as the mineral chalcopyrite. Some features which may be relevant to the control of this ore body include the following.

1) It is present in the peculiar garnet chlorite rock within an andalusite schist.

2) It lies on a North Westerly trending lineament (Thompson). Date, please

3) The "deformation zone" through the Aclare mine, if extended to the north, passes through the copper deposit.

4) If fold axes plunge to the north to the north of the orebody, then the ore lies in a domal structure.

5) The ore body, as defined by assay limits, is a tabular body pitching 80° to the north in the schistosity, (i.e. roughly parallel to L1) hence it is not conformable with the lithological layering which is folded in shallow south plunging folds. The Cobar deposit in N.S.W. has almost exactly the same control, and the rocks are of a broadly similar age also. One major difference is that the metamorphism has been considerably lower - chlorite grade in fact.

Some deposits in Norway also are elongate parallel to the mineral streaking.

6) The lower grade uneconomic mineralisation surrounding the ore body may be broadly conformable with the lithological layering. (Roberts 1969 pers. com).

7) Linquist (1966) concludes that the ore has undergone metamorphism and deformation.

## DISCUSSION

From a consideration of the above points it is possible that the copper was originally dispersed in the sediment which is now an andalusite schist, and that, during the deformation and metamorphism, a thrust developed parallel to the schistosity, along which the copper was metamorphically concentrated parallel to the movement direction.

### Other minor Copper mines.

These invariably occur in andalusite schists and are associated with metamorphic quartz veins parallel to S2 (fig. 49). The ore consists mainly of malachite and azurite, and in one mine gahnite, a metamorphically produced zinc spinel occurs as green crystals. Minor east west crush zones are occasionally associated with these mines. The shafts pitch $90^{\circ}$ in the schistosity, i.e. parallel to the mineral streaking. Once again these minor deposits are probably formed by metamorphic concentration of originally dispersed sedimentary copper.

# CONCLUSION

This area is of interest because of two reasons. The first is that it is one of the few areas in the eastern portion of the Mount Lofty Ranges where early deformation structures exist and can be easily recognised. In most of the region, later generation structures are most predominant, and it is hoped that some of the material in this thesis may be of use in sorting out the earlier structures in the rest of the region.

Secondly, the structural control of the ore deposits is very interesting, and may prove of use in exploration in other areas of a similar geological environment.

# ACKNOWLEDGEMENTS

I wish to thank my supervisor Dr. Tim Hopwood for suggesting this project and for his encouragement during the year. I also wish to thank Professor Rutland and Dr. Oliver for helpful discussions concerning the regional structure and metamorphism.

Broken Hill South hold leases over a large portion of the area and I thank them for permission to work in the area and for assistance while in the field. In particular I wish to thank John Roberts of Broken Hill South for very helpful discussions on the geology of the area and on the Kanmantoo Copper deposits.

Also I wish to thank Don Brown who owns most of the property in the area for his help during the year.

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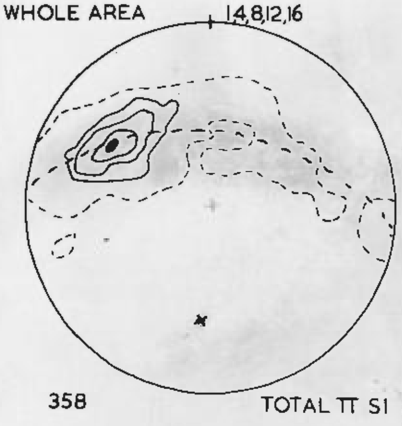
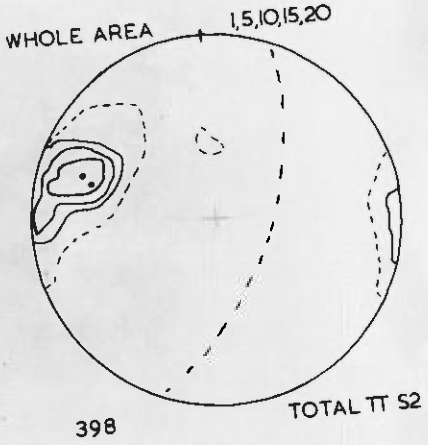
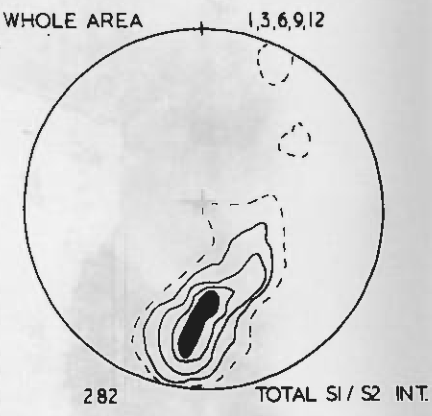
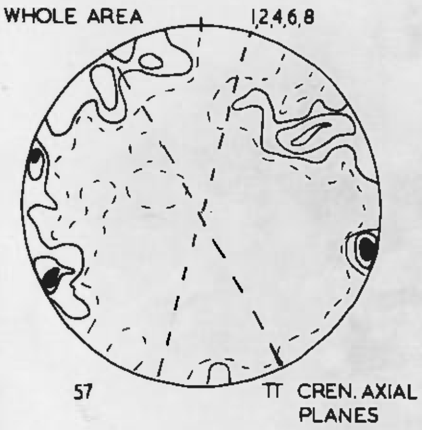
# APPENDIX .

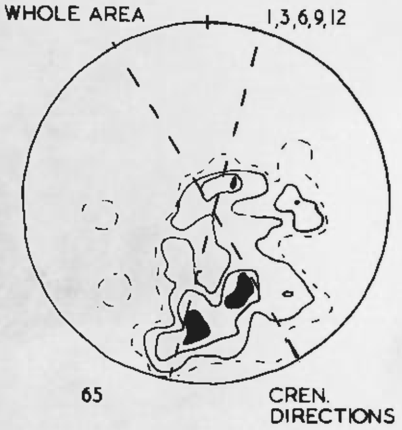
# Structural Data

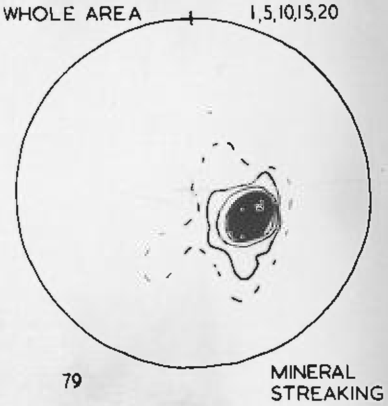


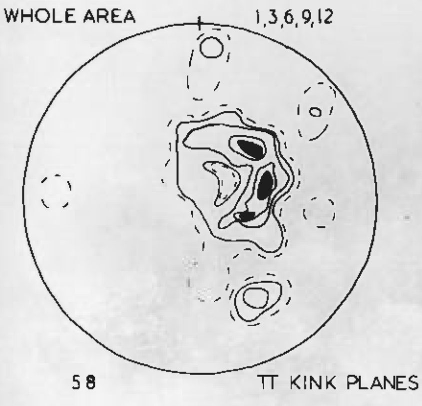


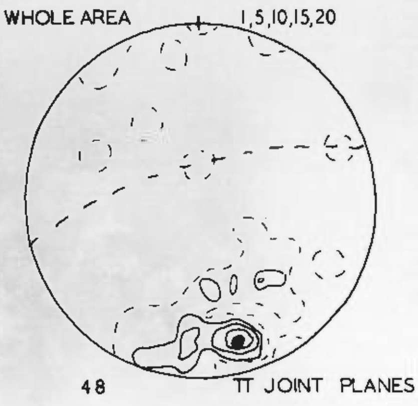












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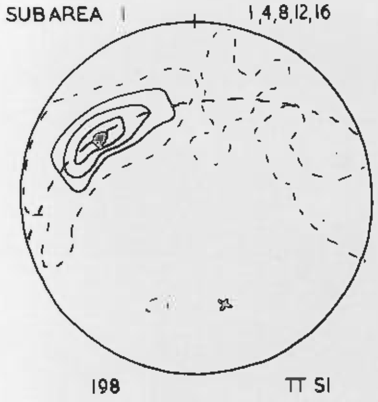

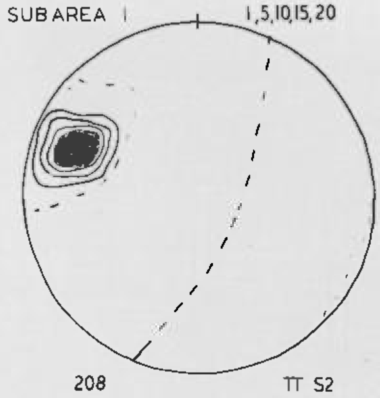

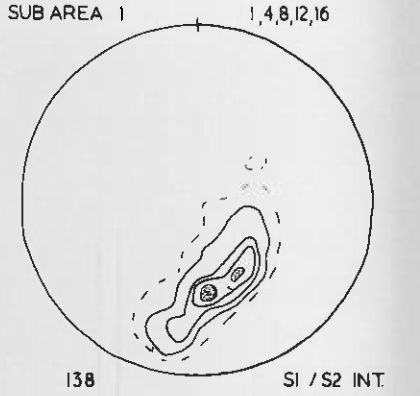

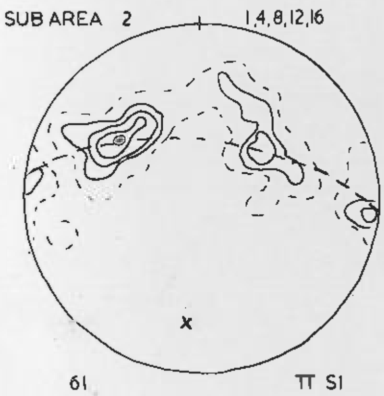

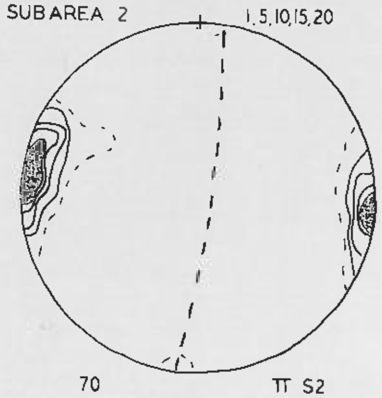

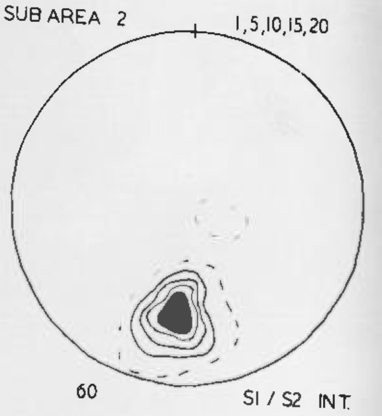

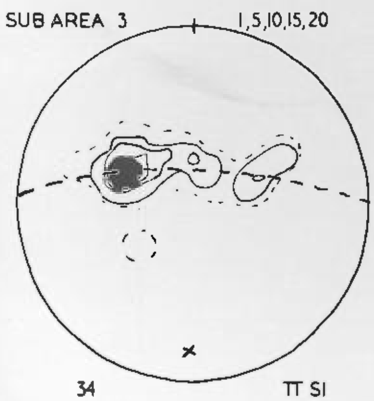

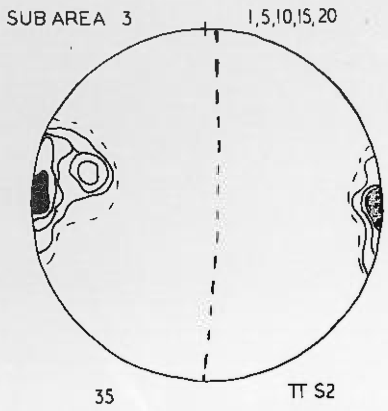

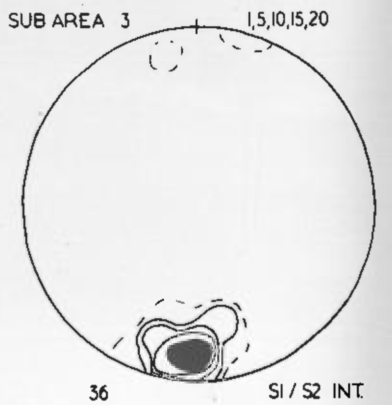

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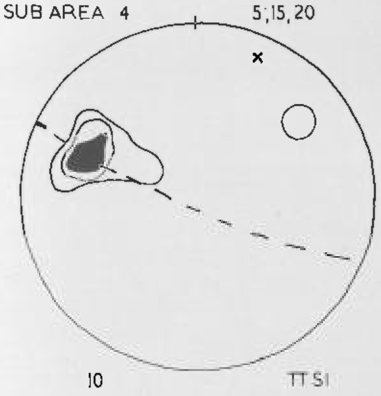
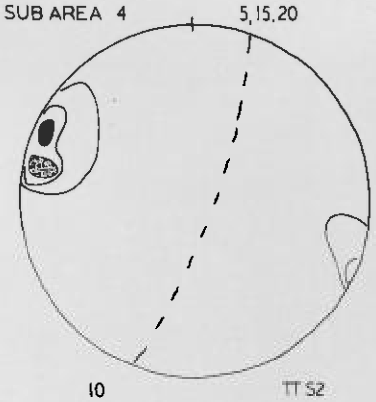
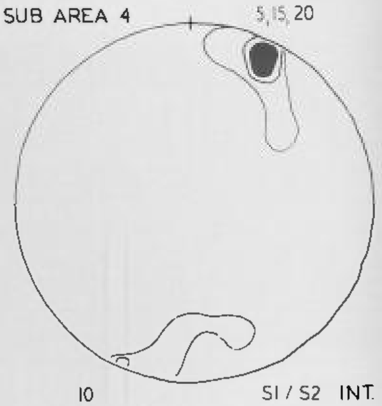
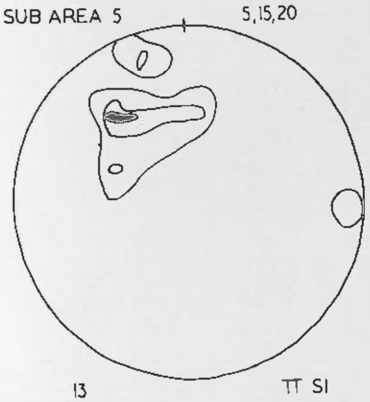
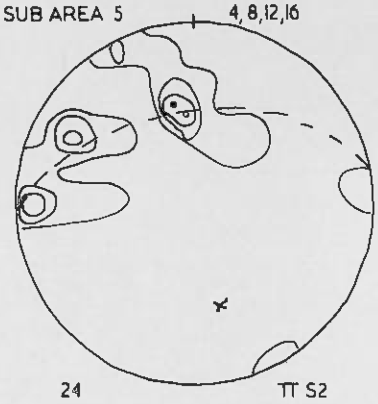
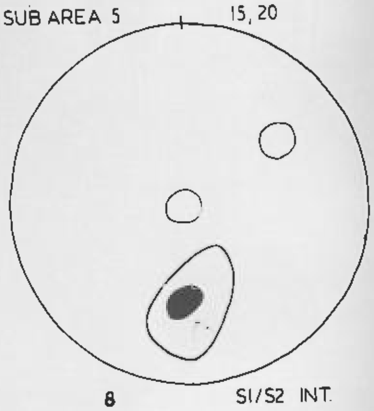


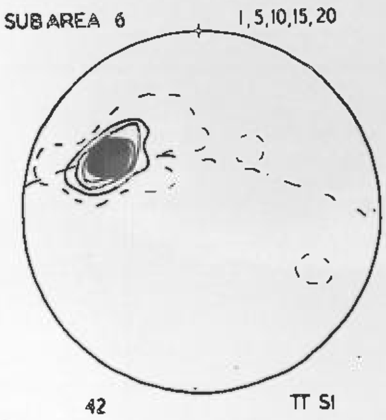


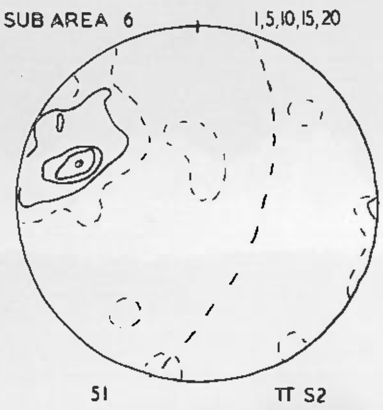


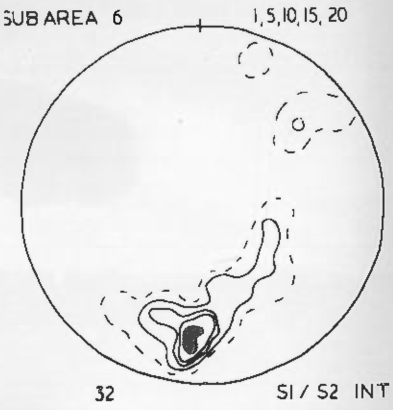




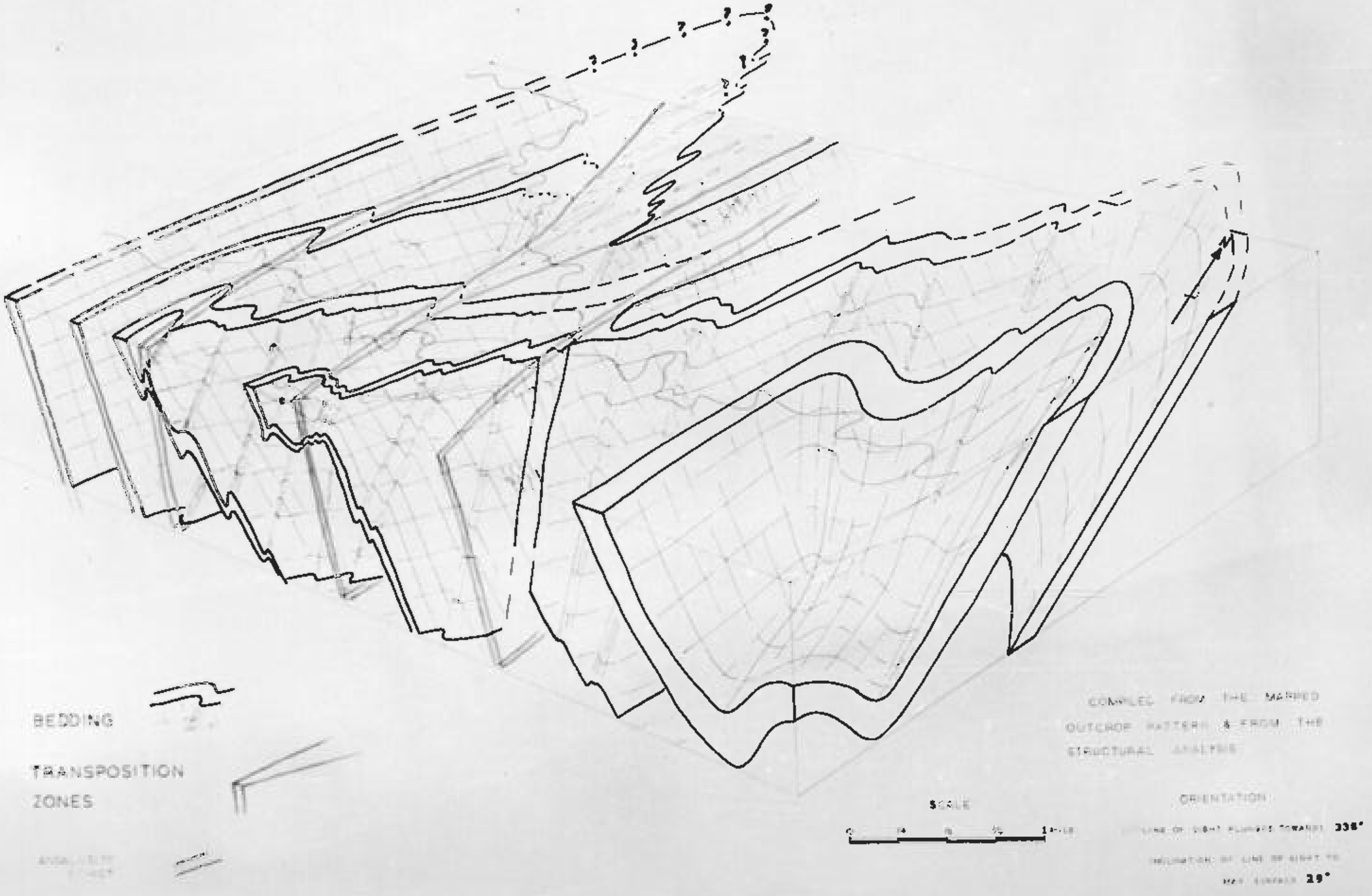








# PERSPECTIVE BLOCK DIAGRAM 1
OF
AN AREA SOUTH OF KANMANTOO

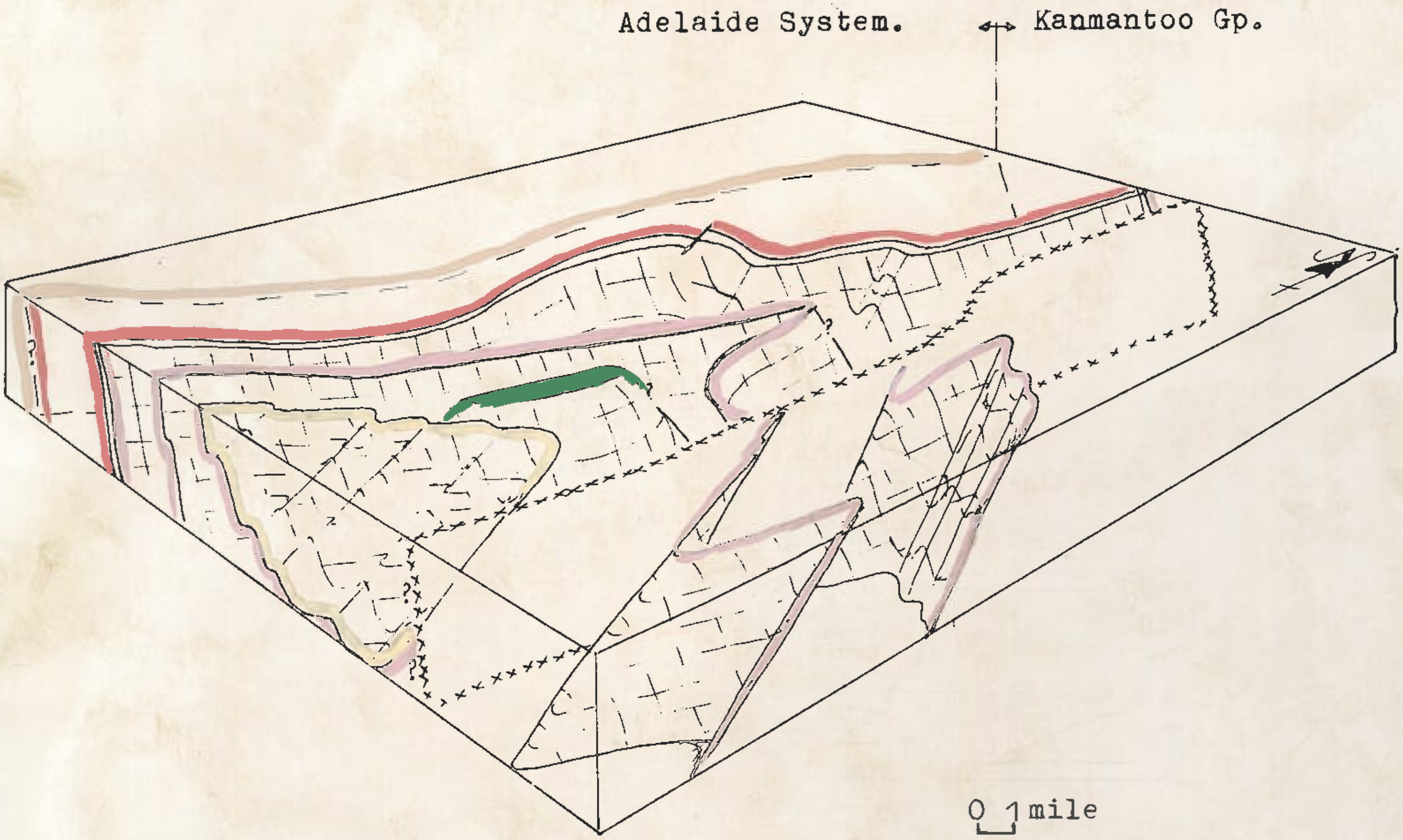


COMPILED FROM THE MAPPED OUTCROP PATTERN & FROM THE STRUCTURAL ANALYSIS

ORIENTATION

LINE OF SIGHT PLUNGES TOWARDS 338°

INCLINATION OF LINE OF SIGHT TO MAP SURFACE 29°



Block diagram 2. REGIONAL GEOLOGY (Interpretation)

# SUMMARY OF PETROLOGICAL DESCRIPTIONS

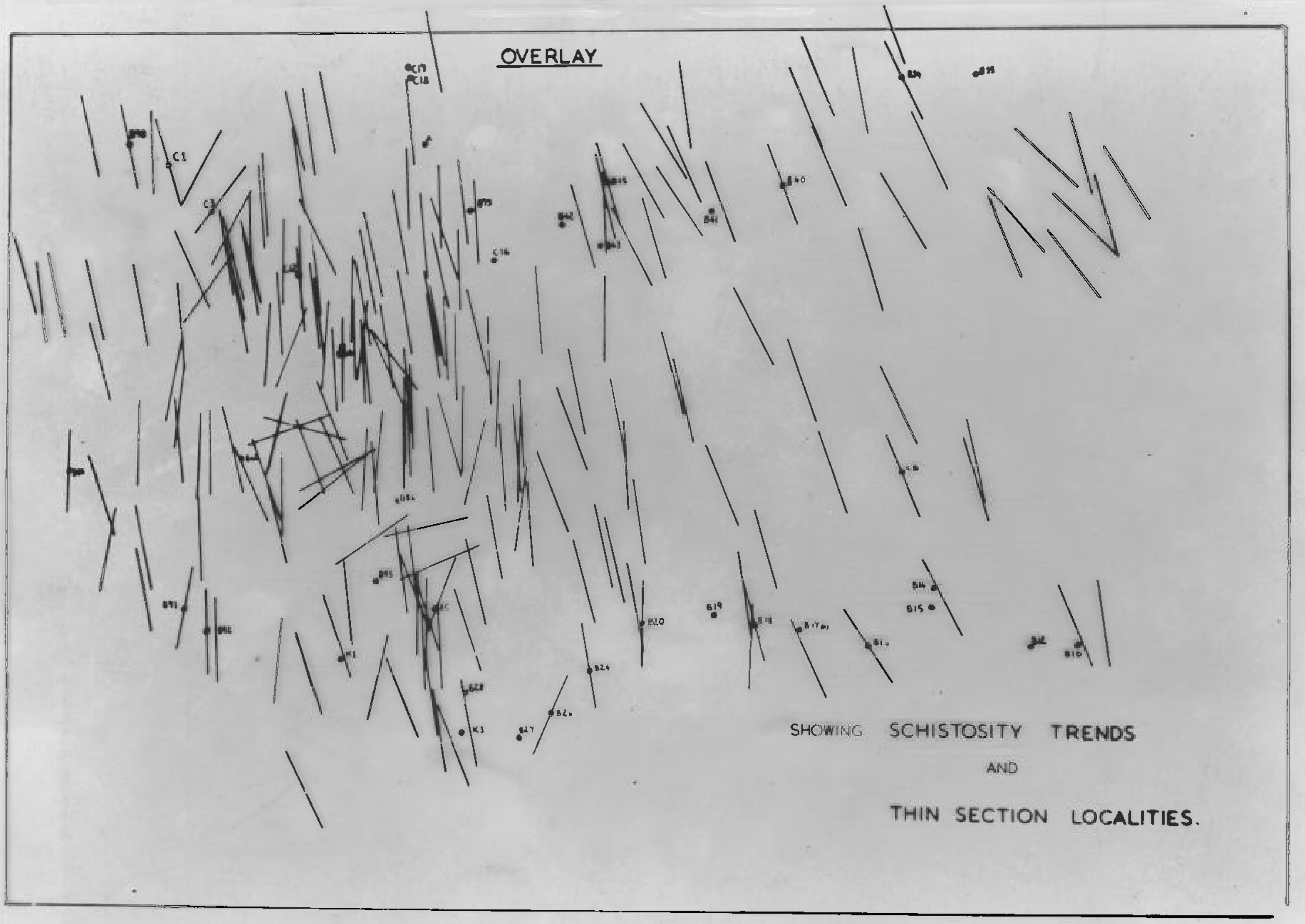
(The following descriptions apply to S-section slides; i.e. the plane of the slide is parallel to S2. )

| SPEC. | C.B. | B10 | B8 | B12 | B14 | B15 | B16 | B18 | B19 | B24 | B28 | B33 | B34 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Biotite% | 35 | 15 | 0 | 40 | 10 | 30 | 5 | 25 | 0 | 30 | 10 | 5 | 25 |
| Quartz% | 60 | 40 | 65 | 40 | 40 | 55 | 60 | 45 | 60 | 40 | 60 | 40 | 45 |
| %undulose extinction | 0 | 0 | 70 | 60 | 5 | 50 | 0 | 5 | 20 | 0 | 0 | 0 | 20 |
| Tot.Feld.% | 2 | ? | 5 | 20 | 40 | ? | 20 | 20 | 10 | 30 | 30 | 10 | 20 |
| (K-spar) | | | | | 20 | | | 10 | | 20 | | | |
| (Plag. ) | | | | | 20 | | | 10 | | 10 | | | |
| Muscovite% | 2 | 5 | 30 | 0 | 0 | 5 | 10 | 5 | 30 | 2 | 0 | 0 | 0 |
| Chlorite% | 0 | 0 | <1 | 0 | 10 | 10 | 5 | 1 | 0 | 0 | 0 | 0 | 10 |
| Garnet% | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |
| Hornblende% | 1 | 0 | <1 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| Apatite% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Other | | | | | | | | | Actinolite- | | | 45 | |
| Grain size | v. un. | v. fg. | v. un. | v. un. | v. un. | v. fg. | v. un. | un. | vv. un. | un. | v. un. | v. un. | ev. |

| SPEC. | B40 | B41 | B42 | B43 | B45 | B56 | B59 | B62 | B91 | B92 | C12 | K1 | K2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Biotite% | 30 | 10 | 30 | 20 | 25 | 25 | 15 | 15 | 20 | 25 | 25 | 25 | 20 |
| Quartz% | 55 | 65 | 50 | 60 | 50 | 50 | 45 | 35 | 55 | 60 | 60 | 55 | 60 |
| %undulose extinction | 0 | 0 | 5 | 10 | 5 | 5 | 5 | 5 | 5 | 5 | 80 | 70 | 60 |
| Tot.Feld.% | 10 | 10 | 10 | 10 | 10 | 15 | 10 | 5 | 20 | 20 | 10 | 20 | 15 |
| (K-spar) | | 5 | | 5 | | 10 | | | | | | | |
| (Plag. ) | | 5 | | 5 | | 5 | | | | | | | |
| Muscovite% | 0 | 0 | 1 | 5 | 5 | 5 | 10 | 15 | 1 | 1 | 1 | 0 | 0 |
| Chlorite% | 1 | 10 | 5 | 5 | 5 | 5 | 5 | 5 | 1 | 1 | 0 | 1 | 1 |
| Garnet% | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| Hornblende% | 0 | 1 | 1 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Apatite% | 5 | 0 | 1 | 1 | 1 | 1 | 5 | 5 | 1 | 1 | 3 | 1 | 2 |
| Other | Andalusite + Staurolite - | | | | | | | 15 | | | | | |
| Grain size | ev. mg. | ev. mg. | un. mg. | un. cg. | v. un. | v. ev. cg. | v. ev. | v. ev. | v. ev. | v. ev. | ev. | v. ev. | v. ev. |

v.=very. fg.=fine grained .05mm.
mg.=medium " .1 mm.
cg.=coarse " .3 mm.

ev=even grained
un=uneven grained



## OVERLAY

SHOWING SCHISTOSITY TRENDS
AND
THIN SECTION LOCALITIES.

# INTERPRETATION MAP