THE UNIVERSITY OF ADELAIDE.

A. The geology and petrography of an Archaean inlier, south of Normanville.

B. The origin of the "Houghton" granulite.

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CONTENTS.

Abstract, 1.
Introduction, 2.
Geology, 3.
Petrography, 4.
Structure, 13.
Faulting, 15.
Metamorphism, 16.
Metasomatism, 18.
Igneous activity, 18.
Mineralisation, 19.
Geophysics, 19.
Geochemistry, 20.
Conclusion, 23.
Acknowledgments, 24.

Appendix I, List of rocks described in appendix II.
Appendix II, Slide descriptions.
Appendix III, Analytical methods used in chemical research.
Appendix IV, ACF and ARF diagrams.
Appendix V, Results of chemical analyses and interpretive graphs.

Bibliography, 25.
Detailed mapping established definite rock units within the Archaean inlier south of Normanville. The distribution of the rock types is suggestive of a major antiform structure. Only metamorphic layering is recognised in the area. 

The first Archaean orogeny produced this layering and reached upper amphibolite grade of metamorphism as defined by the minerals, sillimanite, garnet, diopside, and scapolite. The temperature and pressure conditions were 750°C and 2-3 kbars. This was established using mineral assemblages and the presence of considerable partial melting, pegmatitic masses, and migmatites.

This same orogeny was also responsible for the development of a strong schistosity, which was always parallel to the metamorphic layering.

A Proterozoic orogeny produced a strong crumulation of the schists. This crumulation is parallel to the fold axis of a major antiform, which plunges 35° to 135°.

The deformation reached biotite grade of metamorphism as shown by the minerals biotite, sericite, and epidote, which commonly replace the higher grade minerals. An antiform overturned to the west was the major structure. Its underlimb was sheared away, so that the inlier represents the eastern limb only. The western outcrops of the inlier represent the shear zone.

Geochemical analyses of the Houghton granulite suggest a sedimentary origin. This, coupled with its conformability with the surrounding rocks, and its association with a zircon-rich meta-quartzite, support this conclusion.

Introduction.

This project was completed under the supervision of Doctor Robin L. Oliver. The object of this thesis was to map in detail, describe, and interpret the mineralogy, metamorphic grades, and structural elements of the area, and to examine the field
relationships, along with the chemistry, to decide if it is of sedimentary or igneous origin.

An area of about 6 square miles was geologically mapped in about 6 weeks. The remaining laboratory work involved making thin sections of the different lithologies, describing these slides using the petrological microscope, and carrying out a detailed chemical analysis of the chosen specimens. Messrs S. Wicks and A. McEwin completed similar projects on Archaean inliers at the Mt. Compass and Yankalilla areas respectively.

My area was some 40 miles south of Adelaide and just below Normanville. The Archaean basement rocks are overlain by Adelaide geosynclinal sediments. Generally the outcrop was poor, but good sections were found along the Yankalilla River gorge, and on a cliff face on the seaward side of the inlier. The cliff face section provided about 300 feet of outcrop across the strike. Small streams also provided useful sections.

The climate is temperate, with an annual rainfall of 30", the area is intensely cultivated, with natural scrub remaining on isolated hilltops. The maximum elevation occurs on the cliff face section, and is about 300 feet. Generally, the area is very hilly, with the prominent feature being the large Yankalilla River gorge, which winds through the inlier.

The Permian sediments present a cover much of the inlier. They are mostly sands, clays, and minor tills and conglomerates. Many basement outcrops show glacial pavement features, such as smooth surfaces and striations. Other cover sediments were scree slopes on the cliff face, alluvial sand in the river gorge, and soil cover on most hillsides.

Mapping was done on enlarged aerial photographs, on a scale of 1" represents 600 feet. Smaller scale photos were used for stereo photographic interpretation, but were of no use.
Geology. Geological mapping of the area was carried out on a large scale (as shown on the outcrop map.), with meticulous care taken in recording the lithologies of the outcrops, noting differences such as degree of feldspathisation, and sillimanite content. In this way a sequence of units was built up, with approximate lithological boundaries drawn in. These boundaries were parallel to nearby Proterozoic boundaries. New outcrops of the Houghton granulite were discovered, but did not prove to be good marker beds, because of their discontinuous nature. The outcrop patterns of the granulite and sillimanite gneiss could be interpreted as reflecting the major anti-formal structure of the area. The outcrop map is the most important map, as it is an accurate record of the rock type. Faulting, thrust zones, and migmatisation, have all complicated the geology, such that many interpretations can be made to this map. The interpretive map is my contribution.

PETROGRAPHY.

Houghton granulite. This rock type has been known by many names, by past workers, such as Houghton Diorite, and Houghton Syenite, but because these names are biased toward an igneous origin, I will refer to the rock as a granulite throughout the thesis. The granulite is very resistant to weathering, with fresh surfaces showing a pink and pale green colour. Excellent metamorphic layering of these minerals is observed in most outcrops. This layering is planar, for the most part, but in places, forms tight overturned folds. No axial plane features are recognized, but the fold axis plunges in a S.E. direction.

The feldspar is mainly microcline, which is pink in hand specimen. In thin section it has a granoblastic texture, with an average grain size of 1.0mm. The percentage varies, from trace amounts to 45%, with an average of 30%. The grains are only
slightly sericitized and show a very prominent cross-hatched
twining. The amphibole present is thought to be hornblende, but is
difficult to distinguish from actinolite. The extinction angles
range from low angles to 25°, which suggests it is hornblende. The
grains have a very ragged appearance, with epidote replacing the
amphibole to a large extent.

Quartz is not present in all slides, but where it does
occur it has a very embayed shape, with a strong undulose extinction.
Definite bands of quartz-rich and microcline-rich layers can be
seen.

Two minerals which are closely associated in a granoblastic
aggregate are diopside and scapolite. The diopside is recognised
in hand specimen by its dark green colour. In thin section its
pleochroism is distinctive. The scapolite is a tan colour in
hand specimen, with many excellent cleavage surfaces present. In
thin section its excellent uni-axial (−ve) figure, birefringence,
and parallel extinction are most distinctive. The scapolite
contains small, xenoblastic inclusions of epidote within the
grains. One particular slide shows, in addition to scapolite,
diopside and microcline, a tan coloured garnet, which is probably
a grossularite-andradite garnet. (see plate II)

Plagioclase is rare and only a few grains have been
found. Epidote is a very prominent mineral, it has a distinctive
yellow to green pleochroism, high refractive index, and mottled
bi-refringence. It varies from 10 to 50%, with an average of 30%.
Instances can be seen where the epidote is replacing the
amphibole, but in most instances the epidote has completely
replaced the original mineral.

Common accessories are apatite and sphene. The sphene
grains are rounded and become very abundant in slides contain-
ing the diopside-scapolite assemblage. In one particular slide (H5)
Calcite is associated with epidote, both being alteration products
of amphiboles. Very minor amounts of opaques occur.
Field relationships of the granulite are, that it is conformable with the surrounding rocks, in all instances. No igneous or sedimentary features are noticed. I interpret this as due to complete destruction of such features by the high grade of metamorphism to produce the granoblastic texture. The granulite is the least altered unit by the Proterozoic orogeny.

Quartzite. This unit is closely associated with the granulite, being found on either side of it, in all instances. In hand specimen, it is a white rock, consisting almost entirely of quartz, with small amounts of pink feldspar scattered throughout. In thin section, the quartz exists in two forms. Firstly, there are large embayed grains, showing a strong undulose extinction, which sometimes shows a preferred orientation within the grain. The preferred orientation is parallel to the poor foliation developed.

The other form of quartz is a polygonal recrystallized form. This type occurs between the larger grains, and in pressure shadows around microcline grains. Within the larger grains trails of dusty inclusions occur and in some instances seem to indicate former grain boundaries.

Rounded grains of microcline are prominent, showing the distinctive cross-hatched twinning (Plate 13). The grains show minor sericitization around the edges.

Zircon is a prominent accessory. It is oval shaped, and evenly distributed throughout the slides. No sedimentary layering is seen, I consider the zircon to be of sedimentary origin, because of its concentration and shape.

The original sediment may have been a slightly arkosic sandstone, its association with the granulite may represent a sedimentary assemblage of a close to shore sand (marine), with the facies more seaward being a calcareous marl.

The strain features of the quartz were caused by the Proterozoic orogeny. Other horizons occur, distinct from those associated with the granulite, and they show the same features.
One particular horizon is cross-cutting the layering of the surrounding gneisses. It may be intrusive, although there is no evidence to support this, but I favour a tectonic explanation for the relationship, i.e.,

The Archaean orogeny may have produced tight isoclinal folding of the original unit. As I suspect, considerable shearing may have occurred in the area, and the noses of these tight folds may have been sheared away (as in diag above), to result in the observed outcrop pattern.

The majority of the rocks in the area are gneisses, but by detailed descriptions, using mineralogical and textural differences, I was able to sub-divide these rocks into smaller units.

Augen gneisses. These rocks have a strong foliation developed, which, in places, is a schistosity. The rock appears mainly sericite, with large augens of quartz strung out along the foliation. The strike of the foliation varies in a gently wavy manner, with a strong crumulation developed on the foliation surfaces.

In thin section, considerable sericitization is evident. Layers of quartz alternating with sericite are a common feature. The sericite is replacing plagioclase, so this indicates the original rock had quartzose and felspathic layers, which I would attribute to the original sediment and not to a metamorphism or granitization process.
Mostly the quartz grains are very embayed, with strong undulose extinction, but a few show uniform extinction, and contain very few inclusions. The average percentage is 40%, with a mean grain size of 0.7 mm. The amount of recrystallization is widely varying.

Biotite is a common constituent, averaging at 20%. It is always associated with muscovite and opaques, possibly representing a chemical reaction between these three minerals. The opaques form exsolution features in the biotite grains.

Sericite forms 40% of the slides. Occasionally plagioclase can be recognized beneath the sericitic mass. In most slides remnant sillimanite is found, which is also sericitized. (Plate 5). The distinctive diagonal cleavage, high refractive index and parallel extinction are most obvious. The mineral is sillimanite.

A pink garnet is found in some slides. The original grains are quite large, up to 3.0 mm, but are now shattered and greatly chloritized. The garnet is probably grossularite.

Other more exotic minerals occur, such as large bladed grains of muscovite, and bladed and fibrous aggregates of pyrophyllite. Both these minerals are pseudomorphing sillimanite.

The foliation and schistosity are Archaean features. While the lineations and folding are Proterozoic.

12. Augen schist. These rocks have a strong schistosity developed. As in the augen gneisses, these rocks show an undulation of the schistosity along the strike. Large augens of quartz can be seen, and very tight folding of the micas results in the formation of a pronounced crumulation. (Plate 2). The schistosity is of the same generation as the foliation in the gneisses.
Figure 1. 

Nylonitic augen schist, showing larger augens of strained quartz and microcline. There is considerable recrystallization of quartz. The micas are aligned along the strong foliation developed.

Plate 2. 

Augen schist. Shows the development of a new crumulation. It is a crumulation of micas and recrystallized quartz.
Texture of a thrust zone.

Figure 1.

Plate 2.
Plate 3.

AUGEN GNEISS. Larger strained quartz and smaller recrystallized quartz, with considerable sericite present. Minor opaques.

Plate 4.

HOUGHTON GRANULITE. Granoblastic texture of microcline, showing cross-hatched twinning, and epidote.
Plate 5. GRANITE GNEISS. Shows a large, cross-hatched microcline grain, with blebs of plagioclase, i.e., perthitic texture. Also considerable quartz.

Plate 6. GRANITE GNEISS. Shows zoning of the central plagioclase grain, with a mermekitic texture developed around this grain. Also plagioclase with albite twinning prominent.
Houghton-granulite,
Metasomatized amphibolite.

Granoblastic texture of Hornblende and Plagioclase. Epidote forms coronas around hornblende and an alteration product of plagioclase.
Plate 8. Augen gneiss.
Sill. = Sillimanite.
Ser. = Sericite.
qu. = Quartz.
shows the sericitization of sillimanite.

Plate 8, 9. Metasomatized Amphibolite.
Am. = Amphibole
Pl. = Plagioclase
Ep. = Epidote
Op. = Opaques
Sp. = Sphene
shows the alteration of Plagioclase to Epidote.
Plate II. Augen schist.

shows the development of a new crumulation (S4) on the older schistosity surface (S2). It is a crumulation of micas.

Plate 10. Augen schist.

Am. - Amphibole. Occurrences of Am.

shows the growth of Amphibole grains across the foliation direction as developed by biotite(bi) and opaques.
Plate 12. Haughton granulite.

Di. - Diopside.
Sc. - Scapolite.
Ml. - Microcline.
Gn. - Garnet. - Calcite. Octahedrals.

Plate 13. Quartzite.

Mi. - Microcline.
Qu. - Quartz.
Ser. - Sericite.

The commonest minerals are quartz and feldspar, with minor amounts of biotite and muscovite.
Plate 14.  
Augen Gneiss.
Very similar to the augen schist, but more quartz rich. It shows excellent folding of quartz layers. The micas are folded around with the quartz, which is completely recrystallized.

Plate 15.  
Sillimanite gneiss.
Shows a central quartz grain, surrounded by a garnet mass, which is extensively chloritized. The garnet is almandine, related to the upper amphibolite facies, whilst the chlorite is a retrograde mineral.
Biotite is very prominent and is parallel to the schistosity surface. From this we deduce the biotite to belong to the Archaean phase. The quartz is completely recrystallized, forming a polygonal matrix, with a mean grain size of 0.1 mm. Muscovite is of the same generation as the biotite, but much less concentrated. Other accessories are opaques and tourmaline.

One slide, (376-197), is markedly different in mineralogy, although it shows the same texture. A strong orientation of almost colourless biotite, and unidentified, tabular opaques occurs, developed in a matrix of recrystallized quartz. The opaque may be graphite. An elongate, mottled, hornblende is developed cross-cutting this orientation direction, and, in some instances, paralleling it. This suggests the hornblende grew at the same time, or just after the development of the foliation.

This unit is easily recognized, and could be used as a marker unit. On the geological map, several long horizons are seen and they are all straight. The interpretation is that the area represents the eastern limb, only, of a major antiform, and so folding is lacking, not evident.

The complete recrystallization of the quartz, resembles that found in thrust zones of similarly aged rocks. For this reason, I would add to the geological complexity of the area.

**Sillimanite gneiss.** This is the most widespread gneiss in the area mapped. It is poorly foliated in most instances. On the foliation surface elongate grains of relic sillimanite occur. They show a rather poor mineral lineation. More quartzose varieties can be differentiated, but are not mappable units.

In thin section the minerals are quartz, muscovite, biotite, microcline and opaques. The quartz is mostly recrystallized with some larger elongate grains present. The muscovite and biotite are parallel to the foliation. The same crystallization as
was found in the augen schist occurs.

The rock is, mineralogically, very similar to the augen gneiss, but distinguished in the field by its poorer foliation and the most characteristic elongate, helic crystals of sillimanite, which are sericitized in thin section.

This extensive unit shows no recognizable meso-folding, although considerable variation in strike of foliation occurs. Stereo plots of these measurements defined a poor great circle which defined a fold axis, parallel to the known fold axis of the major antiform. This unit is extensively affected by the retrograde metamorphic event.

Migmatite gneiss. As the name implies, this unit has undergone more feldspathization than the other gneisses. It is more similar, mineralogically, except for the higher concentration of feldspars. The augens are predominantly pink feldspar, strung out along the foliation plane.

Microcline is the dominant feldspar, showing only slight sericitization. The augens vary considerably in size, from 0.5 mm to 2.0 mm. Minor amounts of plagioclase are recognizable, but mostly sericitized beyond recognition. One particular slide contains considerable unaltered plagioclase, and the albite twinning gives a composition of Ab75. In this slide many basal sections of biotite occur. Needle inclusions in these grains suggest this biotite is of the Archean orogeny. Accessories are opaques and tourmaline.

Migmatitic Sillimanite gneiss. This unit is identical with the sillimanite gneiss, apart from the considerable migmatization which has occurred. Quite good pink feldspar layering occurs, with large augens of feldspar, commonly 5.0 mm, found. Sillimanite, biotite and quartz still occur, but microcline is much more prominent. Sericitization is not as severe, and only partly sericitized plagioclase grains are recognized.

Biotite-rich gneiss.
It is most distinctive in the field, being a very black rock, with the most obvious minerals being biotite, quartz and plagioclase.

It contains about 30% biotite. The biotite is most unusual in that, there are many basal sections, showing a uni-axial (−ve) figure, and full of needle-like inclusions in a hexagonal pattern. The quartz is very embayed and the plagioclase shows little sericitization.

This is one of the puzzling units of the area, as the outcrops of it appear to bear no relationship with the other units. It appears 'squashed' in between the other rock types. I consider that faulting may have caused this complication of the sequence.

**Amphibolites.** In hand specimen, they have a granoblastic texture, are a dark green to black colour, and the plagioclase grains show excellent cleavage surfaces. Minor sulphides appear disseminated in some.

In thin section, the granoblastic texture is most prominent, with many triple points evident. The average grain size is 0.8 mm. A pale green, mottled mineral, often rounded, inclined extinction, 2V = 50–60°, has been identified as augite. A dark green hornblende often rims the clinopyroxene. Other hornblende is a brown variety, and may reach 40%. The remainder of the slide is plagioclase. These grains show slight alteration along the twin planes, which are well developed. The composition of the plagioclase is most consistent, ranging from Ab65–Ab75.

Apatite is a very common accessory occurring in large rounded grains. Sphene occurs as a corona around opaques, quartz is rare. Epidote rims hornblende in one slide, and other accessories are sericite and biotite.

The amphibolites occur as a distinct unit within the granite gneiss terrain. The boundaries between these units are sharp, and not crosscutting. Excellent layering of some resembles layering seen in sedimentary calc-silicates.
Chemical analyses were carried out for various trace elements (see appendix V), and using these, plus field evidence, I favour a sedimentary origin of the amphibolites.

**Clinopyroxene unit.** It is a most distinctive unit, being dark green and very heavy. The rock weathers to give a very red soil, which reflects the high iron content of this rock. There is no layering, nor any igneous features, such as chilled edges or igneous differentiation. It is very coarse grained and the mineralogy suggests it has been highly metamorphosed.

The main mineral is augite, with minor amounts of a retrogressive hornblende and plagioclase occurring.

Chemical analyses of these rocks was also done for trace elements only, but these results were inconclusive.

Examination of the outcrop map shows these rocks as occurring in large masses and small blobs, seemingly randomly distributed which would indicate, to me, that they were intrusive. Because they are affected by the Archaean phase, they would be very ancient.

**Metasomatized amphibolite.** These units are confined to the cliff face section of the area, on the western extent of the inlier. They are often of a very blotchy appearance, with large crystals of hornblende, up to 2" across, found. In other instances good layering is exposed, which is markedly cross-cutting.

Flesh coloured feldspar and pale green epidote are the main minerals. The hornblende often has a corona of epidote. The plagioclase is strongly sericitized along the twin planes, with the composition ranging from Ab 57 to Ab 73. Epidote forms a corona around these grains as well. Rounded microcline grains appear surrounded by the plagioclase grains. This feature suggests growth of the plagioclase around the microcline.

I think that these rocks have undergone sodium metasomatism, and at the time of mobility, the forces present caused the formation of a layering, parallel to the axial plane
present at that time, which would be the Archaean axial plane. The measurements of the layering give a reading of Strike 170° Dip, 70° W. Another possible explanation is that the layering represents the nose of a fold, where the cross-cutting relationship is preserved, and the limbs of the fold, where the layering is parallel, have been sheared away.

**Granite gneiss.** Mostly pink feldspar, with minor biotite. The rock has well developed metamorphic layering. It has a granoblastic texture, with an average grain size of 1.5 mm. Both microcline and plagioclase occur, each recognisable by its distinctive twinning. There are about equal quantities of each. Minor perthitic microcline occurs, i.e., plagioclase exsolution from microcline. The composition of the plagioclase ranges from Ab65 to Ab72. Larger and recrystallized quartz forms about 30% of the slides.

Cleavage traces of biotite, showing a strong pleochroism are prominent. Pale green hornblende forms as much as 30% of one slide. It is altered to epidote at the edges. Accessories are apatite, sphene, rutile, muscovite, sericite and zircon.

Small folds in this unit are tight, showing the same S.E. fold axis. The rocks are very similar, mineralogically, to the granites. Three distinct types of granite gneiss are recognised. There is the well layered type, another containing mafic minerals, and a third resembling a poorly foliated pegmatite. These rocks are almost free from retrogradation.

**Granite.** The minerals are coarse grained pink feldspar, white quartz, and black biotite.

The biotite shows a strong pleochroism and slight chloritization. Microcline and plagioclase are present in equal amounts. The plagioclase shows large variation in degree of sericitization, and a composition of Ab77. The microcline is unaltered. Quartz is very strained, with trails of inclusions and needles occurring within the grains.
The plagioclase shows excellent zoning in one slide, an excellent igneous feature. A mermekitic texture is observed in this same slide, showing exsolution blebs of quartz within plagioclase. A prominent accessory is a large zircon grain, 1.5 mm long.

Pegmatites. In hand specimen they are the same as the granite, but lack biotite. They form large vein-like intrusions, and huge structureless masses. On the beachfront they are crosscutting, but more often, they are conformable with the surrounding rocks.

Basaltic dyke. The most prominent igneous texture is the random orientation of plagioclase laths, very minor retrogradation has occurred. In hand specimen it is readily identified as a basalt, and its field occurrence as a cross-cutting dyke, about 6 feet wide suggest that this is a recent event, related to the Proterozoic event.

Cambrian. Occurs faulted against the Archean on the South-east boundary. It is a grey, slightly calcareous siltstone.

In hand spec thin section, it shows a matrix of quartz, with a strong preferred orientation of muscovite and biotite evident.

STRUCTURE.

An interpretation was attempted, using field relationships of folding, layering, cleavage-layering intersections, and measurements of schistosity and lineations. From examination of the Proterozoic-Archean boundary, as established by previous geologists, an overturned anticline to the west was the major structure present, and was related to a Proterozoic orogeny.

The measurements taken were mostly metamorphic layering, which appears in most units, including the granulite. No evidence is found to suggest the layering mimics sedimentary layering. An Archean orogeny produced this layering.

In all instances the schistosity surfaces are parallel to
the metamorphic layering. My interpretation of this, is that tight isoclinal folding occurred in the Archaean orogeny, as in figure(s)

(a)

The result is shown in figure(b), where the two surfaces are parallel. The noses of the tight folds were destroyed by shearing. From measurements of the schistosity surfaces, the axial plane of the Archaean orogeny would appear to be strike, 030°, dip, 40° S.E.

On the cliff-face section, one of these nose sections is found. In a more quartzitic section of an augen gneiss, a very tight fold is found. The limbs of the fold are parallel with the surrounding schistosity, with the axial plane also parallel to the this surface.

The next orogeny is protorozoic and produced the major antiform present. This being the case, we should expect to find meso and micro folds mimicking the major structure. No meso-folds are found, but micro-folds and folds up to 6 feet across are. All these folds are overturned to the west, although the plunges of the folds are quite variable. The sense of the folds is random, giving no clues to mesofolds.

Intersections of the cleavage and layering can be used to determine whether the beds are overturned. Two outcrops show this interaction. One occurs on the eastern extent of the inlier, where the cleavage is at a steeper angle than the layering. This is interpreted as the beds being right way up. The other outcrop occurs in "Little Gorge", on the western side of the inlier, and shows the same relationship. The conclusion reached is, that the inlier represents the eastern limb only of the antiform.

The fold axis of the antiform, as defined by lineations and minor folds was 19° to 137°.
Figure 1. Plot of poles to layering, contoured on 1%, 3%, 4%, 5%, 8% and 10% intervals, of the eastern section of Yankalilla River gorge. The fold axis thus defined is 35° to 135°.

Figure 2. Represents contour plots (same intervals as fig 1) of the lineations of the whole area. The maximum occurs at 40° to 134°. The rounded section in the south-west section represents rodding. Fold axis of this is 10° to 207°.

Figure 3. Plots of poles to layering in sub-area I (see interpretive map). Represent lineations. The fold axis is 35° to 126°.

Figure 4. Poles to schistosity in sub-area I. The fold axis is 35° to 138°.

Figure 5. Poles to schistosity in Yankalilla River gorge, north of sub-area I. The fold axis is 31° to 135°.

Figure 6. Poles to layering in the same area as figure 5. The fold axis is 32 to 126°. The lineations seem to define a small circle, suggesting it is folded by a later event.
Figure 7. Poles to layering on northern section of beachfront. Fold axis 23 to 148°.

Figure 8. Poles to layering schistosity in same area as figure 7. Fold axis 20° to 125°.

Figure 9. Overturned fold in a pegmatitic gneiss from the area of the prior two figures. Poles to layering. Fold axis 19° to 137°.

Figure 10. Poles to layering in sub-area 2. Fold axis 45° to 175°.

Figure 11. Poles to layering on southern portion of the beachfront section. Fold axis 27° to 135°. The lineations seem to lie on a small circle, i.e., folded by a later event.

Figure 12. Same sub-area as figure II. Poles to schistosity. No great circle defined. The lineations are crinulations, and show a large spread of readings, which may be related to later events.
Macrofolds were found in pelitic and granitic lithologies. Only one generation of folds was recognized. A prominent quartz layer occurs within one of the augen schists, which showed excellent folding and, most importantly, the micas were folded around with the quartz. This is proof that the schistosity is earlier than the proterozoic folding.

Although no large scale folding was recognized, plots of schistosity and layering were done using an equal area net. A change in strike directions was noted in the field, but could not be related to any folding. These plots of poles to layering defined a great circle, and the pole of this circle defined the fold axis of the plots. This plot always defined a fold axis, the same as the Proterozoic fold axis. We can conclude the shortening in strike is due to the Proterozoic orogeny.

The area was divided up into sub-areas, which contained different rock units. A sub-area containing schists defined a great circle most clearly, but sub areas of layering were less clear.

A weak lineation in the form of a broad warp is found in some outcrops. The dominant crinulation is folded around this lineation, making it later than the Proterozoic lineation. Geologists in nearby Proterozoic terrains have recognized at least three periods of deformation. Assuming the lineation is parallel to the fold axis of one of these deformations, its direction is 6° to 78°.

FAULTING.

A thrust zone occurs on the western extent of the nunatak, in "Little Gorge". This zone is recognized by the mylonitic augen schists, considerable feldspathization, and occurrence of large cross-cutting pegmatites. This zone may be represented as thrusting on the underlimb of the antiform.
Other faults are less well defined. It may be that the schists that occur within the granite gneiss terrains represent old shear zones. These rocks appear very mylonitic.

Small faults are seen in "The Gorge", with only a small displacement noticed. There is intense fracturing, and pegmatization. The granulite between these two small faults dips from gently north to low south-east, but either side of these faults the granulite dips steeply south-east. Tilting of a block of the granulite seems to have occurred. The faults are not folded, and are steep.

The boundary between the Archean inlier and Cambrian siltstone is extremely eroded, suggesting it to be faulted. In "The Gorge", feldspathization occurs on the lower boundary between the granulite and gneisses. I think it represents a thrust fault.

Mr. D. Maughan, using geophysical measurements, has defined anomalies which may represent steep faults. If this is so, it may explain the outcrop pattern of the granulite, which may be an expression of these faults.

In my opinion, there are many faults in the area, which complicate the geology, making interpretation of the outcrop map most difficult.

**METAMORPHISM.**

Two metamorphic grades are recognised in the area, one reaching upper amphibolite facies, and the other a retrograde metamorphism, reaching biotite grade. The higher grade is related to the Archean orogeny, and the lower grade to the Proterozoic phase. No isograds are recognised.

The Houghton granulite appears the least altered, and shows the best high grade assemblages. When plotted on ACP and AKF diagrams, as used by Winkler, the mineralogies indicate
upper amphibolite facies. The use of these diagrams assumes 
equilibrium was reached at this high grade, and that no 
metasomatism occurred. The granoblastic texture rules out the 
possibility of large scale mobility of elements, required for 
metasomatism, and also suggests complete reconstitution of the 
original texture, explaining the lack of igneous or sedimentary 
features.  

Plagioclase composition is most consistent, ranging 
from Ab63 to Ab75. Turner and Verhoogen suggest this composition 
is most indicative of a high grade of metamorphism, such as 
upper amphibolite. 

Other units are much more altered, but do show relic 
minerals, which are not as specific as those of the granulite. 
ACF and AKF plots of these assemblages also indicate upper 
amphibolite facies. (see appendix 4).

Assuming water saturation conditions, the reaction of 
muscovite converted to sillimanite is most indicative of this 
high grade. If temperature and pressure conditions were such 
that they delineated a point on the curve of this reaction, 
(appendix 4 fig. 3), then both minerals should occur. But only 
sillimanite is recognised, the muscovite present belonging to 
the lower grade, so temperature and pressure conditions must lie 
above this curve.

To pinpoint these conditions, the considerable granitization 
is taken into account. The granite melt curve (appendix 4 
fig. 3) intersects the above mentioned curve, thus defining the 
conditions reached. These were, temperature 750°C and 2-3 K-bars.

Other high grade features are perthitic textures and 
needle inclusions in Archaean biotite grains.

The retrograde metamorphism reached biotite grade of the 
Greenschist facies. Prominent field features of this grade, are 
a strong lineation, and tight folds.

Considerable recrystallization of quartz occurred,
with larger grains showing pronounced strain features.

In the granulite retrograde minerals are epidote, calcite, chlorite and biotite. In the gneisses sericite is prominent, with other minerals being biotite, opaques, sphene, muscovite and hornblende. These assemblages, when plotted on ACF, and AKP, diagrams support the biotite grade (appendix 4).

**METASOMATISM.**

An extensive area of a metasomatized amphibolite occurs on the beachfront. The amphibolites show a very blotchy character, with large crystals of hornblende coexisting with good layering of mafic minerals.

The plagioclase content indicates sodium metasomatism. The plagioclase is retrograded by epidote, indicating the metasomatism occurred prior to the Proterozoic metamorphism. I suspect it took place the same time as the granitization event. The metasomatism is related to the amphibolites only, suggesting the Na was mobilized because of its higher concentration in these rocks. Because the surrounding rocks are not affected, it seems the Na had only limited mobility, and was not widespread.

**IGNEOUS ACTIVITY.**

The most obvious igneous activity occurs in the form of two cross-cutting basaltic dykes. They are unaffected by later retrogradation, so must postdate the Proterozoic orogeny.

Some dark green amphibolites, of older appearance, in that they are coarse grained, may represent an earlier basalt. Chemical analyses of a few trace elements were carried out, but were not conclusive. They occur as isolated pods and large masses, which would suggest an igneous origin, and I conclude that they represent an early igneous phase, prior to the Archaean phase.

Extensive outcrops of pegmatite and minor outcrops of
granite, occur. The granites are cross-cutting and affected by the retrograde event. Large structureless "blobs" of pegmatite occur along with the granite, so are the same generation as it.

I interpret this granitization as late stage Archaean activity. I think that minor intrusions of granite did occur, but the majority of the pegmatite represents the low melt fraction of the country rocks. This represents considerable mobility of the potassium content, along with some silica mobility. Where the rock composition has been suitable, Na mobility has occurred. The high K content may support the theory that the gneisses represent sediments. Migmatitic rocks are an intermediate expression of the K mobility.

MINERALISATION.

Slides 376-263 & 264, describe an amphibolite which shows copper mineralisation. Polished sections show the minerals are chalcopyrite mainly, with minor pyrrhotite. The copper content, by chemical analysis (appendix 5 fig.), is 1600 ppm. Acid digestions by different leaches show the Cu is confined to the sulphides. Minor disseminated sulphides occur in other sahpi amphibolites.

Blue disseminated azurite occurs in augen gneisses, and small adits are found at these outcrops.

In the pegmatitic region of the beachfront, large veins of ilmenite are found. One pegmatite has been worked extensively for monazite and rutile.

GEOPHYSICS.

Mr. D. Maughan carried out an extensive magnetic survey on the Permian sediments surrounding the inlier. He discerned an anomaly which he attributed to the granulate.

Using this information I was able to extend the main horizon of granulate considerably to the north-east.
The "Houghton" granulite was chemically analysed to determine whether it was of igneous or sedimentary origin.

Field relationships were inconclusive. The granulite was conformable in all instances. Associated with it was a zircon rich quartzite. The boundary between these units was very sharp, and the strictly conformable nature of all outcrops of the granulite, which includes outcrops in other areas, together with the mineralogy, lead me to favour a sedimentary origin.

The major elements, plus certain trace elements, are then used to solve this question (Appendix 5 fig.).

The major elements were analysed by X-ray Fluorescence spectrometry (XRF). A search of the literature revealed that the rocks with almost identical major element content as the granulite, were Syenites, Diorites and ferruginous, dolomitic marls. Thus we have reduced our search to two possible igneous parents and one sedimentary parent. The most distinctive major elements were FeO and Fe2O3, as well as K:Na ratios.

Having pinpointed likely parents, the trace element contents of these rocks must be examined. I was able to gather sufficient information for the pliorite model, but was less successful with Syenites and marls, making these comparisons less reliable.

It was argued that the different processes of igneous and sedimentary fractionation would result in different contents of elements, or different ratios of elements. A comparison with literature values would help define these trends.

Niggli numbers were used by Leake and Evans to distinguish between ortho and para amphibolites, so I tried the same, hoping to distinguish between Diorites, greywackes, and the granulite. I was not able to do so for Syenites or marls. Appendix 5 figures 1 to 10 show various plots of results. Figure 1 shows the granulite plotting midway between a pelite
and a limestone. This fits very nicely with our concept of a rock of a calcareous marl origin. Diorites and Syenites plot in a slightly different field.

Figure 3 does not distinguish between diorites, syenites, and granulites, which all plot in similar positions.

Figure 4 shows the granulite plotting in a sedimentary field in all cases, separate from the igneous fields, but, not at all, conclusive evidence.

Figures 5, 6, 7, 9, and 10 show the same trend as Figure 4. Figure 8 shows the granulite plotting in a sedimentary field, quite distinct from any igneous trends, particularly the mg to k plot.

An overall examination of the niggli number method reveals two promising plots which reveal sedimentary origins of the granulite. These plots are Figures 2 and 8. The remainder were inconclusive. But, still, the evidence is not conclusive and log-log graphs were used, to further define any sedimentary trends.

Some of these plots show the granulite plotting in a field of its own. These graphs are of no use, as no comparisons can be made. More useful graphs are V-Cr; Cr-Cu; Zn-Cu; La-Ce; Cr-V; Co-Cr; and Ni-Cr;

Examination of these graphs shows the granulite to plot in the marine sediment field in all cases, and in igneous fields, seldom. Once again there are no conclusive graphs, but a sedimentary field does seem evident to be more the trend.

Tables 2 and 3 of Appendix 5 contain lists of the various lithologies showing the ranges of major and trace elements present. Examination of these tables supports the conclusions reached from the graphs.

My final conclusion is that the Houghton granulite is
of sedimentary origin, probably a dolomitic, ferruginous marl.

My conclusions could be substantiated by analysing for more trace elements, and by analysing more specimens of granulite to establish any trends.
CONCLUSIONS.

There were three periods of deformation recognized. The first was an Archaean orogeny, which produced a strong metamorphic layering. This phase reached upper amphibolite grade of metamorphism. The second phase was recognized by the tight isoclinal folding, with a south-east plunging fold axis.

The third phase was a weak tertiary orogeny producing a weak lineation in a north-east plunge, of very low dip. The second phase produced a major overturned anti-cline and it reached biotite grade of metamorphism. This phase also affected the Adelaidean sediments surrounding the inlier.

A thrust zone was recognised on the underlimb of the anti-cline, by the presence of mylonitic rocks. The main lineation of the area is parallel to the fold axis of the anti-cline, and is plunging 20° to 137°.

Field relationships proved inconclusive as to deciding whether the granulite was igneous or sedimentary. The granulite was conformable with the surrounding rocks in all instances. It was associated with a quartzite in all instances, which itself was interpreted as being sedimentary, due to the high-concentration of zircon found in thin section. This association suggests a sedimentary origin of the granulite.

Chemical results reveal sedimentary trends of the granulite, but there is no conclusive evidence. To reach a positive conclusion I would recommend further work to be carried out on the granulite, such as analysing for Th, U and all the rare earths Sc, and Zr. I would also recommend many more analyses of the granulite to be done, to define any trends which may be present.

A more detailed analysis of the quartzite may also be beneficial. Also examination of the zircon grains of the quartzite to see if they define sedimentary layering.
Acknowledgements

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APPENDIX I.
Slide numbers which correspond to the rock units.

Houghton Granulite. 376- H5, H6, H7, H8, H9, H11, H17, 238, 269.

Quartzite unit. 376- 5B2, I4B, 69.

Amphibolite. 376- A18, 28, 265, 264, 263, 300, 29.

Metasomatized amphibolite. 376- A17, 83.

Sillimanite gneiss. 376- 4A, 5A, I16, I73, 223.

Micmatitic sillimanite gneiss. 376- I68, I71, 249, 253.

Augen gneiss. 376- I1A, I, 79, 97, I92, 99.

Calc-silicate. 376- 286.

Augen schist. 376- I42, I97, 252.

Granite gneiss. 376- I44, I86, 221.

Granite. 376- 3A

Pegmatite. 376- 8I, I17, I46.

Clinopyroxene unit. 376- 90, I2I.

Pegmatic dyke. 376- 26I.

Biotite unit. 376- I30.

Cambrian. 376- K
APPENDIX II.
Slide Descriptions.

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**Macro.** Medium grained granoblastic texture, with a weak foliation developed. Main minerals are pink feldspar, dark green amphibole, and pale green epidote.

**Micro.** Granoblastic texture, with a mean grain size of 0.7 mm.
- **Quartz.** About 35% Size 0.2 mm. Uniform extinction with an embayed shape.
- **Amphibole.** About 10% Size 0.7 mm. Commonly associated with calcite. Pale green, weakly pleochroic. Extinction angles range from 5-23. Probably hornblende.
- **Epidote.** About 50% Size 0.7 mm. Commonly associated with calcite. **Plagioclase.** Trace amounts. Size 0.5 mm.

Excellent albite twinning giving a composition of Ab, 75. **Microcline.** Trace amounts. Size 0.7 mm. Cross hatched twinning prominent. **Calcite.** 5%. Size 0.5 mm. Distinctive cleavage showing twining effect.
- **Accessories.** Sphene, apatite, dark green mineral. Uniaxial (-ve), distinctive maximum absorption with the c-axis normal to the polarizer vibration direction, i.e. Tourmaline.

**Macro.** Same as above. A courser layer of pink feldspar and epidote is seen.

**Micro.** Same as above. A small section of the slide contains diopside and scapolite, with a sharp boundary existing between this section and the remainder of the slide.

**Microcline.** About 30% Size 0.7 mm. **Quartz.** About 30%. Uniform extinction. 
- **Epidote.** About 30%
- **Diopside.** About 5%

Distinctive dark green, with prominent cleavage traces. **Scapolite.** High birefringence, uni-axial (-ve), parallel extinction. **Accessories.** Sphene and opaques.

**Macro.** Weak foliation developed.
- **Amphibole.** 10%. Irregular shape, very pale green, non pleochroic. Extinction angles 5°-17°. Probably actinolite.
- **Epidote.** 60%
- **Quartz.** 30%

Weak undulose extinction. **Microcline.** Trace amounts. **Accessories.** Sphene and apatite.
376-HQ. "Houghton" granulite.

MACRO. Darker coloured rock, foliation well developed.

MICRO. Granoblastic texture, Scapolite, 5-10% Size I, 0.5 mm, 8 sided crystals. Amphibolite, 5% very pleochroic, bi-axial (-ve), 2V=70° maximum extinction angles are 24. Probably hornblende. Microcline, 40%. Epidote, 20% alteration product of the amphibole in most instances. Diopside, 10% Confined to small section of the slide. Accessories. Sphene 2%, apatite, opaques and quartz.


MACRO. Fine to medium grained.

MICRO. Same as above. Microcline, 50% well developed granoblastic aggregates. Amphibolite, 10% Pale green hornblende. Epidote, 25% Sphene, 2% rounded grains of high relief. Opaques, 2% embayed shapes. Accessory, apatite.

376-HII. "Houghton" granulite.

MACRO. Grey coloured rock with lineation of dark green minerals.

MICRO. Same as above, Scapolite, 30% tabular crystals occur within the grains, epidote? Diopside, 30% closely associated with diopside, scapolite. Microcline, 40% Accessories. Sphene and apatite.

376-269. "Houghton" granulite.

MACRO. Pale green, obviously much more quartz content.

MICRO. Prominent quartz rich layer. Amphibolite, 5% actinolite. Quartz, two distinct layers recognizable, one is quartz rich, the other microcline rich. The quartz layer contains, bboth, large grains showing strain features, and undulose extinction, and small re-crystallized quartz grains. This layer comprises quartz: epidote 1:1. Overall it is 40%. The other layer is quartz, microcline, and epidote. Microcline, 30% Epidote. 30% Accessories. Apatite, opaques, sphene, amphibole.
376-A18. Amphibolite.

**MACRO:** coarse grained black amphibolite, mainly hornblende.

**MICRO:** Hornblende. 60% dark green, strongly pleochroic, maximum extinction angle 23°. Often found as an alteration product on a paler mottled mineral, probably hornblende. Actinolite. 5% albite twinning prominent, surrounded by a corona of epidote. Plagioclase. 30% albite twinning, composition Ab74. Forms a granoblastic aggregate. Microcline. 10% The plagioclase forms around the se grains. Accessories. Opaques surrounded by a spase corona, i.e., ilmenite or rutile, quartz.

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**MACRO:** fine grained granoblastic texture, black, and white speckled appearance.

**MICRO:** mean grain size 0.4mm. Plagioclase. 75% albite twinning gives composition of Ab73. Sericitization along the grain boundaries and along the twin planes. Quartz. 15% uniform extinction, very clean grains. Biotite. 10% closely associated with muscovite. Needles of inclusions within the biotite. Accessories. Zircon within the quartz grains. An absence of opaques is prominent.

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376-582. Quartzite.

**MACRO:** coarse grained gneiss, almost all quartz, a poor foliation is developed.

**MICRO:** quartz. 70% large grains with a strong undulose extinction showing a preferred orientation, parallel to the foliation developed. Surrounding these grains is a mass of small re-crystallised quartz. Many inclusions occur. Muscovite. 30% trace. Microcline. 30% very rounded, recrystallised quartz, sometimes, forms large pressure shadows around these grains. Minor sericitization. Accessories. A single plagioclase grain occurs, sericite masses, iron oxides forming yellow stain-like areas, and prominent zircon.

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376-3A. Granite.

**MACRO:** coarse grained, pink granite.

**MICRO:** Biotite. 5% Size 2.5mm slight alteration to chlorite, minor...
muscovite, quartz, 30% inclusions of needles and trails of bubbles. 
**Plagioclase**, 35% almost completely sericitized. **Microcline**, 30% weak perthitic texture. **Accessory**: A large zircon grain, 1.5 mm, corona of opaques, uni-axial (+ve).

**376-K. Cambrian siltstone.**

**MACRO**: fine grained grey silstone, cleavage well developed.

**MICRO**: well oriented biotite and muscovite, inaa groundmass of quartz. **Quartz**, 60% size 0.06 mm. **Muscovite-Biotite** is 60:40 and total age of micas is 35%. **Plagioclase** trace, unaltered. **K-feldspar** 5%. **Accessories**: zircon, opaques.

**376-142. Augen schist.**

**MACRO**: grey schist with a wavy foliation. The gentle undulation along the strike forms small folds, in places whose fold axes are responsible for a strong crinulation developed on the schistosity surface.

**MICRO**: excellent crinulation of micas seen. **Quartz** 30% most is recrystallised, but a few very large grains exist, showing considerable strain features. **Biotite** 50% strong preferred orientation. Very elongate grains. **Muscovite** 20% same form as biotite. **Accessories**: ilmenite.

**376-99. Feldspar-biotite gneiss.**

**MACRO**: well foliated gneiss, very prominent black biotite content.

**MICRO**: strong preferred orientation of biotite and sericite. **Biotite**: 30% pleochroic from grey-green to pale yellow. Uniaxial (-ve) figure obtained. **Plagioclase**: 40% dusty sericitisation along the twin planes. A few grains completely sericitized. Composition Ab75. **Quartz**: 20% mostly large, strained grains, surrounded by a mass of polygonal recrystallised quartz.

**376-26I. Rhyolitic dyke.**

**MACRO**: fine grained basalt, minor sulphides.

**MICRO**: random laths of elongate plagioclase. **Plagioclase**: 60% **Amphibole**: 30% 120° cleavage traces prominent. Pleochroic from
olive green to yellow-green, bi-axial (-ve), ragged appearance probably hornblende. **Epidote.** 5% colourless, high relief, bi-axial (-ve), straight extinction, length slow. **Accessories.** Opaques.

376-81. **Pink pegmatite.** MACRO: Coarse grained, pink feldspar and white quartz.

**MICRO.** **Microcline.** 50% size ~4 mm, prominent cross-hatched twinning, minor sericitization. **Perthitic microcline.** Plagioclase within the microcline. **Quartz.** Very strained, minor re-crystallisation.

376-221. **Granite gneiss.** MACRO: Coarse grained granodiorite.

**MICRO.** **Quartz.** 30% size 1.0 mm, straight trails of inclusions, mainly in two directions, running perpendicular, minor re-crystallised quartz. **Plagioclase.** 50% both twinned and untwinned grains present. Ab77. Prominent zoning of plagioclase. **Microcline.** 10% a merelakitic texture, of quartz exsolved within microcline, is noticed. **Biotite.** 10% size 2.0 mm, associated with apatite in clusters.

376-186. **Granite gneiss.** MACRO: Coarse grained granoblastic texture of pink feldspar and green amphibole.

**MICRO.** **Plagioclase.** 30% granoblastic texture, but grain boundaries very embayed. **Perthitic microcline.** 5% Amphibole, 10% pale green, non pleochroic, length slow, extinction angles low to 19. **Hornblende.** Epidote, 10% Opaques, 5% rhombic shapes with sphenite coronas. **Quartz.** 10% minor re-crystallisation. **Accessories.** Sphene and zircon.

376-121. **Clinopyroxene unit.** MACRO: Coarse grained, green mafics in a granoblastic texture.

**MICRO.** Mean grain size 1.3 mm. **Plagioclase.** 60% Ab73. **Clinopyroxene.** 30% bi-axial (+ve), weak pleochroism, 2V = 60°, length fast, extinction angles 35° to 52°. **Augite.** **Quartz.** 5% **Accessories.** Sphene, Opaques.

376-286. **Calc-silicate unit.** MACRO: Amphibolite, consisting of medium-grained granoblastic aggregate of hornblende and plagioclase
MICRO. Plagioclase. 50% size 1.0mm, albite twinning prominent, Ab75. Hornblende. 30% brown to green pleochroism. Amphibole. 15% rounded grains, surrounded by hornblende. Opaques. 5% sphene corona. Accessories.apatite.

376-5A. Sillimanite gneiss. MACRO. Quartz, sericite gneiss, well foliated.

MICRO. Garnet. 1% size 0.3mm, colourless to pale pink. Thin anisotropic needles within the grain. Extensively chloritized. Grossularite. Biotite. Associated with chlorite, IO% Chlorite. 50% low birefringence. Bi-axial, length slow, pleochroic. Quartz. 20% mostly recrystallized, some larger grains. Plagioclase trace, almost completely sericitized. Sericite. Prominent alteration product. 30% Accessories. Fe staining, opaques.

376-240. Migmatitic sillimanite gneiss, MACRO. Well layered

MICRO. Alternating bands of sericite and quartz. Sericite. 50% alteration product. Plagioclase. 10% large variations in degree of sericitization. Quartz. 40% mixture of recrystallized and larger unaltered grains. Sillimanite. 5% forms relic cores in the sericite layers. Accessories. Zircon in the quartz grains.

376-265. Amphibolite. MACRO. Very granoblastic texture, grey colour.

MICRO. Mean size 0.5mm. Hornblende. 25% form between the granoblastic aggregate of plagioclase, dark green, pleochroic. Plagioclase. 65% grain boundaries somewhat lobate, Ab68. Clinopyroxene. 5% bi-axial, V=50-60°, colourless, extinction angles low to 68°, ie. Augite. Apatite. 5% rounded and hexagonal grains, high relief, low birefringence. Opaques. 5% sphene forms a corona around the opaques, ie. Rutile.


MICRO. Mean size 0.7mm. Microcline. 30% Diopsid. 20% very pleochroic, minor alteration to epidote. Scapolite. 15% small inclusions can be traced from a few crystals, to a more concentrated mass, identifiable as epidote. Garnet. IO% tan colour, grossularite-andradite.

376-130. Biotite rich unit. MACRO. Dark grey gneiss with poor schistosity developed.
MICRO. Mean grain size 0.7 mm. Groundmass of recrystallized quartz, with a few larger quartz grains scattered about. Biotite. 30% brown variety, many basal sections showing a uni-axial (-ve) figure. Long needles with a hexagonal configuration within the grains. Plagioclase. 75% I. 2 mm. Considerable dusty sericitization. Quartz. 30% larger grains show sutured boundaries, uniform extinction, about 20% is recrystallized. Tourmaline. 2% characteristic pleochroism. Opaques. 3%.

376-83. Metasomatized amphibolite. MACRO. Coarse grained, granoblastic
MICRO. Plagioclase. 60% I. 2 mm. Considerable dusty sericitization, Ab7I, contains rounded microcline grains. Epidote. 5% forms a corona between amphiboles and plagioclase. Amphibole. 30% extinction angles range from 7-17. Probably hornblende. Accessories. Sphene andapatite 5%. No opaques.

376-477. Metasomatized amphibolite. MACRO. Well layered gneiss.
MICRO. Plagioclase. 60% dusty sericitization, especially around the edges of the grains, often an epidote corona. Amphibole. 20% pale green, mottled, surrounded by a greener, more pleochroic hornblende. Epidote. 30% alteration product of plagioclase. Accessories. Sphene and biotite.

376-118. Sillimanite gneiss. MACRO. Well layered gneiss, with schistosity developed along more micaceous layers.
MICRO. Distinctive quartzose and sericitic layers, much fractured and recrystallized. Quartz. 30% strong undulose extinction, preferentially oriented parallel to the layering. Sericite. 50% alteration product of feldspars. Sillimanite. 1% Prominent diagonal cleavage, and higher refractive index, also strongly sericitized Biotite. 5% Occurs in between the quartz grains, in a more quartzose layer. Opaques. 5% occur in layers.
Sillimanite gneiss.  
**MACRO.** dark, fine grained, well layered gneiss, mostly sericite. 
**MICRO.** Can see 3 layers, consisting of sericite and quartz, microcline quartz and sericite, with a mean grain size of 1.5 mm., and a layer of quartz, sericite, and plagioclase with a mean grain size of 0.7 mm. 
*Garnet.* 2% Actually is one large grain, broken up and chloritized. 
*Quartz.* 40% strong undulose extinction, considerable recrystallization. Needle-like inclusions seen. 
*Plagioclase.* 10% Ab72. All have undergone various degrees of sericitization. 
**MICROcline.** 10% 1.5 mm.

**Sillimanite gneiss.** 
**MACRO.** well foliated gneiss, prominent augens of quartz. 
**MICRO.** *Quartz.* 30% 0.7 mm. Mostly uniform extinction, few inclusions. 
*Biotite.* 30% many basal sections, intimately related with muscovite and opaques. 
*Sillimanite.* 2% almost completely sericitized. 
*Plagioclase.* 5% very much altered. 
*Pyrophyllite.* Long tabular grains pseudomorphing sillimanite. Form fibrous bundles.

Augen schist.  
**MACRO.** extremely schistose, mostly micas. 
**MICRO.** Minor crumulation of micas seen. 
*Muscovite.* 30% bi-axial (-ve), associated with biotite. 
*Quartz.* Granoblastic aggregates, some larger grains show a preferred orientation. 45% opaques 10%, evenly scattered throughout the slide. 
*Chlorite.* 5% 
*Accessories.* apatite, sphene, and considerable Fe staining.

Clinopyroxene unit.  
**MACRO.** dark green rock, allmafics 
**MICRO.** coarse grained. 
*Plagioclase.* Ab67. 5% *Hornblende.* 90% green mineral, bi-axial (-ve), faintly pleochroic, length slow. 
*Epidote.* 5%

Ore containing amphibolite.  
**MACRO.** Prominent chalcopyrite and pyrrhotite, and opaline quartz. 
**MICRO.** *Apatite.* 20% high refractive index, low birefringence. 
*Quartz.* Strong linear features, slight undulose extinction. 
*Pyroxene.* 30% bi-axial (+ve). 2V = 30°-35°, weak pleochroism, i.e. *Augite.* 
*Hornblende.* Forms a corona around the pyroxene. 
*Plagioclase.* Prominent albite twinning minor sericitization.
376-1A. Augen gneiss. MACRO. Very schistose gneiss, with many augens of quartz.

MICRO. Biotite. Needle-like inclusions, 20%, pleochroic from dark brown to straw yellow, preferred orientation parallel to the layering. Quartz, 40%, slight undulose extinction, clean grains. A few xenonblastic opaques, poor layers of quartz seen, larger grains are very embayed, with recrystalization around the edges. Feldspar. 30% same habitat as quartz, but grains more embayed, mostly microcline, minor plagioclase is extremely altered. Muscovite. 10%, high birefingence, elongate, encased in sericite. Opal rods with sub parallel distribution within grains, length slow, parallel extinction, mostly associated with biotite, and quartz. It seems to be pseudomorphing an elongate, bladed mineral, i.e. Sillimanite. Accessories. Opaques.

376-264. Amphibolite. MACRO. Granoblastic texture, grey.

MICRO. Granoblastic texture of plagioclase, mean grain size of 0.5mm. Grain boundaries somewhat lobate. Clinopyroxene, bi-axial (+ve), 2V=50-60⁰, colourless, non pleochroic, extinction angles low to 60°. Augite, Plagioclase. 65% composition Ab68, form a prominent granoblastic aggregate, grains only slightly sericitized along twin planes. Hornblende. Form anhedral shapes between the granoblastic plagioclase grains, very pleochroic, dark green to pale green, bi-axial (-ve), 2V=40-45°. Alteration product of the rounded clinopyroxene grains. Opaques, 5% sphene coronas, some show a rhombic shape. Apatite, 5% rounded, high refractive index.

376-168. Migmatitic sillimanite gneiss. MACRO. Fine grained, well foliated.

MICRO. Quartz. 45% very embayed shapes, slight undulose extinction, clean grains. Little recrystallization. Sericite. 45% some, slightly larger muscovite grains, associated with opaques. Biotite. 5%.

Garnet. One large, broken grain, surrounded by red Fe staining, and a corona of chlorite.

376-146. White pegmatite. MACRO. Coarse grained, rounded quartz.
MICRO quartz, 35%, very strained, prominent recrystallization, in and around plagioclase grains, strong undulose extinction. Plagioclase, 60%, grains rounded, with sutured edges, multipletwinning prominent, size 0.7 mm, composition Ab67. Very little alteration, opaques, 5%. Rhombic shapes. Accessories: biotite.

376-192. Augen gneiss. MACRO. Mylonitic rock, minor folding seen. MICRO. Quartz completely recrystallized, complete preferred orientation of micas, strong crinulation developed, in one instance the micas are folded around a small quartz fold. Quartz completely recrystallized, 50% muscovite-biotite, 50:50. Overall is 50%. Accessories: opaques scattered randomly, chlorite, anatase.

376-144. Granite gneiss. MACRO. Medium grained granoblastic rock. MICRO. Large grains with an undulose extinction, much recrystallization, 40%, size 2.0 mm. Plagioclase, 20% Ab70. Dusty alteration, and some multiple twinning. Microcline. Cross-hatched twinning prominent, unaltered. Biotite, closely associated with muscovite and opaques.

376-79. Augen gneiss. MACRO. Excellent folding of quartz augens and crinulation of micas. MICRO. Same as 376-192. In this slide the folding of quartz and micas is even more spectacular. It has the same mineralogy.

376-300. Amphibolite. MACRO. Black, medium grained, granoblastic, minor sulphides disseminated throughout. MICRO. Hornblende, 60% bi-axial (-ve), 2V moderate, cleavage sets at 120°. Extinction angles 0-24°, strong pleochroism. Plagioclase, 30%. Considerable dusty sericitization, with minor, coarser sericitization around the edges of the grains. Albite twinning not prominent. Biotite, associated with hornblende in some instances. Accessories: opaques (sulphides).

376-191. Augen schist. MACRO. Fine grained black schist. MICRO. Extremely well developed orientation of micas and opaques.
Hornblende. 15%, green pleochroic, mottled grains, whose outstanding feature was their cross cutting relationship with the micas. Tendency of micas to be displaced around the hornblende, the grains are random in their orientation, with a significant proportion parallel to the micas. Quartz forms a large portion of the groundmass, and is recrystallized. Biotite 30%, pleochroic from colourless to brown, very elongate shape. Opaccues, tabular shapes, most strongly oriented, IO%, Accessory, apatite.


276-142. Quartzite unit. MACRO, Poor foliation, specks of opaccues. MICRO, About 60% of the quartz present is recrystallized, quartz. 80%, larger grains are very embayed, and strained. Microcline, more fractured, slightly recrystallized, Accessories, biotite, tourmaline, sericite, opaccues, muscovite, prominently scattered through the slide is a hexagonal grain, uni-axial (ve), elongate, length fast, parallel extinction, zircon.

276-171. Migmatic siliimanite gneiss. MACRO, well foliated, pink feldspar layered, Fe stained gneiss. MICRO, Biotite. 10%, strong pleochroism, associated with opaccues. Quartz, No preferred orientation, in definite layers, clean grains, uniform extinction, remnant granoblastic texture, associated with muscovite containing needles of opaccues, Siliimanite, minor unweathered cores in a sericite mass. Sericite, 50%

276-23B. "Houghton" granite. MACRO, Poor foliation developed. MICRO, Epidote, 60%, high birefringence, very mottled, pleochroic, parallel extinction. Biotite, Pale green, uni-axial (ve), Quartz. A few larger grains, but most recrystallized, Accessories, calcite, sphene, and apatite, rare, rounded opaccues.
376-69. Quartzite unit. **MACRO.** Granoblastic texture, black-grey rock, poor feldspar foliation, minor lineation on layered surface. **MICRO.** Quartz, 70%, size 0.5mm, strong undulose extinction, a trail of bubbles meeting in a triple point, suggest recementation. Plagioclase, 20%, completely sericitized, Microcline, 5% less altered. Biotite, 5% preferred orientation. **Accessories.** Scattered opaques, muscovite, zircon.

376-77. Sillimanite gneiss. **MACRO.** Grey, fine grained, well foliated **MICRO.** Opaques, 5% larger, embayed grains and small disseminated specks. Quartz, 60%, forms definite layers, usual mixture of larger and recrystallized grains. Sillimanite, trace, very sericitized. Sericite, 36%, alteration of feldspars. **Accessories.** Chlorite, biotite, muscovite, Fe staining.

376-251. Migmatitic gneiss. **MACRO.** Black, poor foliation. **MICRO.** Quartz, masses of fractured grains, considerably recrystallized, uniform extinction, 40%, size 0.7mm. Plagioclase, 40%, uniform extinction, forms very large grains. Biotite, 15%, within the matrix of recrystallized quartz, very mottled, broken grains. Opaques, 2% scattered about the slide. **Accessories.** Muscovite.

376-1. Augen gneiss. **MACRO.** Well foliated, many quartz augens, blue azurite disseminated throughout. **MICRO.** Quartz, 40%, larger grains show slight undulose extinction on trails of bubbles, most is recrystallized, forming a polygonal matrix. Microcline, 10% very large grains, weak sericitization, serrated edges, broken, and fractured. Plagioclase, 5% smaller size, sericitized, biotite, closely associated with the polygonal quartz. Red staining, looks like Fe staining, but the azurite in hand specimen is a more likely answer. **Accessories.** Epidote, muscovite.

376-11. White pegmatite. **MACRO.** Very coarse grained, prominent multiple twinning in hand specimen. **MICRO.** Plagioclase, 95% most grains show dusty sericitization,
and some coarser sericitization. Good albite twinning. Ab 57.
Quartz 5%, occurs as a small veinlet, crosscutting plagioclase &
grains.

78497. Epidosed augen gneiss. Macro. Prominent pale green,
epidote, well layered, slightly migmatitic.
Micro. Biotite. Forming foliation between the granoblastic textures
of present, 1%, very pleochroic, uni-axial (-me), quartz 5%, trails
within the grains suggest former grain boundaries. Recrystalliza-
tion has occurred between the larger grains, plagioclase 45% Ab 76,
all grains sericitized, some extensively. Microcline. Trace.
Epidote 15%, alteration product of plagioclase. Accessories.
muscovite, opaques, apatite, green biotite.
APPENDIX III.
Analytical techniques.

**Sampling.** Large unweathered blocks of granulite were gathered and 5 samples chosen, of the most widely varying texture and mineralogy, i.e., 376-H6, H7, H8, H9, H11. Also two amphibolites were chosen to act as controls for the element ranges expected in the area, i.e., AI7 and AI8. These rocks were crushed and then ground to a very fine powder, in an agate mill, to avoid possible contamination from Ni or Cr.

**X-ray Fluorescence (X.R.F.)**

The fine powder was pressed into briquettes for each sample, using boraxic acid as the binding agent. Trace elements were analysed using these briquettes. Fused buttons were prepared for the major element analyses, using the method of Norrish and Hutton.

**Rb and Sr.** U.S.G.S. standards were run with our samples. Our results were calculated using values of these standards obtained from the literature. This proved to be a most satisfactory method as I was able to check my precision, by running through the X.R.F. 2 or more standards, to compare the values obtained, with those values listed in the literature. The confidence limit of the X.R.F. was found using the formula

$$\frac{\text{Cb}}{T}$$

where m = number of counts/sec/ppm.

T = total analytical count time.

Cb = c.p.s. on background position.

The mass absorption of the samples was calculated using Compton's scattering. Background counts were obtained using ultra-sil. A combintron programme was used to calculate the final ppm.

**La, Ce and Ba.** These elements were analysed in the same manner as Rb and Sr, but a computer programme was used to calculate the mass absorption, instead of Compton's scattering. This programme
was devised by A.W. Kleeman and K. Collerson in 1971. Once again the U.S.G.S. standards were used, with success. Various books of tables were used to determine correct angles, crystals, etc., for the X.R.F.

**Atomic absorption spectroscopy (A.A.S.)** The fine powder was digested in acids. To 1 gm. of rock powder was added 30 mls of HF, and the mixture let stand for 12 hours in a plastic beaker. It was then evaporated to a sludge, over a hot water bath, when 8 mls of HClO₄ was added. This mixture was evaporated to dryness and the residue dissolved in a small volume of distilled water. This was then made up to a final volume of 50 mls, using a volumetric flask. For Na and K determinations, by flame photometry, the final volume was 1000 mls. The calculation was,

\[
\text{ppm. (rock)} = \frac{\text{ppm. (soln) } \times \text{ vol. (cc)}}{\text{wt. of sample (gms)}}
\]

\[
50 = \frac{I \times 50}{\text{wt.}}
\]

wt. = 1 gram.

A techron, number 3 was the spectrophotometer used, and the elements analysed were Ni, Cr, Co, V, Pb, Zn, and Cu.

**FeO determination.** An accurately known weight of rock powder, about 0.5 to 0.7 grams, was digested in HF and H₂SO₄. This was done in a reducing environment, to prevent oxidation of the FeO present, by using a platinum crucible with a lid. After complete digestion, usually 5 minutes, the solution was rapidly plunged into a beaker, containing 300 mls of a solution of H₂O, 10 cc I; I Sulphuric acid, 10 cc saturated boric acid solution, and titrated immediately to prevent oxidation by the air. The end point was a faint pink. Calculation,

\[
\% \text{ FeO} = \frac{\text{titration (mls)} \times 0.07184 \times 100 \times \text{Normality KMnO}_4}{\text{Weight of sample}}
\]
B.C.R.I. and B.H.N. were used as standards. The results were,

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<th>Sample</th>
<th>Value</th>
<th>Notes</th>
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<tr>
<td>B.C.R.I.</td>
<td>8.90%</td>
<td>(This thesis)</td>
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<td>B.H.N.</td>
<td>6.37%</td>
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<td>B.C.R.I.</td>
<td>8.91%</td>
<td>(Standard from literature)</td>
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<tr>
<td>B.H.N.</td>
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APPENDIX IV.
Figure 1.

Almandine-amphibolite facies.

+ = assemblage in "Houghton".

Figure 2.
Appendix 4  Figure 3.

Almandine-amphibolite facies.
APPENDIX 4.

Figure 4.

Greenschist facies.
Quartz-albite epidote biotite subfacies.

+ "Houghton" assemblage is
Musc-Epidote-Biott.
Results of chemical analyses.

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Trace elements (ppm.)

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ANALYSES OF AMPHIBOLITES.

(in ppm.)

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(Silicate leach.)

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(Sulphide leach.)

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### TABLE 2.

Whole rock analyses of rocks similar to the Houghton granulite (%ages)

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<td>1.67</td>
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<td>P₂O₅</td>
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<td>Total</td>
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<td>99.91</td>
<td>100.27</td>
<td>100.40</td>
<td>99.3</td>
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**TABLE 2** (continued.)
INDEX OF WHOLE ROCK ANALYSES(\%).


7. Siliceous ooze. Ibid.


10. Syenite. Ibid.

II. & I2. Diorite and Syenite respectively.

Wedepohl, K.H. Executive director, Handbook of Geochemistry.
TABLE 3.

TRACE ELEMENT VALUES FOR DIFFERENT LITHOLOGIES.
(in ppm.)

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<th>7.</th>
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<td>230</td>
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<tr>
<td>Rb</td>
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<td>125</td>
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<td>391</td>
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<tr>
<td>Sr</td>
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<td>465</td>
<td>440</td>
<td>260</td>
<td>600</td>
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<td>18</td>
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<tr>
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<td>8</td>
<td>65</td>
<td>253</td>
</tr>
<tr>
<td>Cr</td>
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<td>76</td>
<td>68</td>
<td>200</td>
<td>300</td>
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<td></td>
</tr>
<tr>
<td>Co</td>
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<td>8</td>
<td>32</td>
<td>8</td>
<td>56</td>
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<tr>
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<tr>
<td>Zn</td>
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<td>120</td>
<td>200</td>
<td>160</td>
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TABLE 3 (cont.)

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<td>140.</td>
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<td>Sr.</td>
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<td>600.</td>
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<td>10.</td>
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<td>V.</td>
<td>21.</td>
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</tbody>
</table>
INDEX OF TRACE ELEMENT ANALYSES.

2. Average Canadian shield basalt. Ibid.
5. Syenite. " " "
6. Basalts. " " "
7. Red clay. " " "
8. Shales. " " "
10. Ancient marine sediments. Ibid.
12 & 13. Calcareous clays. Ibid.
16. Syenites. Ibid.
**Niggl Numbers of Various Lithologies.**

Sh. = Marine shale.
Dio. = Diorite.
Sy. = Syenite.

<table>
<thead>
<tr>
<th></th>
<th>Si.</th>
<th>Al.</th>
<th>Fm.</th>
<th>C.</th>
<th>Alk.</th>
<th>Ti.</th>
<th>P.</th>
<th>K.</th>
<th>Mg.</th>
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<td>27, 28, 27, 26, 28, 34, 20, 31, 33, 39</td>
<td>26, 25, 26, 26, 21, 36, 44, 23, 27, 36</td>
<td>30, 35, 35, 35, 34, 29, 21, 17, 17, 9</td>
<td>16, 12, 11, 13, 16, 11, 14, 28, 24, 15</td>
<td>1.4, 1.5, 1.4, 1.4, 1.4, 1.4, 1.7, 5.1, 2.5, 2.4, 2.4</td>
<td>.35, .2, .3, .34, .34, .43, .64, .45, .40, .31</td>
<td>.83, .80, .81, .84, .70, .31, .27, .31, .40, .59</td>
<td>.43, .41, .47, .37, .43, .61, .38, .19, .45, .43</td>
</tr>
</tbody>
</table>

\[ k = \frac{K}{Na + K} \]

\[ mg = \frac{Mg}{Fe + Mn + Mg} \]
List of symbols of lithologies.

Houghton Granulite, = ●
Diorite, = ●
Marine sediments, = ▲
Syenite, = ▼
Ortho-amphibolites, = ○
Para-amphibolites, = ◼
Greywackes, = ◇
Basalts, = △

For appendix 5, figures I to IO, the symbols are the same as those for figure 2, which is the plot of 100mg + (al+alk) +c = 100.

Field of Ortho-amphibolites is, (●)
Field of Pelites and semi-pelites is, (◇)
Appendix 5  Fig. 1.

1. Al-rich clays & shales
2. Clays & shales free of carbonate or containing up to 35% carbonate, between arrows: marls with 35-65% carbonate.
3. Greywackes
4. Ultrabasic rocks.
5. Basaltic & andesitic rocks.

- Basaltic rocks
- Tonalites
- Granodiorites
- Calc-alkali granites
- Alkali granites

Field of graywackes:
- Clays
- 3 Continental clays of the tropical belt
- Marine clays
- "Houghton" granulite
APPENDIX 5. FIG. 2.

= Houghton granulite

= Keno dolerite + Ortho-amphibolites of the Adirondacks, N.Y.

= Littleton & Connemara dolerites

= 376-A17.

= 376-A18.

Plot of 100 mg + (ol+alk) + c = 100.
Fig. 9.

Fig. 10.
Outcrop map of Archaean basement rocks south of Normanville.
Outcrop map of Archaean basement rocks south of Normanville.
Outcrop map of Archaean basement rocks south of Normenville.
Interpretative map of the geology of the Archaean inlier south of Normanville.

- **F** = Fault
- Thrust fault zone
- Main road
- Sample location
- **F** = Interred fault

For key and rock type indexes refer to the outcrop map of this area.

Scale: 1" to 700 yds.