THE UNIVERSITY OF ADELAIDE

# THE PETROLOGY, GENESIS AND ALTERATION OF ALUMINOSILICATE BEARING SCHISTS AND GNEISSES AT SPRINGFIELD, NEAR WILLIAMSTOWN, SOUTH AUSTRALIA

by

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## ABSTRACT

The high grade aluminosilicate bearing schists and gneisses are believed to be due to prograde regional metamorphism to T 600-700$^{o}$C, P 4-6kb. under falling potassium activity. This leads to dealkalisation of K-feldspars and immediately preceeds or accompanies the $F_2$ deformation. Shearing also seems an important genetic control.

The dominant rock types are subdivided:

1 Aldgate Sandstone Equivalent

2 High Grade (sillimanite) zone
- Sillimanite Quartz Gneiss
- Kyanite Quartz Gneiss
- Muscovite Quartz Gneiss
- Kyanite Muscovite Kaolinite Shear rocks
- Schists (coarse)
- Tremolite marker horizon

3 Kyanite Andalusite zone
- Sandstones, Marbles, Schists, and Calc-silicate rocks

The retrogression of the aluminosilicates took place in two distinct steps. Preceeding the $F_3$ deformation and associated with initial stages of thrusting, muscovitisation occurred, producing green muscovites (referred to by Alderman as Damourite) and sericite pods in the high grade schists. Introduction of potassium and water was involved. Following the $F_3$ deformation kaolinisation of sillimanite and K-feldspar occurs. This is a low temperature hydrothermal alteration

X-Ray diffraction studies demonstrate the equivalence of the green muscovite and sericite and show the alteration of sillimanite to kaolinite.

# INTRODUCTION

## 1.1 AIM

The unique nature of the clay sillimanite deposit 7 km south-east of Williamstown has attracted the attention of many workers in the past. The presence of boulders of nearly pure sillimanite with fibrolitic texture, scattered throughout a massive kaolinite body with relict fibrous texture, indicate a large quantity of original sillimanite. The size and purity of the aluminosilicates present the problem of petrogenesis. The aim of this study is to show, by geologic and petrologic means, the genesis of the aluminosilicates and the history of the deposit.

## 1.2 LOCATION

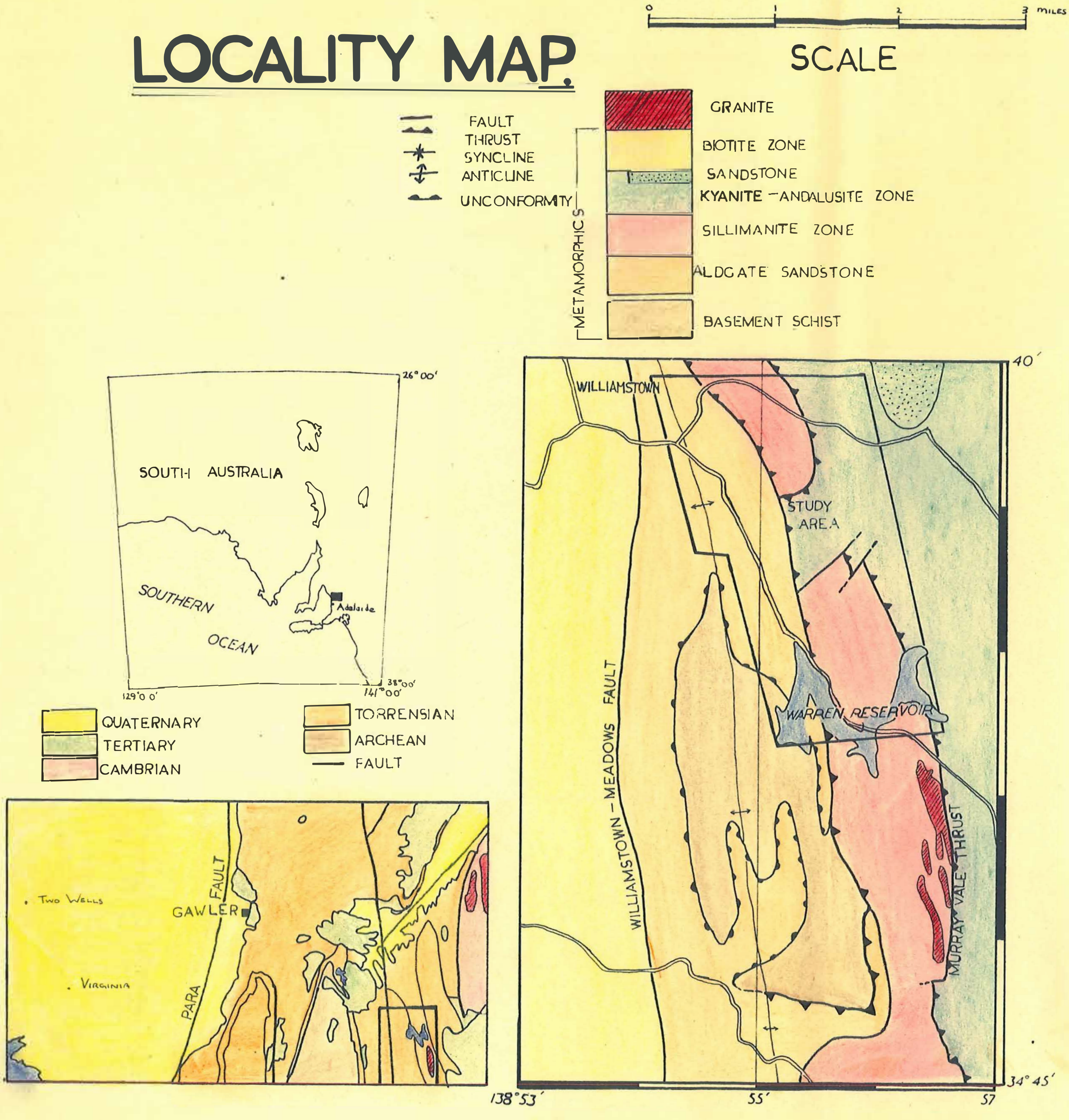
The area under study is contained within a narrow belt of high grade schists and gneisses and is bounded in the south by the Warren Reservoir and in the north by the Williamstown-Springton road. It is approximately 40 km north-north east of Adelaide. The mapped area is about 5 sq.km in area and contains a number of sillimanite and clay mines. Currently an open pit mine is being worked by Australian Industrial Minerals (A.I.M.)

## 1.3 PREVIOUS WORK

Workers early this century studying regional geology in the Mount Lofty Ranges made reference to the Williamstown deposit (Howchin 1926; Jack 1926; Hossfield 1935). Professor A. R. Alderman, in the early 1940's, studied the sillimanite-clay deposits and surrounding schists and postulated metasomatic replacement of country rocks by aluminous solutions. In 1950 he illustrated, by electron-

FIGURE 1.

Locality Map also showing regional geology


LOCALITY MAP
SCALE
0 1 2 3 MILES
FAULT
THRUST
SYNCLINE
ANTICLINE
UNCONFORMITY
METAMORPHICS
GRANITE
BIOTITE ZONE
SANDSTONE
KYANITE - ANDALUSITE ZONE
SILLIMANITE ZONE
ALDGATE SANDSTONE
BASEMENT SCHIST
SOUTH AUSTRALIA
SOUTHERN OCEAN
Adelaide
26°00'
38°00'
129°0 0'
141°00'
QUATERNARY
TERTIARY
CAMBRIAN
TORRENSIAN
ARCHEAN
FAULT
Two Wells
Virginia
GAWLER
PARA FAULT
WILLIAMSTOWN
STUDY AREA
WARREN RESERVOIR
WILLIAMSTOWN - MEADOWS FAULT
MURRAY VALE THRUST
40'
34°45'
138°53'
55'
57

microscopy, the change from sillimanite to kaolinite. Studies by other later workers have largely accepted Alderman's metasomatic scheme (Betheras 1953; Campana 1953). Cochrane in 1955 mapped portions of the area showing the relations of the sillimanite and Kyanite gneisses and the clays. In mapping and interpreting the Gawler 1 mile sheet Campana attributed the rocks of this region to a metasomatic origin. K. J. Mills (1963) worked south of the Warren Reservoir and attributed the formation of aluminosilicates to prograde metamorphism of upper amphibolite grade. His 1973 paper concentrates on structure and provides convincing evidence for the existence of thrust zones bounding the pelitic schists.

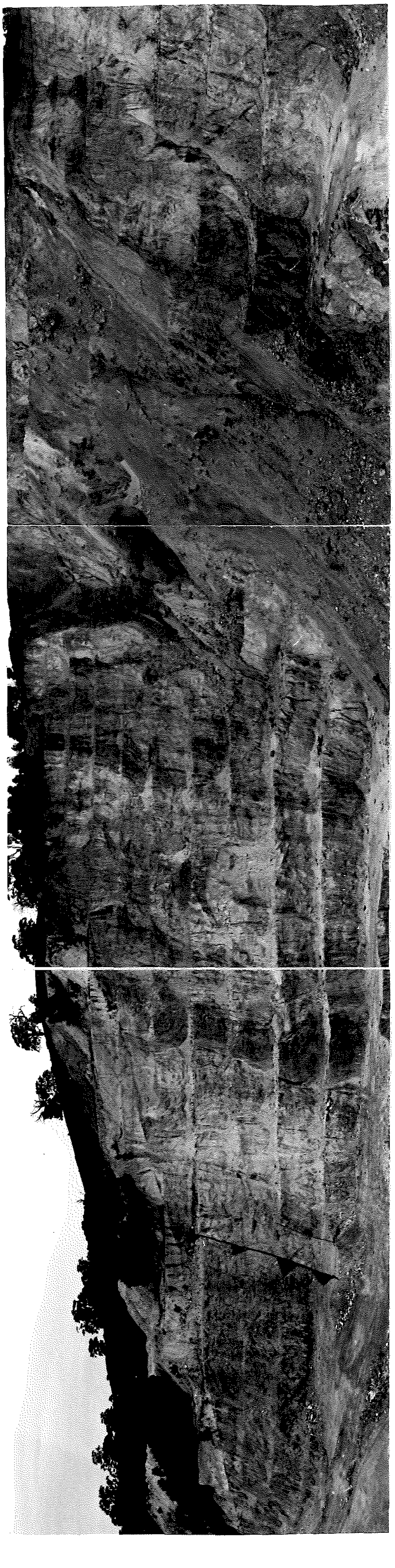
## 1.4 REGIONAL GEOLOGY

The rocks under study are part of the Torrensian Series of the Adelaide Geosyncline. In the general region (Fig.1 - adapted from the Gawler 1 mile sheet) numerous pegmatites outcrop and larger igneous bodies such as the Mount Crawford Granite to the south and Mount Kitchener Granite to the north also occur. Approximately 5 km to the east of the area to be described, Cambrian Kanmantoo Group is faulted against the older Torrensian.

Schists and Gneisses 3 km south-west of the study area have been interpreted by Mills (1973) as a pre-Adelaidian basement inlier, (called by him the Warren inlier) uncomfortably underlying the Aldgate sandstone equivalent, which outcrops within the study area. The deformational history of the area south of the study area is well documented by Mills (1973) and is considered to apply generally to the present study area. Three compressive deformations are found to be present. The first produced an $S_1$ schistosity in the Aldgate sandstone equivalent, but is only expressed

PLATE 1

View of south wall of quarry, section S950, showing lithological boundaries



as a relict early schistosity and as layering folded in tightly appressed $F_2$ folds. The $S_2$ schistosity dominates in the schists. The $S_2$ surface is folded and crenulated by the $F_3$ event and large scale warping occurs.

Several thrusts are found in the area and produce extensive shearing.

## 1.5 METHODS OF STUDY

The area was mapped using two overlapping aerial photographs as a base map. Some slight distortion in the final map is therefore inevitable. Traverses of the area were made to collect samples, determine lithology, and trace mappable features. Due to the soil and alluvial cover detailed mapping in the pelitic schists is difficult and that which is shown is largely interpretation between scattered outcrop, artificial cuttings and mines. Thrusts are continued northwards from the area to the south mapped by Mills (1973) and verified in the study area by metamorphic differences on opposite sides of elongated zones of highly sheared rock extrapolated from road cuttings and quarries and by lines marked by drainage channels. Displacement of some lower grade lithologies by faulting is apparent. The large quarry was mapped by pace and compass and triangulation. The final map(Fig.6) is a compilation of this work with a map produced in 1971 by McPhar Geophysical for A.I.M.

Thin section studies (Appendix I) gave information about the mineralogic composition and textural features of the rocks. X-ray diffraction was used to identify the clays and micas found. Microscopic examination of powdered clay under Refractive Index 1.60 oil provided information about the sillimanite content of the clay.

# PETROGRAPHY

## 2.1 ALDGATE SANDSTONE EQUIVALENT

The base of the Adelaidian sequence in the area is a white friable meta-sandstone containing numerous pelitic interbeds which are now composed of muscovite or clay. The microcline(0-30%) content of the sandstone upon weathering produces the friability. Howchin 1906 and Mills 1973 describe this formation in some detail so only important features are noted here. Titaniferous haematite lamellae outline bedding, cross-bedding and festoon bedding. In some places the opaque is magnetite rather than haematite, so that the beds are magnetic. Some tectonic flattening of the cross-bedding is observed though facing directions are still indicated. Minerals present include quartz 20-80%, microcline 0-30%, muscovite 5-55%, biotite 0-10%, titaniferous haematite and/or magnetite up to 15%. Accessories include Tourmaline, apatite and zircon. Frequent pegmatitic intrusions occur generally having the feldspar extensively kaolinised and in places bearing Tourmaline or beryl.

2.2 The high grade aluminosilicate bearing schists and gneisses are distinguished by coarse grain size, absence of potash feldspar and presence of sillimanite and kyanite or their retrograded products. The rock types comprising this zone are described below.

(a) Sillimanite Quartz gneiss

Rocks containing predominantly sillimanite (20-98%) and quartz (2-70%) with muscovite (0-15%) minor rutile (0-10%) and Tourmaline have been found in the sections S950 and S3101 minor relict kyanite is also present. These gneisses occur in the form of tectonically lensed horizons.

The sillimanite is fibrolitic and has a decussate interlocking texture accounting for the extraordinary toughness of boulders of pure sillimanite found in the A.I.M. Quarry (S950). These gneisses form blocky to rounded outcropping boulders and when broken reveal white and grey layering (Plate 2a). Sillimanite poor varieties may resemble ordinary quartzites in the field requiring microscopic examination to reveal their aluminous nature. Interlayering with muscovite schists is observed. Similar quartz sillimanite muscovite rocks are seen in section S959 where garnet is a common associate. Here sillimanite is found in pods and lenses concordant with layering and sheathed in fine claylike material (Plate 2b). XRD studies reveal this to be sericite.

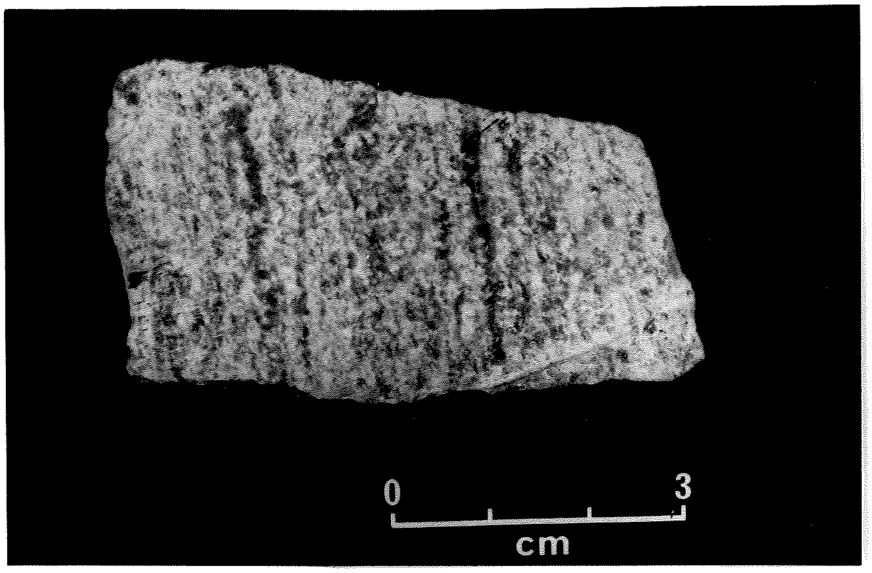
In section S950 pure sillimanite occurs as boulders and elongate lumps within layered clays. The exterior surface is often coated by a translucent relatively hard form of kaolinite which was identified by XRD. Areas containing variable amounts of fine pale green muscovite mixed with kaolinite occasionally occur on these surfaces. Breaking the lumps reveals the typical decussate fibrolite texture although it may be partially kaolinised (Plate 9, Table 1). In certain areas the sillimanite lumps are elongate and occur within distinct layers of kaolinite which separates them. Such layers are intercalated with coarse, slightly crenulated and partly kaolinised muscovite schists of pale greenish white colouration. Many quartz grains within these gneisses contain abundant fibrolite inclusions (Plate 3a,b). Some kyanite is found to occur in some of the gneisses as fine bluish granules; indeed a gradation from from quartz - sillimanite gneisses to quartz-kyanite gneisses is observed in places.

PLATE 2

(a) Layered gneiss 462-206

(b) Sillimanite sericite transition 462-310
x 32 crossed polars
Sillimanite pods sheathed in sericite.
Sillimanite inclusions in quartz.
sill. = sillimanite, qtz. = quartz
se. = sericite, ru. = rutile

(c) Kyanite sillimanite inversion 462-206
x 60 plane polarised light
Sillimanite appears to be growing out of the kyanite
ky. = kyanite


0
3
cm


qtz
qtz
qtz

(b) Quartz Kyanite Gneiss

Throughout the quartz sillimanite gneisses west of section S950, zones where kyanite is the dominant aluminosilicate occur. These have gradational boundaries where sillimanite and kyanite coexist in disequilibrium. The anhedral high relief grains of kyanite within the kyanite gneisses show alteration to coarse muscovite (Plate 3c). Within the transition zone kyanite is altered to both muscovite and fibrolite sillimanite. The degree of inversion to sillimanite increasing away from the kyanite gneisses. The kyanite is frequently twinned. These gneisses have compositional layering made up 1-3mm thick layers rich in aluminosilicate alternating with quartz layers. Rutile also forms fine layers.

The kyanite gneisses seem more highly strained than the sillimanite rich ones. Many are sheared with the layering now retrograded to fine green muscovite and white sericite. Relict kyanite remains as cores round which a fine sericitic zone is formed, itself being rimmed by a coarser grained muscovite zone. Occasionally the original crystal shape of kyanite is maintained. (Plate 4c). The quartz in the kyanite gneisses is more highly stressed than in the sillimanite gneisses. It is more elongate and have better developed ribbon like undulose extinction and probably has some degree of C-axis preferred orientation.

(c) Quartz Muscovite Gneiss

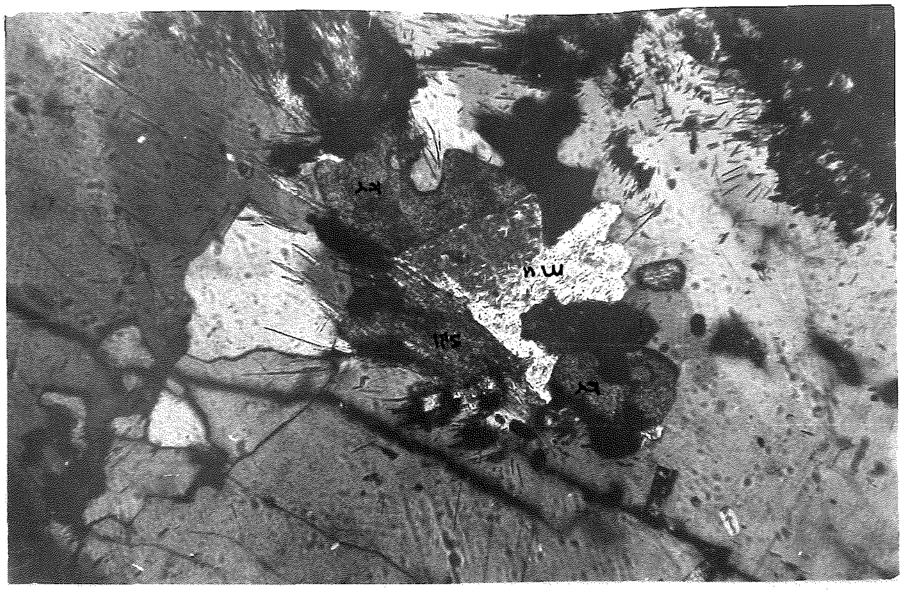
Gneissic rocks containing no aluminosilicates but much fine green muscovite (identified by XRD) are found in sections S942 and S949. They are attractively layered in green and grey (quartz) with scatterings of minor rutile. Tightly appressed $F_2$ folding of the layering occurs. Micas are not observed to be folded around the hinge region but

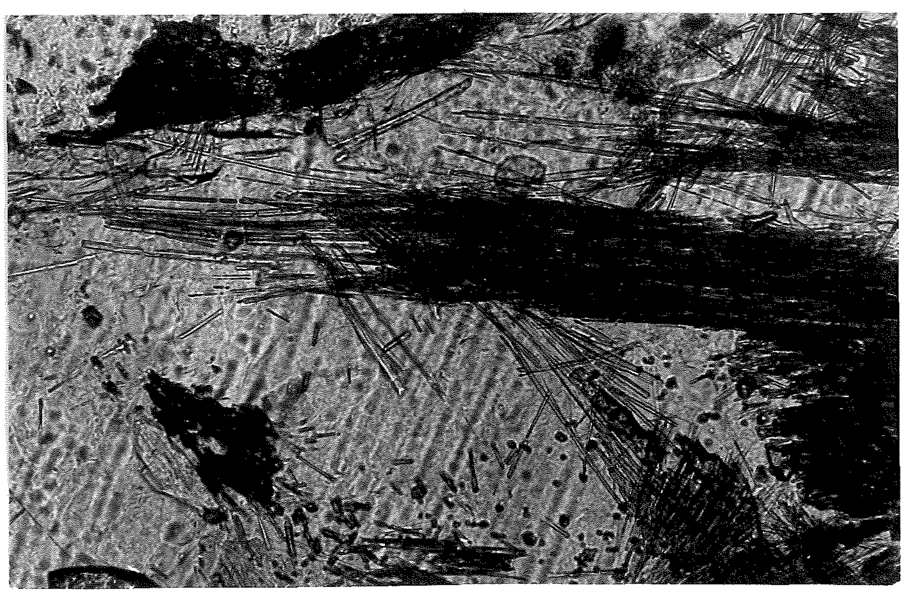
PLATE 3

(a) Sillimanite inclusions in quartz 462-150
x 100 plane polarised light

(b) Fibrolitic texture of sillimanite rock 462-150
x32 crossed polars
sillimanite inclusions in quartz grain
at centre.

(c) Kyanite muscovite transition
x60 crossed polars, similar photograph
as 2c.
Both sections of kyanite in optical continuity.
Twinning extends through top of both , cut by
coarse muscovite.





lie in the $S_2$ schistosity. Parallelism with layering occurs only in the hinge areas where the $S_1$ and $S_2$ surfaces are parallel. The limb region is complex, having a series of tight $F_2$ "M" folds developed in it. The fine green muscovite is considered to be due to the complete retrogression of aluminosilicates that originally made up the layering.

(d) Kyanite Muscovite Kaolinite Shear Rocks

These are common cross cutting rocks and Alderman used them as evidence for hydrothermal fluid action. However they are possibly better classified as shear rocks. Three types may be distinguished, although some overlap occurs:-

i Kyanite shears

ii Muscovite shears

iii Kaolinite kyanite muscovite shears

i This type was found only at the base of the quarry in section S950 as a solitary cross-cutting body of unoriented bladed kyanite crystals up to 5cm in length (Plate 4a). In contrast to the surrounding sillimanite rich country rock, the body contains remarkably little kaolinite. Some rutile and kaolinised sillimanite are associated with the kyanite in this body. XRD studies have shown much pseudomorphic replacement of kyanite by muscovite although the replacing muscovite is not the usual green colour.

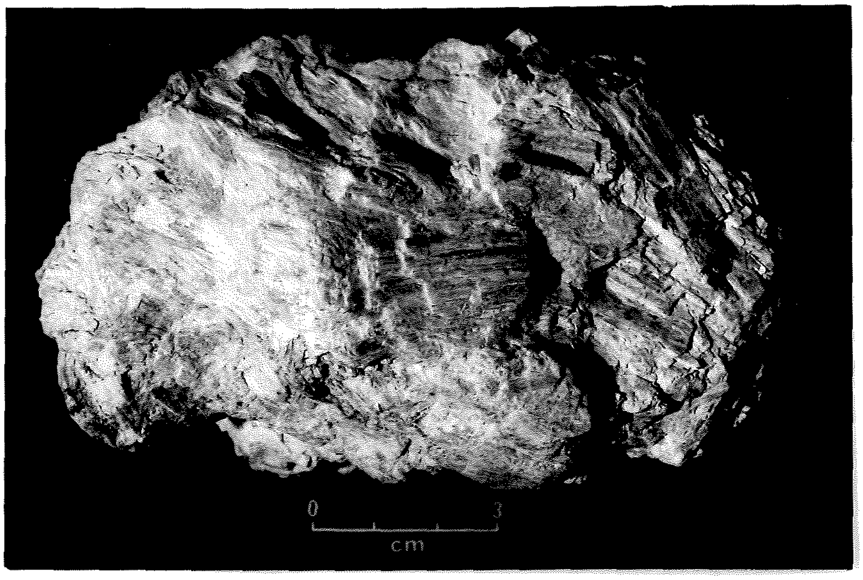
ii The second type consists of coarse green muscovite in irregular pockets and pods and in occasional planar structures which cut across the layering in the sillimanite quartz kaolinite country rock displacing this layering by dragging. From these shears the green muscovite forms wedges into the country rock (Fig.2). These shears appear parallel to the nearby Murray Vale Thrust implying some genetic relation which will be discussed later. The

PLATE 4

(a) Hand specimen of bladed kyanite 462-424

(b) Kyanite in sheared Kaolinite kyanite muscovite rock 462-141 x32 crossed polars
Twinned kyanite and large muscovite (mu), both embayed, in fine grained mixture of sericite and kaolinite.

(c) Kyanite altering to sericite. 462-145a x10 crossed polars
Core of kyanite rimmed by fine sericite and exterior rim of coarser muscovite


0
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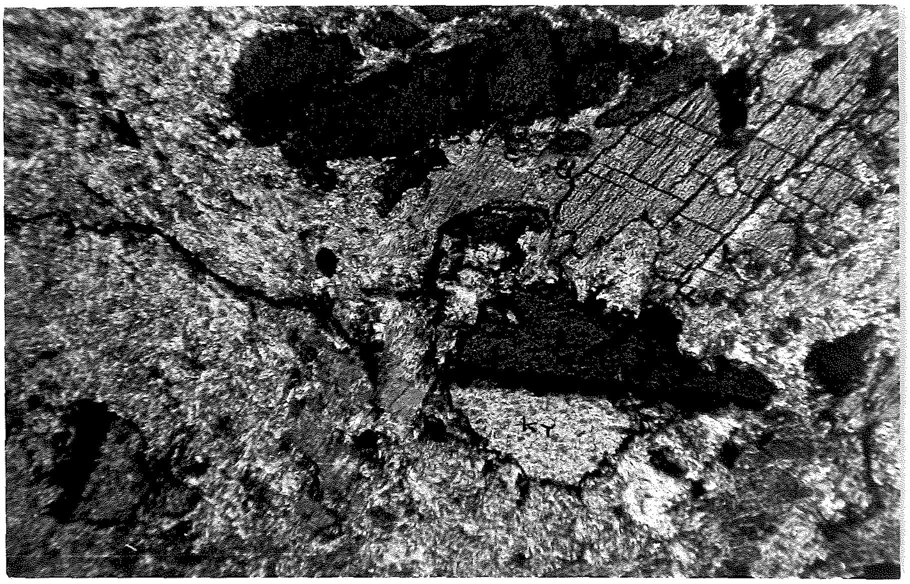
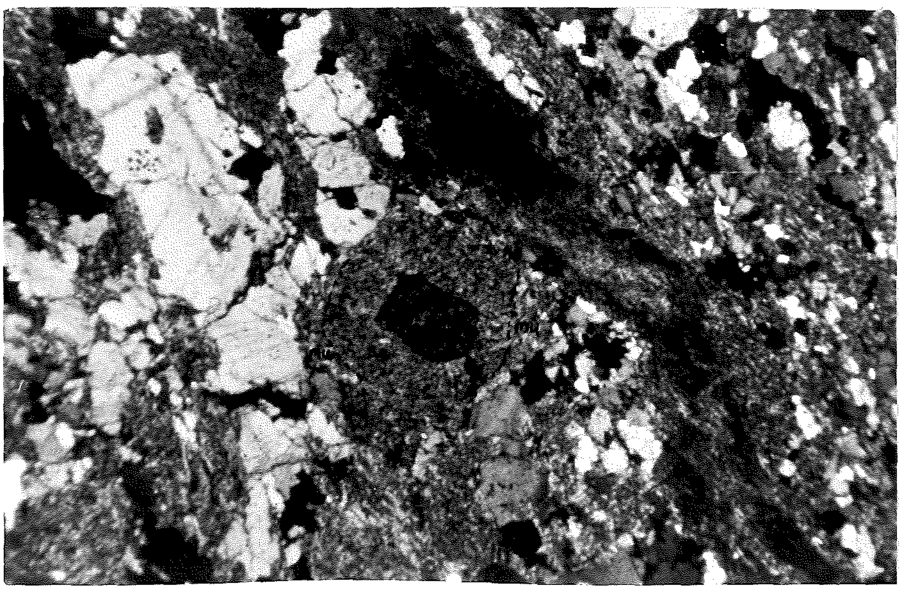




coarse muscovite within these structures shows a significant crenulated preferred orientation. X-Ray Diffraction studies have shown the equivalence of coarse and fine grain green muscovite.

iii The third type is found as cross cutting shear mainly in the area west of section S950. The bodies are 2-3 metres in width, largely kaolinised, yet preserving friable kyanite muscovite nodules and pods. These contain up to 50% anhedral embayed kyanite in a matrix consisting of muscovite. Some well preserved samples however show the kyanite as almost subhedral randomly oriented elongate grains in a matrix of crystalline muscovite. There is therefore some doubt whether the kyanite and muscovite were cogenetic or muscovite replaced kyanite. Plate 4b shows sericitisation of kyanite and attack of pre-existing muscovite. The borders of these shears consist of kaolinite, without sillimanite needles containing accessory well crystallised rutile and tourmaline. The cores of these shear zones consist of a banding made up of muscovite kyanite pods aligned in a contorted layering and embedded in kaolinite rich matrix. This together with herringbone fracturing of surrounding sillimanite gneiss indicates extensive early shearing. Slickensliding in the clay borders indicates late movement and extended mobile history of these shears.

(e) Schists

Coarse grained micaceous rocks with a well developed $S_2$ schistosity dominate the area. Abundant $F_3$ crenulations and lensoidal rods of fine grained material established by XRD to be sericite with minor quartz occur. Quartz and muscovite dominate with biotite and chlorite present in lesser amounts. Potash feldspar is absent and albite is is almost exclusively confined to the northern area. Rutile (1-10%) is almost universally present as brownish semi-transparent grains with very high relief. Garnet (0-10%) is not uncommon, occurring with idioblastic form in quartz layers, but having ragged elongate form in sericitic regions. This is presumably due to shear effects. (Plate 5a). High strain is also indicated by the presence of lenses of strained quartz grains around which cataclastic flow accompanying shearing or thrusting has taken place. Pyrite and chalcopyrite form common opaques though in weathered biotite schists fine haematite is dominant. The quartz present is highly strained, showing undulose and patchy extinction, and often includes sillimanite needles, especially adjacent to sericitic pods. Powdered material from these pods when examined microscopically under R.I. 1.60 oil show many sillimanite needles. This indicates these pods originally contained significant sillimanite which was subsequently sericitised. Fine rounded inclusions also occur in lines perpendicular to elongation of some of the quartz grains. These may be healed fractures (Plate 5d).

The alignment of micas in the $S_2$ schistosity is caused by the $F_2$ event. There is however a second generation of muscovite nucleating epitaxially on biotite and on primary muscovite (Plate 6b). Chlorite is also produced during this time although it usually follows the orientation of original biotite. In the North, around section S959, partially sericitised albite is an important constituent of the schist.

Special types of schist occur when one or other mineral vastly predominates. Muscovite predominates in the quartz muscovite schists, which are interbedded with

PLATE 5

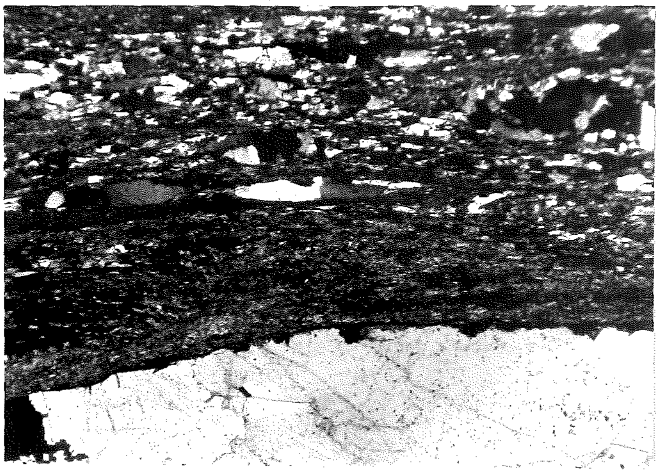
(a) Garnets in schist,462-308
x32 plane polarised light
note smooth outlines of garnet
in quartz layer, rough and
elongate in sericite. Also
note sillimanite inclusions
in quartz.
ga = garnet, qtz = quartz
bi = biotite, se = sericite

(b) (c)

Shearing around a quartz lens 462-166
x10 crossed polars
note fine grainsize on left,
coarser on right. Indicates shearing
is left to right.

(d) Quartz containing lines of fine
inclusions and showing undulose
extinction 462-144
x32 crossed polars


qtz
qtz
qtz



the sillimanite gneisses. These schists were extensively crenulated during the $F_3$ event, the hinges of some of these crenulations being selectively replaced by kaolinite (Plate 7b). This suggests that kaolinisation occurred contemporaneously with or soon after, the $F_3$ event. In a shaft in the section S3101 much crenulated muscovite-quartz schist is found. Within this however discrete blocks of gneissic material are seen indicating shearing and transposition during the $F_2$ event.

(f) Amphibolites

Two types of amphibolites are observed in the area. One type occurs as small irregular bodies, which are discordant with the layering. They contain unoriented poikioblastic large dark green-yellow hornblende with some orthoclase and quartz and minor plagioclase. An intrusive origin is suggested. The other type which may be a metasediment is concordant to bedding, possesses a lineation of aligned euhedral hornblende crystals, is rich in quartz and lacks orthoclase.

(g) Pegmatites

Pegmatitic bodies occur only in the sillimanite grade rocks and contain the usual pegmatite assemblage - quartz, orthoclase, plagioclase and greyish muscovite with minor tourmaline and occasional beryl. In section S942 a pegmatite cuts an amphibolite of the first type, producing a yellow alteration zone in the amphibolite indicating post amphibolite emplacement of pegmatite.

(h) Tremolite Marker Horizon

A Tremolite-actinolite rich horizon is found as discontinuous lenses in the northern part of the area. Variation in actinolite content is noted from pure asbestiform actinolite to predominantly quartz-plagioclase rock with radiating clusters of light green actinolite. The weathered surface of the outcrop is highly irregular and distinctive. The southern equivalent of this horizon has been used as a marker bed by Mills (1973) in the area south of the reservoir.

## 2.3 KYANITE-ANDALUSITE ZONE

Rocks of this zone are obviously lower grade than the previously described lithologies. They are finer in grain size, contain few aluminosilicates and abundant potash feldspar. The cleavage is slaty and probably related to the $F_1$ deformation (Mills 1973). No pegmatites or amphibolites are observed in this zone. The sequence is stratigraphic and begins with a horizon of white, fine grained, well laminated feldspathic metasandstones. Weak graded bedding and cross lamination are visible. The variable composition is usually dominated by quartz (25-90% and feldspar (5-60%). Both microcline and plagioclase are present. Cubic pyrite, haematite, tourmaline, apatite and zircon are common accessories with fine muscovite being a further variable. Clayey interbeds are seen in places. A purple-grey micaceous sandstone up to 1m in thickness marks the top of this horizon.

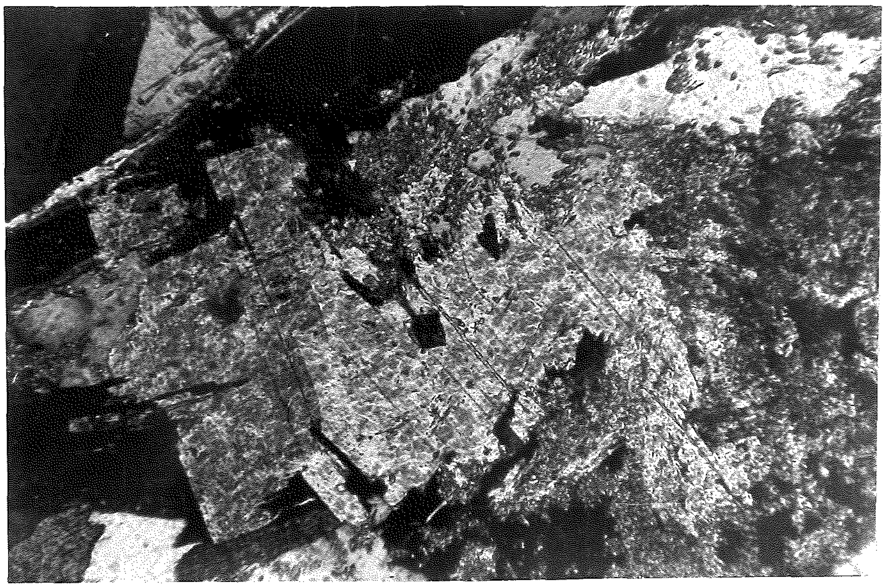
Overlying this is a series of tremolite marbles and tremolitic sandstones. The marble contains variable proportions of tremolite (5-40%) and calcite (10-40%) in contrast to the calcite free actinolite marker of the sillimanite zone. Where uncommon, tremolite forms a lineation but where abundant a random orientation is displayed. Rhombic sections of calcite are found where tremolite predominates. Minor muscovite and quartz are also present.

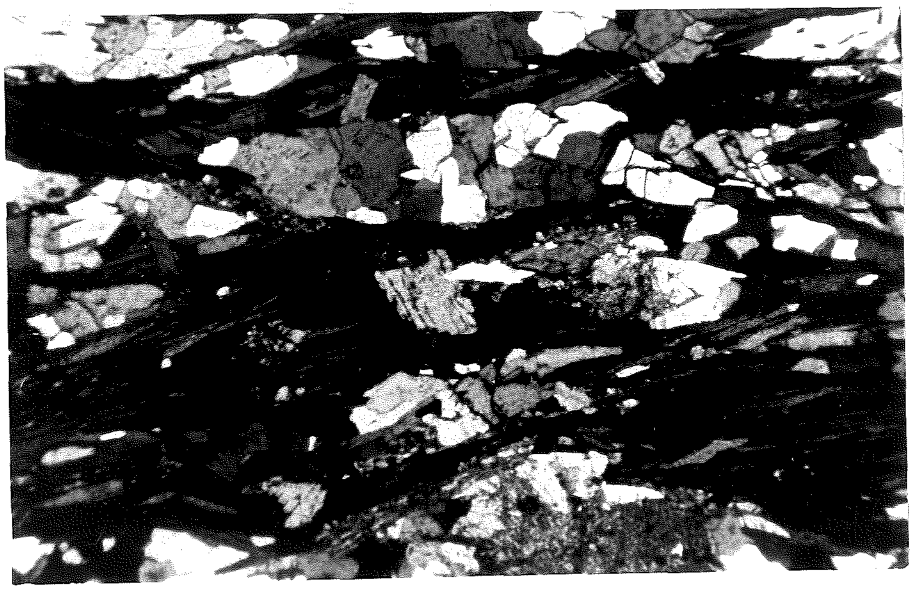
PLATE 6

(a) Coarse muscovite in fine sericite 462-312
x100 crossed polars
The coarse muscovite is embayed

(b) Second generation muscovite cross-cutting biotite chlorite layering 462-312
x10 crossed polars

(c) Porphyroblastic scapolite (sc) and plagioclase (pl) in fine knotted schist 462-111
x10 crossed polars






Pl
SC
SC
SC

This horizon is overlain by a series of schists and interbedded sandstones. The schists are generally fine grained, dominated by biotite (up to 60%) quartz (up to 40%) with lesser muscovite and chlorite. Orthoclase (0-10%) and oligioclase plagioclase (0-15%) are found. Common accessories opaques, zircons, euhedral zoned tourmaline and apatite are found. A few relict andalusites are found and patches of sericite are elsewhere present. Kyanite is very rare. In more calcareous beds, knots of porphyroblastic oligioclase, scapolite and actinolite are found. All are somewhat poikioblastic, fine quartz, opaques, muscovite and occasionally apatite being the inclusions. Biotite and coarser muscovite are bent around the plagioclase porphyroblasts. Subhedral pale green actinolite and scapolite cut mica layering and scapolite seems to be forming from plagioclase. Reactions plagioclase scapolite and biotite actinolite are indicated. Interbedded sandstones are similar to those of the underlying horizon including a locally pyritic pink sandstone which is useful as a marker. A schist of particularly strong outcrop was also used as a marker.

Overlying the schists is a series of coarse calc-silicates and interbedded knotted schists. The calc-silicates are very rich in porphyroblastic pale green actinolite, with diopside, epidote, zircon, quartz, scapolite, and oligioclase appearing in significant quantities. Many of these rocks have a lineation due to alignment of actinolite prisms. These were originally impure dolomitic limestones metamorphosed to lower amphibolitic facies.

## 2.4 KAOLINITE ROCKS

Areas rich in kaolinite are developed in the gneisses throughout the area, but the greatest volume of kaolinite is found in section S950. Here kaolinisation is produced in the eastern portion of sillimanite rich gneisses and schists and the western part of the lower grade feldspathic sandstones. The northern and southern limits seem to pass gradationally into country rock. Minor bedding displacement and en echelon faulting with displacement of a few centimetres along fissures filled with pure kaolinite is common throughout the kaolinised zone. These minor structures cannot be conclusively related to major faulting or thrusting. In the area west of the thrust, clay is formed by alteration of sillimanite commonly preserving the decussate texture and containing abundant sillimanite needles (Appendix II & III). When it is formed from a quartz rich rock, a grainy friable mixture of quartz and kaolinite is formed. In places the presence of diaspore indicates local deficiency of silica. Some muscovite is always present and is considered to be pre-kaolinisation. Rutile is a common accessory being unaffected by alteration of sillimanite. Cubic pyrite occurs within one particular horizon within the clay. The kaolinites vary in friability and hardness depending on the amount of sillimanite present and probably on crystallinity. The crystallinity is moderate in all samples studied by XRD powder photography though no concerted attempt was made to examine this property (Appendix II). Kaolinite in the kyanite muscovite kaolinite shears tends to be more compact and is sillimanite free, having altered from kyanite in these areas.

The clayey sandstones east of the thrust contain no coarse muscovite or sillimanite needles. These are due to the alteration of original feldspar in a sandstone which is equivalent to the lowermost horizon of the kyanite-andalusite zone. Nodular clay horizons within these sandstones represent the more pelitic beds which have been kaolinised and sheared.

## 3.1 STRUCTURAL HISTORY

The area south of the Warren Reservoir has been thoroughly discussed by Mills (1973). Some of the lithologies, particularly the aluminous schist, and their structural relationships can be extrapolated to the area here under discussion. The structure need, therefore only be discussed briefly.

$S_0$ appears in the Aldgate equivalent where titaniferous haematite lamellae delineate primary bedding and cross bedding. Primary bedding is also traceable in the kyanite andalusite zone where distinct lithologies are continuous.

Fine laminations are also seen in many of the sandstones. Within the kyanite and sillimanite gneisses large scale bedding is not traceable for any distance. However, well developed fine layering is seen. This is composed of alternating layers of quartz and sillimanite and/or kyanite and is considered a primary feature due to the low probably mobility of aluminium (Charmichael 1968).

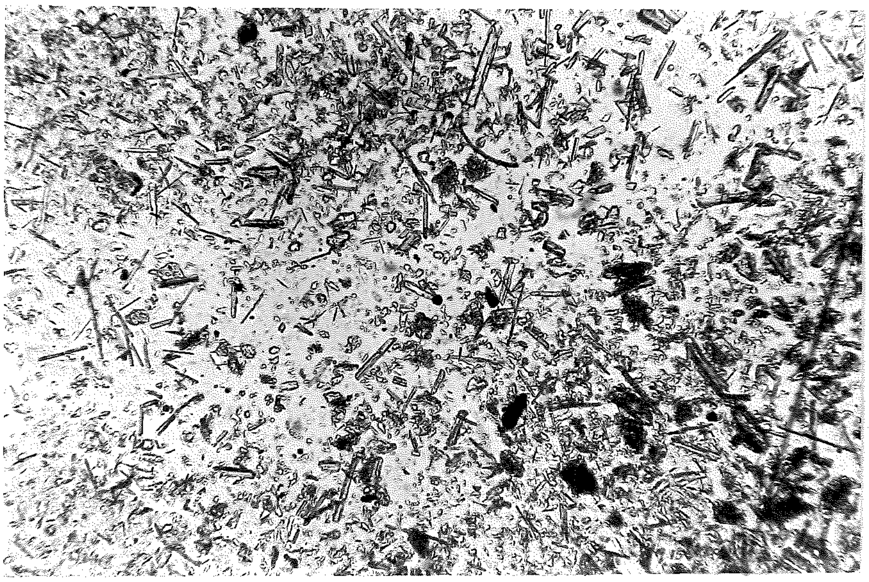
The area was affected by three strong deformations, $F_1$, $F_2$, $F_3$, the former two being strongly compressive. $F_1$ produced the dominant schistosity. Within the kyanite-andalusite zone and the early schistosity in the Aldgate Sandstone. Later $S_2$ schistosity and transposition have largely obscured $F_1$ effects in the pelitic schists, though a compositional surface $S_1$ in gneisses is seen to be folded by the $F_2$ phase. The $F_2$ deformation occurred soon after the peak metamorphism and folded aluminosilicate layering into tightly appressed isoclinal folds with considerable hinge thickening. An $S_2$ schistosity is produced by this folding phase. The plunge of these $F_2$ folds is variable and lies within the $S_2$ axial plane schistosity. Much shear movement took place at this time as shown by cataclastic flow round quartz layers and development of shear zones

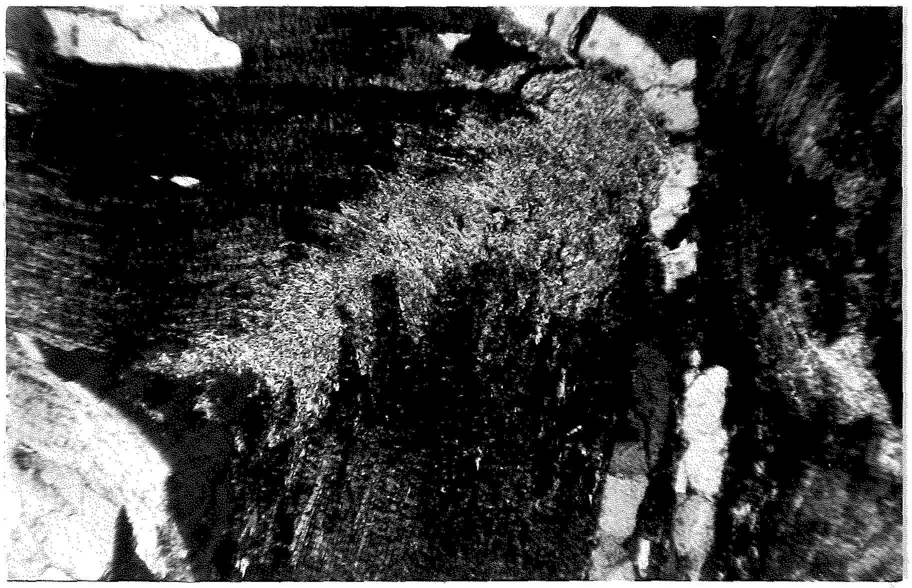
PLATE 7

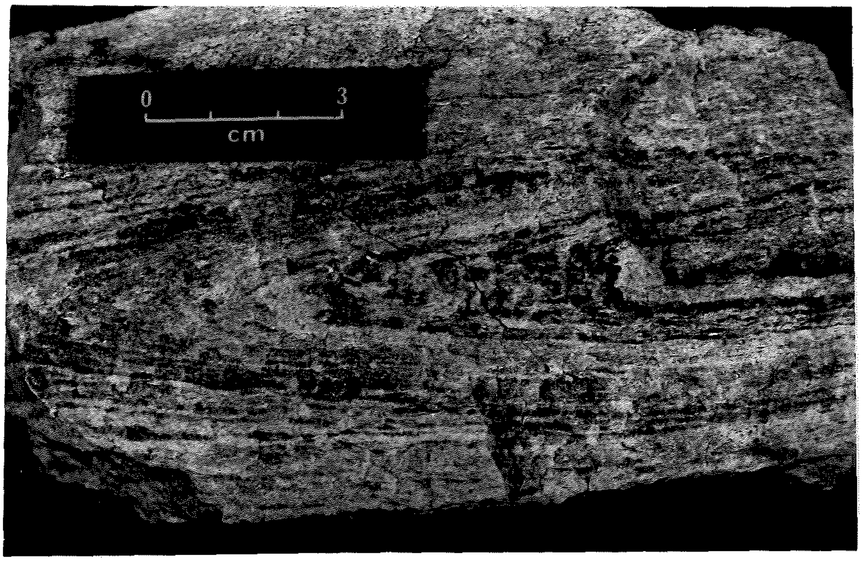
(a) Sillimanite in refractive index 1.60 oil
x32 plane polarised light
from clay sample 462-131

(b) Development of kaolinite in hinge of $F_3$
crenulation in muscovite layer 462-144
x32 crossed polars

(c) $F_3$ folding of $S_1$ or $S_0$ layering in
Quartz muscovite gneiss 462-166






0 3
cm

rich in kyanite and muscovite. These shear zones have a variable orientation averaging north easterly.

A retrogressive phase followed the $F_2$ event, during which sericitisation of the aluminosilicates occurred. Some of the new formed micas were recrystallised into coarse grained green muscovite. Concentrations of these occur in planar features showing some movement and trending in a general northerly direction with steep easterly dip. Similar orientation is expressed by the Murray Vale Thrust and these muscovite shears may have been produced by early incipient thrusting movements. The main thrusting from the east occurred after the formation of these coarse micas however.

The curvature of the Murray Vale thrust is partly due to the initial form, and partly due to $F_3$ folding. In the area S959 absence of repetition of beds indicate faulting is unlikely and no compositional change due to facies variation can explain the change in metamorphic grade. Folding of $S_2$ schistosity is not evident, so an $F_3$ fold structure is unlikely. In the quarry S950 however $F_3$ folding is clearly visible. Faulting, involving repetition of beds near S950, and displacing the thrust occurred. Development of the Wirrianda Thrust followed.

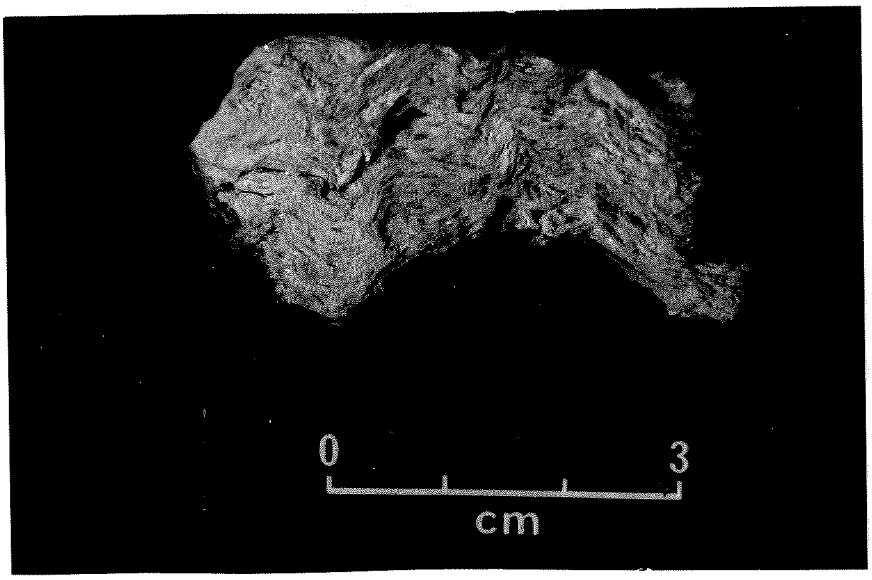
The $F_3$ deformation produced open to tight folding (Plate 8c) and crenulation (Plate 8a) of the $S_2$ schistosity. The plunge of these folds and crenulations shows considerable variation in steepness. The small mesoscapic folds being steep to the north east to south east, whereas larger folds and warps in the A.I.M. quarry have shallower plunges in a north easterly direction. The $F_3$ deformation also caused movements on the pre-existing thrus and shears, giving the slickensliding observed in the kyanite muscovite kaolinite rocks.

PLATE 8

(a) $F_3$ folding of $S_2$ schistosity in schist

(b) $F_2$ folding of $S_1$ or $S_o$ layering in vareigated schists, S950

(c) $F_3$ crenulation of $S_2$ schistosity in muscovite schist 462-144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# DISCUSSION

## 4.1 FORMATION OF ALUMINOSILICATES

The origin of rocks composed of almost pure sillimanite presents a serious problem. Nowhere except perhaps in some bauxites will sediments be made up so exclusively of aluminous minerals. Some component mobility must therefore be involved.

At Springfield, Alderman (1942) believed aluminium, along with titanium and silicon, was mobile. He postulated the metasomatic addition of alumina to country sandstones and siltstones to produce the aluminosilicate rich gneisses and schists. Metasomatism was considered necessary because the high grade sillimanite bearing schists are confined to a relatively narrow band and seemed to cut across lower grade rocks just west of Springfield Station. The high grade schists seemed to replace lower grade schists, sandstones and marbles without there being any structured break between the zones. The sequence was regarded as stratigraphic and a regional metamorphic origin did not seem plausible. Alderman argued against a metamorphosed bauxitic origin because of the localised nature of the lithologies and on textured evidence. No subsequent workers have mentioned any unconformity, as might be expected in case of a lateritised surface, nor has personal study revealed such a surface, so such an origin seems unlikely.

Some experimental workers have proposed that aluminium has only limited mobility (Kwak 1971, 1973) or is immobile (Carmichael 1968). Others however postulate aluminium is an active species in metamorphic fluids (Vrana 1973; Chinner 1966, 1973). Most of these studies are concerned with ionic mobility over only a few centimetres not on the scale proposed by Alderman to explain the Williamstown deposit.

Furthermore structural discontinuities have now been recognised between low and high grade zones so that a metasomatic replacement mechanism is unnecessary in producing narrow high grade bands which cross-cut at the extremities. Mills (1973) suggests that the aluminosilicates were formed by prograde metamorphism to a grade corresponding to muscovite-sillimanite equilibrium conditions within the sillimanite zone of the amphibolite facies.

Personal petrographic studies show agreement with this hypothesis and suggest conditions $PH_2O$ = 4-6 kb, temperature 600-700°C, and $PH_2O$ 3-4 kb temperature 450-500°C for the Kyanite Andalusite grade rocks (Fig.3). Metastable persistence and the sluggish nature of inversion makes these determinations uncertain.

To achieve the purity of the sillimanite rock and the assemblage present in the quartz-sillimanite and quartz-kyanite gneisses, it is necessary for at least some of the components to be mobile. The most likely mobile ion present is $K^+$ and to a lesser extent $Na^+$ and $Ca^+$. These are all found in feldspars, in the arkosic sandstones of the adjacent lower grade zone. The high grade rocks have no potassic feldspars. Albite is found in small quantities in the southern sillimanite schists and in larger quantities in some of the more quartzose coarse schists in the northern area. Within the Mount Lofty Ranges considerable albitisation and pegmatite activity occurred as well as some granitic intrusion. These are rich in alkalis and represent the first formed phases of partial melting.

Their formation will cause an alkali gradient to be set up causing alkali movement toward the site of formation.

This provides a sink for the alkalis and a mechanism for dealkalisation of feldspars. In such an area of falling potassium activity potash feldspars may be converted to sillimanite (Eugster 1970)

$$6KAlSi_3O_8 + 6H^+ \rightarrow 3Al_2SiO_5 + 6K^+ + 5SiO_2 + 3H_2O$$

K feldspar Aluminosilicate

$PH_2O$ and ph are also important variables (see Fig.5) but ph is assumed to be effectively buffered by other reactions and the $PH_2O$.

A greater problem is that the above reaction is also quartz producing and unless silica is mobile it will not be possible to produce a pure sillimanite rock from even a pure K-feldspar rock. The abundance of pegmatites and quartz veins in the rocks concerned may be sufficient to account for the silica excess.

The distributions of kyanite and sillimanite in the high grade gneisses also presents problems. Within the schists alteration to sericite renders mapping of the kyanite and sillimanite distribution difficult, however acicular inclusions in quartz indicates the presence of sillimanite in many of these schists. Corchrane (1953) produced a series of small scale maps showing the distribution of sillimanite and kyanite in the gneisses. Kyanite-gneiss occurs within the sillimanite gneisses as linear zones usually bounded by gneiss containing both kyanite and sillimanite. These zones may parallel or crosscut and gneissosity and as far as can be determined, are not due to compositional variations. The kyanite content of the aluminosilicate varies from zero to 100%. Where it coexists with sillimanite, textured relationships as mentioned above, indicate the inversion kyanite to sillimanite, implying all the kyanite present is metastable.

According to Holdaway (1971) the fact that all the sillimanite present is in fibrolitic form also implies disequilibrium, and considerable overstepping of the kyanite-sillimanite equilibrium boundary. Kyanite, then, is first to form; inverting to sillimanite with increasing temperature.

The presence of kyanite alone in some areas may be due to greater shear stress in these areas. A concept of tectonic overpressure (Clark 1961) may be useful in accounting for kyanite stability in these zones. Current opinion does not favour such a concept (Rutland 1965).

However it is evident that considerable shear did occur in the area and that in the kyanite gneisses quartz grains seem to be more severely strained and fractured than in similar sillimanite rich rocks. Alternatively it may be that in certain areas the aluminium content of the metamorphic fluids may have been too high to allow dissolution of kyanite and precipitation of sillimanite (Vrana 1973).

The crosscutting structures previously described as containing the kyanite muscovite kaolinite rock appear to be small shear zones in which kyanite has been preserved due to the presence of a high stress. Contorted kyanite layering and herringbone jointing in the surrounding sillimanite gneiss contribute to this shear concept. The assemblage of aluminosilicates biotite while muscovite and quartz and accessories rutile, epidote and garnet was found during the metamorphic peak accompanying or just preceeding the second deformation.

4.2 A period of retrogression follows. In this time the aluminosilicates in the schists were sericitised forming the white knots currently visible. The mica in these has been shown by XRD to be identical, whether associated with sillimanite or kyanite (see Appendix III) in both cases, as the 2M form of muscovite. These micas are also equivalent to the so-called damaurite (here referred to as green muscovite) in both coarse and fine grained states, the only apparent difference being the colouration. Textural similarity between the sericite and fine green muscovite is also noted.

Two generations of muscovite are sometimes seen. The first, which partly makes up the $S_2$ schistosity, is white in colour, and the second, which cross-cuts the $S_2$ schistosity and **nucleates** on biotite and primary muscovite, is formed during the retrogressive event. Transition of sillimanite and kyanite into both sericite and green muscovite is clearly observed,

$$3Al_2SiO_5 + 2K^+ + 3H_2O + 3SiO_2 \rightarrow 2KAl_3Si_3O_{10}(OH)_2 + 2H^+$$

It is therefore evident that these two forms of muscovite should not be regarded as distinct on a genetic basis, rather they are products of the same genetic event and caused by introduction of potassium and water during the period following the $F_2$ event with falling temperature.

The coarse green muscovite is found in irregular pods and in planar structures within the gneisses. These planar structures are clearly planes of movement in which the eastern hanging wall has been thrust over the western wall (Fig2). As far as can be estimated, their orientations parallel that of the thrust, implying they were formed contemporaneously. Foliation observed in these coarse green micas from shear zones expresses the presence of a stress field on crystallisation.

Figure 2

Coarse green muscovite in shear.
Hand drawn from projection of slide.
Country rock is kaolinised Sillimanite gneiss

Figure 3

Diagram of stability boundaries with respect to Pressure and Temperature, (from Hyndman)
Abbreviations: Kaol. = kaolinite,
pyr. = pyrophyllite, ms. = muscovite,
mont. = montmorillonite, ep.=epidote,
sp. = spessartite, preh. = prehnite,
and. = andalusite, act. = actinolite,
stil. = stilpnomelane, ky.= kyanite,
bi. = biotite, alm. = almandine,
hb. = hornblende, ch. = chlorite,
chd. = chloritoid, st. = staurolite,
cord. = cordierite, sil. = sillimanite,
K-fp. = potash feldspar.

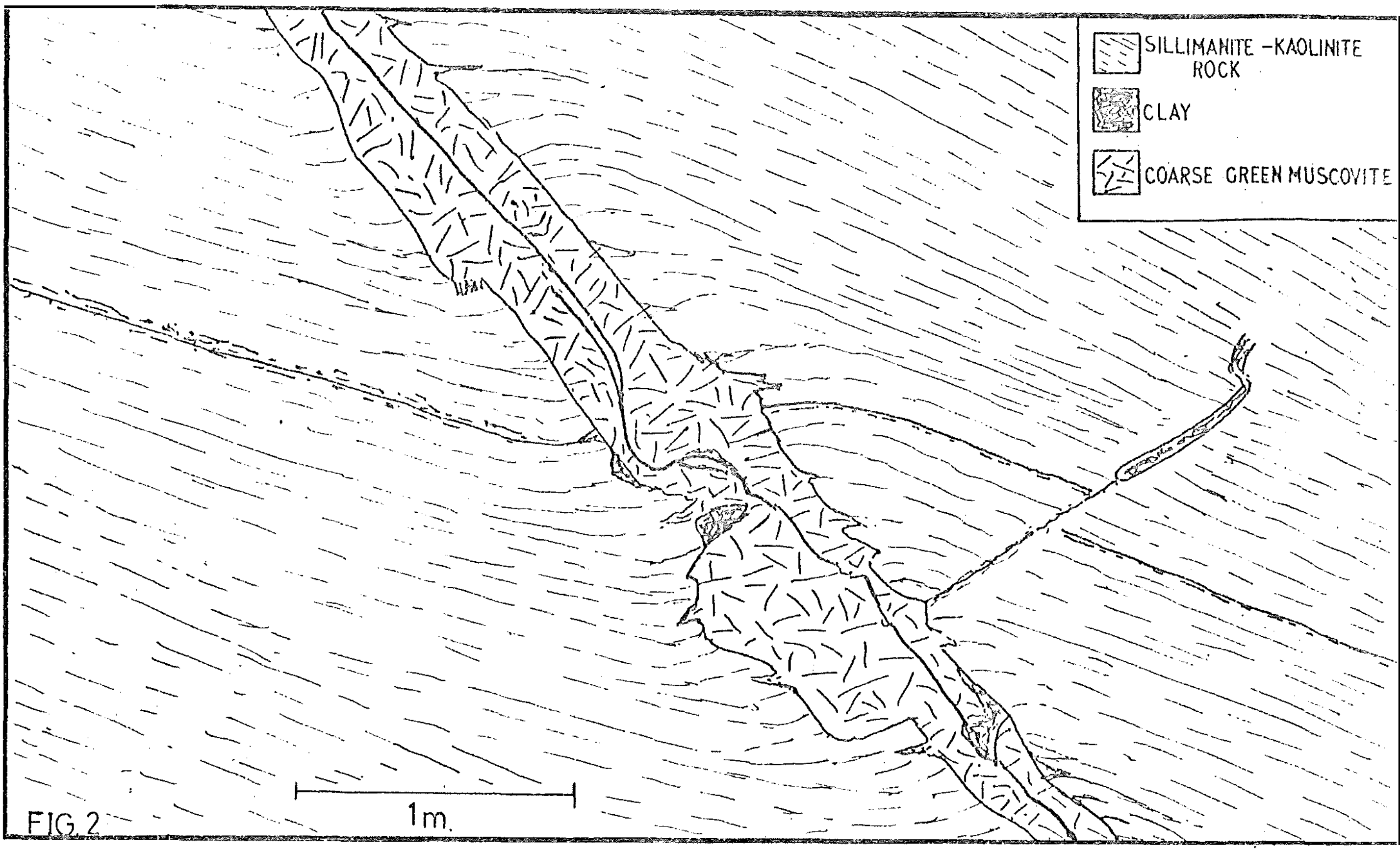

SILLIMANITE -KAOLINITE ROCK
CLAY
COARSE GREEN MUSCOVITE
1m.

FIG. 2

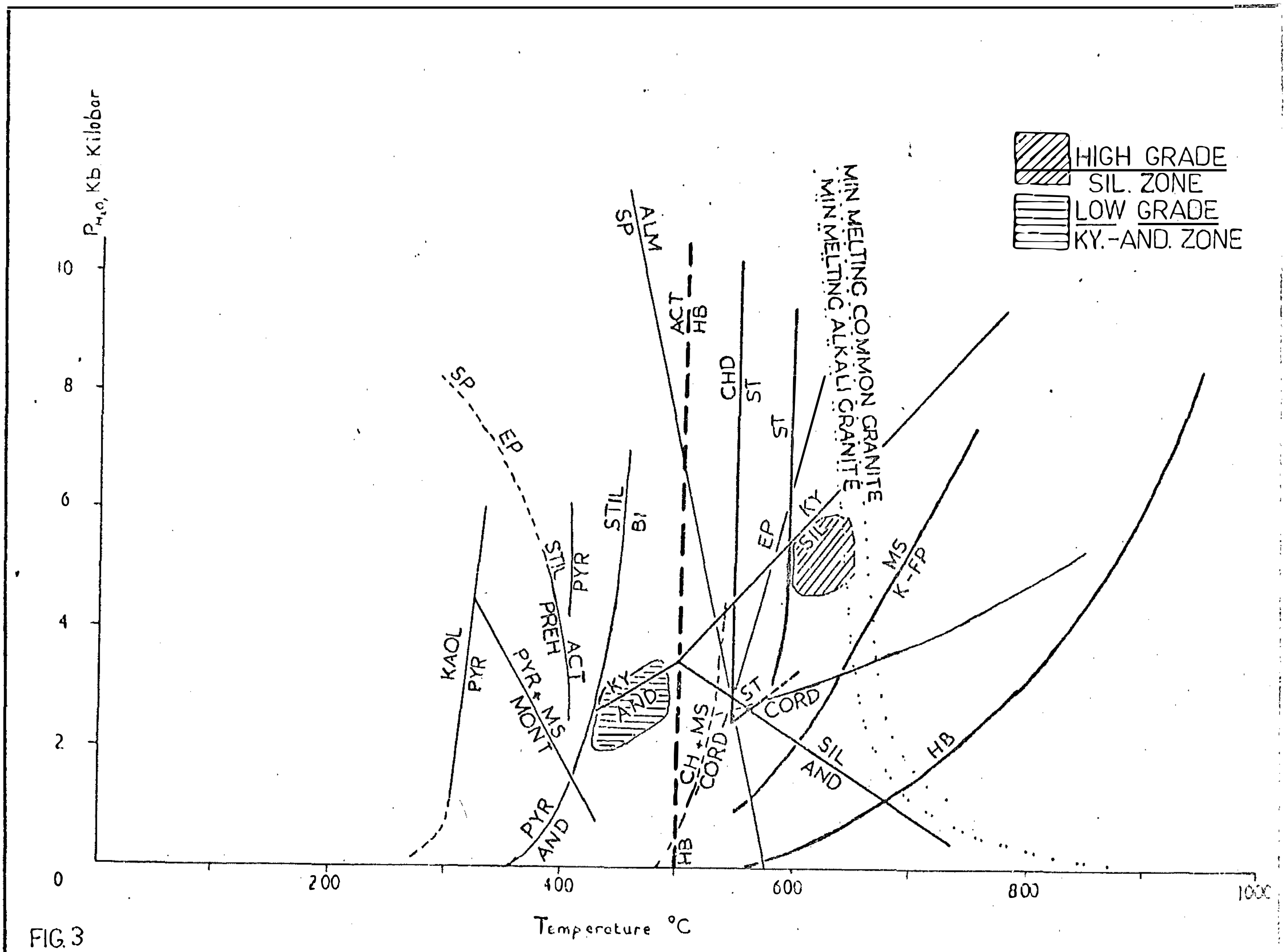

HIGH GRADE SIL. ZONE
LOW GRADE KY.-AND. ZONE
MIN MELTING COMMON GRANITE
MIN MELTING ALKALI GRANITE
ALM
SP
ACT
HB
CHD
ST
KY
SIL
EP
MS
K-FP
STIL
BI
PYR
PREH
ACT
KAOL
PYR
PYR + MS
MONT
KY
AND
CH + MS
CORD
CORD
SIL
AND
HB
PYR
AND
$P_{H_2O}$, Kb Kilobar
Temperature °C
0
2
4
6
8
10
200
400
600
800
1000

FIG. 3

The presence of embayed porphyryblasts of kyanite in kyanite muscovite kaolinite rocks surrounded by a variably sized crystalline matrix of muscovite is evidence that these muscovites were formed at least in part by retrogression of kyanite. The lack of small relict kyanite and presence of subhedral kyanite within the muscovite matrix in other specimens of the same type however, indicates that not all the muscovite in these bodies formed by retrogression, rather that a large amount formed during peak metamorphism, intergrown with the kyanite. The absence of coarse green micas in the lower grade zone indicates that most of the thrusting was post regression though its initial stages were contemporaneous and had some catalytic influence on the formation of the green muscovite shears. Chloritic alteration of biotite is also observed during the retrogressive phase.

4.3 Kaolinisation is not confined to the high grade schists but occurs on both sides of the thrust in section S950. In the high grade schists and gneisses, both sillimanite and kyanite are kaolinised,

Aluminosilicate Kaolinite Diaspore

$$2Al_2SiO_5 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2HAlO_2$$

In places, presence of diaspore indicates deficiency of silica. Elsewhere quartz veins indicate excess silica.

The kaolinisation seems to be associated with the $F_3$ deformation slickensliding in the kaolinites of the kyanite muscovite kaolinite bodies, small cross cutting clay veins within low grade sandstone and high grade schists and en echelon fracturing in grey schists in the quarry indicate movement during kaolinisation. Alderman (1942) believed these are due to volume changes during kaolinisation, but with the recognition of faults and thrusts, tectonic causes are more likely. These movements allowed the introduction of water at relatively low temperature and pressure and with a low potassium content. This caused hydrothermal alteration of alumino-silicates to kaolinite. The absence of other hydrothermal clay minerals such as pyrophyllite and montmorillonite, indicate alteration took place below 350°C (Fig.3). Under a hydrothermal scheme as described by Alderman (1942) a zonation of the above minerals would be expected. No such zonation is found. Further, the association of the kaolinisation with $F_3$ deformation and of aluminosilicates with metamorphism associated with $F_2$ presents too long a time span for any single sequence of hydrothermal alteration.

Kaolinisation of potash feldspars in feldspathic sandstones has produced the clays and clayey sandstones east of the thrust line in section S950.

$$2KAlSi_3O_8 + H_2O + 2H^+ \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 4SiO_2$$

Feldspars in the pegmatite in the west of the quarry are likewise altered. The possibility that weathering caused the kaolinisation was rejected on the basis that a weathered surface with soil horizon was seen to cap the clay deposit, that slickensliding is visible in clays in the cross cutting kyanite rich bodies, that much clay occurs within veinlets and stockwork structures which cross cut layering in sandstones and schists. The latter feature especially, implies a hydrothermal origin. The presence of large tourmalines, occasional quartz veins and goethite veinlets, indicates mobility of boron, silica and iron. Chemical comparison studies on sillimanite and clay minerals by Alderman (1942) and Corchrane (1953) indicate addition of silica or removal of aluminium during

Figure 4

Stabilities of the minerals with regard to temperature and mole ratio KCl/HCl (from Krauskopf)

Figure 5

Influence of potassium activity and temperature on the minerals muscovite (ms), potash feldspar and aluminosilicates.
(from Eugster)

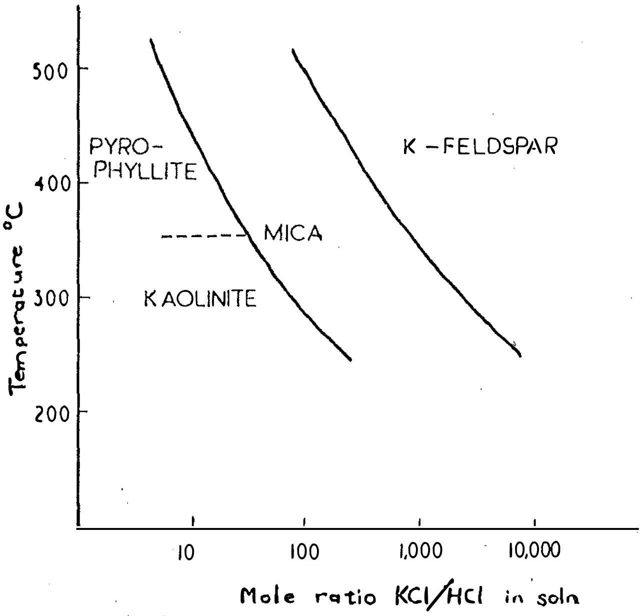



FIG. 4 (after Krauskopf)

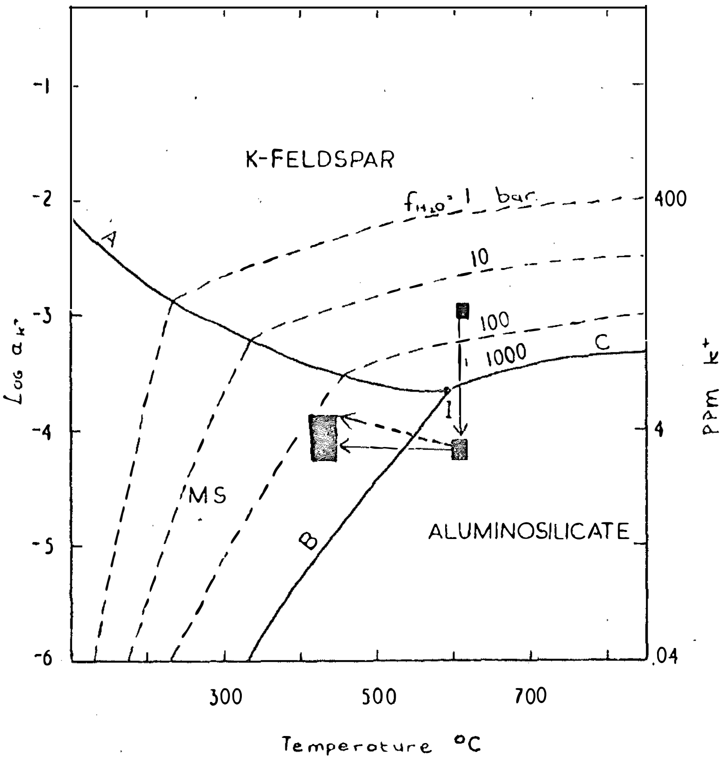



FIG.5 (after Eugster 1970)

kaolinisation. The presence of quartz veins suggests the former.

TABLE I

CONVERSION OF SILLIMANITE INTO KAOLINITE

| Source of Line | Film No. | 13900 | | 13901 | | 13898 | |
|---|---|---|---|---|---|---|---|
| | Spec. No. | -222c | | -222d | | -222b | |
| | Identity | Sill. | | Sill. + Kaol. | | Kaol. | |
| | | dA° | I | dA° | I | dA° | I |
| K | | - | | 7.11 | 4 | 7.17 | 1 |
| Sill | | 5.42 | 6 | 5.35 | 6 | - | |
| K | | - | | - | | 4.27 | 2 |
| K | | - | | - | | 3.57 | 3 |
| Sill | | 3.36 | 1 | 3.37 | 1 | - | |
| Sill | | 2.88 | | 2.87 | | - | |
| Sill | | 2.67 | | 2.67 | | - | |
| Sill, K | | 2.54 | 3 | 2.53 | 3 | 2.55 | 5 |
| Sill | | 2.41 | | 2.41 | | - | |
| K | | - | | - | | 2.35 | 6 |
| K, Sill | | 2.27 | | 2.29 | | 2.27 | |
| Sill | | 2.20 | 2 | 2.20 | 3 | - | |
| Sill | | 2.10 | | 2.11 | | - | |
| K | | - | | - | | 1.99 | |
| Sill | | 1.87 | | - | | - | |
| Sill | | 1.81 | | - | | - | |
| K, Sill | | 1.68 | | 1.70 | | 1.66 | |
| Sill | | 1.59 | | 1.60 | | - | |
| Sill | | 1.51 | 4 | 1.50 | 4 | - | |
| K | | - | | - | | 1.48 | 4 |
| Sill | | 1.44 | 5 | 1.44 | 5 | - | |
| Sill | | 1.33 | 7 | 1.33 | 7 | - | |

ABBREVIATIONS

K = Kaolinite

Sill = Sillimanite

I = Intensity order

This series of XRD powder photographs demonstrates the transition of sillimanite into kaolinite. Pure fibrolitic sillimanite is seen in -222c and transitionally changes to slightly kaolinised -222d. The change is noticeable in both the hand specimen and powder photograph. The final stage is pure kaolinite -222b.

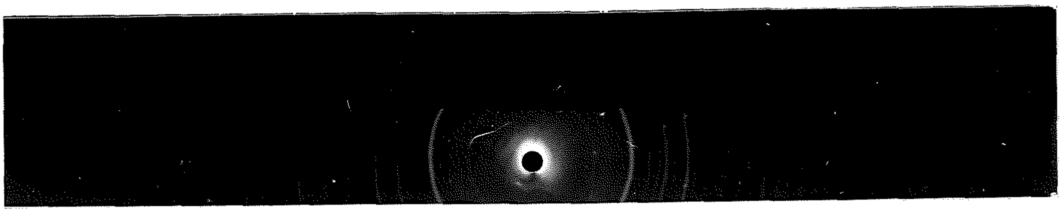
PLATE 9

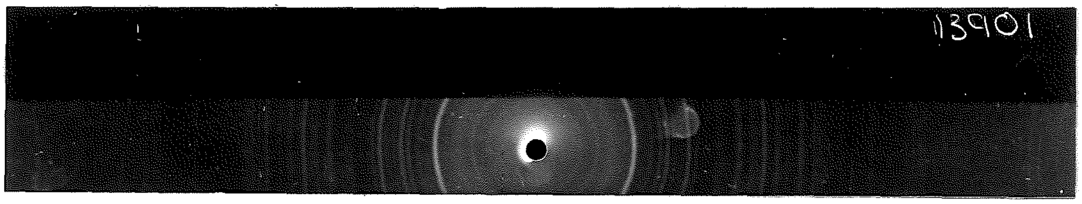
X-RAY POWDER PHOTOGRAPHS

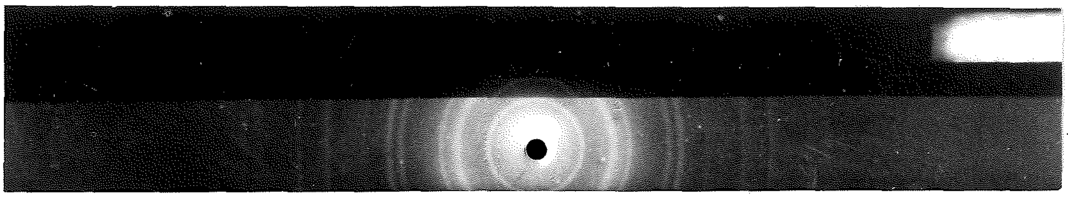
(a) 13900 Sillimanite
462-222c

(b) 13901 Sillimanite and minor kaolinite
462-222d

(c) 13898 Kaolinite
462-222b




13901



## 5.1 CONCLUSION

The results of this study suggest formation of aluminosilicates by prograde regional metamorphism, without the necessity of additional aluminium. Experimental evidence does not support widespread aluminium metasomatism as a major geological process. Removal of potassium from K-feldspars to form aluminosilicates is favoured. Dealkalisation at moderate to high temperatures (600-700°C) moderate pressures (4-6 Kb) and falling K activity, is postulated to have formed the sillimanite and kyanite gneisses and schists during the metamorphic peak associated with early $F_2$ deformation. Shearing was active and seems to have favoured the retention of kyanite in certain areas though further study is necessary. Geochemical and geothermometric studies may be of value in determining the precise conditions of metamorphism.

Lower temperature retrogression following the $F_2$ folding, possibly being catalysed by shearing associated with initial stages of movement along the Murray Vale Thrust and contemporaneous introduction of potassium and water. Second generation fine and coarse grained green muscovites, sericite, chlorite and possible epidote were formed during this time. Thrusting from the east along the Murray Vale line brought high grade and low grade zones into adjacent positions.

An $F_3$ deformation crenulating the $S_2$ schistosity and producing folding and warping and associated faulting occurred. Kaolinisation was associated with this phase and took place under low pressure, low potassium activity, locally silica deficient, conditions. Temperature is placed at below 350°C and introduction of water is necessary. The timing of the Wirrianda Thrust is uncertain, but follows the Murray Vale movements preceeds the $F_3$ folding.

## 6.1 ACKNOWLEDGEMENTS

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# APPENDIX I

## THIN SECTION AND HAND SPECIMEN DESCRIPTIONS

Of the total 80 thin sections examined a representative sample were chosen and are described here. One or more section from each of the lithologies, except the clays which could not be sectioned, are given. Mineralogy, important textural features, and reactions occurring are described. The clays are described from hand specimen only.

1. GNEISSES

462-150 Quartz-Sillimanite gneiss.

85% Sillimanite, fibrolitic and inclusions in quartz
10% Quartz
5% Muscovite
Rutile accessory

Massive fibrous rock, decussate texture.

462-310 Foliated Quartz-Sillimanite gneiss

20% Sillimanite, fibrolitic and inclusions in quartz
20% Quartz, Patchy undulose extinction
5% Biotite } Show preferred orientation
5% Muscovite, coarse } Show preferred orientation
50% Sericite, forms sheaths around nodules and layers of remnant sillimanite
Rutile accessory

Reaction Sillimanite + Quartz → Sericite.

2 generations of muscovite, later crosscuts earlier schistosity

462-206 Quartz-Sillimanite-Kyanite gneiss

50% Sillimanite, fibrolitic and inclusions
25% Quartz, undulose patchy extinction
15% Kyanite, twinned, high relief, anhedral grains embayed by muscovite and sillimanite
10% Muscovite, coarse grained
Rutile accessory

Grey and white layering 1-2mm. thick, Blue patches indicate kyanite in hand specimen.

Reactions: Kyanite → Sillimanite
Kyanite + Quartz → Muscovite

462-147 Quartz-Kyanite gneiss

50% Quartz, ceratitic and strained.
30% Kyanite, in layers, twinned, anhedral, cleaved grains
15% Muscovite, altered from kyanite, mainly in kyanite layers
5% Rutile, brown, very high relief, translucent, in short grain trains

Weak layering in hand specimen, pale blue colour due to kyanite, slight foliation

Reaction: Kyanite + Quartz → Muscovite

462-145 Sheared Quartz-Kyanite gneiss

10% Kyanite, twinned, embayed relicts
30% Quartz, small, strained lenses, surrounded by sericite,
15% Muscovite, coarse grained
45% Sericite, extensively developed alteration of kyanite and quartz. Muscovite also attacked. Green colour in sericite.
Rutile accessory

Little remnant layering, lensed by shearing

462-132 Quartz-Muscovite gneiss

60% Quartz, polygonal coarse matrix interlayered with fine, pale green muscovite, contains sillimanite inclusions

35% Muscovite, fine green in layers and irregular patches; coarse grained embayed by fine muscovite

Minor biotite and chlorite also present

Probably retrograded sillimanite-quartz gneiss.

Hand specimen shows grey and green layering.

2. KYANITE MUSCOVITE KAOLINITE ROCK

462-141 30% Kyanite, twinned, embayed crystals

15% Muscovite, coarse, embayed by sericite

50% Sericite and Kaolinite, fine grained, difficult to differentiate. Form from earlier kyanite and muscovite.

5% Rutile

Reactions: Kyanite + Quartz → Sericite

Kyanite + $H_2O$ → Kaolinite

Hand specimen:- Pale blue and white, friable rock. Kyanite as altered grains, remnants of unaltered kyanite up to 3mm. in length.

3. BLADED KYANITE ROCK

462-424 Hand specimen only. Confined to elongate body at base of pit. Contains pale blue kyanite, bladed, up to 5cm. in length. Much white muscovite is psuedomorphing the kyanite. Minor kaolinite present between the kyanite blades.

4. MUSCOVITE SHEAR ROCK

462-203 Hand specimen only. 90% coarse green muscovite. Well defined preferred orientation and crenulation. Patches of white kaolinite irregularly distributed throughout the rock. Minor rutile.

5. SCHISTS

462-151 Knotted Biotite Schist

20% Biotite, common pleochroic halos around zircon inclusions

2% Chlorite

15% Muscovite, small, euhedral, crosscutting crystals on biotite. Larger crystals in matrix

20% Quartz, embayed in clay layers, polygonal in quartz layers. Ribbon-like undulose extinction. Frequent sillimanite inclusions.

3% Garnet, isotropic rounded grains confined to quartz layers. Slight pink pleochroism.

40% Sericite, in lenses and crenulated layers giving knotted appearance. Partly preserves fibrous sillimanite texture.

Coarse micas form dominant schistosity, crenulated.

462-144 Muscovite Schist

50% Muscovite, layered, in schistosity which is crenulated, Kaolinite occaisionally in hinges.

30% Quartz, elongate grains with undulose extinction. Some bent crystals, Fine lines of rounded inclusions perpendicular to elongation.

10% Kaolinite, in irregular patches and some fold hinges

Schistosity is extensively crenulated.

462-105 Sillimanite Sericite Schist

15% Quartz, in layers and lenses, ceratitic texture, often embayed

20% Muscovite, 2 generations, first- coarse forms schistosity, second is fine grained and cuts schistosity.

20% Sillimanite, fibrolitic, in lenses elongate in schistosity, sheathed by sericite

30% Sericite, fine grained, altering from sillimanite

10% Chlorite

3% Biotite, 2% Rutile

462-209 Garnetiferous Muscovite Schist

30% Muscovite, mostly second generation, large crystals random orientation

10% Chlorite, clumps and aggregates, random orientation.

10% Garnet, rounded isotropic grains rimmed by iron staining, rough outline in sericitic layers.

20% Quartz, in composite lenses interlayered with sericite, undulose extinction, fibrolite inclusions.

25% Sericite, partly retains sillimanite texture, in layers, some recrystallisation to coarser muscovite.

5% Rutile

462-338 Muscovite Schist

30% Muscovite, mainly in preferred orientation, crenulated

25% Quartz, slight undulose extinction, few sillimanite needles near sericite patches

15% Sericite, in sporadic patches

10% Chlorite, random orientation

10% Plagioclase, highly fractured and altered, iron stained, infrequent multiple extinction

8% Biotite, with muscovite in schistosity.

2% Opaques

## 6. AMPHIBOLITES

### 462-118 Coarse Amphibolite

60% Hornblende, poikioblastic, pleochroic yellow-green, olive-blue green, unoriented

10% Quartz, polygonal, granoblastic, undulose extinction

20% Orthoclase, Biaxial (-), slight alteration, dusty appearance

10% Plagioclase, multiple twinning, E.A. uncertain,
Accessory opaques uncommon.

Grains are coarse and unoriented.

### 462-220 Schistose Amphibolite

40% Hornblende, pleochroic yellow-green, fine acicular, euhedral diamond cross-section, alignment of crystals produces lineation

25% Biotite,

20% Quartz,

12% Plagioclase, zoned, multiple extinction, E.A. 22$^{\circ}$ andesine

3% Accessories, opaques, apatite

Rock has lineation. May be metasediment.

## 7. TREMOLITE ROCK

### 462-318

95% Tremolite, asbestiform fibrous sheaths, interlocking, highly weathered and iron stained, pale green colour

2% Kaolinite, crystalline in fissures

3% Weathering products, goethite, etc.

### 462-119

25% Tremolite or Actinolite, radiating fibrous, fine grained, occurs in fractures, green colour

10% Muscovite

30% Quartz, ceratitic sutures, variable grainsize

30% Albite, multiple twinning, E.A. 15$^{\circ}$

10% Rutile

## KYANITE-ANDALUSITE ZONE

462-320 Tremolite Sandstone

30% Quartz,
40% Orthoclase,
15% Plagioclase, EA 13, Andesine, multiple twinned.
15% Tremolite, euhedral poikioblastic crystals.
Minor biotite, accessories apatite, opaques.

Matrix polygonal fine grained quartz and orthoclase. Plagioclase subhedral to polygonal grains. Biotite laths in random orientation. Locally cracked and heavy iron staining, Finely laminated.

462-116 Tremolite Marble

80% Calcite, rhombic cleavage, elongate straight sided grains, polygonal network.
10% Tremolite, elongate, euhedral, acicular, crystals in cleavage plane, no lineation, some twinning.
10% Muscovite, mainly lie in plane of cleavage, lath-shaped.

Hand specimen shows weak cleavage.

462-114 Fine Chloritic Schist

50% Chlorite, uniformly distributed fine lath shaped crystals. Pale green- brown, distinct well developed preferred orientation.
20% Quartz, fine polygonal grains, mild undulose extinction.
10% Plagioclase
5% Biotite, fine grains, well developed preferred orientation.
5% Orthoclase, dusty appearance due to alteration.
3% Andalusite, high relief, pleochroic lemon- pale yellow, pale brown- pale yellow.
2% Accessories, muscovite, apatite, tourmaline.

Clhorite and biotite in preferred orientation form schistosity. Cross cutting viens carry higher concentrations of pale green chlorite (no biotite). Relict highly embayed andalusite, muscovite spatially associated.

Reaction: Andalusite + Quartz $\rightarrow$ Muscovite

462-305 Feldspathic Sandstone

35% Quartz,

30% Microcline, typical crossed twinning

15% Plagioclase, Oligioclase composition

10% Tourmaline, pleochroic. pale brown- green, zoned.

8% Chlorite,

5% Tremolite, elongate sections form microscopic lineation.

2% Accessories, Rutile , apatite

Fine grained, interlocking quartz and feldspars, recrystallised sandstone,

462-111 Knotted Biotite Schist

20% Biotite, in layers with preferred orientations, cernulated

5% Chlorite,

3% Muscovite

25% Plagioclase, porphyroblastic,composite,multiple extinction.

10% Orthoclase, fine to ,oderate grained.

17% Scapolite, Porphyroblastic, includes micas quartz and opaques, forming from plagioclase.

20% Actinolite, Poikioblastic porphyroblasts,euhedral sections cut mica layering.

Knotted porphyroblasts as above, biotite layering bends around plagioclase but not scapolite and actinolite.

462-300 Actinolite Rock

50% Actinolite, pleochroic colourless- pale green, has frequent pleo. halos,slight preferred orientation, coarse grained.

30% Quartz, fine grained

5% Plagioclase,

5% Zircon, small, high relief grains, elliptical section, surrounded by small halos.

5% Orthoclase,

5% Accessories, opaques, apatite,epidote,monazite.

Actinolite is slightly poikioblastic, variable grain-size, subhedral to euhedral, forms weak lineation, zircons distributed throughout the rock.

## KAOLINITES

As these specimen are too soft to enable thin sections to be cut, description is restricted to hand specimen and oil studies (appendix II).

462-201 Kaolinite, from margin of Kyanite-muscovite-kaolinite shear in quartz-kyanite gneisses. Absorbs water readily. slightly slippery feel. Includes radiating aggregate of tourmaline. XRD shows low- moderate crystallinity.

462-140 Kaolinite, from similar environment as -201 but much harder and more compact, conchoidal fracture, high water absorption on fresh surface, traces of slicken-sliding visible on hand specimen, well developed in outcrop, XRD shows low- moderate crystallinity.

462-221 Kaolinite, white, from kaolinised sillimanite zone of quarry, contains disseminated micas, softand friable. Some sillimanite needles present. Breaks with irregular fracture XRD shows moderate crystallinity.

462-220 Kaolinite, white, from kaolinised sillimanite zone of quarry. Very rich in sillimanite, soft, friable, gritty feel.

462-405 Kaolinite, from interbed with kaolinised sandstones, soft, adsorbs water, contains quartz but no sillimanite, bed made up of cream coloured, slickensided, nodular clays. Coarse grained muscovite absent.

APPENDIX II

Microscopic Examination of Clays in Refractive Index 1.60 Oil

Clays from various samples were powdered and examined microscopically under RI 1.60 oil. By this method sillimanite stands out in high relief, (sillimanite - R.I. 1.66) as fine needles. Quartz and micas (R.I.
become low relief or almost invisible. Kyanite ( R.I.
is occaisionaly seen as high relief irregular grains. Acicular actinolite or tremolite may be confused with sillimanite but may be distinguished by inclined extinction. The oil also serves to break up aggregates of powdered clay which otherwise remain as white translucent lumps. The kaolinite becomes invisible. No Quantitative estimate of mineral abundances is possible since minerals with R.I. close to 1.60 are rendered invisible.

| Sample | Origin | |
|---|---|---|
| -221 | Kaol. Sill. zone, Quarry S950 | Common Sill. needles |
| -150 | Sill. rock Section 3101 | Mostly " " little quartz |
| -151 | Sericite pod in schist | Few Sill. needles mainly mica, |
| -220 | Kaol. Sill. zone, Quarry S950 | Abundant Sill needles |
| -144 | Muscovite Schist, S950 | Few sill needles mainly musc. |
| -105 | Sill. bearing schist | Common sill. needles |
| -203 | Coarse green musc. shear rock Quarry S950 | Few sill. needles in micas. More common in white patches |
| -140 | Kaol. from Kaol. Ky. Musc. shear rock. S950 | Very rare sill. |
| -131 | Sill. Kaol. rock.Diggings at S941 | Sill. very abundant |
| -120 | Kaol. origin unknown. | Sill.rare |
| -141 | Kaol. Ky. Musc. rock S950 | Sill. absent,KY. abundant |
| -202 | Fine green musc. rock, Quarry S950 | Few small sill. needles, POssibly Ky. mainly Musc. |
| -165 | S942 Sandy clay layer | Very rare sill. musc. ky. present |
| -160 | Sericitic pod in schist | Few sill needles |
| -163 | " " " " | Few sill needles |

| | | |
|---|---|---|
| -310 | S959 Foliated Quartz Sill. gneiss | Sill. abundant, quartz present |
| -147 | S950 Sheared Ky. Quartz gneiss | Sill. reasonably common ky. musc. present. |
| -117 | Schist from northern section White patches | Rare sill. |

THE FOLLOWING SPECIMENS ARE ALL FROM QUARRY ON SECTION S950

Low grade zone ( sandstones, fine schists, clay interbeds

| | | |
|---|---|---|
| - 402 | Clay interbed. | Sill. absent. |
| - 405 | Clay vein in sandstone | " " |
| - 407 | Clay interbed | " " Few actinolite needles |
| - 408 | Fine grained schist | Sill absent, common actinolite needles |

High grade zone

| | | |
|---|---|---|
| - 409 | From grey schists | Few sillimanite needles |
| - 411 | Clay from coarse mica schist | Common Sill. |
| - 416 | Clay interlayer with musc schist | " " |
| - 417 | Kaol. Quartz rock | " " , Few hornblende crystals |
| - 418 | Clay surrounding sill nodules | Sill very abundant |

# APPENDIX III

## X-Ray Diffraction Identification.

X-Ray diffraction was used to identify the clays and micas found in the retrogression products of the aluminosilicates. Most samples were examined by a powder photograph method but a slide was prepared for the coarse mica -203 because difficulty in packing was experienced.

### Tecnique

The sample was ground to fine size using an agate mortar. Ideal size is in the range $10^{-4}$ to $10^{-5}$ cm. Powder is then packed firmly into a fine glucose capillary tube which is inserted in position in a 57.3mm. camera. This is loaded with Kodak X-Ray film and set in position on the X-Ray unit PW1010. Copper $K_\alpha$ radiation of wavelength employing a nickel filter is used. The film is exposed for 20min. at 20mA. 40kV. It was then developed for 5min, fixed for 8min, washed and dried.

The lines produced were measured and the diameter2s of the rings was found. with the 57.3mm camera 2s = 2θ and d is calculated using $d = \frac{\lambda}{2\sin\theta}$ for a first order line. The set of dA° values obtained was compared to A.T.S.M. index cards and files for an identification of the mineral examined.

Tables of intensity and dA° values are found below

### Abbrevations

Abbreviations used are

- I = order of intensity
- Sill. = Sillimanite
- Ky. = Kyanite
- K. = Kaolinite
- M. = Muscovite
- Q. = Quartz

### Crystallinity

From the multiplicity and broadness of the lines an estimate of the crystallinity of the kaolinite may be made (fig. III 1). This is believed to be related to the genesis of the clays, being of a higher order with higher temperature of altering fluids. Within the studied samples some variation is seen (plate III 1) but the crystallinity is always moderate or low, indicating fairly low temperatures. The kaolinite developed as a coating on lumps of sillimanite is of higher crystallinity than that in the Kyanite Muscovite Kaolinite shear rocks.

## KAOLINITES

| STANDARD * | | Film No. / Spec. No. | 13890 | | 13896 | | 13899 | | 13898 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 462-201 | | 462-140 | | 462-221 | | 462-222b | |
| dA° | $I/I_1$ | (hkl) | dA° | I | dA° | I | dA° | I | dA° | I |
| 7.15 | 50 | 001 | 7.10 | 1 | 7.20 | 1 | 7.14 | 1 | 7.17 | 1 |
| 4.46 | 75 | 020 | - | | 4.44 | 3 | 4.42 | 3 | - | |
| 4.34 | 85 | $0\bar{1}0$ | 4.34 | 3 | - | | - | | 4.27 | 2 |
| 4.16 | 65 | $11\bar{1}$ | 4.16 | 6 | - | | 4.21 | 5 | - | |
| 4.11 | 40 | $1\bar{1}\bar{1}$ | - | | 4.12 | 4 | - | | - | |
| 3.83 | 50 | $02\bar{1}$ | - | | - | | - | | - | |
| 3.72 | 20 | 021 | - | | - | | - | | - | |
| 3.56 | 50 | 002 | 3.57 | 2 | 3.58 | 2 | 3.56 | 2 | 3.57 | 3 |
| 3.37 | 12 | 111 | - | | - | | - | | - | |
| 3.15 | 4 | $11\bar{2}$ | - | | - | | - | | - | |
| 2.74 | 4 | 022 | - | | - | | - | | - | |
| 2.55 | 85 | $20\bar{1}$ | 2.55 | 5 | 2.60 | | 2.55 | | 2.55 | 5 |
| 2.52 | 50 | $13\bar{1}$ | - | | - | | - | | - | |
| 2.48 | 85 | $1\bar{3}\bar{1}$ | 2.48 | | 2.49 | | 2.47 | | 2.48 | |
| 2.37 | 25 | 003 | - | | - | | - | | - | |
| 2.33 | 95 | $20\bar{2}, 11\bar{3}$ | 2.33 | 4 | 2.34 | | 2.33 | 6 | 2.35 | 6 |
| 2.28 | 65 | 131 | 2.27 | | 2.29 | | 2.27 | | 2.27 | |
| 2.24 | 20 | $13\bar{2}, 032$ | - | | - | | - | | - | |
| 2.18 | 12 | $1\bar{3}\bar{2}$ | - | | - | | - | | - | |
| 2.11 | 6 | $2\bar{1}1$ | - | | - | | - | | - | |
| 1.99 | 12 | $20\bar{3}, 1\bar{3}2$ | 2.02 | | 1.99 | | 1.98 | | 1.99 | |
| 1.94 | 6 | $221, \bar{2}13$ | - | | - | | - | | - | |
| 1.89 | 6 | $13\bar{3}$ | - | | - | | - | | - | |
| 1.87 | 8 | 042 | - | | - | | - | | - | |
| 1.85 | 6 | $1\bar{3}\bar{3}, 22\bar{3}$ | - | | - | | - | | - | |
| 1.78 | 4 | 004 | - | | - | | - | | - | |
| 1.68 | 20D | $\bar{2}\bar{2}2$ | - | | - | | - | | - | |
| 1.66 | 25D | | 1.65 | | 1.67 | | 1.66 | | 1.66 | |
| 1.61 | 16D | | - | | - | | - | | - | |
| 1.58 | 4D | | - | | - | | - | | - | |
| 1.53 | 8D | | - | | - | | - | | - | |
| 1.48 | 100 | | 1.45 | 7 | 1.49 | 5 | 1.48 | 4 | 1.48 | 4 |

* From MELKA & SLANSKY, Acta Universitatis Carolinae Geologica p.3 (1959)

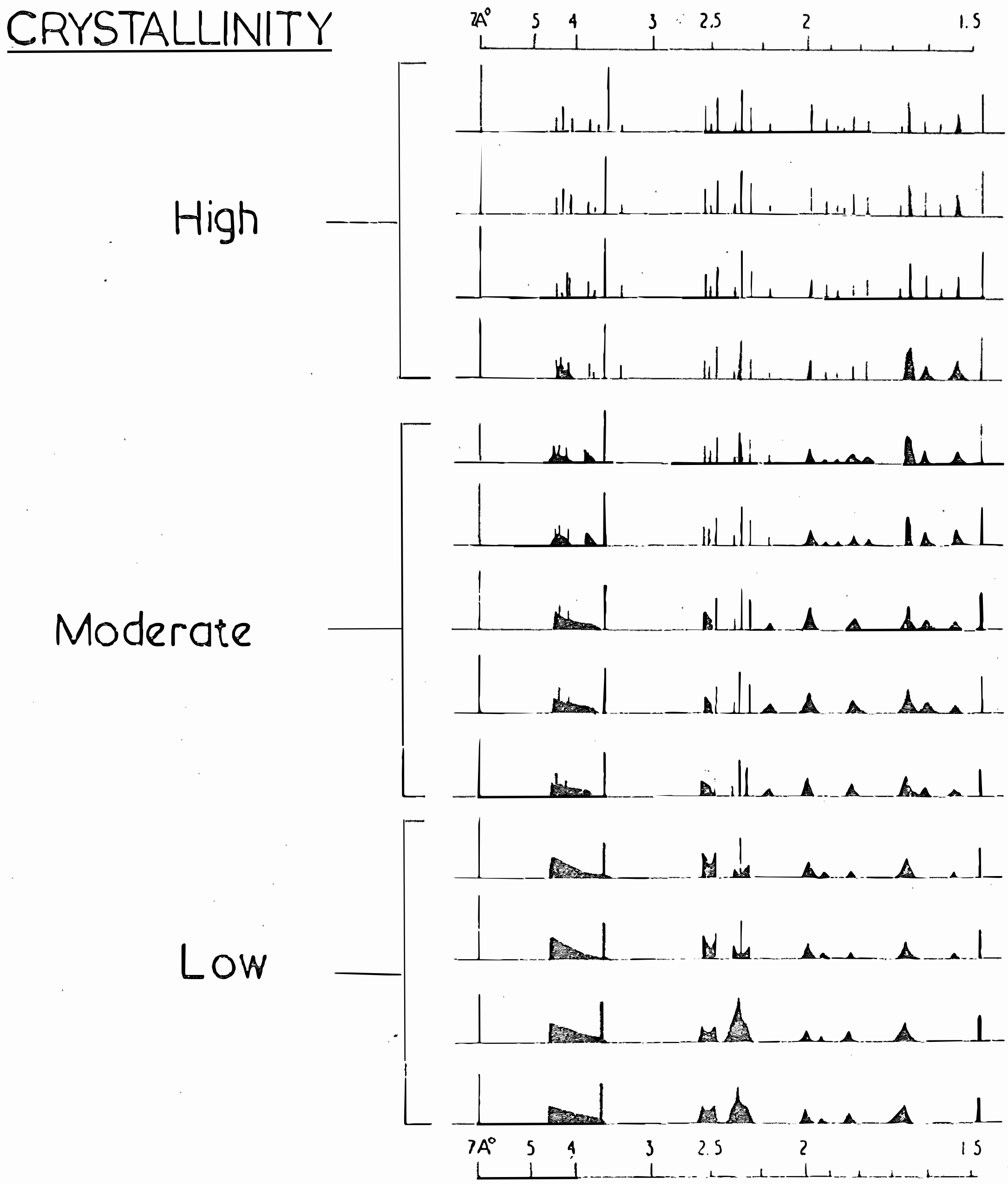



Fig III 1 (after Grim)
Crystallinity of kaolinites and appearance of X-Ray diffraction.

# MUSCOVITE

| Source of Line | 13897<br>462-202 | | Trace -1<br>462-203 | | 13895<br>462-203b | |
|---|---|---|---|---|---|---|
| | Fine green Muscovite | | Coarse green Muscovite | | Fine white Muscovite | |
| | $2M_1$ | | $2M_1$ | | $2M_1$ | |
| | dA° | I | dA° | I | dA° | I |
| M | 10.05 | 6 | 9.83 | 2 | 9.88 | 3 |
| M | - | | 4.94 | 3 | - | |
| M | 4.50 | 3 | 4.42 | | 4.47 | 1 |
| Q | 4.32 | | - | | - | |
| M | - | | 3.47 | | - | |
| M | 3.35 | 1 | 3.30 | 1 | 3.36 | |
| M | 3.22 | | 3.18 | | 3.16 | |
| M | - | | 2.96 | | 2.96 | |
| M | - | | 2.83 | | - | |
| M | - | | 2.76 | | - | |
| M | 2.56 | 2 | 2.55 | | 2.56 | 2 |
| M | 2.45 | | 2.47 | | 2.45 | |
| M | - | | | | 2.35 | |
| M | 2.12 | | | | 2.12 | |
| Q | 1.82 | | | | - | |
| M | 1.68 | | | | 1.60 | |
| M | 1.55 | | | | 1.52 | 4 |
| M | 1.49 | 4 | | | 1.48 | 5 |
| M | 1.38 | 5 | | | | |

-203 was done on a trace due to the difficulty of grinding the sample finely enough to pack. Preferred orientation effects will strengthen some lines above others. Composition and hydration differences will result in considerable variation in dA°. -203 and 203b are from the same sample, -203b coming from whitish fine patches in otherwise coarse green foliated rock. -202 contains quartz.

MUSCOVITE cont.

| Source of Line | 13913 | | 13967 | | 13968 | |
|---|---|---|---|---|---|---|
| | 462-166 | | 462-310 | | 462-145 | |
| | Muscovite fine (sericite) | | Muscovite fine (sericite) | | Muscovite fine (sericite) | |
| | $2M_1$ | | $2M_1$ | | $2M_1$ | |
| | dA° | I | dA° | I | dA° | I |
| M | 10.05 | 4 | 10.05 | 4 | 9.99 | 4 |
| M | - | | 4.99 | | 4.98 | |
| M | 4.46 | 3 | 4.46 | 3 | 4.47 | 3 |
| Q | 4.23 | | - | | - | |
| M | 3.87 | | - | | - | |
| M | 3.69 | | 3.69 | | 3.67 | |
| M | 3.48 | | 3.49 | | 3.49 | |
| M | 3.35 | 2 | 3.33 | 1 | 3.34 | 1 |
| M | 3.19 | | 3.19 | | 3.19 | |
| M | 2.97 | | 2,96 | | 2.97 | |
| M | 2.85 | | - | | - | |
| M | 2.56 | 1 | 2.55 | | 2.57 | |
| M | 2.45 | | 2.45 | | 2.45 | |
| M | 2.37 | | 2.37 | | 2.36 | |
| M | 2.12 | | 2.13 | | 2.13 | |
| M | 1.98 | | 1.99 | | 1.99 | |
| M | - | | 1.95 | | 1.94 | |
| Q | 1.81 | | 1.81 | | 1.81 | |
| M | 1.65 | | 1.64 | | 1.64 | |
| M | 1.54 | | - | | - | |
| M | 1.49 | 5 | 1.49 | | 1.49 | |
| M | 1.37 | | 1.35 | | 1.35 | |

-161 is from a sericite knot in the high grade schists

-310 is from a sericite pod in Quartz- Sillimanite gneiss in the process of forming from sillimanite.

-145 is from a sericite pod in Sheared Kyanite- Quartz gneiss which formed from kyanite.

Quartz is probably present in all samples

-310 and -145 give identical patterns, showing the equivalence of retrogression of Sillimanite and Kyanite.

-166 is only slightly different, probably due to greater content of quartz.

# KYANITE - MUSCOVITE - KAOLINITE

| Source of Line | 13939 | | 13943 | | 13942 | |
|---|---|---|---|---|---|---|
| | 462-424a | | 462-424b | | 462-141 | |
| | M.+ Ky.+ K. | | M.+ Ky.+ K. | | M.+ Ky.+ K. | |
| | dA° | I | dA° | I | dA° | I |
| M. | 9.41 | | 9.45 | | 9.83 | |
| K. | 7.17 | | 7.08 | | 7.10 | |
| Ky.(M.K.) | 4.35 | 2 | 4.44 | 2 | 4.37 | 2 |
| Ky. M. | 3.75 | | 3.78 | | 3.75 | |
| K. (M.) | 3.54 | | 3.55 | | - | |
| Ky. (M.) | 3.34 | | 3.36 | | 3.34 | |
| Ky. | 3.18 | 1 | 3.17 | | 3.18 | 1 |
| Ky. | 3.03 | | - | | - | |
| Ky. (M.) | 2.93 | | - | | 2.98 | |
| Ky. | 2.69 | | 2.67 | | 2.65 | |
| Ky.K.(M.) | 2.51 | 4 | 2.54 | 1 | 2.52 | 3 |
| K. | - | | 2.42 | | - | |
| Ky. K. | 2.35 | 5 | 2.35 | | 2.36 | 4 |
| Ky. | 2.22 | | - | | 2.22 | |
| Ky. | 2.15 | | 2.16 | | - | |
| K. | - | | 2.08 | | - | |
| Ky. | 1.96 | 7 | 1.96 | | 1.96 | 7 |
| Ky. | 1.93 | 6 | 1.93 | | 1.92 | 6 |
| Ky. | 1.76 | | - | | 1.76 | |
| Ky. K. | 1.67 | | 1.67 | | 1.67 | |
| M | 1.62 | | - | | - | |
| Ky. | 1.59 | | 1.59 | | 1.59 | |
| Ky. | 1.50 | | - | | 1.50 | |
| Ky. K. | 1.47 | | 1.48 | | 1.47 | |
| Ky. | 1.39 | 3 | 1.37 | 3 | 1.37 | 3 |

462-424a &b are from same rock ie. Bladed Kyanite rock a is from blade, b from white altered area. -141 is Kyanite Muscovite Kaolinite Shear rock with sample taken from blue Kyanite rich part. Patterns from -424a and -141 are virtually identical. -424b has extra line at 2.42 indicating more kaolinite content. Absence of certain lines indicates less kyanite.

| Source of Line | 13912 | | 13897a | | 13914 |
|---|---|---|---|---|---|
| | 462-220 | | 462-131 | | 462-201 |
| | Sill.+ K. | | K.+ Q.+ Sill(minor) | | Tourmaline |
| | dA° | I | dA° | I | dA° |
| K. | 7.14 | 4 | 7.20 | 2 | 6.30 |
| Sill. | 5.29 | | 5.31 | | 4.98 |
| K.(Q) | 4.26 | 5 | 4.27 | | 4.52 |
| K. | 3.51 | 6 | 3.58 | | 4.19 |
| Sill. Q. | 3.36 | 1 | 3.34 | 1 | 3.95 |
| Sill. | 2.88 | | - | | 3.47 |
| Sill | 2.72 | | - | | 3.33 |
| Sill. K. | 2.54 | 2 | 2.53 | | 2.95 |
| K. | - | | 2.38 | | 2.35 |
| K. | - | | 2.34 | | 2.17 |
| K. Sill. | 2.27 | | 2.28 | | 2.10 |
| Sill. | 2.20 | 3 | 2.20 | | 2.03 |
| Sill. | 2.10 | | 2.12 | | 1.90 |
| K. | 1.98 | | 1.98 | | 1.64 |
| Sill. | 1.86 | | - | | 1.58 |
| K. Sill. | 1.81 | | 1.82 | | 1.50 |
| Sill.K. | 1.67 | | 1.67 | | 1.44 |
| Sill. | 1.59 | | - | | 1.40 |
| Sill. | 1.56 | | 1.54 | | 1.32 |
| Sill. | 1.51 | | - | | 1.30 |
| K. | 1.49 | | 1.49 | | 1.27 |
| Sill | 1.44 | | - | | |
| Sill | 1.33 | | 1.33 | | |

-220 is a white fraible clay with abundant sillimanite needles,
-201dark green tourmaline is present in a radiating cluster.
-131 is a white fibrous looking rock with large clay content.

## APPENDIX PLATE 1

X-Ray diffraction powder photographs

(a) 13890 Kaolinite 462-201

(b) 13897 Fine green muscovite 462-202

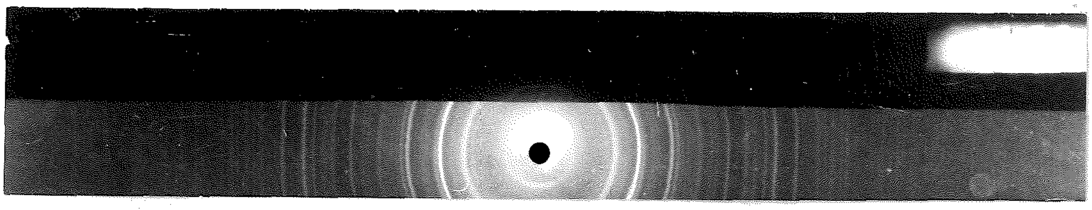
(c) 13895 Muscovite 462-203b

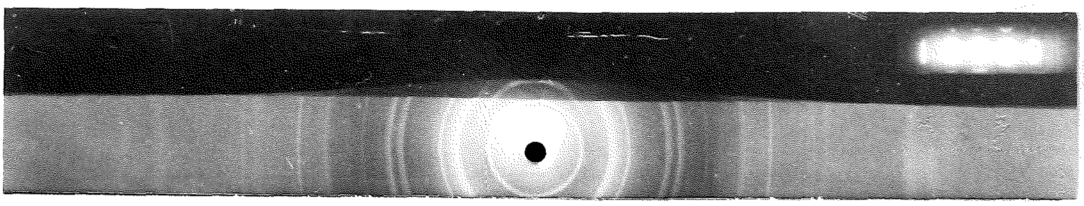
(d) 13968 Sericite from kyanite 462-145

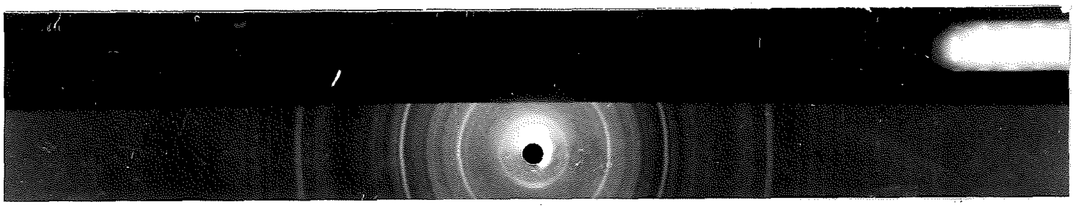
(e) 13967 Sericite from sillimanite 462-310

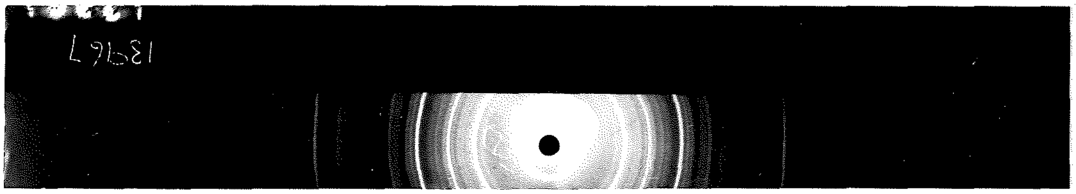
(f) 13939 Muscovite, Kaolinite and Kyanite 462-424

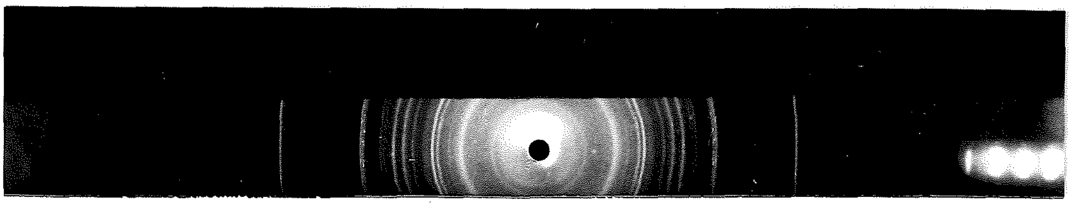
(g) 13912 Sillinamite and Kaolinite

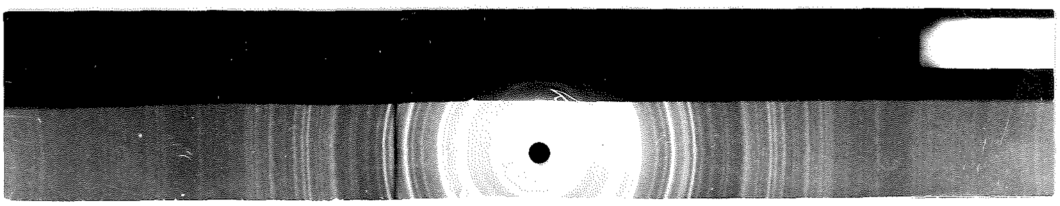




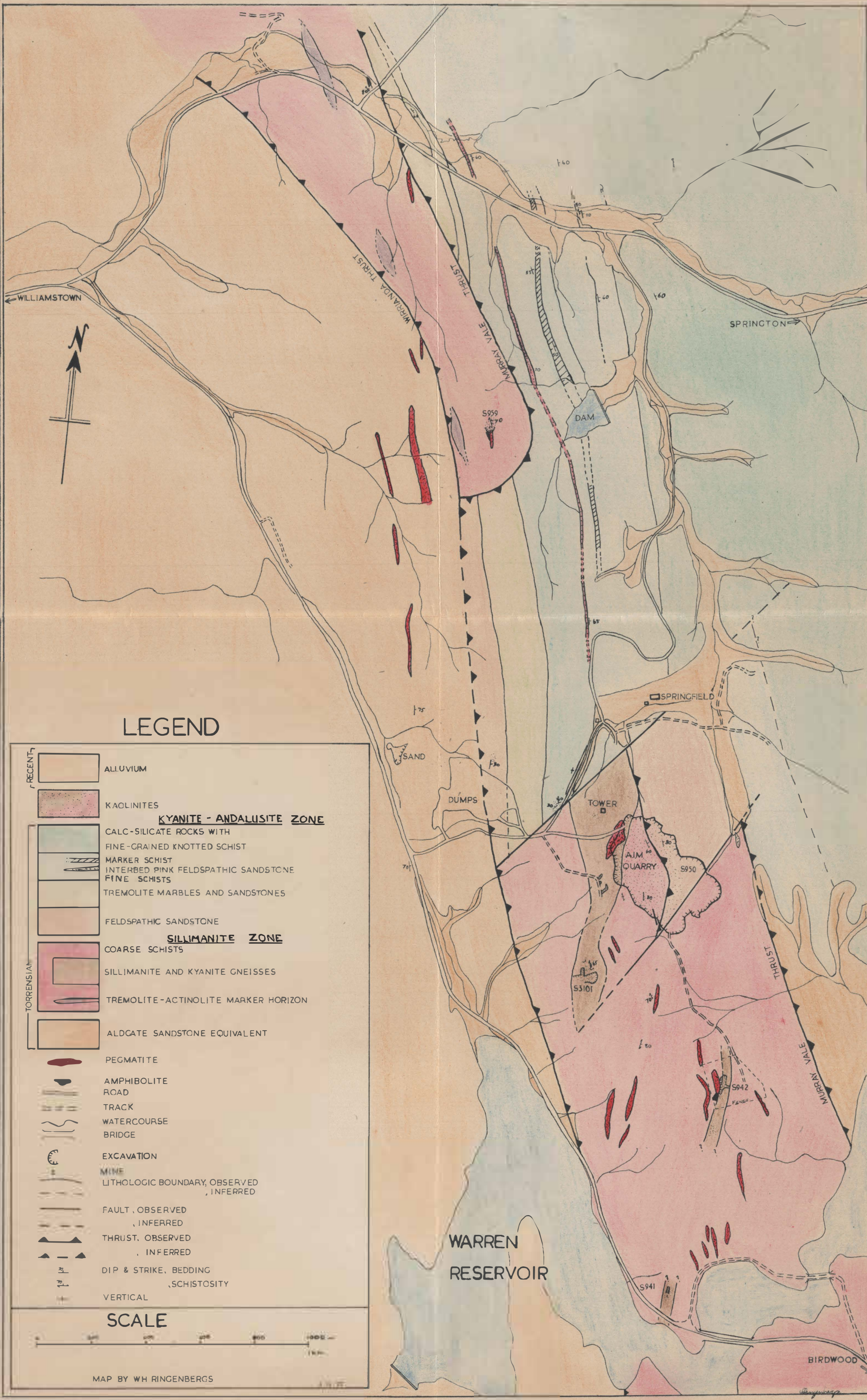








# GEOLOGICAL MAP OF SPRINGFIELD AREA



# GEOLOGICAL MAP OF THE WILLIAMSTOWN SILLIMANITE DEPOSIT