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Pure scheelite (light blue)  
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wavelength ultraviolet  
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DEPARTMENT OF GEOLOGY AND MINERALOGY

THE PETROLOGY AND GEOCHEMISTRY OF THE  
KING ISLAND SCHEELITE DEPOSITS  
AND ASSOCIATED INTRUSIVES

by

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A thesis submitted in partial fulfilment  
of the requirements for the Degree of  
Bachelor of Science with Honours in Geology.

23rd November, 1973.

ABSTRACT.

In the south-east part of King Island three skarn tungsten deposits occur in the contact aureoles of two granitic intrusions. Nos. 1 and 2 orebodies are associated with the Grassy Adamellite and No. 3 orebody with the Bold Head Adamellite. The two intrusions are virtually identical petrologically and geochemically, hence the smaller Bold Head Adamellite is believed to be an offshoot of the Grassy Adamellite, intruded along the zone of weakness associated with the Grassy River Fault.

The age of the intrusions, determined using the  $Ar^{40}/Ar^{39}$  method, is about 370 m.y. (late Devonian). This is 25 m.y. to 30 m.y. older than the early Carboniferous ages determined by McDougall and Leggo (1965) for the Grassy Adamellite.

Units of the Mine Series of No. 1 orebody are discussed with regard to petrology and geochemistry. The calcareous units, especially the andradite skarn, are discussed in detail. Textural features of the skarn indicate that it formed in two main phases. The first involved the formation of the andradite and the second the partial breakdown of the garnet due to an increase in  $P_{H_2O}$  with the consequent deposition in sequence of clinopyroxene, hornblende and scheelite followed by the remaining skarn minerals. The trace element geochemistry of the skarn indicates that it was formed from impure marble. The positive correlation of tin and germanium with tungsten in the skarn, and the anomalously high concentration of tungsten in the sphene of the adamellite, indicates that the source of the tungsten was the adamellite and not the sediments of the Grassy Group as suggested by Burchard (1972).

The control on the metasomatic fluids in the Grassy Adamellite appears to have been the Grassy River Fault which restricted the mineralizing fluids to its vicinity. In the country rocks the main control is the relative permeability of the various units, the impure marble being

the most permeable. From the occurrence of scheelite in the skarn containing significant clinopyroxene and hornblende, the mechanism of tungsten mineralization is believed to be similar to that proposed by Bryzgalin (1958). This involves an alkaline solution carrying the tungsten as a sodium tungstate which is neutralized by the fixation of sodium during the amphibolization of the clinopyroxene. The calcium released from this reaction combines with the tungstate ion to be precipitated as scheelite.

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M A P S (see pocket inside back cover)

Map 1	Traverse along the coast through the Grassy Adamellite.
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CHAPTER 1

INTRODUCTION

## 1.1 INTRODUCTION.

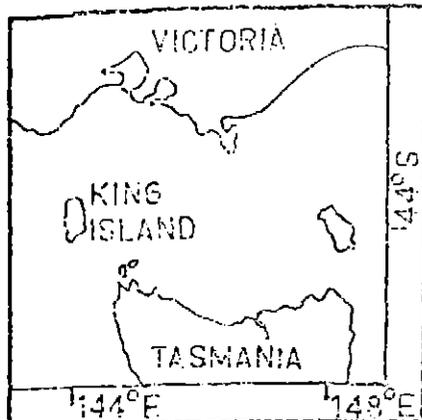
The scheelite deposits near the township of Grassy in the south-east part of King Island, Tasmania (Figs. 1 and 2) consist of three known orebodies. No.1 orebody was the first discovered and has been mined intermittently for the last 60 to 70 years. It is being mined by open cut methods at present. However, nearly all the ore has been removed. No.2 orebody is an extension of No.1 orebody being separated from it by a fault (No.3 fault). Both orebodies occur in the contact aureole of the Grassy Adamellite. No.3 orebody occurs in the contact aureole of the Bold Head Adamellite and is located three kilometers north of the other orebodies. Both Nos. 2 and 3 orebodies are presently being mined by underground methods.

This thesis is primarily a geochemical and petrological study of the contact metamorphic and metasomatic rocks of the No.1 orebody. The main aim was to determine the mechanism and control of the mineralization and also the origin of the mineralizing solutions. In order to establish trace element associations that would be indicative of mineralized regions, areas away from No.1 orebody were also studied. These are the unmineralized sequence in the Investigator 6 area, just to the west of the open cut and the unmetamorphosed sequence of the Grassy Group and overlying volcanics exposed along the coast a few kilometers north of Grassy. The Grassy Adamellite was studied in a traverse along the coast to the south of Grassy and compared petrologically and geochemically with the Bold Head Adamellite.

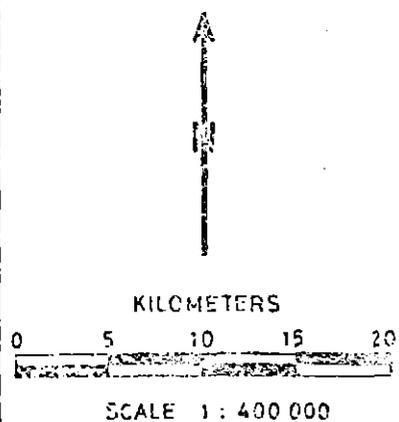
## 1.2 PREVIOUS WORK.

No.1 orebody of the King Island scheelite deposits was discovered in 1904 by a prospector, Tom Farrell, and since then numerous reports, papers and theses have been written on the deposits. As Nos.2 and 3 orebodies have been discovered comparatively recently, most of the previous work has been on No.1 orebody.

Nye and Knight (1943) give a complete list of all known reports on the mine up till 1943. The following list contains all the known



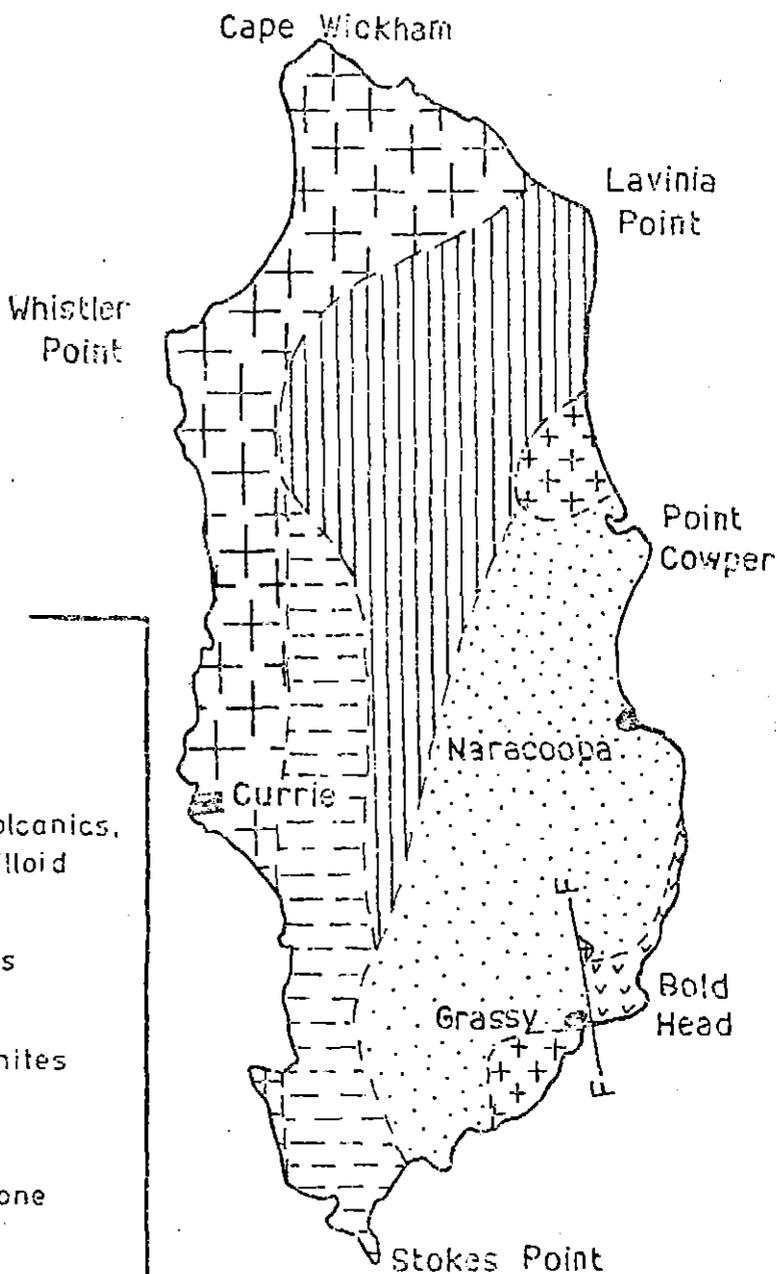
001012  
GEOLOGICAL MAP OF  
KING ISLAND



5 cm

LEGEND

-  Cambrian basic volcanics, shale, dolomite, tilloid
-  Devonian granites
-  Precambrian granites undifferentiated
-  Sandstone - siltstone
-  Muscovite sericite schists
-  Precambrian quartzites, muscovite schists



Compiled from Map G1-46, Geopeko Ltd.

Fig. 1

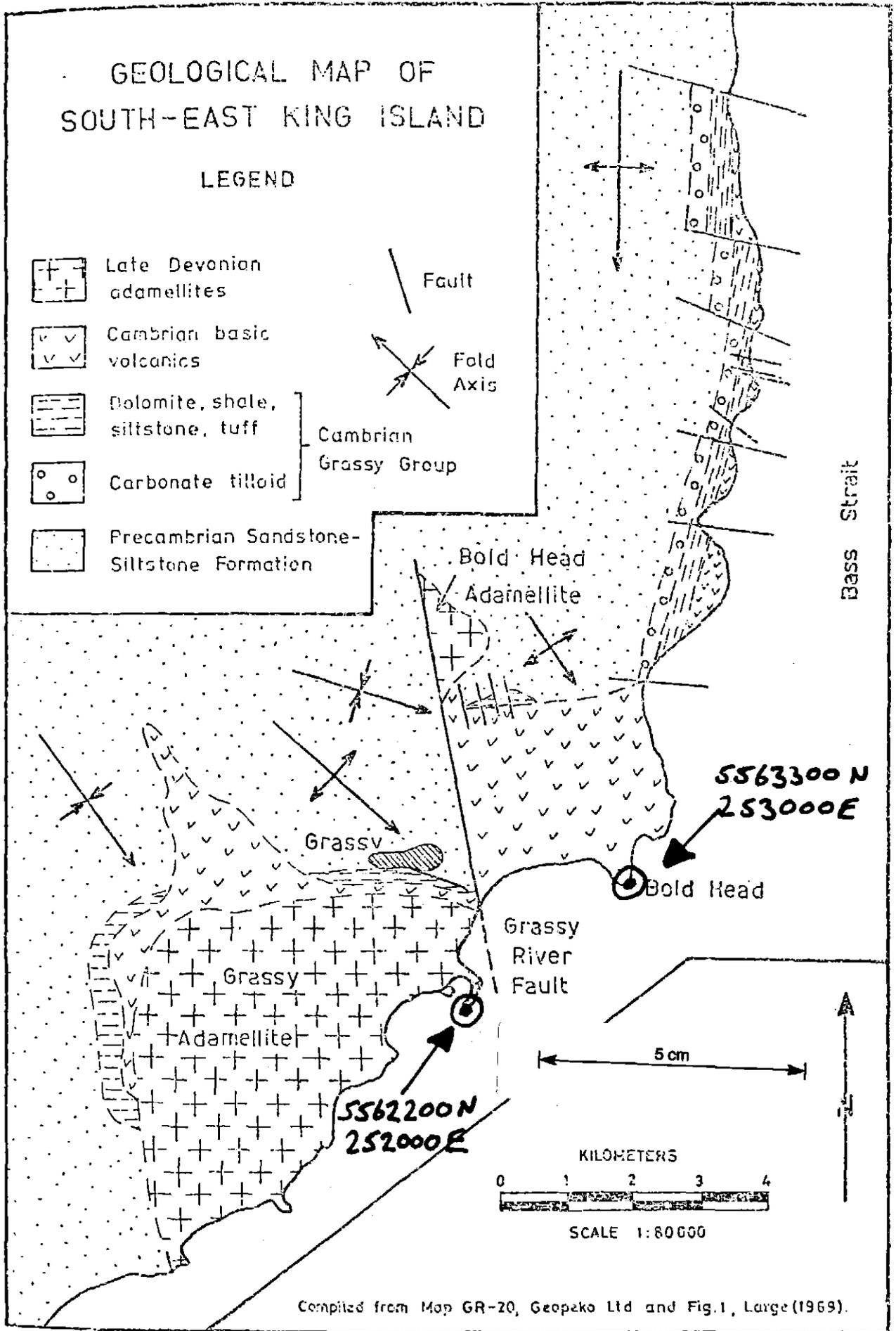


Fig. 2

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literature on the scheelite deposits from 1944 to the present.

Reports:

- C.S.I.R.O. Mineragraphic Investigations Reports 411(1944),  
582(1954), 583(1954), 742(1959), 798(1959). (Unpublished).
- FINUCANE, K.J. 1953. Report on King Island Scheelite Mine,  
Grassy, King Island. (Unpublished).
- FINUCANE, K.J. 1953. Supplementary report on diamond drill  
results at King Island Scheelite Mine. (Unpublished).

Papers:

- Knight and Nye (1953).
- Edwards Baker and Callow (1955).
- Knight and Nye (1965).
- Large (1971).

Theses:

- Kinnane (1968).
- Large (1969).
- Burchard (1972).

### 1.3 GENERAL GEOLOGY.

A full description of the general geology of the south-east part of King Island is given by Large (1969). Only a brief summary is given here.

The Sandstone-Siltstone Formation covers most of the area and consists of alternating beds of sandstone and siltstone with the latter predominating. The age of the formation is probably Precambrian. It is overlain, possibly conformably, by the Grassy Group, a Cambrian sequence comprised of a basal tilloid, 60-120 meters thick, of glacio-marine origin, overlain by 30-120 meters of limestone, dolomites, siltstones, shales and minor tuffs. Both the Sandstone-Siltstone Formation and the Grassy Group have been folded. Axes in the Sandstone-Siltstone Formation trend generally N-S but changing to SE-NW to the south. The Grassy Group, which is of much smaller extent, strikes parallel to these fold axes.

Overlying the Grassy Group is a volcanic sequence of spilitic and picritic lavas and pyroclastic rocks, possibly of Cambrian age. The volcanic sequence is more extensive than the Grassy Group and in many places directly overlies the Sandstone-Siltstone Formation. Along the east coast the volcanics appear to lie conformably on the Grassy Group. However, elsewhere they are demonstrably unconformable.

The area was intruded in the early Carboniferous (McDougall and Leggo, 1965) by the Grassy Adamellite and also by the Bold Head Adamellite which thermally metamorphosed the adjacent rocks to hornfels and developed skarns in the calcareous units. The two intrusions are very similar petrologically and are probably closely related. The major fault in the area, the Grassy Giver Fault, passes between the Grassy Adamellite and the Bold Head Adamellite, trending NNW. Its horizontal displacement is not certain.

#### 1.4 MINE SERIES AND ASSOCIATED ROCKS.

In areas of the contact aureole where metasomatism has occurred, resulting in scheelite mineralization, the sequence of units is termed the Mine Series. The Mine Series of No.1 orebody is fully exposed in the open cut (Map 2) and a description of each of the units comprising it is given below. The terminology given is that in current use by Geopeko Ltd. except where stated otherwise. The units are listed from the top to the bottom of the sequence (refer stratigraphic succession with Map 2).

##### 1.4.1 Volcanics.

This unit represents the metamorphosed sequence of basic volcanics described in the previous section. In the region of No.1 orebody it is distinctly unconformable on the underlying metamorphic equivalents of the Grassy Group. Variations within the unit reflect the spilitic and picritic composition of the original lavas. The silica deficient metamorphic assemblage of the volcanics is tremolite, spinel, forsterite, phlogopite + magnetite. The assemblage of higher silica content consists of biotite, actinolite, oligoclase, magnetite and quartz.

#### 1.4.2 Biotite Hornfels.

The Biotite Hornfels is divided into two parts by B lens, the upper part referred to locally as the Banded Hornfels. The rocks were originally pelites and were metamorphosed to a tough, fine grained hornfels consisting of predominantly biotite, actinolite, quartz, ilmenite and magnetite. The Biotite Hornfels may be massive, schistose or compositionally banded with respect to the proportion of biotite.

#### 1.4.3 B lens.

B lens consists chiefly of marble interspersed with pyroxene rich bands locally referred to as "tuffite". In parts the marble has been altered to andradite and grossularite skarns and is mineralized, especially the andradite skarn, in the eastern section of the open cut. However, nearly all the mineralized parts have been mined out. The marble consists of calcite, dolomite, humite minerals, diopside and magnetite.

#### 1.4.4 Pyroxene Garnet Hornfels.

The characteristic feature of this unit is the occurrence of irregularly shaped and sized ovoids of predominantly calcite set in a fine grained dark groundmass of clinopyroxene and grossularite with minor quartz and calcite. The ovoids, besides containing calcite, also consist of quartz, actinolite, epidote, vesuvianite, cordierite and sphene, and are surrounded by a rim of grossularite and then clinopyroxene. In parts the Pyroxene Garnet Hornfels is mineralized. Here the rock approaches an andradite skarn, the ovoids becoming less distinct.

#### 1.4.5 C lens Orebody.

This is the main orebody and is divided into three parts.

(i) Top Orebody: The andradite skarn comprising this part of the orebody is massive, showing no sign of the original bedding. Its grain size varies from fine to coarse and the main constituents are andradite, clinopyroxene, hornblende, quartz, calcite, epidote, vesuvianite, sphene, scheelite, magnetite and sulphides (mainly pyrite, chalco-

pyrite and molybdenite). The average scheelite content is 0.5 - 1.0%. The grade tends to be higher in the coarser grained skarn.

(ii) Marble Marker Bed: The Top and Bottom Orebodies are separated by a thin (about three meters thick) but persistent bed of marble. The bed only disappears in the extreme east of the orebody. It has the same mineral assemblage as the marble in B lens.

(iii) Bottom Orebody: This is an andradite skarn but, unlike the Top Orebody, it is usually distinctly banded, reflecting the original thin alternating beds of calcareous and pelitic rocks. The rock consists of bands of coarse grained andradite, clinopyroxene, calcite and quartz separated by bands of fine grained grossularite and clinopyroxene.

#### 1.4.6 Banded Footwall Beds.

The change from the andradite skarn to the underlying barren hornfels is transitional with the Banded Footwall Beds being the transition zone. The base of the Bottom Orebody is set at the level in the sequence at which the pelitic bands become dominant over the calcareous bands in the original rock. This boundary, therefore, is not very distinct except where it can be delineated by the limit of metasomatic effects. Where mineralization ceases at the base of the Bottom Orebody, the Banded Footwall Beds consist of very distinctive, almost monomineralic bands of calcite, melilite, grossularite, clinopyroxene and biotite hornfels. In parts of the unit, andradite skarn has formed in the marble bands. Here the rock grades into the Bottom Orebody. In Map 2, the unit is shown to be especially extensive since it is defined on the presence of grossularite in the rock. The grossularite extends lower in the sequence than does the distinct banding.

#### 1.4.7 Biotite Actinolite Hornfels. (Biotite Pyroxene Hornfels).

This unit is termed the Biotite Pyroxene Hornfels unit by Geopeko Ltd. but, on examination of several samples, the greenish bands in the rock were found to be actinolite. For this reason, the name has been changed by the author. The alternating bands of biotite hornfels and

actinolite hornfels are usually 2 to 10 mm thick. Other constituents of the unit are quartz, ilmenite and minor pyrite. The ilmenite is mainly concentrated in the biotite hornfels and occasionally forms thin bands itself. The unit is completely barren of scheelite as is the Biotite Hornfels unit.

#### 1.4.8 Older Volcanics.

The rocks of this unit were intruded into the Grassy Group at some time before the emplacement of the Grassy Adamellite and take the form of a laccolith or lopolith. The metamorphic mineral assemblage of tremolite, forsterite, phlogopite, spinel and magnetite indicate a silica deficiency. Therefore, the intrusion was probably an ultrabasic igneous rock before metamorphism.

#### 1.4.9 Quartzite.

The Quartzite unit is the contact metamorphosed part of the Sandstone-Siltstone Formation. It has been brought into the region of No.1 orebody by faulting and is separated from the other units by No.3 fault. The unit consists of quartzite and hornfels with quartzite predominating in the open cut. The mineral assemblage in the quartzite is quartz, muscovite and pyrite.

#### 1.4.10 Basic Dykes.

Two basic dykes up to two meters wide cut the Mine Series. They were intruded after metamorphism and are probably related to the basic dykes intruding the Grassy Adamellite. The dykes are porphyritic with a groundmass of plagioclase (andesine), hornblende and magnetite, and phenocrysts of plagioclase and hornblende. They are contaminated slightly with calcite and quartz from the skarn and marble beds.

#### 1.4.11 Grassy Adamellite Contact.

The contact of the intrusion is exposed in the open cut only in the south west part (Map 2). Towards the east the contact lies south of the open cut. From diamond drill holes it was found to be moderately steeply dipping (about  $45^{\circ}$ ). However, drill holes in the region of No.2

orebody indicate that the contact levels off at depth as does that of the Bold Head Adamellite.

CHAPTER 2

THE INTRUSIVES

## 2.1 INTRODUCTION.

The first and major phase of intrusion in the south-east region of King Island resulted in the emplacement of the Grassy and Bold Head Adamellites. The largest of these is the Grassy Adamellite\*. Part of it extends out to sea leaving a roughly triangular land exposure (Fig.2). The N-S and E-W trending parts of the contact are both about five kilometers long and the diameter, as measured along the coast, is about seven kilometers. The intrusion lies just south of the township of Grassy, the E-W contact coming to within 200-300 meters of it. Due to the gently undulating topography of the area and its coverage of moderately dense scrub, outcrop is very poor. The area mapped, therefore, was restricted to the coastal parts where outcrop was very good. This gave a complete section across the intrusion.

The Bold Head Adamellite is located three kilometers north of the Grassy Adamellite and is actually four kilometers north-west of the coastal landmark of Bold Head. It is a comparatively small intrusion with dimensions of about 1 x 1.5 kilometers. As outcrop is almost non-existent, the intrusion was studied from drill cores alone. The western boundary of the Bold Head Adamellite appears to coincide with the Grassy River Fault which passes between the Bold Head and Grassy Adamellites. The relationship between the Grassy River Fault and the Bold Head Adamellite has not yet been established owing to the lack of outcrop. A similar situation exists with the Grassy Adamellite as the fault intersects its contact out to sea.

The second and minor phase of intrusion is the injection of a number of basic dykes which intrude the Grassy Adamellite and its contact aureole. They were not found in the Bold Head Adamellite.

\* Referred to in previous literature as the Grassy Granodiorite.

Discussed further in Section 2.2.6.

## 2.2 GRASSY ADAMELLITE.

### 2.2.1 Petrography.

Samples 100, 115, 142, 155. Plate 1.

The Grassy Adamellite is a distinctly porphyritic rock containing 10-15% orthoclase phenocrysts in a very coarse grained groundmass. The phenocrysts are rectangular, up to 6 mm long and show well developed carlsbad twinning in hand specimen. There is remarkably little variation throughout the intrusion, the only changes being the discontinuous banding (discussed in the next section), small regions of finer grained, darker adamellite, and contact variations.

In thin section the adamellite (100 and 115) consists of the following minerals, listed with their average modal proportions :

plagioclase (30%), orthoclase (25%), quartz (20%),  
biotite (15%), hornblende (4%), magnetite (2%), chlorite (2%),  
sphene (1%), epidote (tr), apatite (tr), zircon (tr).

The orthoclase phenocrysts are perthitic and poikilitic, containing smaller grains of predominantly plagioclase and biotite. Orthoclase in the groundmass shows no exsolution textures. Normal oscillatory zoning is very well developed in the plagioclase with some grains containing up to 30 distinct zones. The maximum compositional variation in the plagioclase through the intrusion is An 24 to An 38 while the average variation due to zoning is An 27 to An 33. The feldspars are usually partly sericitized, the phenocrysts to a lesser extent than the groundmass.

Biotite occurs as large well formed grains, often partly altered along the cleavage planes to iron-rich chlorite and minor epidote. Sphene is sometimes associated with partly altered biotites and this, along with the deep reddish brown colour of the biotite, indicates a high titanium content. Most of the sphene, however, occurs as euhedral double wedges with inclusions or in the vicinity of apatite and zircon. The hornblende is unaltered and has a Mg/Mg+Fe ratio of 0.45.

A porphyritic hypidiomorphic, inequigranular texture is typical of the Grassy Adamellite. The average grain size of the groundmass is 2-3mm. However, smaller grains increase to a significant proportion in parts giving the rock a characteristically stronger grey colour (142 and 155). In these parts grains of normal groundmass size become the phenocrysts and the average grain size of the groundmass is reduced to about 0.5mm. Dykes of this rock occasionally intrude the normal adamellite indicating that it was a late stage variant. These dykes are cut by the quartz porphyry dykes (discussed in a later section). The orthoclase phenocrysts in the finer grained adamellite usually partially or completely enclose smaller grains near their margins. In extreme cases, sieve textures are developed in the orthoclase (142). The proportion of inclusions decreases as the groundmass becomes coarser.

#### 2.2.2 Banding.

Samples 106, 122, 128. Plate 2.

Throughout the intrusion there is discontinuous and seemingly randomly oriented banding. It may be up to 20 meters long and several meters wide and may consist of one or several straight bands or a more complex system as shown in Plate 1 c .

Biotite rich (upto 30%) adamellite bands are most common and these may be associated with bands low in mafic minerals and bands containing up to 50% orthoclase phenocrysts. Both the biotite rich and biotite poor bands have no orthoclase phenocrysts. Possibly related to the banding are pods up to two meters across containing about 50% orthoclase phenocrysts and surrounded by a rim of biotite rich rock. These occur at 561600N 218500E (Refer map).

The bands have no selective grain orientation and represent purely modal compositional variations. In thin section they are the same as the normal adamellite except in the proportions of biotite and orthoclase phenocrysts. Edwards et al (1955) described these bands as "the remnants

of large bodies of well-bedded sediments assimilated by the granodiorite". However, the complex structure of some of the bands systems (Plate 1 c) their high length/width ratio, and the association of the different types of bands does not support this. They appear to have been formed in an early stage of crystallization by grain settling in the magma and processes similar to sedimentation, and have subsequently been broken up to some extent. The irregular orientation of the bands and the lack of grain alignment within them indicates that they are not flow structures formed during emplacement.

### 2.2.3 Xenoliths.

Samples 114, 143, 169. Plate 3 a.

Dark xenoliths ranging in size from 5mm to 2 meters diameter occur throughout the Grassy Adamellite. They are slightly rounded but their margins are usually quite distinct, although occasionally the xenolith grades into the adamellite. In thin section the mineral assemblage is essentially the same as that of the adamellite, but the proportions are different. They are hornblende 15%, orthoclase 30%, plagioclase 15%, biotite 10%, quartz 15%, magnetite 4%, chlorite 5%, sphene 5%, apatite tr., zircon tr.

The hornblende is similar to that in the adamellite, as shown by the Mg/Mg+Fe ratio of 0.42. Biotite is partly altered to chlorite. The feldspars are not as well formed as in the adamellite, the grains being irregular and poikiloblastic. Porphyroblasts of orthoclase and plagioclase occur in most xenoliths, forming <10% of the rock, and in some, very irregular quartz porphyroblasts are present. The feldspars are usually heavily sericitized. Like the orthoclase of the finer grained adamellite, the porphyroblasts often incorporate smaller grains near their margins.

The high titanium content of the xenoliths is reflected in the considerable amount of sphene (5%) which occurs as well formed double wedges or small needles. Apatite most commonly occurs as small idioblastic crystals enclosed in quartz.

The texture and grainsize in general is very similar to that of the finer grained adamellite. It shows an extremely variable grainsize with poikiloblastic textures very commonly developed and appears to be approaching a granitic texture due to the high degree of recrystallization.

From their mineralogy the xenoliths appear to have originally been a basic rock. The abundance of basic volcanics in the area of intrusion of the Grassy Adamellite implies they are most likely the source of the xenoliths. The distribution of the xenoliths through the intrusion is a result of their detachment from the roof of the magma chamber and subsequent sinking into the magma.

#### 2.2.4 Contact Zone.

Samples 184, 185, 304, 307. Plate 3 b, c.

Where the rocks adjacent to the intrusion are pelitic, the adamellite remains almost unaffected compositionally right up to the contact. However, where calcareous rocks are in contact with the adamellite a contact zone rich in calcium is developed within the intrusion. The average width is about 10 meters. This type of zone has been described by Korzhinskii (1955) as an endoskarn.

In thin section, it differs from the normal adamellite in that plagioclase is the only feldspar developed very near the contact (304). However, orthoclase occurs farther from the contact, still in the contact zone (307) and increases in proportion as the rock grades into the normal adamellite.

The composition and grain size of the plagioclase is the same as that in the adamellite. However, it is partially altered to clinozoisite as well as sericite. The main difference lies in the assemblage developed between the feldspar grains. It consists of actinolite, calcite, quartz, sphene and minor magnetite and apatite. The modal proportions of the minerals in the contact zone are plagioclase 65%, actinolite 15%, calcite 10%, quartz 5%, sphene 4%, apatite trace, magnetite trace. The actinolite occurs both as prismatic grains up to 2mm long and also as small needles

and wedges included in the calcite and quartz. Sphene is more abundant than in the normal adamellite, some occurring as inclusions in the plagioclase, but most is in association with the calcium rich interstitial assemblage. The apatite is associated with the sphene. Calcite is in a very irregular xenomorphic form, being controlled entirely by the form of the other minerals. In parts it forms intergrowths with the actinolite. Fractures in the rock are often filled with calcite. Quartz has a more distinct grain form and is less abundant in the contact zone than in the normal adamellite.

From the assemblage between the feldspar grains, it is obvious that there has been an influx of calcium from the adjacent calcareous rocks. As there are no xenoliths in the contact zone and the contact itself is sharp, the addition of calcium would have occurred by means of diffusion rather than by assimilation. The increase in calcium caused the development of actinolite instead of the biotite and hornblende of the unaffected adamellite. As the composition of the plagioclase was unchanged by the influx of calcium, it must have already crystallized, along with some sphene, at the time of the emplacement of the adamellite.

From the proportion of feldspar in the rock, about 65% by volume of the magma would have crystallized at this stage. That the magma was emplaced in a well crystallized state is supported by the fracturing of the feldspars in the contact zone. This, however, may only apply to the marginal zones of the intrusion which cooled quicker than the rest of the magma.

Since calcium has diffused into the magma then some components may have diffused outwards into the country rocks. The lower proportion of quartz relative to the unaffected adamellite indicates that  $\text{SiO}_2$  was one of these components. Also, the lack of biotite and hornblende indicates that potassium, and possibly aluminium, has also been lost from the intrusion. The titanium in these mafic minerals of the adamellite has gone into the sphene.

Korzhiinskii (1955) and Perry (1969) describe endoskarns in the contact zones of granitic intrusions. In both these cases, the inward diffusion of Ca has had a much greater effect on the magma than it has on the Grassy Adamellite. They observed zones of diopside-garnet, garnet and then pure salite approaching the contact from within the granite. The lack of these minerals in the contact zone of the Grassy Adamellite is probably due to the higher water pressure in the magma as indicated by the development of actinolite instead of a pyroxene. The limited textural change is a result of the extent of crystallization of the magma at the time of the complementary diffusion.

Some diffusion of elements across the contact of the adamellite adjacent to pelitic rocks has occurred, but not to the same extent as when near calcareous rocks. Close to the contact with pelitic rocks there is a slight decrease in biotite and hornblende indicating a small degree of outward diffusion of Fe and K. The inward diffusion from the country rocks into the intrusion probably consisted of mainly Al. The main changes that occur in the adamellite on approaching the contact are textural variations (184 and 185). Grains of normal groundmass size have become separated by smaller grains of predominantly quartz and potash feldspar in the form of microcline. The abundance of these smaller grains is due to the injection of late stage liquids into the earlier mass of crystals as in the finer grained, greyer coloured adamellite described previously. These liquids crystallized in the intrusion because of their inability to escape through the impermeable biotite hornfels.

#### 2.2.5 Aplitic and Quartz Porphyry Dykes.

Samples 101, 125, 175. Plate 3 d, e.

Aplitic and quartz porphyry dykes and numerous veins are distributed through the Grassy Adamellite and range from 5mm to 5 meters in thickness. They were formed by late stage liquids infilling the first set of cooling fractures of the main intrusion.

In thin section the modal proportions of minerals in the aplitic

dykes (125 and 175) are quartz 50%, potash feldspar (orthoclase and microcline) 35%, plagioclase 10%, biotite (mostly chloritized) 4% and magnetite 1%. The average grain size is 0.3 to 0.5mm but it is considerably larger in some dykes (125). In the quartz porphyry (101) the groundmass is similar to this and the rock contains 5% to 15% quartz phenocrysts about 1mm in diameter. The texture is granular with grains often interlocking and phenocryst margins very crenulated. In parts, granophyric textures have developed.

### 2.2.6 Geochemistry.

#### (a) Major Elements.

Chemical analyses by X.R.F. of samples of the Grassy Adamellite, with normative mineralogies, and of the contact zone, are shown in Table 1. These are compared with an analysis of the Grassy Adamellite from Edwards et al (1955) and the composition of an average adamellite from Nockolds (1954). The analyses by the author show the chemical homogeneity of the intrusion (excepting the contact zone) as indicated by its mineralogy. However, the analysis by Edwards et al is significantly different, showing lower  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  and higher  $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$  and  $\text{Na}_2\text{O}$ . Based on these results the rock was classified by Edwards et al as a granodiorite, but it was stated that in some respects it resembles a quartz monzonite (adamellite) and therefore, Edwards et al described it as a contaminated granodiorite. As the composition of the intrusion, determined from the author's analyses, compares well with that of the average adamellite of Nockolds, it has been described as such. However, the intrusion is not an average adamellite in all respects, showing some trends towards a granodioritic composition. The average  $\text{K}_2\text{O}/\text{Na}_2\text{O} + \text{CaO}$  ratio is 0.67 whereas the value for Nockolds' average adamellite is 0.79. The ratio Nockolds quotes for the average granodiorite is 0.42, a figure well below that of the Grassy Adamellite.

TABLE 1

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CHEMICAL ANALYSES OF GRASSY ADAMELLITE.

	<u>180</u>	<u>181</u>	<u>183</u>	<u>182</u>	<u>A</u>	<u>B</u>	<u>304</u>		
SiO <sub>2</sub>	67.55	69.15	69.59	68.13	66.46	69.15	63.06	180	} Normal Grassy Adamellite
Al <sub>2</sub> O <sub>3</sub>	14.91	15.00	14.29	15.03	16.35	14.53	11.31	181	
Fe <sub>2</sub> O <sub>3</sub>	2.88	2.59	2.89	3.33	0.98	1.22	4.80	183	
FeO					2.48	2.27		182	} Finer grained, greyer adamellite in Grassy Adamellite
CaO	2.77	2.65	2.36	2.82	3.37	2.45	10.28		
Na <sub>2</sub> O	3.27	3.39	3.41	3.16	4.31	3.35	2.54		
K <sub>2</sub> O	4.09	3.65	4.22	3.90	2.78	4.58	Nil	304	Contact zone near calcareous rocks
MgO	1.40	1.37	1.26	1.42	1.45	0.99	2.65		Analyst P.H.
TiO <sub>2</sub>	0.49	0.49	0.44	0.51	0.24	0.56	0.62		
MnO	0.03	0.05	0.03	0.07	0.24	0.06	0.26		
P <sub>2</sub> O <sub>5</sub>	0.19	0.18	0.18	0.20	0.14	0.20	0.28	A	Grassy Adamellite from Edwards et al (1955)
L.O.I.	<u>0.73</u>	<u>0.96</u>	<u>0.59</u>	<u>0.73</u>	<u>1.15*</u>	<u>0.54</u>	<u>4.73</u>		
Total	<u>98.31</u>	<u>99.48</u>	<u>99.26</u>	<u>99.30</u>	<u>100.03</u>	<u>100.00</u>	<u>100.53</u>	B	Average adamellite from Nockolds (1954)
K <sub>2</sub> O	0.68	0.60	0.73	0.65	0.36	0.79			
Na <sub>2</sub> O+CaO									

L.O.I.= loss on ignition

\* 1.13% L.O.I. = 0.96% H<sub>2</sub>O<sup>+</sup> + 0.17% H<sub>2</sub>O<sup>-</sup>C.I.P.W. NORMATIVE MINERALOGY.

Qz	25.0	27.8	26.4	26.2		24.8
Or	24.5	21.7	25.2	23.2		27.2
Ab	28.2	28.8	29.1	26.9		28.2
An	12.8	12.0	10.6	12.8		11.1
Co	0.5	1.1	0.2	1.0		Nil
Hyp	5.5	4.9	5.2	6.3		4.7
Mt	1.5	1.5	1.5	1.5		1.9
Il	1.0	0.9	0.8	1.0		1.1
Ap	<u>0.5</u>	<u>0.4</u>	<u>0.4</u>	<u>0.5</u>		<u>0.5</u>
Total	<u>99.5</u>	<u>99.1</u>	<u>99.4</u>	<u>99.4</u>		<u>99.5</u>

The analysis of the sample from the contact zone, when compared with those of the adamellite, indicates more clearly than the mineralogy the movement of elements across the contact. Besides the introduction of Ca and the removal of Si, K and Al indicated by the mineralogy, some Fe and Mg appears to have been introduced as well and minor Na removed.

(b) Trace Elements.

The abundances of Rb, Sr, W and Sn were determined in various samples of the Grassy Adamellite and associated rocks.

#### Rubidium and Strontium:

Rb and Sr determinations were made only on those samples subjected to major element analysis. The results are shown in Table 2 with Rb/Sr and K/Rb ratios. As expected from the homogeneity of the intrusion the results are internally consistent.

The average Rb content is 220 ppm and the average K/Rb ratio is 150. Horstman (1957) gives the average value for Rb in granitic rocks as 170 ppm with the standard deviation,  $\sigma$  Rb, as 83 ppm and the average K/Rb ratio as 240 with  $\sigma$  K/Rb as 88. The Rb content of the Grassy Adamellite, therefore, lies in the higher part of the range and the K/Rb ratios lie in the lower part. This is due to the relatively high modal proportion of biotite (10-15% of the rock) in which Rb can substitute for K.

The average Sr content of the Grassy Adamellite is 490 ppm. Literature values for the abundance of Sr in granitic rocks vary considerably. Vlasov (1964) lists the Sr content as 332 ppm with  $\sigma$  Sr as 25 ppm. Turekian and Kulp (1956) give the Sr content of Ca-poor granitic rocks. Other values vary from 80 to 200 ppm. Overall, the Sr content of the adamellite seems to be slightly higher than average, considering its content of Ca for which Sr substitutes. However, high values of Sr in granitic rocks are not rare, concentrations up to 2000 ppm having been recorded in the literature. The relatively high Sr content of the adamellite is responsible for the low Rb/Sr ratio compared with other granitic rocks.

TABLE 2Rb AND Sr (ppm) IN GRASSY ADAPELLITE.

	<u>180</u>	<u>181</u>	<u>183</u>	<u>182</u>
Rh	212	212	229	227
Sr	522	475	449	511
Rb/Sr	0.41	0.45	0.51	0.44
K/Rb	160	143	153	143

Analyst P.H. (X.R.F.)

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Tungsten and Tin:

W and Sn determinations were made on samples of the adamellite, contact zone, xenoliths, quartz porphyry and aplite dykes and also on sphene fractions from the adamellite and xenoliths. A full list of the results is given in Appendix 5 and the ranges and average values for the various rock types are shown in Table 3.

Since the lower level of detection of W by X.R.F. analysis is about 20 ppm, the values of 0-10 ppm obtained could be subject to significant errors. These have been reduced slightly by making more than one analysis of the same rock type. There appears very little variation between the different rock types. However, the contact zone near the calcareous rocks is slightly higher in W than elsewhere in the intrusion. The contact zone near the pelitic rocks contains the same concentration of W as the normal adamellite.

In relation to the world abundance of W in granitic rocks, the Grassy Adamellite is higher than average. Krauskopf (1970) lists values which vary from 1.3 to 3.7 ppm, the average being 1.5 - 2.0 ppm. However, granitic rocks associated with areas of mineralization have higher contents of W. Jeffery (1959) gives values of 2.6 - 1.2 ppm from Uganda, while Ivanova (1969) gives values up to 7100 ppm from eastern Transbaikalia. The slightly anomalous values of W in the Grassy Adamellite indicate that it could have once contained significant W, but if so, the environment was unsuitable for mineralization within the intrusion in contrast to the situation in eastern Transbaikalia.

The results for Sn were also obtained by X.R.F. analysis. Although the lower level of detection is 2 ppm, the accuracy of the results, found by analyses of rock standards, is not as high as would be expected, the values tending to be slightly high. As for W, the Sn values show little variation between the various rock types except for slightly higher concentrations in the contact zone near the calcareous rocks. The average value of 5 ppm for the adamellite compares with the average abundance of Sn in granitic rocks, ranging from 1 - 15 ppm and averaging about 4 ppm.

TABLE 3

W AND Sn (ppm) IN GRASSY ADAMELLITE AND ASSOCIATED ROCKS

<u>ROCK TYPE</u>	<u>RANGE</u>	<u>W</u> <u>AVERAGE</u>	<u>RANGE</u>	<u>Sn</u> <u>AVERAGE</u>
1	0-9	5	3-7	5
2	5-10	7	9-15	11
3	2-5	4	4-5	5
4	5-7	6	5-10	7
5	3-5	4	3-4	4
6	3-6	4	5-7	6
7	1-4	2	4-5	5

SPHERE FRACTIONS

<u>ROCK TYPE</u>	<u>W</u>	<u>Sn</u>
1	134	118
	152	176
2	136	178
4	92	146
	68	138

1	Adamellite	
2	Contact zone - near calcareous rocks	} near Mine Series
3	Contact zone - near biotite hornfels	
4	Xenoliths	
5	Quartz porphyry dykes	
6	Aplite dykes cutting No.1 orebody.	
7	Contact zone - Investigator 6 area.	

Analyst P.H. (X.R.F.)

The results of the analyses of the sphenes were much more informative (Table 3). Sphene was one of the early formed minerals in the magma and it has the ability to concentrate many rare elements.  $W^{4+}$  and  $Sn^{4+}$  can substitute for  $Ti^{4+}$  in the sphene. Therefore, if any significant concentrations of W and Sn existed in the magma originally, it will be revealed in the sphenes.

The average value for W of 141 ppm in the sphene from the adamellite is very high when compared to the mean values of 20 ppm from Lyakhovich and Balanova (1968) and 16 ppm from Ivanova and Butuzova (1968) in unmineralized granites. Therefore, the Grassy Adamellite has, at some stage, contained a significant amount of W. The average Sn content of the sphene from the adamellite is 157 ppm. This is well below the mean values of 404 ppm from Lyakhovich and Balanova and 370 ppm from Ivanova and Butuzova in unmineralized granites. The intrusion, therefore, never contained significant proportions of Sn. The sphene extracted from the xenolith showed concentrations of W and Sn slightly lower than that in the adamellite. This is due to the introduction of these elements into the barren xenoliths from the magma enclosing them.

Since sphene forms less than 2% of the adamellite, anomalous values of W are not shown in the rock as a whole. W is concentrated to a small extent in the biotite and hornblende and does not enter into the structure of feldspar and quartz. The slightly higher concentrations of W in the contact zone near the calcareous rocks is due to the higher proportion of sphene in this region.

#### 2.2.7 Isotopic Age Determinations.

A hornblende and a biotite fraction from sample 183 of the Grassy Adamellite were dated using the  $Ar^{40}/Ar^{39}$  method (Green 1973). The values obtained were 576 m.y. for the hornblende and 374 m.y. for the biotite. The slightly older hornblende date could be due to the earlier closure of the hornblende lattice to the loss of argon than that of the biotite lattice. However, both dates agree to within the estimated error of  $\pm 5$  m.y.

McDougall and Leggo (1965) dated the Grassy Adamellite and associated aplitic dykes by the K/Ar method and obtained ages ranging from 342 m.y. to 349 m.y. Therefore, they concluded that the age of the emplacement of the intrusion is  $345 \pm 5$  m.y. On the basis of the age of the Devonian - Carboniferous boundary of 360 m.y. used by McDougall and Leggo, they placed the Grassy Adamellite in the early Carboniferous. However, the  $Ar^{40}/Ar^{39}$  ages given above indicate the intrusion was emplaced in the late Devonian. In view of the known ability of biotites, and to some extent hornblendes, to lose part of their argon in any subsequent tectonic event the dates recorded in this thesis are probably more accurate than those given by McDougall and Leggo.

### 2.3 BOLD HEAD ADAMELLITE.

Samples 191, 194, 195. Plate 3 f.

Several samples of the Bold Head Adamellite were collected from drill core in order to compare them with the Grassy Adamellite. In hand specimen and thin section both intrusions are very similar mineralogically and texturally. Also, the type and extent of alteration of the feldspars and biotite were the same. In the samples of the Bold Head Adamellite studied, the plagioclase was not zoned to quite the same degree as that in the Grassy Adamellite and also it was slightly more sodic. The composition of the unzoned grains is An 28 with little variation and the zoned grains ranges from An 21 to An 24.

Features such as banding and regions of finer grained adamellite were not observed, probably due to the limited access to samples. However, small clusters of hornblende and biotite were found (361) and these represent the small basic xenoliths that also occur in the Grassy Adamellite.

The contact zone of the Bold Head Adamellite has been described by Large (1969 and 1971). It differs from that of the Grassy Adamellite near calcareous rocks (endoskarn) by the occurrence of salite. Therefore, the water pressure in the contact regions of the Bold Head Adamellite must have been lower than in that of the Grassy Adamellite. Large describes andradite-

sselite assemblages as parts of the contact zone endoskarn. However, his main criterion for placing these assemblages in the endoskarn rather than the exoskarn, namely the occurrence of sphene supposedly derived from the initial adamellite, seems doubtful since sphene is a common constituent of skarns.

Major element analyses were made on three samples of the Bold Head Adamellite. These are shown in Table 4, along with their normative mineralogy, and are compared with an analysis from Large (1969) and the average of the author's analyses of the Grassy Adamellite. Also shown is Large's analysis of the endoskarn from the Bold Head Adamellite compared with that from the Grassy Adamellite. The analyses of the adamellite show little variation apart from the low CaO, Na<sub>2</sub>O and Fe<sub>2</sub>O<sub>3</sub> + FeO in Large's analysis giving the high K<sub>2</sub>O/Na<sub>2</sub>O + CaO ratio of 0.94. The low total from this analysis indicates that the percentages of these elements given, especially CaO, are probably in error. On the basis of chemical composition, the Bold Head Adamellite is almost identical to the Grassy Adamellite.

Comparison of the altered contact zones of both intrusions, however, shows significant differences, the main one being in the proportions of Al<sub>2</sub>O<sub>3</sub>. Large's analysis shows Al<sub>2</sub>O<sub>3</sub> as higher than the unaltered adamellite whereas the author's analysis shows it to be less, therefore implying different movements of Al across the contacts. The inward or outward diffusion of Al probably depends on the rock type in contact with the intrusion (Section 2.2.4). Other smaller differences between the two contact zones are lower proportions of SiO<sub>2</sub>, Na<sub>2</sub>O and CaCO<sub>3</sub> (indicated by the low ignition loss) in the Bold Head Adamellite.

The trace elements Rb, Sr, W and Sn were determined in the three samples subjected to major element analysis. The results are shown in Table 5. They are, as expected, very similar to those of the Grassy Adamellite and therefore the same conclusions can be drawn from them.

A biotite fraction from sample 195 was dated using the Ar<sup>40</sup>/Ar<sup>39</sup>

CHEMICAL ANALYSES OF BOLD HEAD ADAMELLITE AND COMPARISONS WITH GRASSY ADAMELLITE

	<u>191</u>	<u>194</u>	<u>195</u>	<u>A</u>	<u>GA</u>	<u>B</u>	<u>304</u>		
SiO <sub>2</sub>	69.02	68.07	68.53	68.04	68.61	59.48	63.06	191	} Bold Head Adamellite Analyst P.H.
Al <sub>2</sub> O <sub>3</sub>	14.20	14.05	13.76	14.65	14.81	20.22	11.31	194	
Fe <sub>2</sub> O <sub>3</sub> FeO	3.11	3.06	3.11	2.53	2.92	4.10	4.80	195	
CaO	2.31	2.67	2.40	1.26	2.65	8.62	10.28	A	Bold Head Adamellite
Na <sub>2</sub> O	3.45	3.47	3.13	2.87	3.31	1.04	2.54		from Large (1969)
K <sub>2</sub> O	3.82	3.81	4.18	3.88	3.97	0.37	Nil		
MgO	1.34	1.31	1.41	1.58	1.36	1.86	2.65	GA	Average of analyses of
TiO <sub>2</sub>	0.43	0.46	0.45	0.56	0.48	0.58	0.62		Grassy Adamellite.
MnO	0.04	0.04	0.03	0.03	0.04	0.15	0.26		
P <sub>2</sub> O <sub>5</sub>	0.20	0.20	0.19	0.12	0.19	0.04	0.28	B	Contact zone of Bold Head
L.O.I.	1.11	1.23	0.94	1.14	0.75	0.24	4.73		Adamellite from Large (1969)
Total	<u>99.03</u>	<u>98.37</u>	<u>98.13</u>	<u>96.66</u>	<u>99.09</u>	<u>96.70</u>	<u>100.57</u>	304	Contact zone of Grassy
									Adamellite near calcareous
$\frac{K_2O}{Na_2O+CaO}$	0.66	0.63	0.76	0.94	0.67				rocks.

L.O.I. = loss on ignition.

C.I.P.W. NORMATIVE MINERALOGY.

Qz	27.2	25.9	27.1	26.3
Or	22.8	22.9	25.2	23.7
Ab	29.4	29.9	27.0	28.3
An	10.2	11.7	10.9	12.0
Co	0.7	Nil	0.2	0.7
Hyp	6.8	5.7	6.0	5.5
Kt	1.5	1.5	1.5	1.5
Il	0.8	0.9	0.9	0.9
Ap	0.5	0.5	0.5	0.5
Total	<u>99.9</u>	<u>99.0</u>	<u>99.3</u>	<u>99.4</u>

TABLE 5Rb, Sr, W AND Sn (ppm) IN BOLD HEAD ADAMELLITE

	<u>191</u>	<u>194</u>	<u>195</u>
Rb	243	220	224
Sr	497	519	501
Rb/Sr	0.49	0.42	0.45
K/Rb	130	144	155
W	6	3	2
Sn	5	4	5
W in sphene	170	n.d.	158
Sn in sphene	164	n.d.	154

n.d. = not determined.

Analyst P.H. (X.R.F.)

method (Green 1973). The age of  $368 \pm 5$  m.y. obtained agrees with the ages determined for the Grassy Adamellite within the estimated error limits.

From all the aspects of the Grassy and Bold Head Adamellites considered it is clear that they are closely related and probably originated from the same source.

#### 2.4 RELATION OF INTRUSIVES TO GRASSY RIVER FAULT.

As there is no outcrop in the areas where the Grassy River Fault meets the Grassy and Bold Head Adamellites, the relationship between fault and intrusives must be inferred from structural elements within the Grassy Adamellite. The Grassy River Fault strikes  $340^{\circ}$  magnetic and extends about five kilometers on land. Its extent out to sea is unknown.

In the Grassy Adamellite the quartz porphyry dykes and veins, intruded along the first formed cooling fractures in the intrusion, were divided into groups, along the section mapped, based on outcrop patterns. The poles of these in each group were plotted on separate equal area stereographic nets and contoured. These are shown on Map 1. The most northerly group, which is closest to the fault, shows a distinct great circle distribution parallel to the fault and dipping about  $50^{\circ}$  E (Fig.3). For the group to the south of this a similar, but less distinct, pattern is shown, but the great circle has been rotated  $20^{\circ}$  -  $30^{\circ}$  (Fig.4). The groups further south show essentially no trends.

Plots of the unfilled joints in the intrusion show no significant patterns. The banding throughout the Grassy Adamellite, when plotted on an equal area net showed an interesting distribution along a great circle parallel to the fault, but dipping about  $40^{\circ}$  W (Fig.5).

The above features suggest the Grassy River Fault was in existence and active during and probably before the emplacement of the Grassy and Bold Head Adamellites. Therefore, the Bold Head Adamellite is probably a small offshoot from the Grassy Adamellite intruded along a zone of weakness associated with the fault.

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Contours 4%, 8%, 12%

67 readings

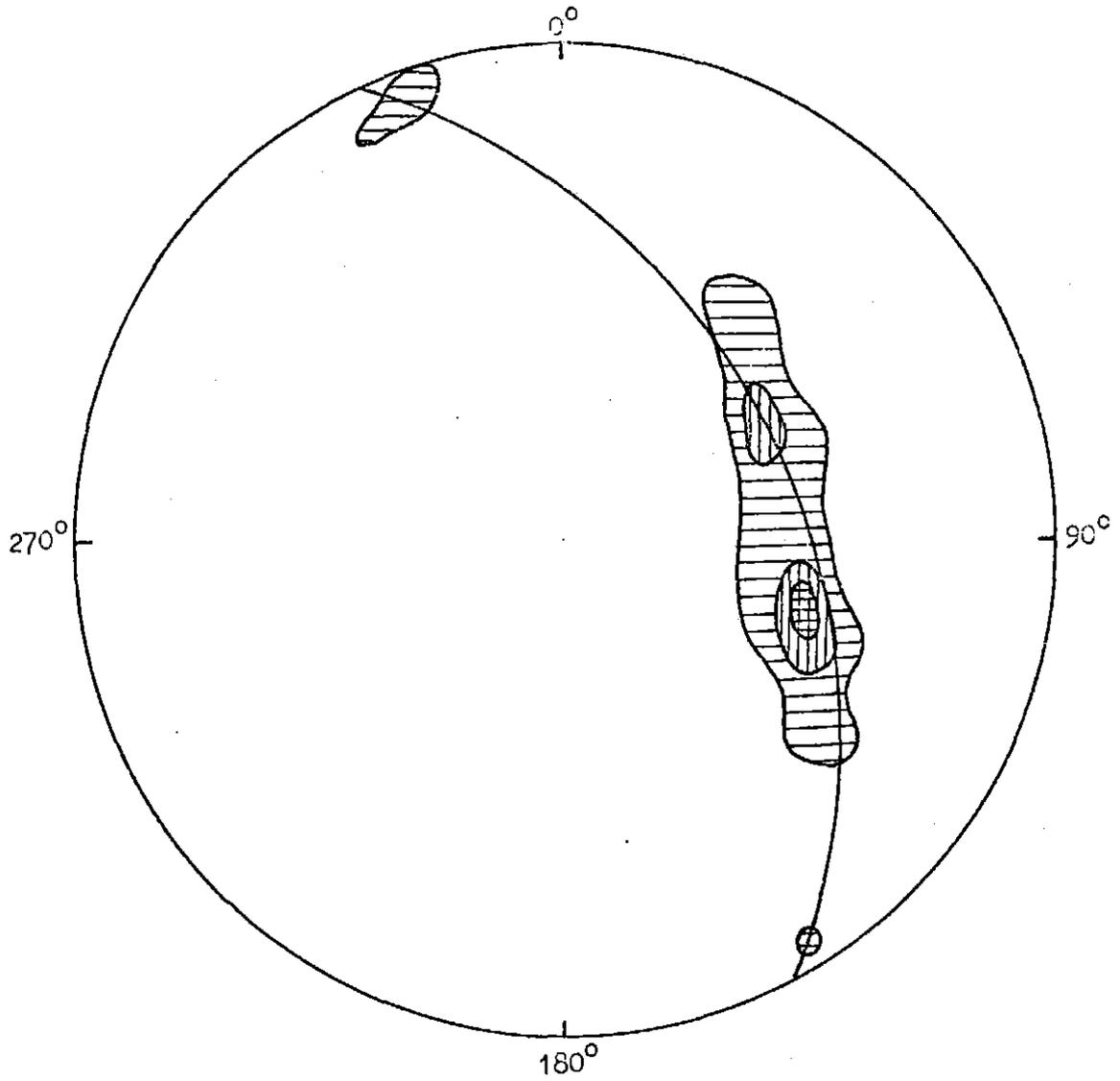


Fig. 3. Plot of the poles of the aplite and quartz porphyry dykes and veins, group 1.

Contours 4%, 6%, 8%

51 readings.

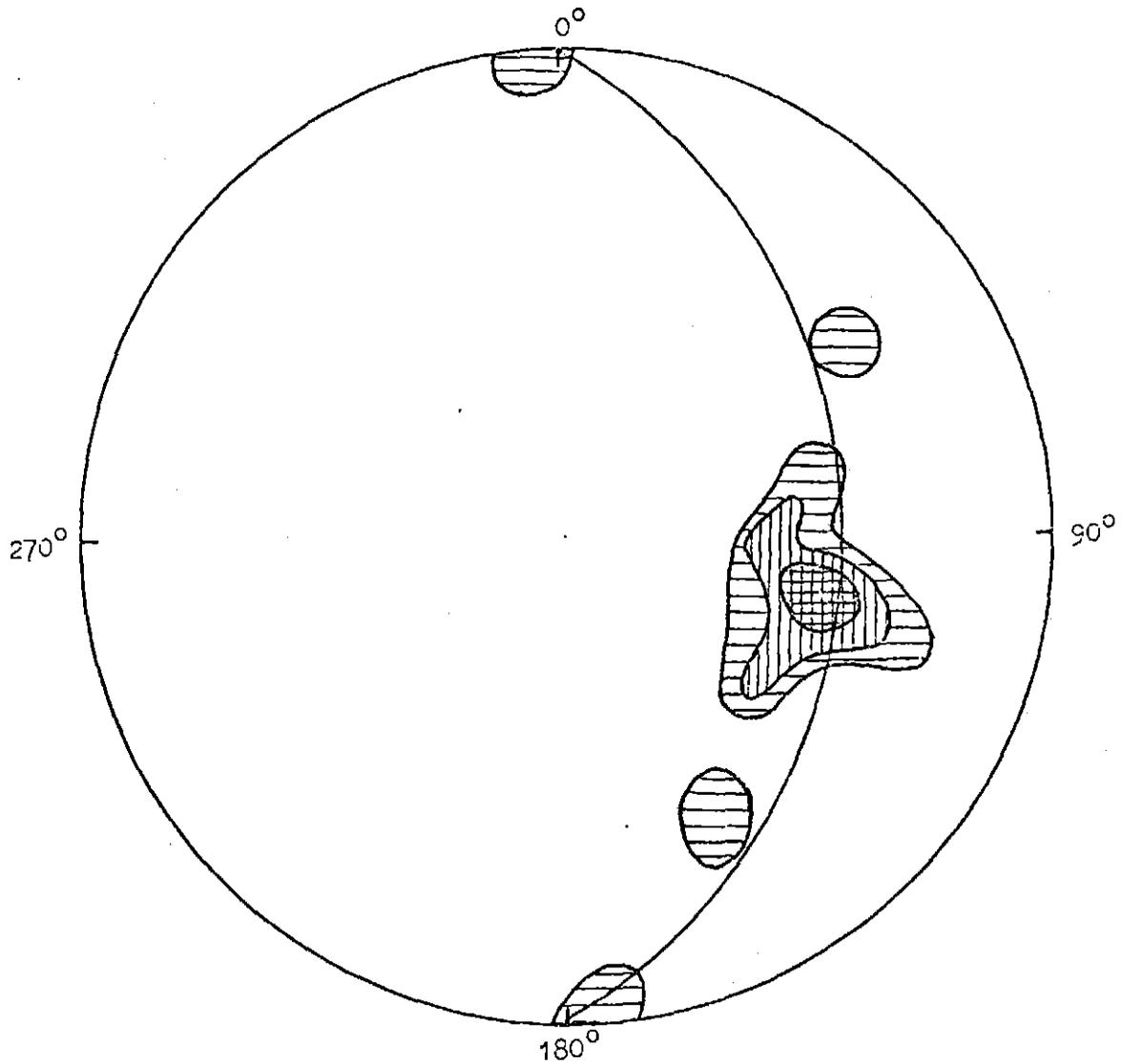


Fig. 4. Plot of the poles of the aplite and quartz porphyry dykes and veins, group 2.

Contours 4%, 6%, 8%

45 readings.

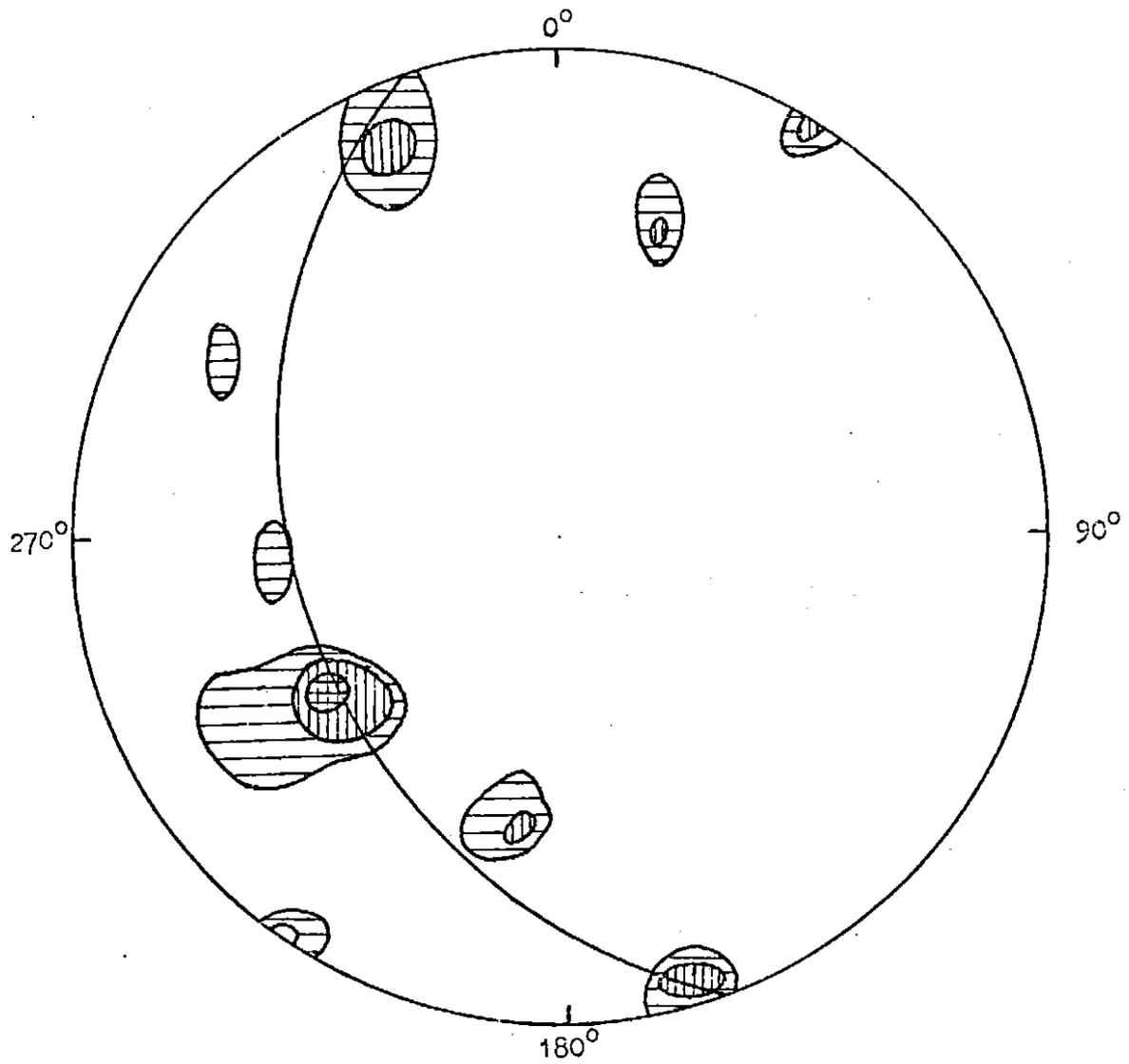


Fig. 5. Plot of the poles of the banding in the adamellite.

## 2.5 MAGNETICS.

An interesting feature of the Grassy and Bold Head Adamellites is the difference between them magnetically as revealed by an aeromagnetic survey. The pattern over the Bold Head Adamellite is regular showing a steady increase in intensity towards the centre of the intrusion. The Grassy Adamellite however, shows a much more variable pattern, being magnetically very "noisy". In the section of the intrusion studied the magnetic highs and lows do not correlate with any petrological variation or the basic dykes. The basic xenoliths could be the cause of the magnetic irregularities but they appear too small and too uniformly distributed to cause them. This problem is discussed further in the next section.

## 2.6 GENERATION AND EMPLACEMENT OF MAGMA

### 2.6.1 Generation.

Normative Ab + Or + Qz makes up 76 - 81% of the Grassy and Bold Head Adamellites and a plot of the Ar - Ab - Qz ratios are shown in Fig. 6. Also shown are the ternary minima at 2, 3, 5 and 10 kb  $P_{H_2O}$  (after Luth, Jahns and Tuttle 1964). The plots show little variation and the plotted points lie close to the minimum at 2 kb  $P_{H_2O}$ , indicating that the melting which generated the magma occurred at a water pressure of or less than 2 kb. However,  $P_{H_2O}$  during melting cannot be fixed with this degree of precision since there is likely to be some error in the proportion of normative feldspars due to the presence of biotite and minor hornblende in the adamellites. Also, this determination of  $P_{H_2O}$  assumes there has been no contamination after melting has ceased.

Fig. 7 is a plot of the same samples on the  $SiO_2$  saturated surface of the Or - Ab - An -  $SiO_2$  system, projected onto the Or - Ab - An face of the tetrahedron. The lines drawn represent the boundary curve between the plagioclase and orthoclase fields at different  $P_{H_2O}$  (after Tuttle and Bowen 1958). The lower solid line applies for  $P_{H_2O}$  of 1 kb and the upper solid line for  $P_{H_2O}$  of 10 kb. This range covers all pressures in the crust at which granitic magmas are generated. The dotted lines mark the limits

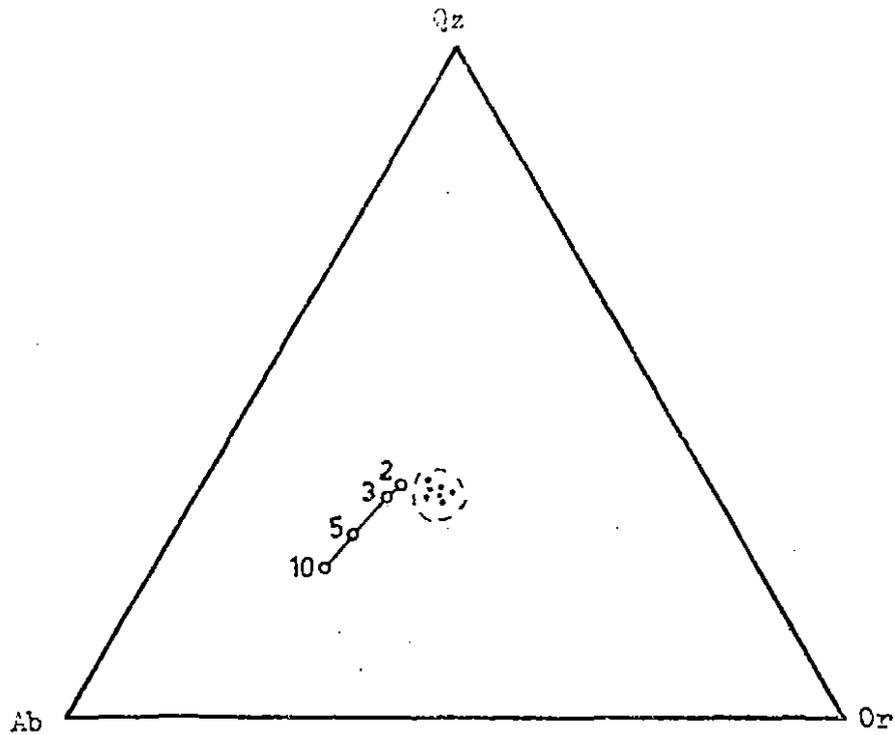


Fig. 6. Plot of Grassy and Bold Head Adamellites in the system Or - Ab -  $\text{SiO}_2$  and comparison with the minima at 2, 3, 5 and 10 kb  $\text{P}_{\text{H}_2\text{O}}$  (after Luth, Jahns and Tuttle, 1964).

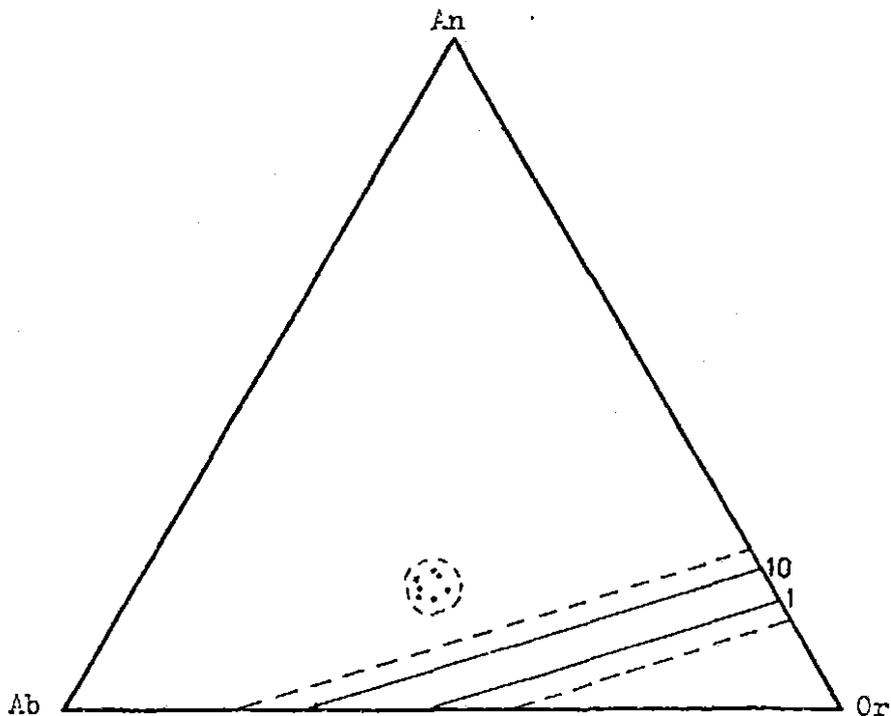


Fig. 7. Plot of Grassy and Bold Head Adamellites on the  $\text{SiO}_2$  saturated surface of the Or - Ab - An system and comparison with the minima from 1 to 10 kb  $\text{P}_{\text{H}_2\text{O}}$  (after Tuttle and Bowen, 1958).

of possible analytical error in determining the position of the boundary curve. Since the boundary curve represents a temperature "valley", the curves in Fig. 7 delineate a low temperature trough into which the compositions of all granitic melts should fall regardless of the  $P_{H_2O}$  at which they are generated. However, the Grassy and Bold Head Adamellites plot well outside this trough, in the plagioclase field. Errors in the determination of normative feldspars are unlikely to have changed the ratios sufficiently to allow for this. Therefore, it appears that the magma was contaminated.

Considering crystallization of the magma, if beginning at the present composition of the adamellites, then plagioclase would have been the first mineral to form. However, the occurrence of large orthoclase phenocrysts indicates that potash feldspar crystallized first. Therefore, at some stage, the composition of the magma lay in the orthoclase field but since the crystallization of the orthoclase it was contaminated, resulting in an increase in Ca.. The occurrence of basic xenoliths in the Grassy Adamellite provides a possible source for the contamination. During recrystallization of the xenoliths elements would have diffused from the basic rock into the magma and vice versa. This then is probably responsible for the tendency of the adamellites towards a granodiorite in some respects.

#### 2.6.2 Emplacement.

##### (a) Depth.

Buddington (1959) considered the depths of emplacement of granitic rocks and recognized three depth levels. These are :

1. Epizone (0 - 4 miles).
2. Mesozone (5 - 9 miles).
3. Catazone (7 - 12 miles).

with transitional zones between them. In determining the depth of emplacement of the Grassy Adamellite and also the Bold Head Adamellite, the following features are significant in the light of Buddington's work:

1. The intrusions are discordant with the country rocks.
2. The Grassy Adamellite is virtually homogeneous in composition.

3. No lineations or foliations occur through the intrusion.
4. Basic xenoliths are distributed through the intrusion.
5. The contact with the country rocks are very sharp.
6. The country rock outside the contact metamorphic zone is unmetamorphosed.
7. Associated basic dykes are common.
8. Some aplite dykes and veins occur but distinct pegmatite veins have not formed.

From the above it is concluded that the Grassy and Bold Head Adamellites were emplaced in the epizone.

The occurrence of contact metasomatism adjacent to the intrusions implies that the present erosional surface is close to the top of the intrusions. It is difficult to determine an accurate depth of emplacement by stratigraphic means as the thickness of the sequence of basic volcanics and the proportion of it into which the plutons have intruded is unknown. Also, there is the possibility that formations overlying the volcanics at the time of intrusion have since been removed by erosion.

Badgley (1965) related the crustal level in which pluton is emplaced and the time of emplacement with reference to an orogenic period. High level intrusions in which the magma has moved considerably from the source region are regarded as post orogenic. The Grassy and Bold Head Adamellites are of this type. The isotopic age determinations indicate that they were intruded soon after the close of the Tabberabberan Orogeny.

(b) Mechanism.

Badgley (1965) gives three possible mechanisms for the emplacement of high level plutons. These are :

1. Forceful Injection. Active rise of an intrusive magma together with its outward expansion and pushing aside of the country rock.
2. Permissive Emplacement. Active rise of the magma but with no active pushing aside of the wall rocks.

3. Magmatic Stopping. Passive rise of the magma by means of sinking of the roof blocks through the magma.

A characteristic feature of plutons emplaced by either of the first two mechanisms, involving active magma rise, is the development of linear or platy flow structures. The banding, as discussed previously, in the Grassy Adamellite is considered not to be a flow structure but an early crystallization feature. Its preservation would imply a passive emplacement of the intrusion. The first mechanism is further ruled out by the lack of deformation of the country rocks near the contact, as a result of the intrusion. This leaves magmatic stopping as the mechanism. Other than the features already mentioned, this mechanism is further supported by the very sharp contacts and the occurrence of xenoliths through the Grassy Adamellite.

Magmatic stopping involves firstly fracturing of the overlying rocks due to stress caused by the intrusion and subsequent foundering of the fracture controlled blocks in the roof of the magma chamber. The blocks sink as their specific gravity is higher than that of the magma and the magma then rises to occupy the vacated spaces.

Since the basic volcanics were the uppermost rocks to be intruded, xenoliths of these are highest in the intrusion. Assimilation is minimal as the magma temperature was well below the melting temperature of the basic volcanics. Due to lower resistance to movement in the magma it is likely that the larger xenoliths sank faster than the smaller ones which are now exposed on the present erosional surface. Therefore, the existence of larger xenoliths below the surface could provide an explanation for the magnetically "noisy" nature of the Grassy Adamellite. The lack of magnetic anomalies within the Bold Head Adamellite implies it contains no large basic xenoliths. This is due to the small size of the intrusion and also to its intrusion along a well brecciated fault zone where xenoliths produced during emplacement would have been too small to be detected on an aeromagnetic survey.

## 2.7 COMPARISON WITH THE MIDDLE PALAEZOIC TASMANIAN TIN GRANITES.

Following the Tabberabberan Orogeny in Tasmania, a number of acid to intermediate plutonic rocks were intruded. Their radiometric ages, from Rb-Sr and K-Ar methods, range from 326 to 375 million years. The intrusions are of the alkaline to calc-alkaline type and show cross cutting relationships, sharp contacts and narrow contact aureoles. The most abundant rock types are granodiorites and adamellites with quartz diorite and diorite developing in parts. Granites are relatively rare. Several of the intrusions contain, or are associated with, tin deposits and also some tungsten (wolframite) and sulphide mineralization.

Klominsky and Groves (1970) list the average chemical compositions of various tin bearing intrusions in Tasmania. They show little variation but differ significantly from the Grassy and Bold Head Adamellites. Typical examples are the Meredith and Pine Hill intrusives. Their average chemical compositions and Rb, Sr and Sn contents are shown in Table 6 along with the average values for the King Island rocks. The tin granites contain more  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  and less  $\text{CaO}$ ,  $\text{MgO}$  and  $\text{Fe}_2\text{O}_3 + \text{FeO}$  than the Grassy and Bold Head Adamellites. The difference in  $\text{CaO}$  and  $\text{K}_2\text{O}$  contents is reflected in the lower anorthite content of the plagioclase (An 6 - An 9 in the Pine Hill Complex) and the higher proportion of orthoclase relative to plagioclase (Or 42% and Pl 15% in the Meredith Granite) in the tin granites.

The Rb and Sr contents differ in the tin granites in that Rb is higher and Sr is lower than in the Grassy and Bold Head Adamellites as shown by the Meredith and Pine Hill intrusives. Tin mineralization associated with the Meredith Granite is less than that associated with the Pine Hill Complex. This is shown in their respective Sn contents. It is interesting to note that the Rb and Sr contents of the Meredith Granite, whose Sn content is similar to those of the Grassy and Bold Head Adamellites, approach the Rb and Sr contents of the King Island rocks more closely than do those of the more mineralized Pine Hill Complex.

TABLE 6

AVERAGE CHEMICAL ANALYSES OF MEREDITH AND PINE  
HILL INTRUSIVES COMPARED WITH AVERAGE OF GRASSY  
AND BOLD HEAD ADAMELLITES.

	<u>A</u>	<u>B</u>	<u>GBA</u>
SiO <sub>2</sub>	73.28	73.30	68.58
Al <sub>2</sub> O <sub>3</sub>	13.67	14.85	14.46
Fe <sub>2</sub> O <sub>3</sub> )	2.03	2.64	2.99
FeO )			
CaO	0.58	0.61	2.57
Na <sub>2</sub> O	3.30	1.88	3.33
K <sub>2</sub> O	4.55	4.30	3.96
MgO	0.77	0.63	1.36
TiO <sub>2</sub>	0.25	0.04	0.47
MnO	0.03	0.05	0.04
P <sub>2</sub> O <sub>5</sub>	0.03	0.03	0.19
H <sub>2</sub> O <sup>+</sup> )	0.69	1.16	0.90
H <sub>2</sub> O <sup>-</sup> )			
F	< 0.2	0.40	n.d.
Total	99.46	100.06	98.85
Rb	263	768	224
Sr	47	7	496
Sn	4	43	5

n.d. = not determined.

A	Meredith Granite	) From Groves et al (1972)
B	Pine Hill Complex	
GBA	Grassy and Bold Head Adamellites.	

There are two possible explanations for the differences between the Grassy and Bold Head Adamellites and the Tasmanian tin granites. One is that there has been contamination of the King Island rocks with basic material. The other possibility explains the differences on the basis of a lesser degree of differentiation than in the tin granites. Sr isotope data would resolve these problems but, as discussed in section 2.6. contamination seems a more likely explanation.

From isotopic age determinations on granitic rocks from Tasmania, McDougall and Leggo (1965) recognized two phases of granitic emplacement in the Middle Palaeozoic. One was during the late Devonian (centred about 370 m.y.) and the other during the early Carboniferous (centred about 340 m.y.). They placed the Grassy Adamellite in the second phase. However, the  $Ar^{40}/Ar^{39}$  ages indicate that the Grassy and Bold Head Adamellites belong to the first phase. The Middle Palaeozoic granitic rocks of north east Tasmania were apparently emplaced predominantly in the first phase and most of those in the north west in the second phase. No significant distinction can be made between intrusions of the first and second phases and tin and tungsten mineralization is associated with granitic rocks emplaced during both phases.

Comparison of the K/Ar and the Rb/Sr results quoted by McDougall and Leggo for the Housetop Granite suggest to the author that the younger K/Ar ages are due to the loss of argon from the biotite as a result of a tectonic event after emplacement. Therefore, the Rb/Sr ages are more accurate. If this applies to all the intrusions apparently emplaced in the second phase in the early Carboniferous then in fact there was only one phase of intrusion in the late Devonian. Hence the Grassy and Bold Head Adamellites were emplaced at about the same time as the rest of the Middle Palaeozoic granitic rocks in Tasmania.

## 2.8 BASIC DYKES.

Samples 75, 76, 149, 165. Plate 4.

The Grassy Adamellite and part of its contact aureole has been intruded by basic dykes up to three meters wide. In thin section, their basic mineralogy consists of a groundmass of plagioclase, hornblende and magnetite, and phenocrysts of hornblende.

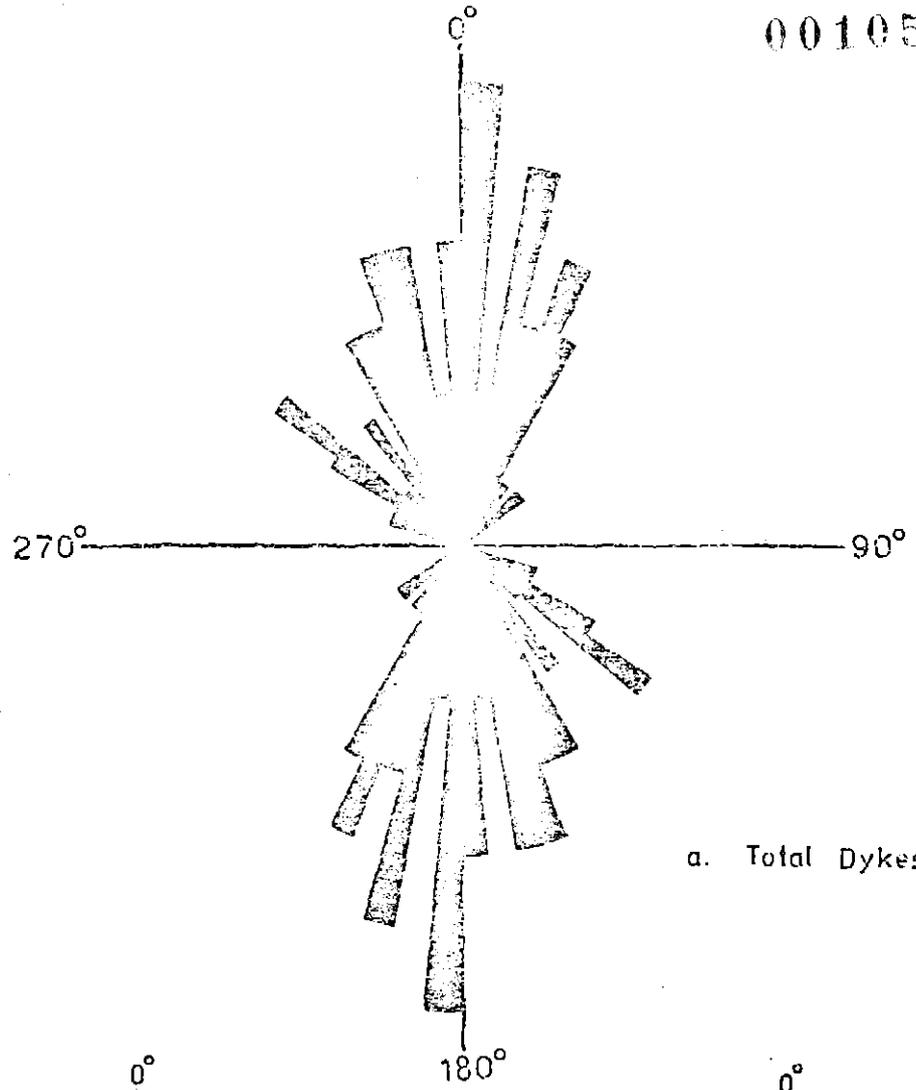
The groundmass plagioclase is well twinned and also zoned. The composition is quite variable. The larger grains in the groundmass have a core of composition about An 50 whereas the smaller grains have a core of about An 35. The more sodic rims have a composition of An 20.

The hornblende is brown and usually well formed and twinned, especially the phenocrysts. The Mg/Mg + Fe ratio is 0.25. The degree of hornblende alteration varies through the dykes, some containing fresh hornblende and others with hornblende completely altered to iron rich chlorite and minor epidote. In parts, hornblende is pseudomorphed by magnetite. In the dykes intruding the adamellite (149 and 165) where alteration is significant, calcite occurs as a late stage mineral. It formed as a result of the calcium release from the alteration of the hornblende. These dykes are contaminated with sericitized orthoclase and plagioclase, quartz and minor sphene from the adamellite. All the contaminating minerals show signs of resorption. In the basic dykes intruding the Mine Series of No.1 orebody (75 and 76) the abundant calcite has formed, more as a result of contamination from the calcareous units than by alteration of the hornblende. The quartz in these dykes has also come from the Mine Series rocks.

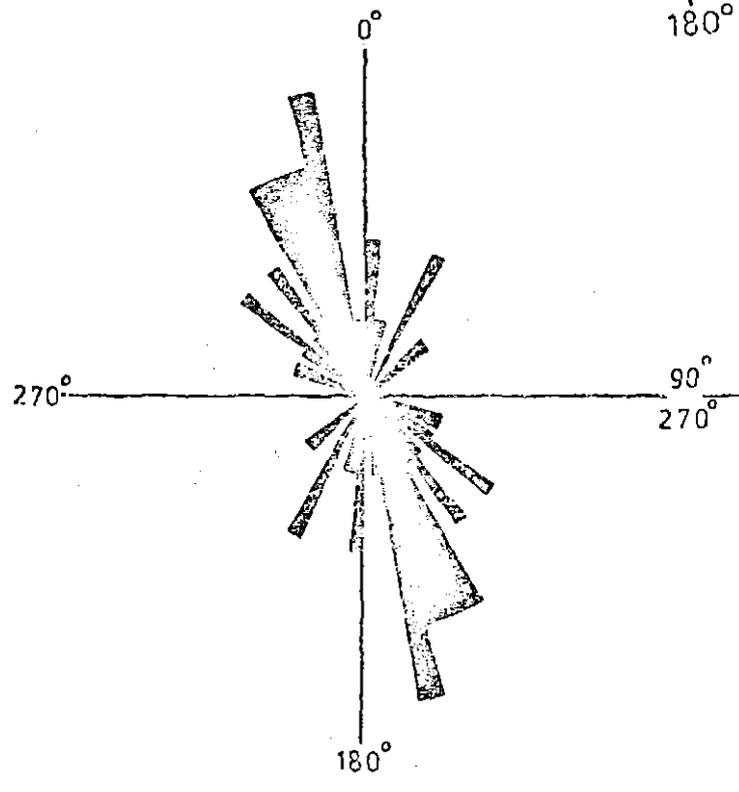
From the mineralogy of the basic dykes, they are described as lamprophyres. The only exception to this observed is the most westerly basic dyke (75) intruding the Mine Series of No.1 orebody. It contains phenocrysts of plagioclase up to 5mm in diameter and hence cannot be termed a lamprophyre. The plagioclase is partly sericitized and altered to zoisite and does not appear to be a contaminant mineral.

Fig. 8a showing a rose diagram of the strikes of all the basic dykes, indicates their general N - S trend. However, they lie over a wide spread of values, but when divided into two groups with the dividing line at 559800N 216300E then the dykes to the north trend generally NNW - SSE (Fig. 8b). This is parallel to the Grassy River Fault. To the south the trend of the dykes changes through  $30^{\circ}$  to about  $10^{\circ}$  as shown in Fig. 8c. As indicated by the quartz porphyry dykes, this is due to a change in the strike of the fault.

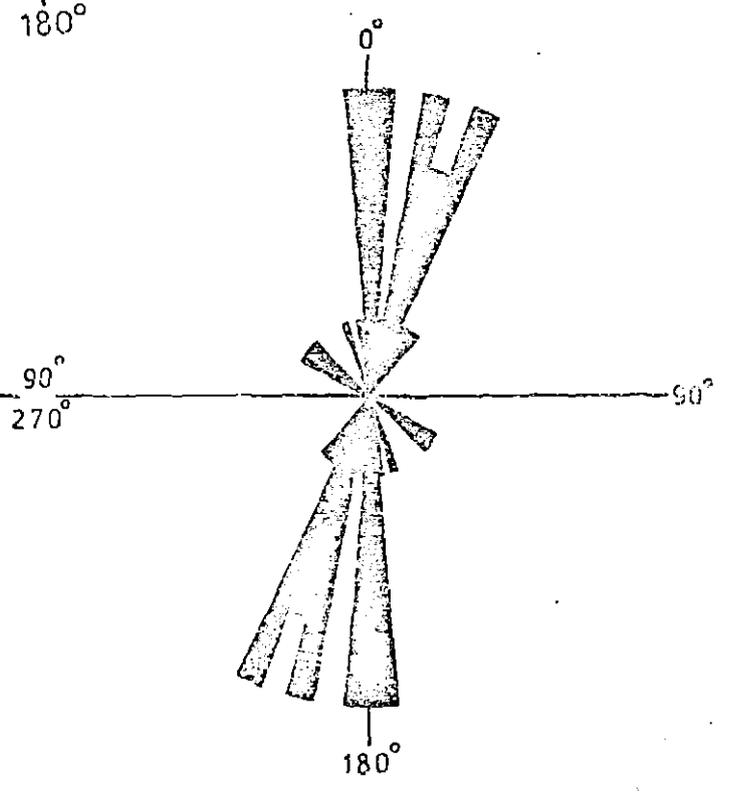
A hornblende fraction from sample 165 was dated by the  $\text{Ar}^{40}/\text{Ar}^{39}$  method (Green 1973). The result obtained was an age of  $345 \pm 5$  m.y. which is only 25 m.y. to 30 m.y. younger than the Grassy and Bold Head Adamellites. Therefore the basic dykes were probably intruded in the same tectonic phase as the Grassy and Bold Head Adamellites.



a. Total Dykes



b. Northern Dykes



c. Southern Dykes

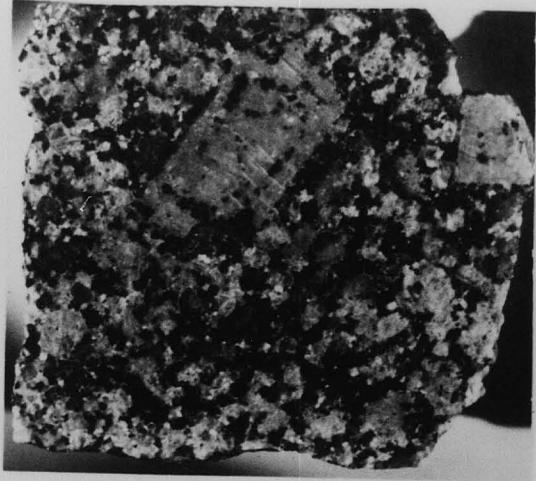
Fig. 8. Plots of basic dykes in Grassy Adamellite.

Grassy Adamellite.

- a. Section through a hand specimen showing large rectangular orthoclase phenocrysts set in a coarse grained groundmass. Inclusions in the phenocrysts are mostly biotite.  
(100, x 0.9).
- b. Typical texture of the groundmass observed in thin section (Or - orthoclase, Pl - plagioclase, Qz - quartz, Bi - biotite).  
(100, crossed polars, x 13).
- c. Well developed oscillatory zoning in plagioclase with sericitization more intense in certain zones.  
(115, crossed polars, x 13).
- d. Finer grained adamellite. Grains grade up to the size of those in the groundmass of the normal adamellite.  
(155, crossed polars, x 13).
- e. Sieve texture developed in large orthoclase grains in the finer grained adamellite.  
(142, crossed polars, x 13).

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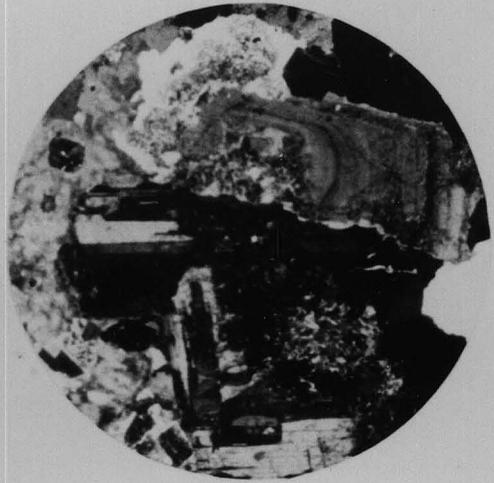
# PLATE I



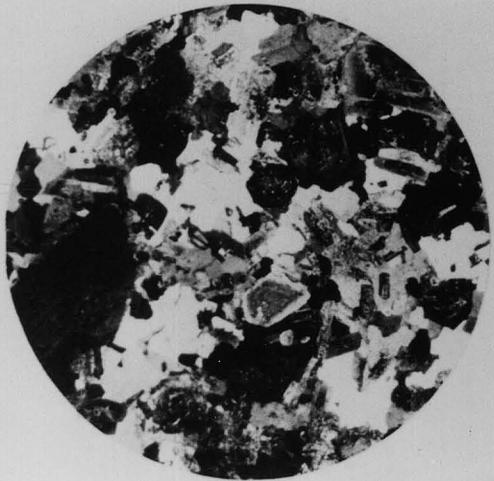
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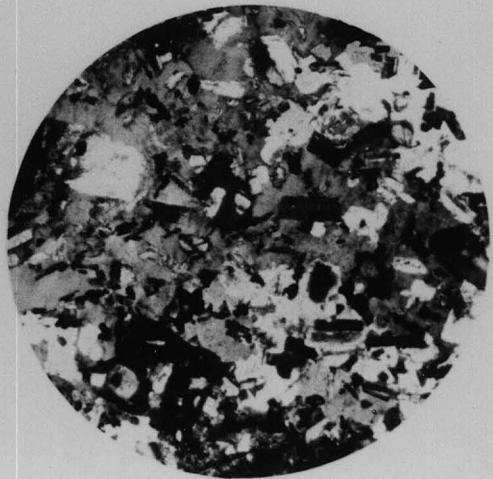
b



c



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e

Banding in Grassy Adamellite.

- a. Straight band rich in biotite and containing no orthoclase phenocrysts.  
(561500N 218100E).
- b. Straight bands both rich in biotite (dark) and containing little biotite (light).  
(560900N 217900E).
- c. More complex system of biotite-rich bands resembling cross bedding.  
(560900N 217850E).
- d. Band containing a higher proportion of orthoclase phenocrysts than the normal adamellite and sandwiched between two thin biotite-rich bands.  
(563050N 220050E).
- f e. Texture of a biotite-rich band as seen in thin section.  
(106, crossed polars, x 13).

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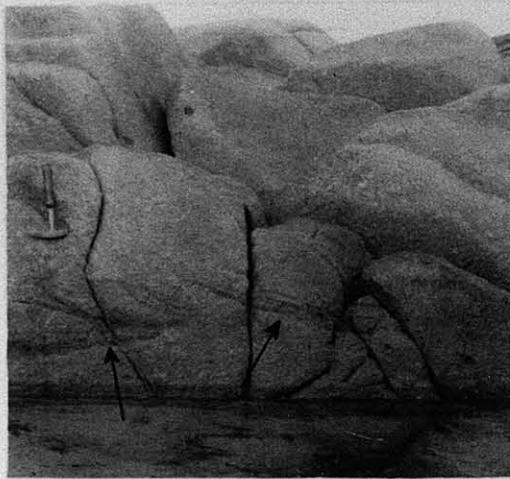
# PLATE 2



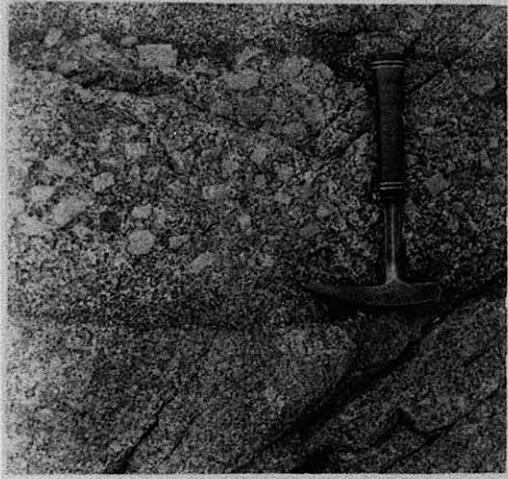
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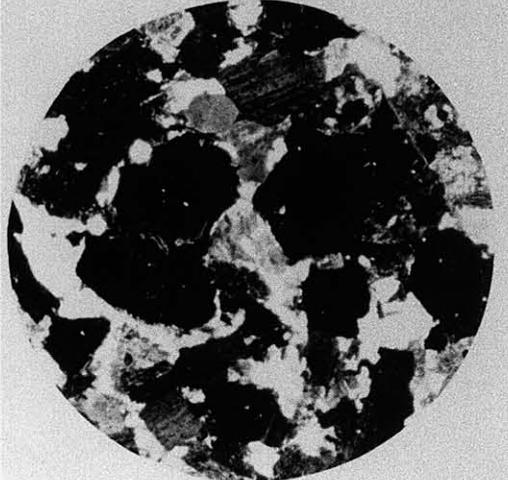
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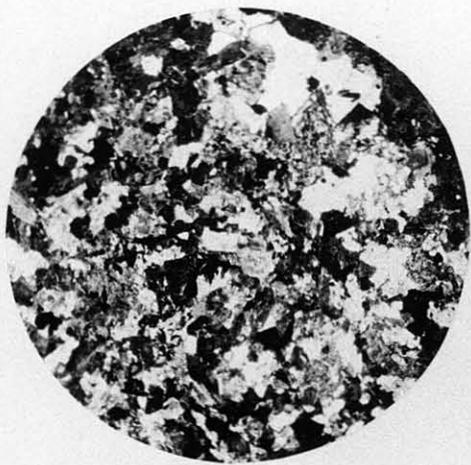
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PLATE 3.Xenolith, Contact Zone, Aplite and Quartz Porphyry, and Bold Head Adamellite.

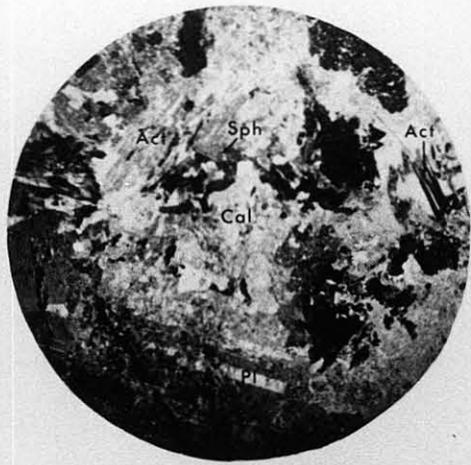
- a. Xenolith in the Grassy Adamellite. Mafic minerals are abundant and many grains have a finely poikiloblastic texture.  
(114, crossed polars, x 13).
- b. Contact zone near calcareous rocks showing the calcareous assemblage of calcite (Cal), actinolite (Act) and sphene (Sph) developed between the large plagioclase grains (Pl).  
(304, crossed polars, x 13).
- c. Contact zone near pelitic rocks. The texture is similar to that in the fine grained adamellite with grains of normal groundmass size becoming the phenocrysts.  
(185, crossed polars, x 13).
- d. Aplite with occasional quartz phenocrysts. Poorly developed granophyric textures in parts.  
(175, crossed polars, x 13).
- e. Quartz porphyry. Groundmass similar to aplite but granophyric textures are not developed. Presence of microcline is shown by the cross-hatched twinning.  
(101, crossed polars, x 13).
- f. Bold Head Adamellite showing great similarity with the Grassy Adamellite.  
(195, crossed polars, x 13).

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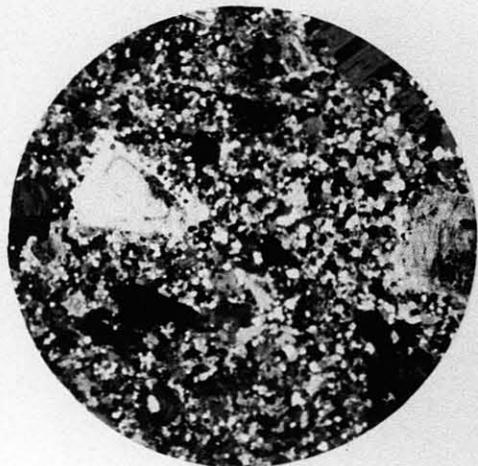
# PLATE 3



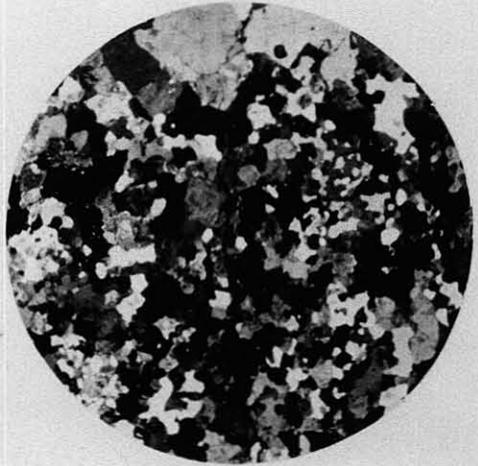
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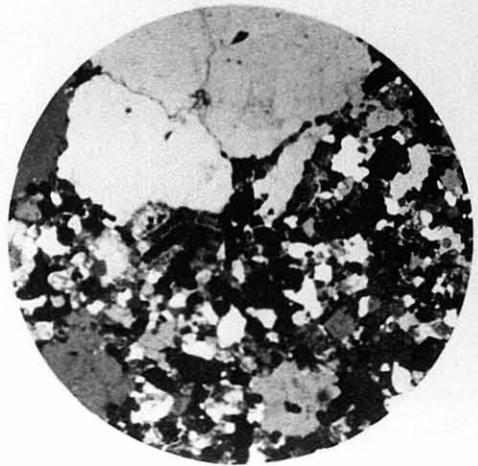
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PLATE 4.Basic Dykes.

- a. Typical basic dyke intruding the Grassy Adamellite. Width 1 meter.  
(561500N 218100E).
- b. Several basic dykes in an area where the Grassy Adamellite has been intruded by a large number of the dykes. They all strike roughly NNW.  
(559800N 216400E).
- c. Lamprophyre showing euhedral hornblende phenocrysts set in a fine grained groundmass of mainly plagioclase laths and hornblende.  
(165, crossed polars, x 13).
- d. Lamprophyre in a dyke intruding the Mine Series of No. 1 orebody. It has been contaminated with calcite (Cal) and quartz (Qz) from the country rocks. Dark grains are chlorite formed by alteration of hornblende.  
(76, crossed polars x 13).

PLATE 4

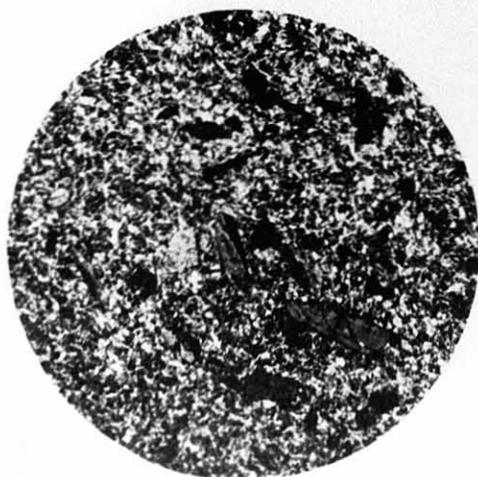
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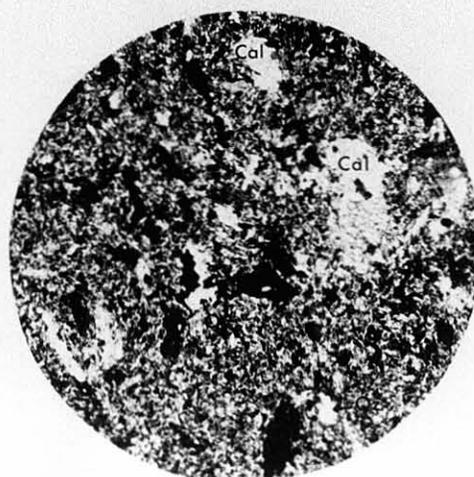
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CHAPTER 3

PETROLOGY OF THE

CALCAREOUS UNITS

OF THE MINE SERIES

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### 3.1 INTRODUCTION.

In studying the mineralization of the rocks forming the scheelite deposit of No.1 orebody the main rock types of interest are the calcareous units. These are the marble beds, pyroxene garnet hornfels, andradite skarn and the banded footwall beds. Samples of these were collected from the open cut and also from drill core of diamond drill holes along section 7 (Map 2).

Detailed thin section descriptions of typical examples of each of the calcareous units are given in Appendix 2. The following sections of this chapter are only a discussion of the significant aspects of their petrology.

The marble studied occurs in beds within B lens and also in the thin marker bed in C lens. The andradite skarn came from both orebodies in C lens and also in the mineralized parts of the banded footwall beds. It has been studied as a whole with no distinctions made between the top and bottom orebodies as the differences that do exist are due to the original bedding and not to metamorphic or metasomatic effects. In B lens the andradite skarn is not very extensive and has been almost completely mined out, so it was not studied in detail. The only unmineralized banded footwall beds examined were those near the top of the unit where marble bands still occur in the rock.

In discussing the types of skarn at King Island, with respect to the processes that formed them, the terminology of Korzhinskii (1955) is used. Korzhinskii distinguishes two types of metasomatism. These are :

1. diffusive metasomatism which involves ions in the saturated pore spaces of the rock moving in the direction of decreasing concentration.
2. infiltration metasomatism in which ions are transported by solutions invading the rock.

At King Island, two way diffusion (bimetasomatic) of ions has resulted in the formation of the endoskarn zone in the Grassy Adamellite, as dis-

cussed in section 2.2.4, and also the mineral banding in the banded footwall beds. Infiltration metasomatism, possibly with minor bimetasomatic diffusion has formed the mineralized andradite skarn (exoskarn) from the suitable calcareous units.

## 3.2 MARBLE.

### 3.2.1 Petrography.

Samples 34, 42, 205, 259, 273, 317, 322, 331. Plate 5.

The carbonate content of the marble is usually 60-70% calcite with small amounts of dolomite (identified from X.R.D.). The silicate minerals present, in decreasing order of abundance are forsterite (0-15%), the humite minerals (0-15%), diopside (2-5%), quartz (0-5%), xanthophyllite (0-2%) and vesuvianite (trace). Green spinel of the spinel-hercynite series (0-2%), magnetite (2-5%) and apatite (trace) are also present. Kimane (1968) records the occurrence of brucite. However, this was not observed by the author in the marble.

Textures are variable, even over the small distances in a thin section. In parts, the marble is granuloblastic with distinct polygonal calcite grains but in other parts, the calcite forms large irregular grains of variable size and often poikiloblastic.

Forsterite and the humite minerals have similar forms and occur as rounded equidimensional grains. Symplectic intergrowths with calcite are common with the larger grains (34 and 205). However, forsterite is most abundant where there is little of the humite minerals (34) and vice versa (205), reflecting variations in the proportions of  $\text{OH}^-$  and  $\text{F}^-$ . The pleochroism of the humite minerals,  $\alpha$  pale yellow to golden yellow,  $\beta$  colourless to lemon yellow,  $\gamma$  colourless to pale yellow, indicates a variation from chondrodite to clinohumite. The high optic axial angle ( $80^\circ - 90^\circ$ ) of the colourless grains of the same form as the humite minerals indicates that they are forsterite and not norbergite. The humite minerals are most abundant near fractures in the marble, especially the clinohumite (259). The diopside is more abundant with the forsterite

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and similarly occurs as small grains but with a more prismatic form.

In one of the samples studied (205) a few grains of scheelite were found. They are xenoblastic, well rounded and appear to have grown at the expense of the calcite.

In the Investigator 6 area, the marble is similar to that in the Mine Series. However, the development of the humite minerals is not as extensive although some occurs around fractures (331). Bedding is visible where impure bands occur (317 and 321). In parts these have reacted with the marble to produce grossularite and diopside bands (321) as in the banded footwall beds.

### 3.2.2 Petrogenesis.

From the Mg content of the marble, it is clear that most of the beds were formed from dolomitic limestone. Most of the Mg became incorporated into the humite minerals and the diopside. In the alteration of the marble little silica was introduced as indicated by the lack of quartz in the fractures and the occurrence of magnetite and spinel near them. Therefore, the silica now present was originally present in the limestone. In some of the marble beds excess silica formed quartz and the coexistence of this with calcite indicates that the temperature was too low and/or  $P_{CO_2}$  was too high for the formation of wollastonite. The metamorphism of the beds tended to purify the marble on a microscopic scale. Iron and aluminium impurities were expelled from the carbonate and deposited as magnetite and spinel between the calcite grains.

During metasomatism, the marble beds were affected to some extent by the introduction of the volatiles P, OH and F. These infiltrated through the marble, especially  $OH^-$  and  $F^-$  ions. Larger elements (eg. Fe) in the metasomatic fluids, however, were unable to pass through the marble and entered only along fractures.

The textures of the marble indicate that equilibrium was attained only in parts of the rock, ie. where a granuloblastic texture occurs. Regions showing large, irregular, poikiloblastic calcite grains and

symplectic intergrowths are indicative of non equilibrium assemblages. That this, in fact, is the more common situation is shown by the erratic results obtained using the percentage of Mg in calcite as a geothermometer. The ratios for four samples, along with the corresponding temperatures (determined from Graf and Goldsmith (1958) are shown below :

	<u>% Mg.</u>	<u>Temperature (°C)</u>
1. (238)	1.4	< 300°
2. (204)	3.2	~ 400°
3. (273)	1.4	< 300°
4. (258)	4.8	500°

The temperatures, except for sample 4, are well below those expected. Sample 4 shows a more well developed granuloblastic texture than the other samples and therefore has approached equilibrium more closely.

The similarity between the marble in the Investigator 6 area and that in the Mine Series indicates that the marble outside the mineralized region has also suffered fluorine metasomatism but perhaps to a lesser extent. The texture of the marble is distinctly more granuloblastic than in the Mine Series marble representing a closer approach to equilibrium, probably due to the lesser degree of metasomatism.

### 3.3 PYROXENE GARNET HORNFELS.

#### 3.3.1 Petrography

Samples 50, 51, 53, 54, 343A and B. Plate 6.

In hand specimen the rock consists of irregular shaped and sized ovoids of predominantly calcite set in a dark, usually fine grained ground-mass. The proportion of ovoids is variable and may be up to 25%.

In thin section the ovoids consist of the following minerals in general decreasing order of abundance: calcite, quartz, actinolite, epidote, vesuvianite, cordierite, sphene and minor scheelite. Where mineralization in the ovoids is significant, sulphides such as chalcopyrite, pyrrhotite and minor molybdenite has been recorded by Edwards et al (1955). Calcite and quartz are invariably present while the other minerals may or may not

be depending on the original composition of the ovoids. In some ovoids quartz predominates over calcite. Actinolite, when present, occurs as long fine needles and wedges growing in the large quartz and calcite grains (53). Sphene and scheelite are similarly included in these grains. Epidote and cordierite however, usually occur as larger well formed grains. Vesuvianite is often associated with the cordierite. A rim of garnet surrounded by a rim of pyroxene often encloses the larger ovoids.

The groundmass consists of predominantly garnet and pyroxene with subordinate quartz. The garnet is essentially grossularite as is that in the banded footwall beds (ie ~75% grossularite and 25% andradite). The pyroxene is diopsidic and appears to have formed from the breakdown of the grossularite. The dominant mineral in the groundmass varies throughout the unit. Quartz and calcite occur interstitially between the grossularite and diopside.

Some parts of the pyroxene garnet hornfels have been mineralized to an economic grade. Where this has occurred, the ovoids become less distinct and the rock approaches an andradite skarn. In general, it becomes more iron rich and is therefore discussed with the skarn. In the Investigator 6 area an iron rich rock (343A and B) containing ovoids in a fine dark groundmass, showed a very different assemblage. The groundmass consists of hornblende and quartz and the ovoids consist of calcite, garnet, cordierite, quartz, chlorite, epidote, vesuvianite, xanthophyllite, and are rimmed by diopsidic pyroxene. From the colour of the garnet, it appears to contain more of the andradite component than that in the pyroxene garnet hornfels.

### 3.3.2 Petrogenesis.

From textural features, the pyroxene garnet hornfels is correlated with the carbonate-bearing tilloid of the Grassy Group outcropping along the coast to the north of Grassy. It is poorly sorted and consists of angular and subangular fragments of limestone, dolomitic limestone and smaller proportions of quartzites and siltstones set in a matrix which varies from predominantly calcite to chlorite-rich or iron oxide-rich.

The variations in the tilloid are probably responsible for variations through the pyroxene garnet hornfels. The carbonate fragments formed the calcite rich ovoids whereas the quartzite and siltstone fragments formed the siliceous and more aluminous ovoids. The pyroxene and garnet groundmass formed from an impure carbonate matrix. The mineralized parts of the pyroxene garnet hornfels represents parts that were more accessible to the mineralizing solutions than were the comparatively barren parts. This could be due to compositional and textural variations or possibly structural control.

During metamorphism, dolomite and impurities such as iron, aluminium and titanium in the fragments resulted in the development of epidote, actinolite, cordierite and sphene. In many ovoids the calcite and quartz probably formed a gel-like medium in which the earlier formed minerals, actinolite, sphene and scheelite grew (53). Epidote, cordierite and vesuvianite appear to have formed later, at about the time the quartz and calcite crystallized. In the groundmass, grossularite was first formed but began to break down, forming the diopside. Silica must have been introduced from the intrusion since the silica content of the tillite matrix is lower than that of the pyroxene garnet hornfels. The presence of minor scheelite in the ovoids indicates that mineralizing solutions have passed through the rock.

The iron-rich rock in the Investigator 6 area is probably the product of metamorphism but little or no metasomatism. The matrix must have been initially siliceous and low in calcium as indicated by the formation of hornblende and quartz. The calcareous fragments, however, have developed a normal skarn assemblage. Cordierite formed in the more aluminous fragments.

### 3.4 BANDED FOOTWALL BEDS.

#### 3.4.1 Petrography.

Sample 56. Plate 7 a, b, c, d.

The banded footwall beds, situated directly below the C lens orebodies,

consist of a series of bands of different minerals parallel to the bedding. The full sequence of bands are marble, melilite, grossularite, diopsidic pyroxene and biotite hornfels. This range may not be completely developed, the end members, marble and biotite hornfels being absent in parts, depending on the abundance of the calcareous and pelitic beds. The thickness of the bands may be up to several centimeters but is usually less than 3 cm.

The marble bands are relatively pure, containing over 95% calcite with a granuloblastic to decussate texture. The melilite bands are not as pure, with large well twinned grains of melilite (34% akermanite, 66% gehlenite) often intergrown with calcite which also occurs along fractures through these large grains. Grain shape and size is very irregular throughout the bands. Minor constituents are quartz and clinopyroxene. The grossularite (73% grossularite, 27% andradite) is similar in composition to that in the unmineralized pyroxene garnet hornfels. The bands may be very distinct and pure but often the grossularite contains inclusions of clinopyroxene and the bands grade into the diopside bands as the proportion of inclusions increases. In the diopside band, the purity is variable. Some bands contain almost solely diopside with a granuloblastic texture. However, most of the bands contain some magnetite or grossularite. The bands grade into or abutt the fine grained biotite hornfels bands and often contain pyrite. Similar banded rocks have been observed in the Investigator 6 area but they are not developed as extensively as in the Mine Series. Often, thin pelitic bands in the marble beds show these diffusion bands.

In parts, the banded footwall beds are mineralized with andradite skarn having formed in the marble bands. The fine grained biotite hornfels, diopside and grossularite bands have remained unaffected and are therefore, barren of scheelite. This rock grades into the bottom orebody as the proportion of calcareous bands increases.

### 3.4.2 Petrogenesis.

The mineral bands in the banded footwall beds have formed as a result of bimetasomatic diffusion between the thin calcareous and pelitic beds. Calcium has diffused from the marble into the biotite hornfels while iron, aluminium and silica have diffused the other way. This is shown by the fact that the minerals formed, in passing from biotite hornfels to marble, show an increase in calcium and a decrease in silica and iron. Metasomatism in the banded footwall beds has been entirely internal with no elements introduced from the intrusion except where the andradite skarn has formed in the marble bands.

Large (1969 and 1971) described these bimetasomatic banded rocks from No.3 orebody. The mineral sequence he lists is more extensive than that in the Mine Series of No.1 orebody. From the pelitic to the calcareous bands it is biotite, anthophyllite(?), actinolite, tremolite, clinozoisite and hornblende, diopsidic clinopyroxene, grossularite and vesuvianite, akermanite and calcite.

### 3.5 ANDRADITE SKARN.

#### 3.5.1 Petrography.

Samples 1, 2, 13, 18, 20, 27, 31, 32, 33, 211, 246, 270, 281, 294, 321, 335. Plate 7 e, f and Plate 8.

In hand specimen the skarn is a dark brownish green rock, very dense and consisting principally of garnet. The grain size varies from fine grained up to garnet crystals over a centimeter in diameter. The larger garnet crystals are usually set in calcite or quartz.

In thin section the skarn shows considerable variation throughout the unit. The minerals, in general decreasing order of abundance, are andradite, clinopyroxene, calcite and quartz, hornblende epidote, actinolite, magnetite, sphene, schcelite and sulphides (mainly pyrite, chalcopyrite, pyrrhotite and molybdenite). The composition of the andradite (determined from refractive indices and unit cell size) is about 73% andradite, 27% grossularite. Its abundance in the skarn usually depends on the development

of the clinopyroxene. Where interstitial quartz and calcite is present, the garnet forms idioblastic crystals commonly zoned (1). The zoning is indicated by variations in the colour of the garnet. Very fine zoning has developed at the margins and the anisotropy of some of these zones indicates that hydrogrossular has formed (13 and 32). In some parts of the skarn, almost the entire garnet grains are composed of hydrogrossular with zoning very well developed (2 and 27). The andradite is rarely pure and contains grains of clinopyroxene, hornblende, calcite, quartz and scheelite. Fractures in the garnet are commonly infilled with these minerals. In regions where interstitial material is lacking the garnet grains are not as well formed and contain a higher proportion of inclusions. This garnet shows no zoning.

In the skarn exposed in the open cut at present, the andradite is usually subidioblastic to idioblastic, but closer to the intrusion the garnet becomes xenoblastic and contains a greater proportion of clinopyroxene. The variation of the form of the garnet with distance from the intrusion is shown by the samples 270, 246, 281, 294 and 211, collected from drill core from the diamond drill holes along section 7.

The clinopyroxene is distributed throughout the skarn but is best developed as a granuloblastic mosaic between the garnet grains. Its composition (determined from refractive indices and  $2V$ ) in relation to the formula  $(Ca Mg Fe)_2 Si_2 O_6$  is Ca 42%, Mg 27% and Fe 31% which places it in the ferro-augite field. It is partly altered to hornblende, the degree of alteration varying throughout the skarn. The deep blue-green to olive-green pleochroism of the hornblende indicates its high iron content which is further shown by the  $Mg/(Mg + Fe)$  ratio of 0.22. Therefore, it is a ferrohastingsite.

Most of the calcite and quartz in the skarn occurs in interstitial positions relative to the garnet. Usually the garnet grains are separated by one large grain of calcite or quartz. Occasionally small needles of actinolite have grown in the interstitial material, especially the quartz.

Epidote, vesuvianite and sphene have grown amongst the interstitial material but not as inclusions. Except for the vesuvianite, they occur as well formed grains. The sulphides, apart from molybdenite occur in a similar form to the calcite and quartz.

Scheelite is distributed through the garnet and amongst the pyroxene and hornblende grains. It is most abundant in the skarn where hornblende has developed. It occurs as small rounded grains, usually less than 1 mm. across, and shows no signs of breakdown or replacement. When viewed under short wavelength ultraviolet radiation the scheelite appears to dust the rock. It rarely occurs in a massive form. Its fluorescence varies from blue (pure scheelite) to yellow. According to Edwards et al (1955) the yellow fluorescence is due to minor amounts of powellite in the scheelite structure and also to small inclusions of molybdenite in the scheelite.

Alteration of minerals in the skarn to a brown iron oxide is very common. Hornblende is most affected by the alteration, closely followed by the clinopyroxene. The andradite is altered to a lesser extent, usually along fractures.

In parts of the orebodies a siliceous skarn has developed (20 and 31). It grades into the normal andradite skarn but the pure siliceous skarn consists of almost solely andradite and quartz. The garnet occurs as very well formed crystals containing less clinopyroxene, hornblende, calcite and iron oxide alteration products as the garnet in the typical skarn. It is zoned but only rarely shows hydrogrossular rims. The quartz forms large irregular grains up to several centimeters across and is very clean apart from the numerous garnet grains it encloses.

In other parts of the skarn there are bands containing a significantly different mineralogy (18 and 33). They contain no garnet and only a small amount of well oxidized pyroxene and hornblende. The main constituents are small, irregular bands of calcite, quartz, chlorite, cordierite and

sulphides (mainly pyrite, with some molybdenite). The calcite is very irregularly shaped and the quartz occurs in a granuloblastic form with numerous small inclusions of actinolite, apatite and xanthophyllite. Chlorite occurs mainly as rosettes, while cordierite occurs as large irregular grains partially replaced by pyrite. Of the sulphides, the pyrite is often interstitial and the molybdenite forms elongate crystals growing through many other grains. There is little scheelite mineralization in these bands.

The andradite skarn in the Investigator 6 area (321 and 335) is similar to that in the Mine Series. Andradite is well developed and in parts clinopyroxene is abundant. However, the alteration of the clinopyroxene to hornblende is not as extensive as in the skarns of the Mine Series.

### 3.5.2 Petrogenesis.

The andradite skarn formed as a result of hydrothermal fluids from the Grassy Adamellite permeating and reacting with the marble beds. The bimetasomatic diffusion of elements across the contact of the intrusion probably occurred before the introduction of these fluids but the effect on the marble was only localized. Therefore, the role of this process in the formation of the skarn can generally be considered insignificant.

From textural features, the formation of the skarn is seen to involve two main phases. The first phase involved the introduction of iron and silica resulting in the formation of andradite. According to Spry (1969) garnet is usually difficult to nucleate, so only a small number of nucleation points form. Therefore, idioblastic grains can develop from these. However, where nucleation is easier due to a greater proportion of impurities, the large number of nucleation points result in the development of xenoblastic garnet grains. Hence the variable form of the andradite in the skarn. Small variations in the relative proportions of iron and aluminium are responsible for the zonation of the garnet, as shown by colour variation within the grains.

The andradite in the siliceous skarn closely resembles that at the end of the first phase of the formation of the skarn. The influx of excess silica resulted in the crystallization of quartz around the garnet grains, virtually "freezing" them and preventing any subsequent alteration.

In the second phase of the skarn formation  $P_{H_2O}$  increased. This first caused the development of the hydrogrossular rims around the idio-blastic garnet grains. Following this, the garnet became unstable and was partially replaced by iron-rich clinopyroxene. In this environment the hydrogrossular was the more stable garnet and hence was not replaced to the same extent as the andradite. Where the garnet was zoned, replacement was more intensive in the more iron-rich zones. The clinopyroxene was subsequently partially altered to hornblende. Deposition of the scheelite also occurred in this phase. Its occurrence in the skarn containing hornblende indicates its deposition was associated with the formation of the hornblende. The scheelite enclosed in the garnet was deposited there while the garnet was breaking down. The lack of scheelite in the garnet of the siliceous skarn indicates that the garnet formed in the first phase in a tungsten free environment. Epidote and vesuvianite formed shortly after the pyroxene, hornblende and scheelite.

The final stage in the second phase was the formation of the interstitial minerals such as calcite, quartz and also the sulphides. Calcium carbonate and silica was present in the skarn throughout the second phase but did not crystallize till the end of it. The silica probably existed in a gel state in which actinolite could grow before crystallization of quartz. Calcium and quartz don't occur to a large extent in the skarn where the garnet is poorly formed since in these parts, there were sufficient impurities to incorporate the calcium and silica in the formation of the andradite.

The bands through the skarn, containing quartz, calcite, chlorite, cordierite, sulphides and little or no garnet probably formed from very fine interbedded pelitic and calcareous rock. The higher proportion of aluminium

in these bands than in the andradite skarn is indicated by the occurrence of chlorite and cordierite. The fine bedding must have provided an easy channelway for the metasomatic fluids since a large proportion of sulphides have formed in thin bands. However, the environment was unsuitable for the deposition of scheelite due to the lack of garnet.

The skarn in the Investigator 6 area is not mineralized, it appears, due to the lack of mineralizing solutions in this region. Conditions for mineralization here are virtually the same as those in the Mine Series. Therefore, the location of the orebodies depended to a large extent on the distribution of the hydrothermal fluids emanating from the Grassy Adamellite.

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CHAPTER 4

GEOCHEMISTRY OF THE

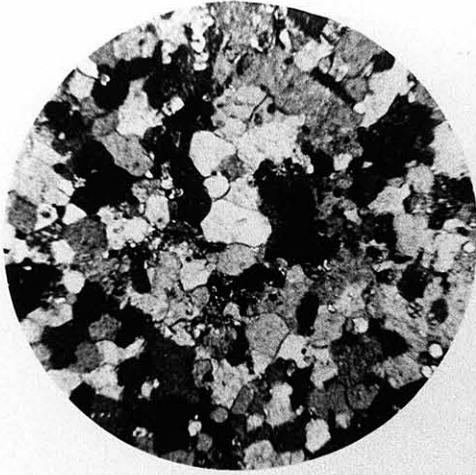
MINE SERIES

Marble in the Mine Series.

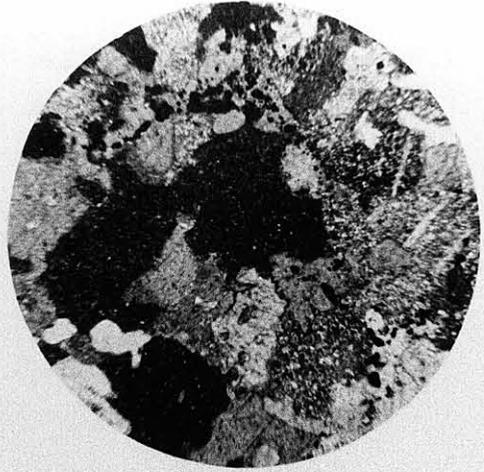
- a. Granuloblastic texture developed in parts of the marble.  
Mainly calcite with a little forsterite and diopside.  
(34, crossed polars, x 50).
- b. Coarser more irregular texture in the same sample as above.  
Blebs of magnetite occur at calcite grain margins.  
(34, crossed polars, x 50).
- c. Intergrowths of forsterite (at extinction) with calcite grains.  
(34, crossed polars, x 50).
- d. Grain of humite showing distinct pleochroism in parts (dark)  
and lack of colour elsewhere.  
(205, plane light, x 50).
- e. Fracture in the marble with spinel (black) and clinohumite  
(dark) developed in its vicinity.  
(259, plane light, x 13).

001078

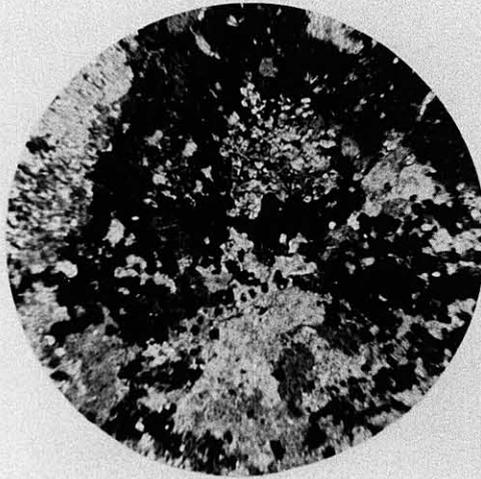
PLATE 5



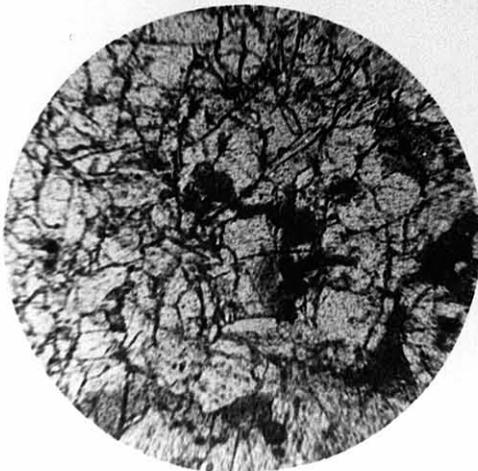
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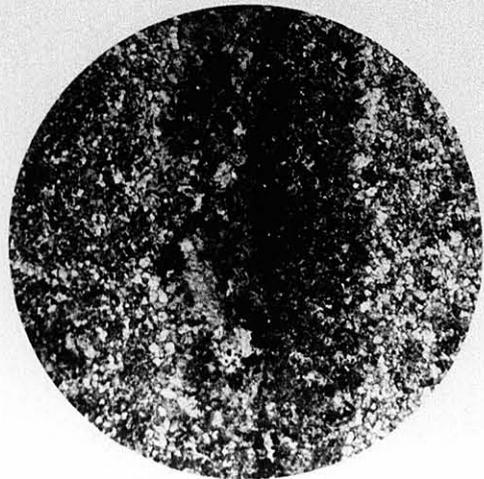
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Pyroxene Garnet Hornfels in the Mine Series.

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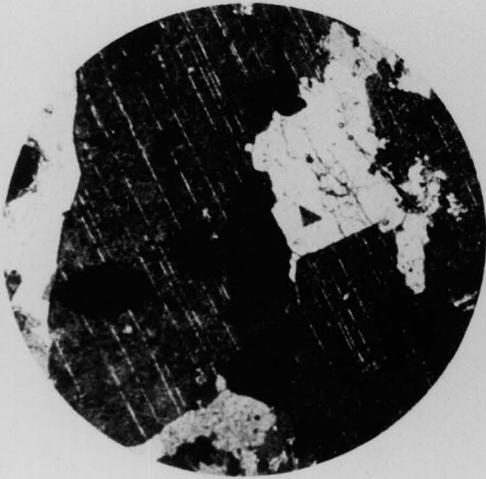
- a. Section through a hand specimen showing the calcareous ovoids set in a fine grained dark groundmass.  
(51, x 0.9).
- b. Typical texture of calcite and quartz in the ovoids.  
(50, crossed polars, x 13).
- c. Epidote (Ep), cordierite (Cord) and vesuvianite (Ves) in the ovoids.  
(51, crossed polars, x 13).
- d. Needles and wedges of actinolite that have grown in large quartz grains in the ovoids.  
(53, crossed polars, x 13).
- e. Typical fine grained pyroxene (light) and garnet (dark) groundmass.  
(51, crossed polars, x 13).

001080

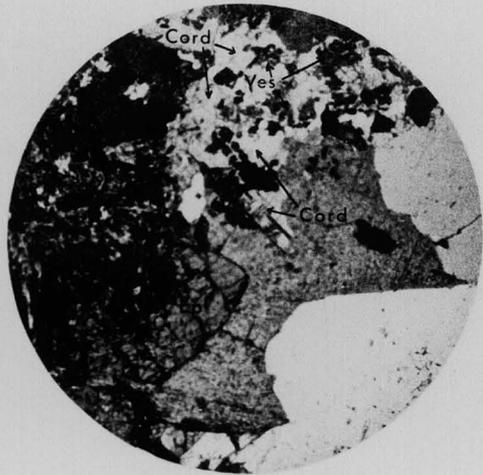
PLATE 6



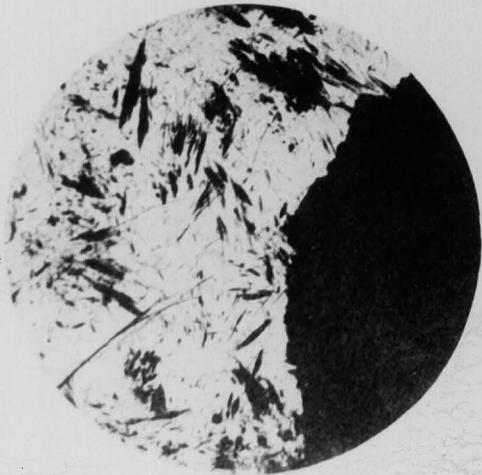
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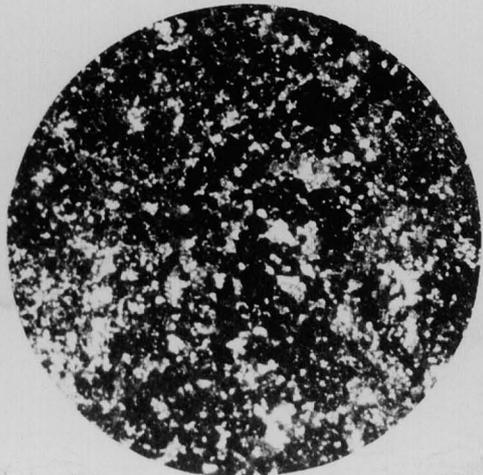
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Banded Footwall Beds.

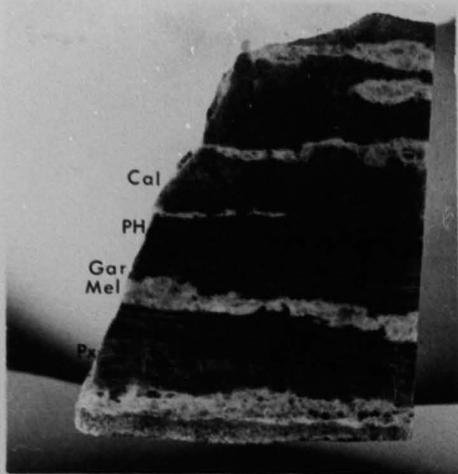
- a. Section through a hand specimen showing distinct bands of pelitic hornfels (PH), pyroxene (Px), garnet (Gar), melilite (Mel) and calcite (Cal).  
(56, x 0.9).
- b. Melilite band with grains showing broad lamellar twinning and strong fracturing with calcite infillings.  
(56, crossed polars, x 13).
- c. Intergrowth of a melilite grain (at extinction) with calcite grains.  
(56, crossed polars, x 50).
- d. Pyroxene bands bordering a thin garnet band.  
(56, crossed polars, x 13).

Andradite Skarn.

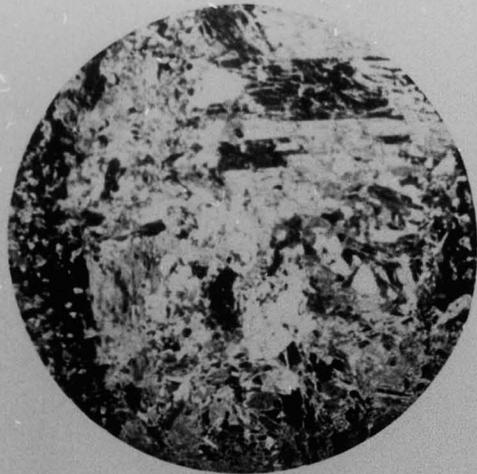
- e. Siliceous skarn showing idioblastic garnet grains set in very coarse grained quartz.  
(20, plane light, x 13).
- f. Calcite (Cal), quartz (Qz), chlorite (Chl) and pyrite (Py) assemblage developed locally in parts of the skarn. Banding is distinct.  
(18, crossed polars, x 13).

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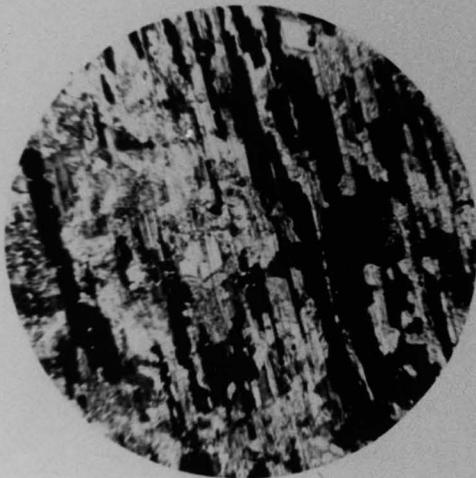
# PLATE 7



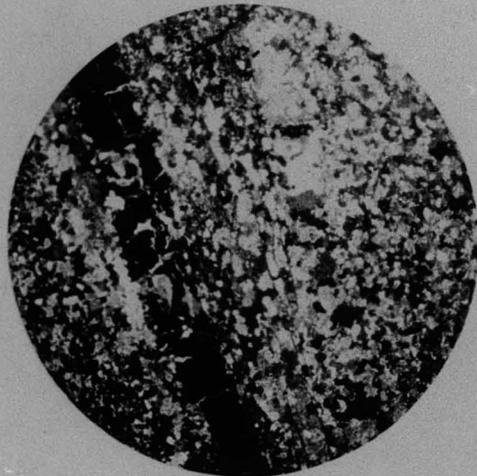
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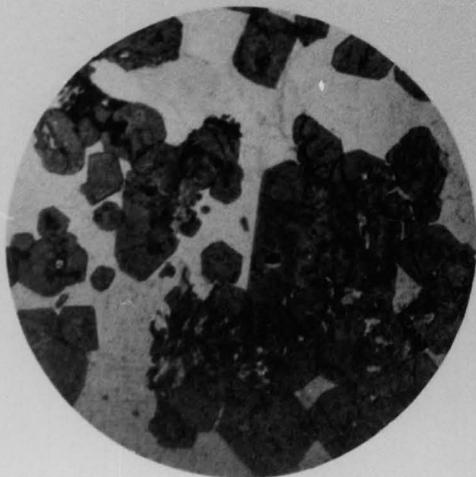
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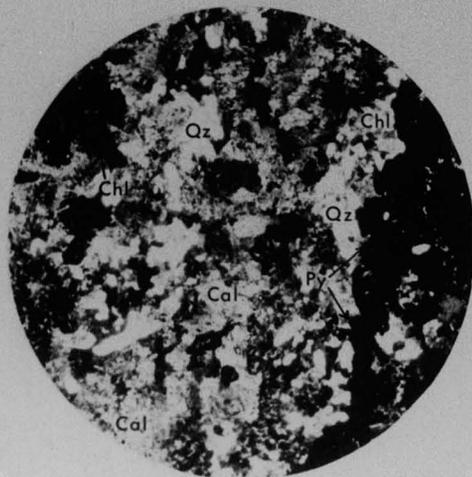
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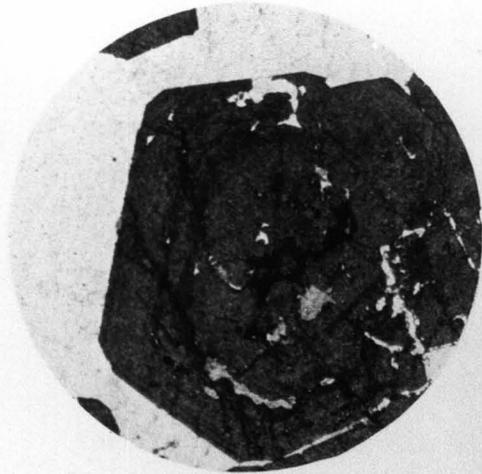
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Andradite Skarn.

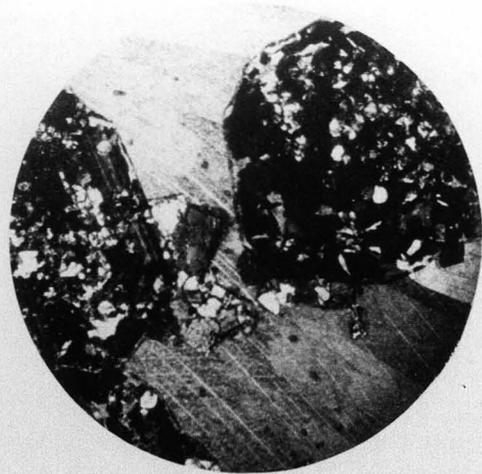
- a. Idioblastic zoned garnet grain set in quartz.  
(1, plane light, x 13).
- b. Idioblastic zoned garnet set in calcite and extensively replaced by mainly clinopyroxene. Replacement more complete in some zones. Hydrogrossular rim (birefringent) developed.  
(32, crossed polars, x 13).
- c. Garnet similar to above but with a more random replacement by clinopyroxene due to a lack of zoning apart from the hydrogrossular rim. In parts granular aggregate of clinopyroxene is interstitial to the garnet.  
(13, crossed polars, x 13).
- d. Hydrogrossular garnet showing distinct birefringence and zoning.  
(27, crossed polars, x 13).
- e. Elongate well formed epidote (Ep) interstitial to the garnet (dark).  
(1, crossed polars, x 13).
- f. Typical scheelite grains (Sch) in a clinopyroxene garnet assemblage. Scheelite in the skarn is usually rounded like the larger grain.  
(32, crossed polars, x 50).

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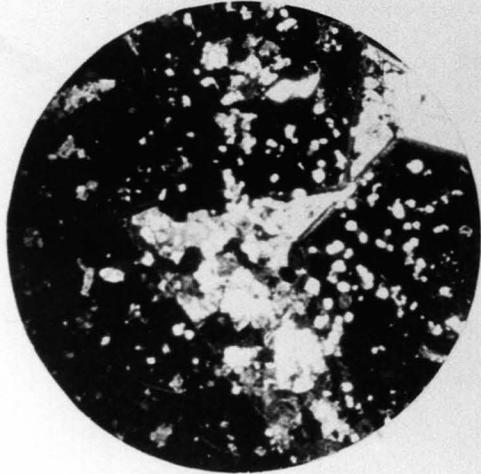
# PLATE 8



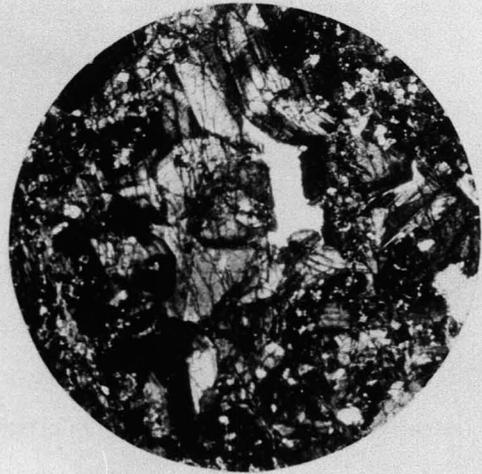
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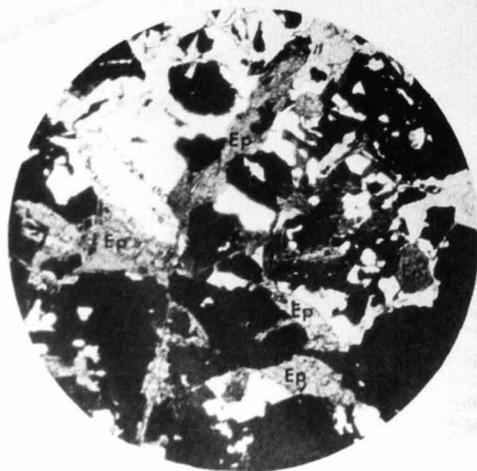
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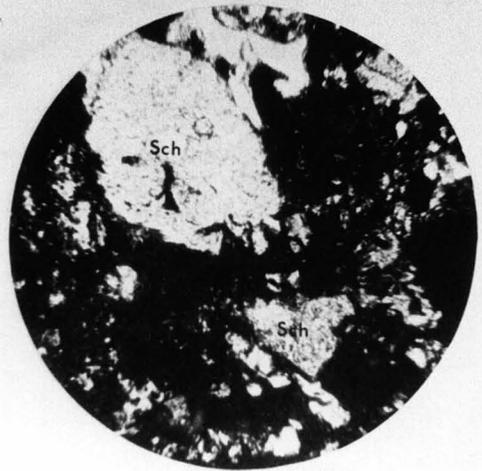
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#### 4.1 INTRODUCTION.

A major and trace element study was made of the Mine Series of No.1 orebody. The procedure for the trace elements involved firstly a preliminary survey of the units exposed in the open cut in order to obtain an idea of the distribution of several elements through these units. This was followed by a more detailed examination of the Volcanics, Biotite and Biotite Actinolite Hornfels, Marble beds, Pyroxene Garnet Hornfels and especially the andradite skarn, based on the results of the preliminary survey. The samples for this were pieces of drill core from diamond drill holes 106, 112, 125, 174, 207 and 422 located along section 7 (Map 2).

For purposes of comparison, samples of unaltered volcanics, shales and tillite, from the Grassy Group exposed along the coast to the north of Grassy, and also samples of metamorphosed unmineralized rocks in the Investigator 6 area to the west of the open cut, were also analysed for selected trace elements.

#### 4.2 MAJOR ELEMENTS.

Most of the major element analyses of the various rock types in the Mine Series were obtained from Edwards et al (1955). Three analyses by the author were made on the andradite skarn from drill holes on section 7. These are shown in Table 7. No significant variation in major elements with increasing distance from the contact was observed. An interesting feature of the skarn is its lack of K. The chemical analysis of the contact zone of the Grassy Adamellite near calcareous rocks indicated that K diffused from the intrusion into the country rock. This would have occurred during the formation of the andradite in the skarn and conditions were apparently unsuitable for the deposition of K. It was either lost from the system or incorporated into the biotite in the pelitic hornfels.

The compositions of the units are best shown on the ACF, AFM and SCM triangular diagrams as in Fig.9. These are standard plots the components being calculated as in Turner (1968). Since the rocks analysed, except for the pelitic hornfels, did not consist of equilibrium assemblages as shown

TABLE 7

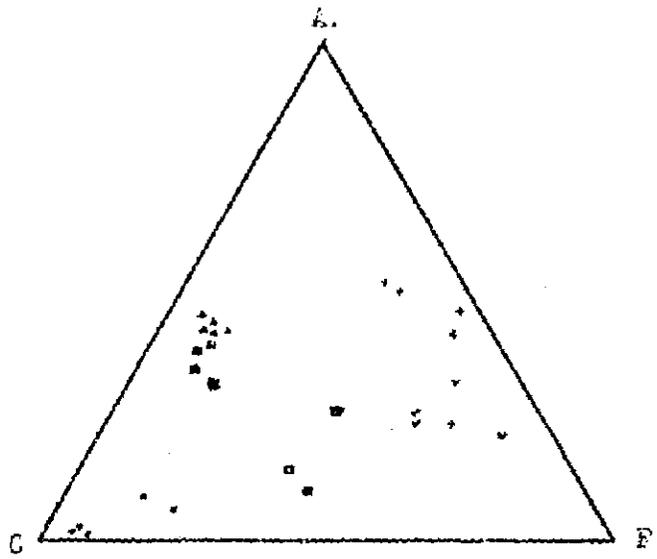
CHEMICAL ANALYSES OF ANDRADITE SKARN

	<u>228</u>	<u>246</u>	<u>211</u>
SiO <sub>2</sub>	36.47	35.95	40.20
Al <sub>2</sub> O <sub>3</sub>	4.54	5.61	4.41
Fe <sub>2</sub> O <sub>3</sub> } FeO }	24.38	22.15	23.15
CaO	28.33	29.30	27.66
Na <sub>2</sub> O	0.35	0.10	0.04
K <sub>2</sub> O	Nil	Nil	Nil
MgO	1.26	1.51	1.74
TiO <sub>2</sub>	0.42	0.22	0.33
MnO	1.24	0.99	1.03
P <sub>2</sub> O <sub>5</sub>	0.07	0.05	0.03
L.O.I.	2.17	2.30	1.99
S	1.13	0.25	0.07
WO <sub>3</sub> (assay)	Nil	1.90	0.80
Total	<u>100.36</u>	<u>100.43</u>	<u>101.45</u>

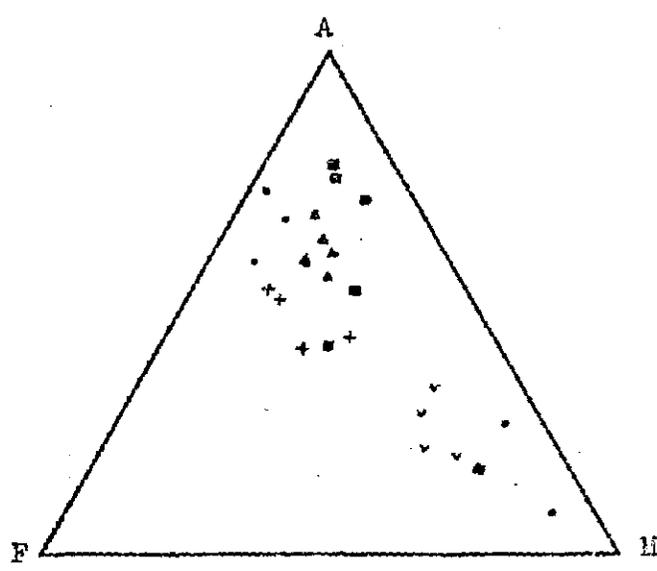
L.O.I. = loss on ignition.

Analyst P.H.

WO<sub>3</sub> assay - King Island Scheelite (1947) Ltd.

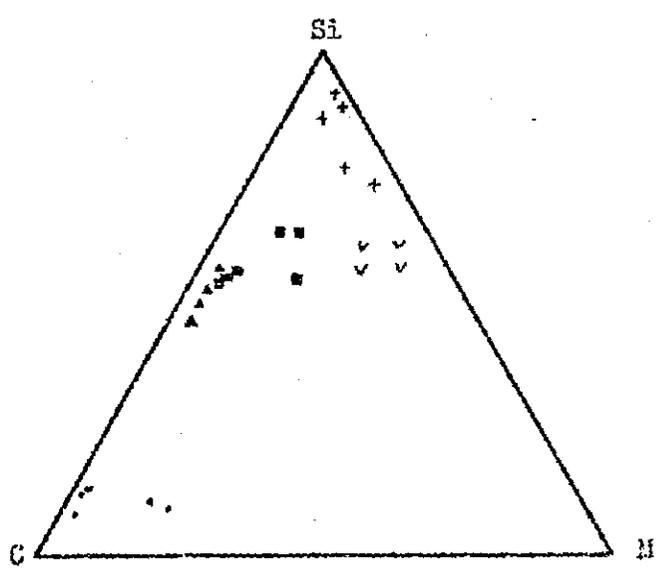


a. ACF diagram



- + Pelitic Hornfels
- ∇ Magnesian Rocks
- Marble
- Impure Marble
- ▲ Andradite Skarn

b. AFM diagram.



c. SCM diagram.

Fig. 9. Plots of units of the Mine Series of No.1 orebody based on analyses by the author and from Edwards et al (1955).

by textural features, tie lines were not drawn as they would be misleading.

The three plots show clearly the consistency in the composition of the andradite skarn. Differences in the Mg content of the marble are shown best in the AFM diagram. This reflects the original dolomite content of the limestone. As the skarn is low in Mg it appears to have formed from a limestone with little dolomite. The pelitic hornfels show some variation in composition, mainly in  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$ , due to slight differences in the original rock.

#### 4.3 TRACE ELEMENTS.

##### 4.3.1 Results.

The results of the preliminary survey are shown in Appendix 3. For each unit studied two samples were taken, one from the eastern and one from the western end of the open cut. No significant trace element variations appear to exist within the units along the strike. Cu values are very erratic due to the distribution of sulphides along fractures and bedding planes and hence are of little meaning in most of the units. The average trace element abundances in each unit are shown in Table 8. Obviously this is not an accurate average of the trace element concentrations in the various units, but it does indicate the order of the values. In addition to these data, trace element data from Burchard (1972) is shown in Table 9.

The results of a detailed study of several of the units are shown in Appendix 3. Variations in trace element concentrations moving away from the contact are erratic and show no definite trends. This is probably due to the small distance along the section of the contact aureole to which sampling was restricted. Trace element concentrations in the unmineralized rocks of the contact aureole in the Investigator 6 area are also shown in Appendix 3.

##### 4.3.2 Discussion.

###### (a) Volcanics.

The W content of the Volcanics is variable with values usually less

TABLE 8

AVERAGE TRACE ELEMENT ABUNDANCES (ppm) IN UNITS OF THE  
MINE SERIES OF No. 1 ORMBODY.

	<u>W</u>	<u>Mo</u>	<u>Sn</u>	<u>Ge</u>	<u>Ti%</u>	<u>Mn</u>
Volcanics	45	<10	<20	<10	0.74	710
Biot.Hfls.	<20	<10	<20	<10	1.34	285
Marble	<20	<10	<20	<10	0.18	1260
Px.Garn.Hfls. <sup>+</sup>	2400	150	120	80	0.20	3000
Px.Garn.Hfls. <sup>*</sup>	50	20	40	20	1.08	1200
Skarn	8700	450	150	95	0.17	3000
Biot.Act.Hfls.	<20	<10	<20	<20	1.63	420
Older Volc.	<20	<10	<20	<20	0.32	470
Quartzite	<20	<10	<20	<20	0.19	125
	<u>Ni</u>	<u>Cr</u>	<u>Co</u>	<u>Cu</u>	<u>Pb</u>	<u>Zn</u>
Volcanics	35	85	55	40	<20	70
Biot.Hfls.	55	120	90	60	20	55
Marble	25	35	<20	40	50	20
Px.Garn.Hfls. <sup>+</sup>	<10	50	70	5	40	20
Px.Garn.Hfls. <sup>*</sup>	50	80	100	5	20	40
Skarn	<10	65	85	35	40	30
Biot.Act.Hfls.	40	70	95	120	20	70
Older Volc.	580	1380	105	20	15	10
Quartzite	10	90	<20	5	<20	25

+ mineralized.

\* unmineralized.

TRACE ELEMENTS (ppm) IN UNITS OF THE MINE SERIES FROMBURCHARD (1972)

	<u>V</u>	<u>Mo</u>	<u>Ni</u>	<u>Co</u>	<u>Cr</u>	<u>TiO<sub>2</sub></u> %
Volcanics	2-40	5-30	60-680	40-110	840	
Actinolite Hornfels	45	40	773		2800	0.25
Actinolite Biotite Hornfels	30	35	835		70	0.37
Hanging Wall Hornfels	2-30	2-5				
Biotite Pyroxene Hornfels	2-40	2-40	36-50	46-345		1.86-3.52
Older Volcanics	2	2-3	820	80	340	0.6
Quartzite	2-20	2-120				
Marble (B lens)	20	15				
Pyroxene Garnet Hornfels	850	50				
Skarn	7400	500	22		36	0.42
	<u>Bi</u>	<u>Sb</u>				
Marble	160	220				
Skarn	75	90				

than 20 ppm but in parts significantly higher. It appears that these rocks were generally impermeable to the mineralizing solutions but some, due to an open texture or fracturing, were more receptive to the W, Ni, Cr and Co in the Volcanics are lower than in the unaltered basic volcanics but the Ni/Cr and Ni/Co ratios are similar showing the similar behaviour of Ni, Cr and Co during metamorphism.

	<u>Ni/Cr</u>	<u>Ni/Co</u>
Metamorphosed	0.41	0.63
Unaltered	0.37	0.48

Burchard's results, however, indicate that in parts Ni and Cr in the Volcanics reach values of 680 and 840 ppm respectively. Zn, which has previously been regarded as an indicator of the Mine Series, shows values in the Volcanics slightly lower than in their unaltered equivalents. Therefore, Zn has been removed slightly during metamorphism.

(b) Biotite and Biotite Actinolite Hornfels.

From the author's results, the pelitic hornfels are barren of W. However, Burchard's results show concentrations up to 45 ppm. This could be due to deposition of scheelite along minor fractures in the rock. Similarly, his high values for Mo could be due to the sporadic occurrence of molybdenite in the rocks. When results from the pelitic hornfels are compared with those of the unaltered sediments, there is little difference between the two with regards to many of the trace elements studied. Mn, Ni, Co and Pb show little variation. Burchard's very high values for Ni and Cr appear rather doubtful. Ti is generally higher in the hornfels than in the sediments, but this is probably a result of differences before alteration since Ti usually remains immobile during metamorphism. The Zn content of the biotite hornfels is similar to that of the sediments, but it is higher in some of the biotite actinolite hornfels due to the preferential incorporation of Zn into the actinolite.

In the pelitic hornfels in the Investigator 6 area Zn and Ti values are comparable with those in the unaltered sediments.

(c) Older Volcanics.

The Older Volcanics are easily distinguished from the Volcanics by their higher Ni, Cr and Co content. The average Ni/Cr ratio of 0.36 is similar to that for the Volcanics, but the average Ni/Co ratio of 5.5 is much higher. Therefore, the Older Volcanics appear to have originally been more basic than the Volcanics, possibly untrabasic. The unit is barren of W and appears to have been unaffected chemically by the metamorphism.

(d) Quartzite.

As expected, the quartzite is low in most of the elements studied, indicating its relative purity and chemical inertness throughout metamorphism. The somewhat high Cr values are probably due to contamination in crushing the samples by the author.

(e) Marble.

Concentrations of certain minor elements in the marble are variable, probably reflecting the extent of metasomatic alteration. One sample which showed the highest W content (30 ppm) also showed higher concentrations of Ni, Co, Ti and Ca than the barren marble. From thin section examination this sample contains higher than usual proportions of impurities such as silicates and magnetite. The high Ni, Co and Ti values suggest that the impurities existed in the original limestone before metamorphism since Ni, Cr and Ti are higher in pelitic than in calcareous rocks. Therefore, metasomatism appears to have occurred more readily where the marble was originally impure. The high Mn content of most of the marble samples suggests that metasomatic fluids have infiltrated the marble beds to some extent. This is also shown by the fluorine in the marble, bound in the humite group of minerals. However, the lack of sufficient impurities which can nucleate the growth of new minerals has limited the extent of metasomatism of new minerals.

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## (f) Pyroxene Garnet Hornfels.

Of the samples of the Pyroxene Garnet Hornfels unit analysed in the preliminary survey, one was metasomatized and mineralized, showing similar results to the skarn and therefore, will be discussed with it. One sample, typical of most of the Pyroxene Garnet Hornfels unit, has not undergone metasomatism to the same extent. The small degree of infiltration metasomatism is shown by the W, Mo, Sn and Ge concentrations of 50, 20, 40 and 20 ppm respectively. These values are intermediate between the barren pelitic hornfels and the mineralized skarn and pyroxene garnet hornfels. Mn has a similarly intermediate value. Ni, Cr and Co contents in the unmineralized pyroxene garnet hornfels are typical of those in the pelitic hornfels. Therefore, it appears to have originally been a very impure calcareous rock. Its trace element composition is similar to that of the tilloid in the Grassy Group as would be expected if the two units are correlated. Zn is lower in the pyroxene garnet hornfels but this is probably due to its mobilization during metamorphism and subsequent metasomatism.

In the Investigator 6 area, a rock of the same origin as the Pyroxene Garnet Hornfels unit (ovoids of calcite, clinopyroxene and garnet in a mainly hornblende groundmass) had similar trace element concentrations as the unmineralized pyroxene garnet hornfels. However, its Sn and Ge content is lower, reflecting a lesser degree of infiltration metasomatism. The Zn content is comparable to that of the unaltered tilloid.

The pyroxene garnet hornfels sampled from drill core along section 7 are metasomatized as shown by the concentrations of Sn, Ge and Mn. Mineralization has occurred but only to a small extent ( $< 0.2\% \text{WO}_3$ ). The samples analysed consisted mainly of groundmass with no ovoids. Mineralization occasionally occurs in the ovoids, but Burchard's results do not show this feature (W - 55 ppm, Mo - 2 ppm). The geochemical results are discussed further with those of the skarn.

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## (g) Andradite Skarn.

In the preliminary survey the andradite skarn and also the metasomatized pyroxene garnet hornfels showed significantly different trace element geochemistry from the other units in the Mine Series. Apart from the high W and Mo values the differences are as follows. The Sn and Ge contents are the highest of all the units. According to Nesterenko et al (1958) Sn and Ge are concentrated in the garnet, pyroxene and vesuvianite. However, the concentration of Sn in garnet, pyroxene and also hornblende from a sample which contained 110 ppm Sn was 58, 11 and 40 ppm respectively. As the proportions of these minerals in the skarn are about 40% pyroxene, 25% garnet and 15% hornblende, it is obvious that a significant part of the Sn occurs elsewhere. It probably occurs as finely disseminated cassiterite which is common in skarns, although none was observed in thin section. Ge follows Sn closely, but most of it would probably be contained in the garnet as indicated by Nesterenko et al.

Ti is low, being similar to the marble beds where Mn is higher in the skarn than in the marble. Ni, Cr and Co are interesting in that whereas Ni is very low, Cr values lie between those for the marble and pelitic hornfels and Co is equal to the values in the pelitic hornfels. They also bear similar relationships to the unmetamorphosed shales. Burchard's analyses of the skarns show slightly lower Cr and higher Ni and  $TiO_2$  than those discussed above, but Ni is still depleted relative to Cr. The Cr and Co values for the skarn indicate the impure nature of the original limestone before metamorphism, as shown by the trace elements in the marble.

From their study of the skarns of the Tyrny-Auz deposit, Nesterenko et al concluded that Ti and Cr are readily removed during skarn formation, Ni at a slower rate and Co remains virtually immobile. The results for the King Island skarns indicate that throughout metamorphism and metasomatism Co and Ti were unaffected, Cr was removed to some extent and Ni was readily removed.

In the detailed study of the skarn, samples of mineralized and unmineralized rock were analysed for selected elements. The results are best illustrated in a number of graphs of the concentrations of the trace elements (ppm) against the percentage of  $WO_3$  as in Figs. 10 to 14. It must be noted that the %  $WO_3$  quoted for each sample may not be strictly accurate since they were determined from assays of samples of drill core up to more than one meter long whereas the samples analysed for the trace elements were taken from only part of this interval. However, the plots are sufficiently accurate to show definite correlation of some elements with mineralization.

Sn and Ge show definite positive correlations with W. A negative correlation could exist between Zn and W but this is not very distinct, mainly due to the scatter of Zn values at low W concentrations. Similarly, Mn shows a scatter of values for the poorly mineralized skarn, but where the W concentration is higher, Mn increases significantly and is usually above 4000 ppm. Cu is very erratic and shows no correlation with W.

The association of Sn and Ge with W indicates that they were deposited in the skarn at the same time and probably originated from a common source, namely the Grassy Adamellite. The lower concentrations of Zn in the mineralized skarn is probably due to its removal by the infiltrating mineralizing fluids. Mn is more difficult to interpret. It appears to have been associated with the mineralizing fluids but high concentrations of Mn are not restricted solely to the mineralized skarn. A possible explanation for this is that Mn was not only associated with the mineralizing fluids but also permeated the rocks in the early metasomatism before mineralization i.e. during the formation of the andradite, producing an irregular distribution of Mn. Further Mn was deposited where mineralization occurred, producing the correlation between Mn and W contents. However, if it is assumed that the Mn was deposited in the skarn only during the early metasomatism (i.e. deposited entirely in the andradite)

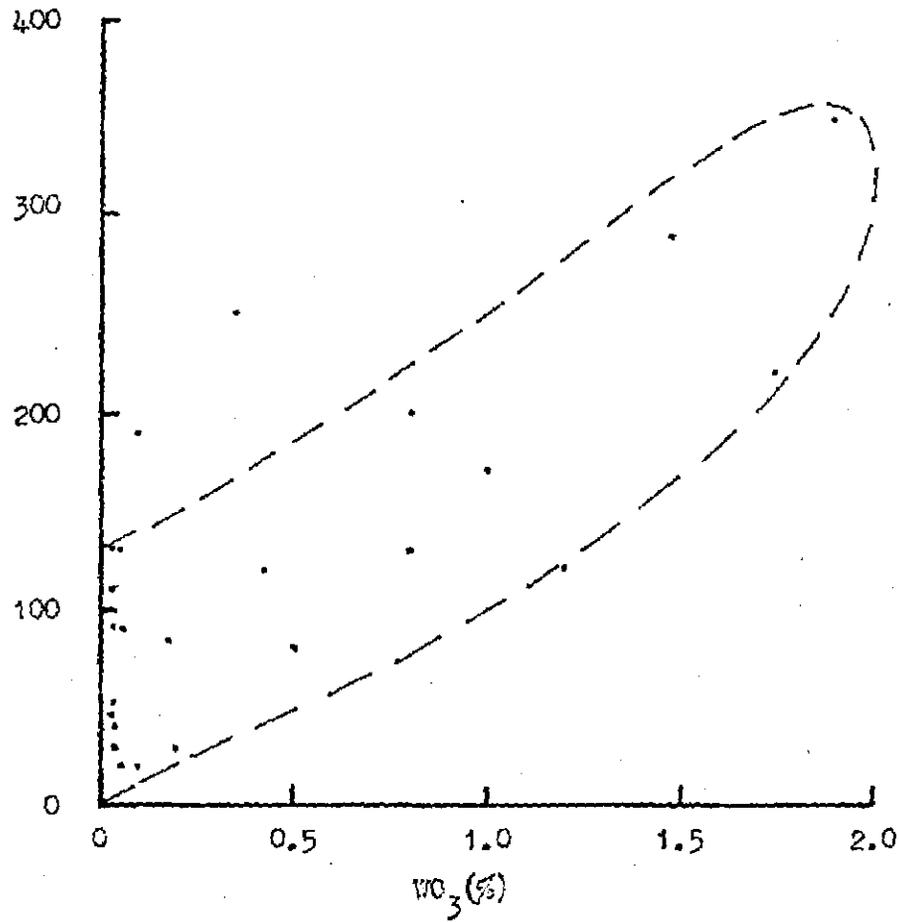
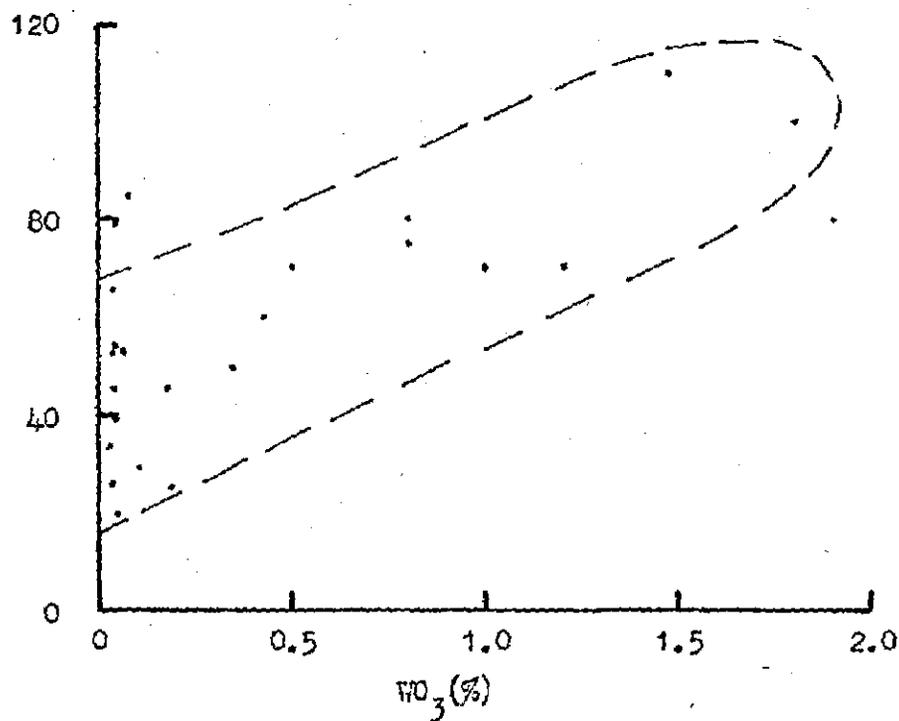


Fig. 10. Plot of Sn against WO<sub>3</sub> in skarn.



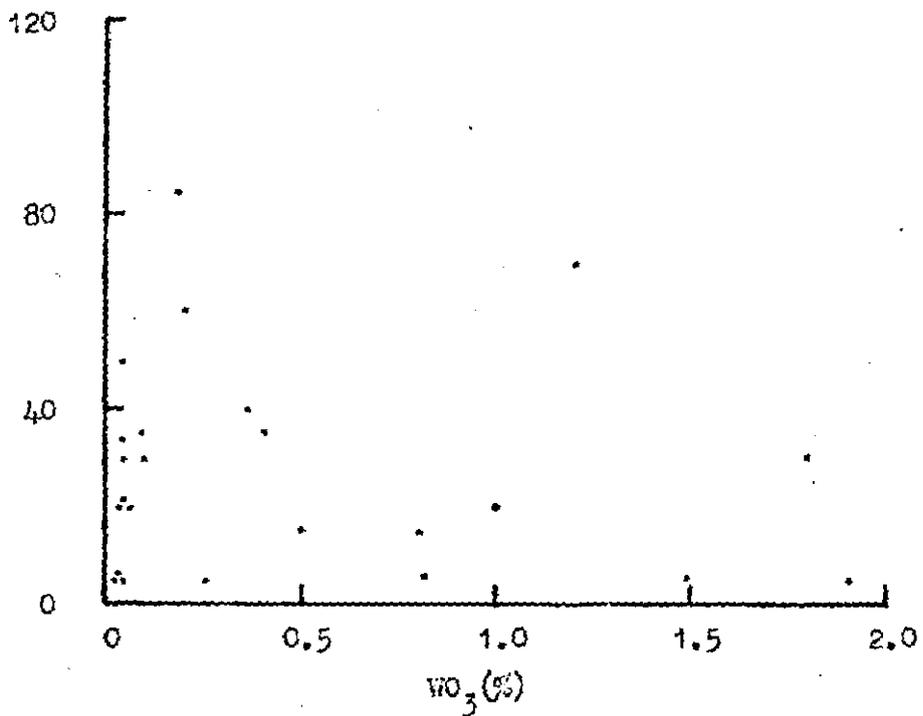


Fig. 12. Plot of Cu against WO<sub>3</sub> in skarn.

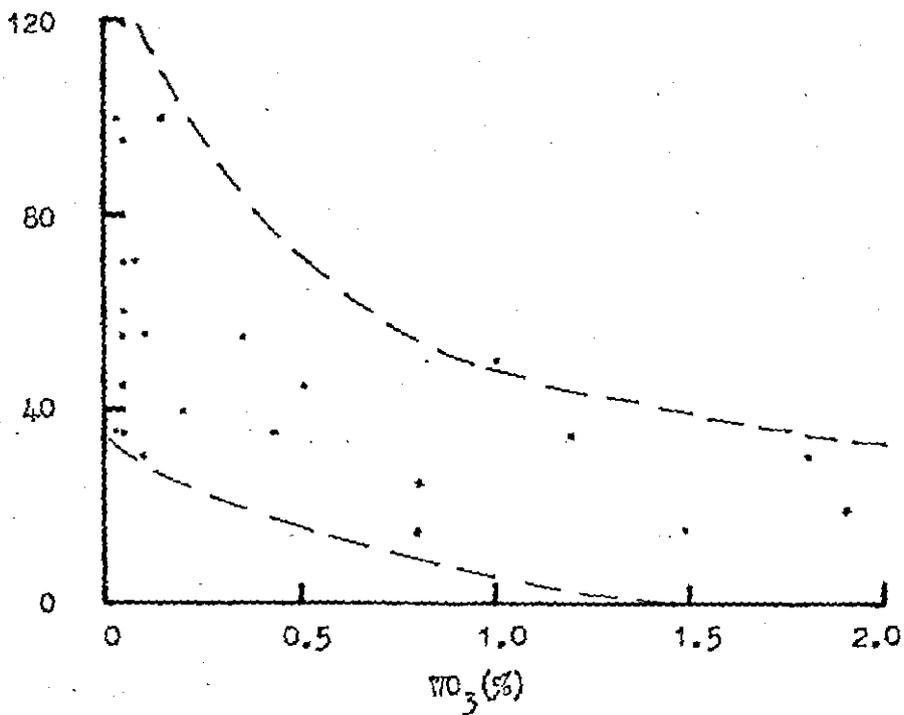


Fig. 13. Plot of Zn against WO<sub>3</sub> in skarn.

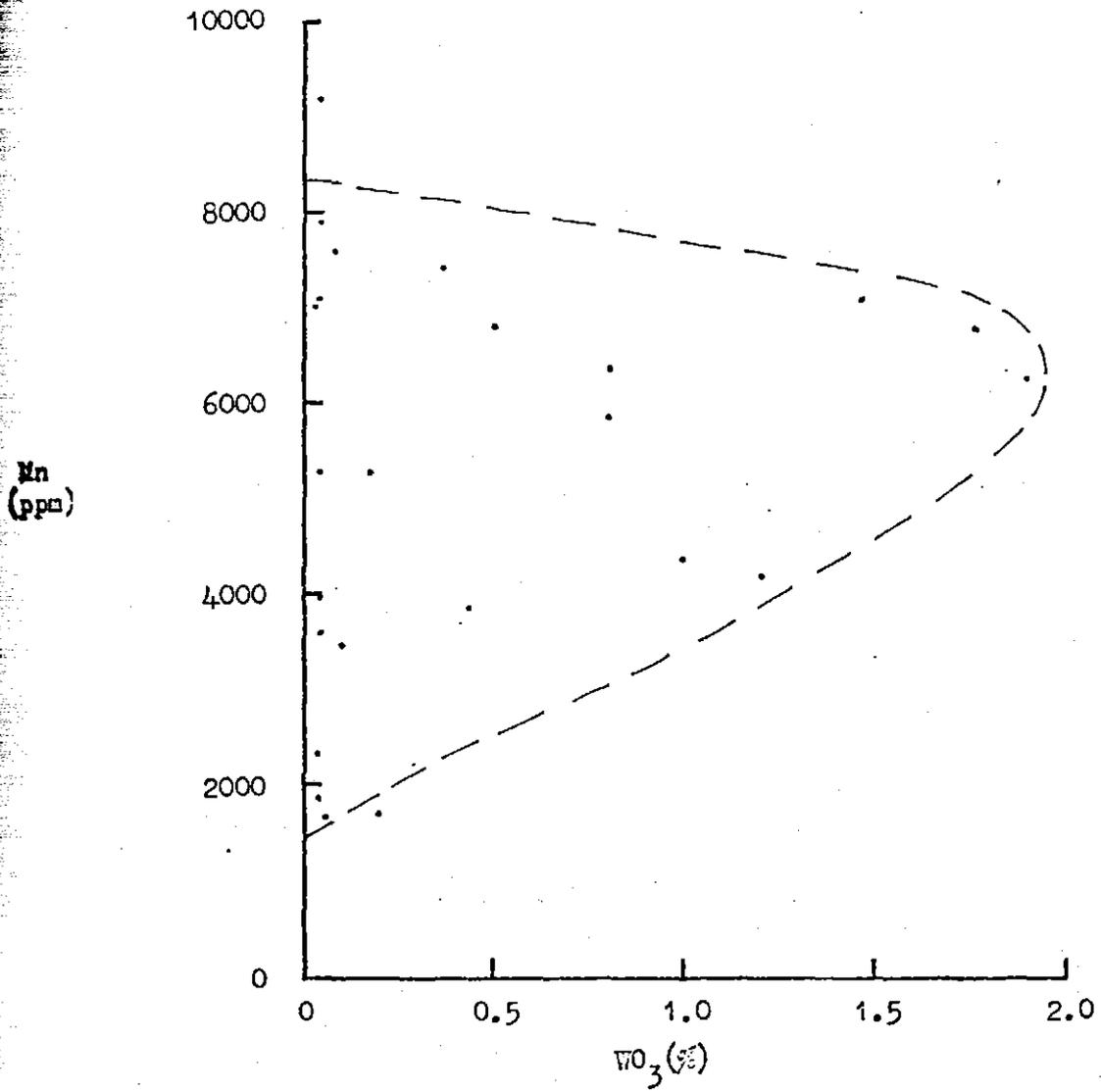


Fig. 14. Plot of Mn against WO<sub>3</sub> in skarn.

then it appears that mineralization occurred only where the concentration of Mn was sufficiently high, but did not reach all parts of the skarn high in Mn.

In the Investigator 6 area two skarn samples were analysed. The skarn in this area is predominantly unmineralized. The lack of W is due, not to an unsuitable environment for mineralization, but to a lack of mineralizing fluids as shown by the low concentrations of Sn, Ge and Mn compared to the mineralized skarn. Zn in these rocks is similar to that in the Mine Series skarn.

CHAPTER 5

TUNGSTEN MINERALIZATION

### 5.1 SOURCE OF TUNGSTEN.

The typical association throughout the world of most tungsten skarn deposits with granitic bodies implies a genetic relationship between the two. However, assuming this is so, there are still several possibilities as to the source of the tungsten. These are :

1. The tungsten was incorporated into the magma when it was first formed and was then concentrated through differentiation into the hydrothermal liquids which were injected into, or permeated through, the country rocks.
2. The magma obtained the tungsten by its diffusion from the country rocks into the magma or by assimilation of the country rocks. The tungsten then follows the same course as in 1.
3. The tungsten was contained solely in the country rocks, the granitic intrusion serving only to mobilize and concentrate it in the appropriate carbonate horizons.

From his study of the King Island scheelite deposit, Burchard (1972) concluded that the tungsten was contained originally in the sediments of the Grassy Group before metamorphism. Moreover, he states that it was mobilized and deposited in its present location as a result of the heating of the sediments, not long after deposition, by basic lavas (now forming the Volcanics unit in the mine series) which were extruded over the Grassy Group. Therefore, according to Burchard's hypothesis, the intrusion of the Grassy Adamellite only served to recrystallize the already present orebodies. His main argument for this is the apparent lack of significant mineralization in the faults and in association with the aplite dykes cutting the mine series. Although mineralization in the faults exposed at present is not abundant, Burchard's argument seems erroneous since, according to Knight and Nye (1953) "The King Island scheelite deposit....  
.....was discovered in 1904 by a prospector, Tom Farrell, while tracing inland a scheelite bearing formation in a fault (the No.3 Fault), that outcropped on the beach at the low water mark".

If the tungsten was originally in the sediments and mobilized by the heat from the basic lavas, then there should be some signs of contact metamorphism and mobilization in areas unaffected by the intrusion of the Grassy or Bold Head Adamellites. In the exposures along the coast to the north of Grassy, this is not evident and therefore, does not support Burchard's theory (assuming the rocks of the Mine Series can be correlated with these sediments and Volcanics). Also, analyses of four samples of unaltered shale for tungsten failed to show anomalous concentrations.

The high concentrations of tungsten found in the sphenes from the Grassy and Bold Head Adamellites (Sections 2.2.6 and 2.3) indicate that the intrusions, at some time, contained a significant concentration of tungsten and therefore, are most likely the sources of the tungsten in the scheelite deposits. The direct correlation of tin and germanium with tungsten in the skarn (Section 4.3.2) indicates a common origin for all three elements and since tin and germanium are known to have been deposited from fluids derived from granitic intrusions, the Grassy and Bold Head Adamellites must have been the source of the tungsten in the King Island deposits.

The stage at which the tungsten was incorporated into the magma cannot be determined with certainty from the present study. The magma has been contaminated as shown in Section 2.6.1 but the material incorporated into it was probably basic and is unlikely to have been a source for the tungsten. Therefore, it is most likely that the tungsten was incorporated into the magma during its formation or shortly after it before crystallization commenced.

## 5.2 CONTROLS ON THE METASOMATIC FLUIDS.

In the Mine Series of No.1 orebody, and also the other orebodies, infiltration metasomatism is restricted to the very calcareous units. Other than the introduction of minor sulphides along fractures and bedding planes, the pelitic hornfels and metavolcanics are unaffected by the metasomatism. The metamorphism recrystallized the pelitic sediments and volcanics into compact, massive rocks impermeable to metasomatic fluids.

The only region where the pelitic hornfels has been metasomatized is where it is adjacent to a calcareous bed. However, the alteration is bimetasomatic, resulting from the two way diffusion of elements across the boundary and only a minor contribution from the infiltrating fluids from the intrusion.

Metasomatic fluids have clearly favoured the beds which now form the andradite skarn. The present marble beds have been comparatively unaffected except for minor alteration restricted mainly to small fractures. This could be due to the relative permeabilities of the skarn and marble during metasomatism. The metamorphism preceding the metasomatism recrystallized the pure limestone to a massive mosaic of mainly calcite grains and therefore, its permeability decreased. On the other hand, the impure limestone recrystallized to a rock containing calc-silicate minerals as well as calcite and this greater degree of mineralogical change resulted in its permeability being greater than that of the pure marble. The metasomatic fluids have therefore, shown a preference for the impure marble beds and altered them to andradite skarn, leaving the more impermeable purer marble beds almost unaffected.

The permeability of the skarn is an important feature in determining the extent of mineralization. A well known feature of the King Island skarn deposits is that the grade of the ore increases with the grain size of the skarn. This result is expected since the permeability would increase with grain size allowing more mineralizing solutions to pass through the coarser grained skarn.

The location of the orebodies at their present sites reflects structural control on the mineralization. Carbonate beds occur in the contact aureole of the Grassy Adamellite on the western side but exploration as yet has failed to find mineralization of the same extent as that in the present orebodies. The beds present a suitable environment for mineralization, forming skarn in parts, but have not been mineralized due to a lack of tungsten rich metasomatic fluids.

The most prominent feature which appears responsible for the localization of the orebodies is the Grassy River Fault which lies just east of Nos. 1 and 2 orebodies and west of No.3 orebody. The control of the fault on mineralization is further implied by the general increase in the grade of the ore in Nos. 1 and 2 orebodies from west to east i.e. approaching the fault. Since the fault is essentially strike-slip in character and was in existence and active while the magma was emplaced, lateral stress applied to the crystallizing magma would have been released along the fault plane. This stress release would have caused the migration of the late stage liquids containing the tungsten towards the fault. Mineralization was therefore, concentrated in regions near the fault and reduced in extent farther away. On this basis, mineralization should have occurred in the fault unless it was very tight due to compression.

### 5.3 MECHANISM OF MINERALIZATION.

Before discussing the actual mechanism by which the scheelite was deposited in the skarn, the form in which the tungsten was transported in the mineralizing solutions must be considered. The oldest view is that tungsten is transported in the form of halides since the halogens, especially fluorine and chlorine, are abundant in late stage magmatic fluids. However, Barabanov (1971) states that on the basis of the heats of formation of tungsten chlorides tungsten cannot be transported in the form of halides or oxyhalides. He also states that under the appropriate conditions the partial pressures of various tungsten halides and oxyhalides are too low for them to be transported in significant quantities. Barabanov concludes that the tungsten is transported in the high temperature solutions in the form of highly soluble potassium tungstates and therefore, the solutions are alkaline.

Bryzgalin (1958), from his study of the Tyrny-Auz skarns, also regards the tungsten bearing solutions as alkaline but, as sodium predominates over potassium in the skarns, he assumed the tungsten was transported as a sodium tungstate which is of similar solubility to

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potassium tungstate.

Transportation of the tungsten in an alkaline solution as either a potassium or sodium tungstate is most likely. Analyses of the King Island skarn show essentially no potassium, so it appears the tungsten was transported as sodium tungstate.

In studying the mechanism of the deposition of the scheelite in the Tyrny-Auz skarns Bryzgalin noted that the scheelite bearing skarns contain sodic plagioclase and amphibolitized pyroxene. He therefore, concluded that scheelite deposition was accompanied by albitization of calcic plagioclase and amphibolitization of pyroxene. The mechanism proposed involved the cation exchange reaction  $2\text{Na}^+ \rightleftharpoons \text{Ca}^{2+}$ . Sodium from the mineralizing solutions became incorporated into the plagioclase and the altering pyroxene and the calcium from these minerals combined with the tungstate anion to form the scheelite. Precipitation of the scheelite resulted from a drop in the pH of the solutions due to the fixation of sodium in the plagioclase and the amphibole. Experimental work has shown that scheelite will precipitate when the pH of the alkaline tungsten-bearing solutions drops to 6 to 7. Experimental hydrothermal work using calcic plagioclase and solutions of  $\text{Na}_2\text{WO}_4$  showed that scheelite can be precipitated by the above mechanism. The possibility that calcium in the scheelite has come from the calcium carbonate in the skarns is argued against by the fact that scheelite is never found associated with the calcite and also the pH of the solutions would not be lowered sufficiently to precipitate the scheelite (Barabanov 1974). Therefore, Bryzgalin's theory explains the deposition of scheelite in the Tyrny-Auz deposits very well.

Application of this mechanism to the King Island deposits seems possible, but some changes must be made. Unlike the skarns of the Tyrny-Auz deposit, the King Island skarn formed only from the very calcareous beds and not the pelitic hornfels and therefore, its aluminium content is much lower. This is reflected in the almost

complete lack of plagioclase. However, amphibole that has formed from calcic clinopyroxene is present and is almost invariably associated with mineralized parts of the skarn. The scheelite is rarely associated with the calcite in the skarn and so the precipitation of the scheelite appears to have been due to the release of calcium and the drop in pH of the mineralizing solutions resulting from the alteration of clinopyroxene to amphibole. Also a necessary prerequisite in the deposition of scheelite is the breakdown of the garnet to produce the clinopyroxene. The occurrence of scheelite completely enclosed in garnet is probably due to the deposition of the scheelite in spaces that had formed in the garnet while breaking down since scheelite doesn't occur in the unaltered garnet in the siliceous skarn.

The alteration of the andradite garnet and its replacement by clinopyroxene suggests that the calcium in the scheelite came directly from the garnet breakdown, since as can be seen from the respective formulae, the garnet is richer in calcium than the clinopyroxene. However, if this is the case, then it is difficult to justify the drop in pH to precipitate the scheelite. Also, garnet commonly reacts to give clinopyroxene where the skarns show little sign of mineralization.

The location of the mineralized regions of the skarn away from the Grassy Adamellite contact reflects unfavourable conditions for the deposition of scheelite close to the intrusion. This is probably due to the very alkaline nature of the metasomatic fluids just after their liberation from the crystallizing magma. In order for the pH to drop to a value suitable for the precipitation of scheelite, the solutions travelled some distance along the beds now forming the andradite skarn. The shape of the orebodies, wedged out against the intrusion (refer cross section 7 of the open cut) suggests that the solutions travelled more readily along the central parts of the units since these regions generally contain the highest grade ore.

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CHAPTER 6

COMPARISON WITH OTHER

MAJOR SKARN TUNGSTEN DEPOSITS

Skarn tungsten deposits are found in numerous localities throughout the world. They are almost invariably associated with granitic intrusions. In this chapter the King Island deposit is compared with two areas of significant tungsten mineralization in skarn, viz. the deposits of the Bishop district, California, U.S.A. and the Tyrny-Auz deposit in Soviet Armenia. These, along with the King Island deposit, are among the largest tungsten producing areas of the world.

#### 6.1 BISHOP DISTRICT.

The skarn tungsten deposits of the Bishop district are located in roof pendants set in the Sierra Nevada batholith. The pendants consist of predominantly interbedded quartzite and pelitic and calcareous hornfels. They range up to several miles long. Most of the commercial deposits are located in the Pine Creek pendant and the Tungsten Hills pendants.

The intrusive rock responsible for the metasomatism and mineralization of the marble in the pendants is a granite which consists of orthoclase (58%), oligoclase (18%), quartz (18%), biotite (5%), accessories (zircon, sphene, apatite and pyrite) (1%) and hornblende (trace) (Lemmon 1941b). This is possibly similar to the composition of the Grassy and Bold Head Adamellites before their contamination.

Skarn has formed in the marble beds close to the contact with the granite. Its mineralogy is similar to that of the King Island skarn. In the Tungsten Hills deposits the minerals comprising the skarn, in approximate decreasing order of abundance, are garnet (mainly andradite with subordinate grossularite), amphibole, pyroxene, epidote, chlorite, quartz, phlogopite, scheelite and sulphides (pyrite, sphalerite and chalcopyrite). The skarn in the Pine Creek pendant consists of garnet (as above), diopside (varying toward hedenbergite), epidote, hornblende, clinozoisite, vesuvianite, quartz, fluorite, sphene, scheelite and sulphides (pyrite, pyrrhotite, chalcopyrite, molybdenite and bornite).

The garnet forms large idioblastic zoned crystals and the pyroxene and hornblende usually occurs as dark green aggregates as in the King Island skarn. The scheelite, however, is often idioblastic with crystals 3 to 25 mm in diameter. The sulphides, apart from molybdenite, are absent from most of the ore indicating that, as at King Island, the scheelite and sulphides formed at different stages.

The petrogenesis of the skarns of the Bishop district, given by Bateman (1965), differs from that proposed by the author for the King Island skarn. Bateman states that the first minerals to develop in the skarn, garnet, pyroxene and scheelite, formed simultaneously and that the proportion of garnet and pyroxene were determined by the relative abundance of silica. Apparently, there is no evidence of garnet altering to pyroxene as in the King Island skarn. The later formed, lower temperature minerals developed in a similar manner in both skarn areas.

As the skarn in the pendants is observed to grade into pure marble, it is clear that it formed from this. However, at King Island the skarn is believed to have formed from impure marble.

Lemmon (1941b) and Bateman (1965) suggest that in the deposits of the Bishop district metasomatic fluids were introduced primarily along fractures and that the extent of skarn development depended on the intensity of fracturing in the marble. At King Island these fluids are believed to have moved mainly along the bedding planes with only minor channelling along fractures. Geochemical data on the deposits of the Bishop district were not available.

## 6.2 TYRNY-AUZ DEPOSIT.

The Tyrny-Auz skarn tungsten deposit is situated in the Tyrnyauz-Pshekish mobile zone which runs along the north slopes of the Front Range of the Caucasian Mountains. Granitic bodies have intruded the zone and the largest of these, the El'dzhurtie biotite granite, is

believed to be responsible for the mineralization of the deposit.

The deposit is distinctly different from both the King Island deposit and those of the Bishop district. The skarn has formed in an anticlinal fold along a stratigraphic boundary between marble and biotite hornfels. Therefore, the metasomatic fluids moved along this boundary so that 80% of the skarns are in hornfels ("hornfels" skarn) and 20% in marble ("limestone" skarn). There is a definite zonation developed parallel to the boundary. Approaching the boundary, the zones in the hornfels are biotite hornfels, amphibole-biotite hornfels, pyroxene hornfels, pyroxene-garnet and garnet-pyroxene skarns. In the marble the zones are marble, vesuvianite-wollastonite skarn, pyroxene and pyroxene-garnet skarns. Therefore, only near the marble hornfels boundary does the composition of the skarns approach that of the King Island skarn. At King Island, this range of skarns has not developed since the biotite hornfels has remained relatively inert to the metasomatic fluids and the development of skarn has therefore been restricted to the marble. The occurrence of wollastonite in the Tyrny-Auz deposit indicates that the skarns probably formed at a higher temperature than that of King Island.

Comparison of the compositions of the biotite hornfels and the hornfels skarn indicates that during skarn formation Fe, Mn and Ca were introduced and Al, Ti and alkalis were removed. The development of skarn in the marble was accompanied by an increase in Fe, Mn, Al, Mg, Ti and Si and a decrease in Ca. Therefore, Fe and Mn must have been introduced to both skarn types from the metasomatic fluids from the intrusion. Bimetasomatic diffusion, as in the banded footwall beds of the King Island deposit, as well as infiltration metasomatism, was significant in the formation of the zoned skarns of Tyrny-Auz deposit.

Besides the zonation parallel to the marble hornfels boundary, there is also a zonation along it. The lower parts of the Tyrny-Auz deposit are nearest the intrusion and are enriched in Fe and Mn while

the upper parts are enriched in Al, Ti and alkalis. The zonation is dependent on the relative proportions of the elements in the metasomatic fluids and the country rock. Fe and Mn are higher in the fluids and therefore are deposited mostly near the intrusion and in decreasing amounts away from it. Al, Ti and alkalis, however, are higher in the hornfels so they are removed by the metasomatic fluids near the intrusion and are redeposited farther away in the upper parts of the deposit. At King Island zonation of this nature has not developed since the skarn formed only in the marble beds which are low in all the above elements relative to the metasomatic fluids.

Comparison of several trace elements in the skarns of the Tyrny-Auz and the King Island deposits have been made in section 4.3.

CHAPTER 7

SUMMARY AND CONCLUSIONS

In the south-east part of King Island the Grassy and Bold Head Adamellites have intruded the Precambrian Sandstone-Siltstone Formation and the Cambrian Grassy Group and overlying basic volcanics. Petrological and geochemical features of the intrusions indicate that they originated from a common source, the Bold Head Adamellite being an offshoot of the Grassy Adamellite and intruded along the Grassy River Fault. Structural elements within the Grassy Adamellite suggest that the Grassy River Fault was active during the emplacement of the intrusions and also at the time of the intrusion of basic dykes into the Grassy Adamellite.

$Ar^{40}/Ar^{39}$  age determinations reveal a late Devonian age (about 370 m.y.) for the adamellites and an early Carboniferous age (345 m.y.) for the basic dykes. From this it appears that the Grassy and Bold Head Adamellites were intruded shortly after the close of the Tabberabberan Orogeny. This is consistent with the post orogenic time of intrusion indicated by the shallow depth of emplacement and the discordant relationship of the intrusions with the country rock. The adamellites were intruded in the same tectonic phase as the Middle Palaeozoic Tasmanian tin granites and are similar to them in many respects.

From a petrological study of the calcareous units of the Mine Series the following conclusions were drawn. The marble beds have undergone mild fluorine metasomatism and have not attained equilibrium as is typical of most metasomatized rocks. The pyroxene garnet hornfels was formed by metamorphism and metasomatism of a calcareous tilloid, the unaltered parts of which are exposed to the north of Grassy. Variations throughout the pyroxene-garnet hornfels are due to variations in the composition of the tilloid. The banded footwall beds originally consisted of thinly interbedded pelitic and calcareous rocks and were formed by the process of bimetasomatic diffusion (defined by Korzhinskii, 1955 and used by Large, 1969 and 1971 in describing the formation of similar rocks in the contact aureole of the Bold Head Adamellite). This involved diffusion of calcium

into the pelitic bands and silica, iron and aluminium into the calcareous bands. Infiltration metasomatism was negligible except where mineralization has occurred in the calcareous bands.

The andradite skarn was formed by infiltration metasomatism of calcareous beds. This consisted of two main phases. The first involved the introduction of iron and silica with the formation of andradite. In the second phase the andradite was replaced by predominantly clinopyroxene which was almost immediately altered in parts to hornblende. Scheelite was deposited at this stage. Following this, the remaining skarn minerals were formed.

Geochemical data supports many of the petrological conclusions. Comparison of trace element distributions in the marble, pelitic hornfels, andradite skarn and unaltered equivalents suggests that the skarn was formed from an impure marble. The determining factor in the metasomatism was the relative permeabilities of the marble beds, the impure marble being the more permeable rock.

The positive correlation of tin and germanium with tungsten in the andradite skarn indicates that these elements originated from the same source, viz. the adamellite intrusions. This is further indicated by the anomalously high concentration of tungsten in the sphene from the adamellite.

The control on the location of the orebodies appears to have been the Grassy River Fault. Stress release along the fault plane during the emplacement of the adamellites caused the localization of the hydrothermal fluids to parts near the fault.

The occurrence of scheelite in parts of the skarn containing hornblende indicates that the deposition of the scheelite was probably associated with the alteration of clinopyroxene to hornblende. Therefore, the mechanism of mineralization is believed to be similar to that proposed by Bryzgalin (1958). By this mechanism tungsten is transported in alkaline hydrothermal

solutions as sodium tungstate which is very soluble in such an environment. During the metasomatism the clinopyroxene is partly amphibolitized and the calcium released by this reaction combines with the tungstate ion. The fixation of the sodium from the solutions into the hornblende results in the lowering of the pH allowing the deposition of the scheelite when it reaches 6 to 7.

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METHODS AND TECHNIQUES

3.1 FIELD METHODS.

The traverse through the Grassy Adamellite was made using a 1:5000 base map No.6016 provided by Geopeko Ltd. Sampling in the open cut (No.1 orebody) was undertaken using an open cut geological plan also provided by Geopeko Ltd. The co-ordinate system used in both maps is the integrated co-ordinate system based on Australian geodetic datum.

3.2 OPTICAL METHODS.

Thin sections were cut in order to make detailed petrographic studies of the rocks. Twenty thin sections were cut by the technical staff of the Geology Department.

High dispersion oils were used to determine refractive indices of the minerals garnet, clinopyroxene, hornblende, actinolite and melilite. Mineral compositions were determined from standard plots of refractive index against composition in Deer et al (1966) and Moorehouse (1959). Plagioclase compositions were determined by the Michel Levy Method involving the measurement of the extinction angles in the zone normal to 010. The plot of extinction angle against composition in Deer et al (1966) enabled the anorthite content of the plagioclase to be determined.

The nodal proportions of the minerals were estimated visually.

3.3 SAMPLE AND MINERAL PREPARATIONS.

Rock samples were crushed initially in a jaw crusher and then in a chrome steel terra to reduce the minerals to a size suitable for analytical work. Mineral fractions were obtained using a Frantz Isodynamic separator. In some instances the heavy liquids bromoform and methylene iodide were used to obtain pure fractions.

### 3.4 X-RAY DIFFRACTOMETRY.

X-ray diffractometry was used for the determination of the magnesium content of calcite and the detection of dolomite in samples of marble. It was also used for the determination of the cell dimensions of garnets in order to determine, with their refractive indices, the occurrence of components other than andradite and grossularite. In all cases Cu K $\alpha$  radiation was used.

### 3.5 X-RAY FLUORESCENCE SPECTROSCOPY.

#### Major Elements:

Eleven total rock samples were subjected to major element analysis by X-ray fluorescence spectroscopy. SiO $_2$ , Al $_2$ O $_3$ , Fe $_2$ O $_3$ , CaO, Na $_2$ O, K $_2$ O, MgO, TiO $_2$ , MnO, P $_2$ O $_5$  and S were determined using the fused borate disc method of Norrish and Chappell (1967). The international geochemical rock standards G-2 and BCR-1 were used. Readings were computerized using a programme supplied by Mr. A.S. Badgley of the Geology Department.

#### Trace Elements:

Rb, Sr, W and Sn were determined by X-ray fluorescence spectroscopy on the intrusive rocks using pressed powder discs with cellulose as the backing.

### 3.6 FURTHER ANALYTICAL WORK.

Many samples were analysed for selected trace elements by McPhar Geophysics Pty.Ltd. W, Mo, Sn, Ge, Ti, Ni, Cr and Co were determined using X-ray fluorescence spectroscopy. Cu, Pb, Zn and Mn were determined using atomic absorption spectroscopy.

APPENDIX 2THIN SECTION DESCRIPTIONS2.1 INTRUSIVES.Sample 100.

Porphyritic Adamellite.

Texture: Porphyritic, hypidiomorphic.

Groundmass coarse grained and inequigranular.

Plagioclase (30%): 0.5 - 5 mm, average 2 mm.

Anhedral to subhedral. Lamellar twinning and normal oscillatory zoning well developed. Average extinction angle normal to 010 is  $13^{\circ}$ , therefore average composition is An 30. Partly sericitized especially along selected zones. Fracturing common.

Orthoclase (25%): Phenocrysts (15%), groundmass (10%).

Phenocrysts: Several centimeters long. Subhedral, distinct rectangular form but margins irregular and accommodate smaller grains. Well developed carlsbad twinning. Perthitic texture. Poikilitic, contain mainly plagioclase and biotite grains. Very little sericitization.

Groundmass: 0.5 - 7 mm, average 3 mm.

Anhedral, very irregular form. Perthitic and poikilitic like the phenocrysts and slightly more sericitized.

Quartz (20%): 0.2 - 4 mm, average 1 mm.

Anhedral. Some grains show irregular extinction indicating strain.

Biotite (17%): Up to 4 mm, average 1.5 mm.

Anhedral, platy. Strongly pleochroic,  $\alpha$  pale brown,  $\beta$  brown,  $\gamma$  dark reddish brown, therefore rich in titanium. Most grains partly altered to chlorite and occasionally epidote and sphene. Some grains completely altered to chlorite.

Hornblende (5%): Up to 3 mm, average 1 mm.

Subhedral, prismatic. Pleochroic,  $\alpha$  light brown,  $\beta$  light green-

brown,  $\gamma$  olive green. Refractive indices,  $\beta = 1.671$ , therefore  
 $Mg/Mg+Fe = 0.54$ .

Magnetite (2%): Up to 0.4 mm, average 0.2 mm.

Anhedral. Usually associated with the mafic minerals.

Sphene (1%): Up to 1 mm, average 0.3 mm.

Euhedral, double wedge form. Slightly pleochroic, brown to darker brown, therefore contains iron. Often contains or is associated with magnetite.

Sample 114.

Xenolith.

Texture: Porphyritic. Approaching a decussate texture. Many grains poikiloblastic.

Orthoclase (25%): Phenocrysts (5%), groundmass (20%).

Phenocrysts: About 5 mm. Subidioblastic. Similar to orthoclase in adamellite.

Groundmass: Up to 1 mm, average 0.4 mm.

Xenoblastic, very irregular form.

Poikiloblastic, contains inclusions of apatite, sphene and zircon. Changed in parts to microcline (cross-hatched twinning).

Partly sericitized.

Hornblende (20%): Up to 1 mm, average 0.5 mm.

Xenoblastic to subidioblastic, prismatic.

Pleochroic,  $\alpha$  pale brown,  $\beta$  olive green,  $\gamma$  green. Refractive indices,  $\beta = 1.683$ , therefore  $Mg/Mg+Fe = 0.42$ .

Occurs in parts as clusters of almost pure hornblende.

Biotite (15%): Up to 1.5 mm, average 0.7 mm.

Xenoblastic, platy. Strongly pleochroic,  $\alpha$  pale brown,  $\beta$  darker brown,  $\gamma$  dark reddish brown, therefore rich in titanium. Most grains partly or completely altered to chlorite.

Quartz (17%): Up to 2 mm, average 0.5 mm.

Xenoblastic. Poikiloblastic, contains inclusions of apatite, sphene and zircon.

Sphene (8%): Up to 0.4 mm, average 0.2 mm.

Xenoblastic to subidioblastic. Dark brown colour. Often occurs as inclusions.

Apatite (5%): Up to 0.5 mm, average 0.3 mm.

Idioblastic, elongate with perfect hexagonal transverse section. Occurs only as inclusions.

Zircon (trace): Up to 0.2 mm, average 0.1 mm.

Xenoblastic. Associated with sphene and apatite.

Sample 304.

Contact Rock - Endoskarn.

Texture: Similar to that for the adamellite apart from the interstitial calcareous assemblage which is very irregular, poikilitic and typical of the textures in the metasomatized rocks.

Plagioclase (60%): 0.2 - 7 mm, average 3 mm.

Anhedral. Well twinned and zoned and same composition as plagioclase in normal adamellite. Well fractured and partly altered to sericite and zoisite especially along the fractures.

Actinolite (15%): Up to 3 mm, average 1 mm.

Subhedral, prismatic to fibrous. Associated with calcite and often grows through it. Faintly pleochroic,  $\alpha$  colourless,  $\beta$  very pale green,  $\gamma$  pale green. Refractive indices,  $\beta = 1.665$ , therefore  $Mg/Mg+Fe = 0.38$ .

Calcite (15%): Anhedral, very irregular form. Poikilitic, contains inclusions of actinolite, sphene and apatite. Interstitial to plagioclase grains.

Sphene (5%): Up to 1 mm, average 0.2 mm.

Anhedral to euhedral. Associated with calcite and actinolite. Contains inclusions of magnetite. Distinctly pleochroic, light brown to dark brown, therefore contains iron.

Quartz (2%): Up to 1 mm, average 0.5 mm.

Anhedral.

Chlorite (2%): Anhedral, irregular form.

Occurs as poorly formed rosettes. Anomalous blue interference colours. Associated with calcareous assemblage between plagioclase grains.

Apatite (1%): Up to 0.3 mm, average 0.1 mm.

Euhedral. Occurs in the calcareous assemblage.

Biotite (trace): 0.2 mm. Anhedral.

Associated and included in plagioclase.

Same as in normal adamellite.

Magnetite (trace): 0.1 mm. Anhedral. Usually associated with sphene.

Sample 165.

Lamprophyre.

Texture: Porphyritic. Groundmass fine grained with a typical basaltic texture.

Plagioclase (65%): Up to 0.3 mm, average 0.1 mm.

Subhedral, lath shaped. Lamellar and carlsbad twinning common.

Normal zoning. Extinction angles normal to 010 vary from  $17^{\circ}$  to  $27^{\circ}$  (An 35 to An 50) in the core of the grains with the larger grains being more calcic. In the rims of the grains the extinction angle is  $3^{\circ}$  (An 22).

Hornblende (32%): Phenocrysts (12%), Groundmass (20%).

Phenocrysts: 0.3 to 4 mm, average 0.7 mm.

Subhedral to euhedral, prismatic elongate. Some grains show carlsbad twinning. Pleochroic,  $\alpha$  pale brown,  $\beta$  light brown,  $\gamma$  darker brown. Refractive indices,  $\beta = 1.697$ , therefore  $Mg/Mg+Fe = 0.25$ .

Some grains partly altered to chlorite with the liberation of calcite.

Groundmass: Up to 0.3 mm, average 0.2 mm.

Anhedral to subhedral. Similar to the phenocrysts.

Magnetite (3%): Up to 0.5 mm, average 0.2 mm.

Anhedral, very irregular form. Occurs in grain clusters.

Contaminants (5%): Anhedral. Mainly orthoclase, 1 to 3 mm, average 2 mm, intensely sericitized. Quartz, up to 0.5 mm, average 0.1 mm, occurs in grain clusters. Also traces of epidote and sphene.

## 2.2 MINE SERIES ROCKS.

Names given are the unit names.

### Sample 237.

Volcanics (silica deficient).

Texture: Granoblastic, fine grained.

Tremolite (60%): Up to 0.4 mm, average 0.2 mm.

Xenoblastic to subidioblastic, prismatic to fibrous.

Randomly oriented.

Spinel (20%): Up to 0.2 mm, average 0.1 mm.

Xenoblastic, very irregular form. Dark green colour, therefore spinel-hercynite composition. Altered in parts to a brown amorphous material.

Phlogopite (13%): 0.1 to 1 mm, average 0.4 mm.

Xenoblastic, platy. Faintly pleochroic,  $\alpha$  pale brown,  $\beta$  pale brown,  $\gamma$  colourless. Poikiloblastic, contains inclusions of tremolite and magnetite.

Forsterite (5%): 0.1 to 1 mm, average 0.4 mm.

Xenoblastic, granular. Grains often occur in clusters with same optic orientation. Poikiloblastic, contains small inclusions of magnetite.

Magnetite (2%): Up to 0.1 mm, average 0.05 mm.

Xenoblastic to subidioblastic, occasionally in the form of small cubes. Usually occurs as inclusions.

### Sample 35.

Volcanics (silica rich).

Texture: Blasto-amygdaloidal. Groundmass fine grained, granoblastic.

Amygdales porphyritic.

Meta-amygdales (50%): 0.5 to 3 mm, average 1.5 mm.

Quartz (15%): Less than 0.05 mm. predominantly. Xenoblastic, granular.

Sericite (15%): Extremely fine grained. Xenoblastic, interstitial.

Biotite (10%): 0.05 to 0.2 mm, average 0.1 mm.

Xenoblastic to subidioblastic, platy.

Magnetite (10%): Up to 0.2 mm, average less than 0.05 mm.

Xenoblastic, rounded.

Groundmass (50%):

Quartz (25%): Up to 0.2 mm, average 0.05 mm.

Xenoblastic, granular. Poikiloblastic, contains small rounded inclusions of magnetite.

Biotite (10%): Up to 0.2 mm, average 0.1 mm.

Xenoblastic to subidioblastic, platy. Poikiloblastic, contains rounded inclusions of quartz and magnetite.

Actinolite (10%): Up to 0.2 mm, average 0.1 mm.

Xenoblastic to subidioblastic, prismatic.

Magnetite (5%): Up to 0.2 mm, average 0.05 mm.

Xenoblastic to subidioblastic, square to rounded shape. Smaller grains usually occur as inclusions.

Sample 44.

Biotite Hornfels.

Texture: Granoblastic, approaching a typical hornfels texture. Fine grained.

Biotite (40%): Up to 0.1 mm, average 0.05 mm. Xenoblastic to subidioblastic, platy. Random orientation.

Quartz (30%): Up to 0.1 mm, average less than 0.05 mm. Xenoblastic, granular. Poikiloblastic, contains small rounded inclusions of magnetite. Some grains occur in elongate grain clusters.

Trenolite (15%): 0.1 to 0.3 mm, average 0.2 mm.

Subidioblastic, fibrous. Fibres usually radiating.

Magnetite (15%): Up to 0.1 mm, average less than 0.05 mm. Xenoblastic, rounded. Smallest grains often occur as inclusions.

Sample 62.

Biotite Actinolite Hornfels.

Texture: Granoblastic. Compositionally banded, bands 1 to 4 mm thick, average 2 mm.

Biotite (30%): Up to 0.1 mm, average 0.05 mm. Xenoblastic to subidioblastic, platy. Randomly oriented. In biotite-rich bands, up to 60% biotite. In biotite-poor bands, up to 15% biotite.

Actinolite (30%): Up to 0.2 mm, average 0.1 mm. Xenoblastic to subidioblastic, prismatic, elongate. Randomly oriented. In actinolite-rich bands, up to 50% actinolite. In actinolite-poor bands up to 15% actinolite.

Quartz (30%): Up to 0.1 mm, average 0.05 mm. Xenoblastic, granular. Evenly distributed through the bands.

Ilmenite (10%): About 0.1 mm. Xenoblastic to subidioblastic, elongate. Randomly oriented. Restricted to biotite-rich bands. Occasionally forms thin bands itself up to 0.1 mm thick.

Sample 66.

Older Volcanics.

Texture: Granoblastic, medium grained.

Tremolite (50%): 0.1 to 1 mm, average 0.4 mm. Xenoblastic to subidioblastic, prismatic. Occasional inclusions of magnetite and spinel.

Forsterite (20%): 0.1 to 0.5 mm, average 0.3 mm. Xenoblastic, very irregular form. Poikiloblastic, contains small inclusions of magnetite.

Spinel (15%): Up to 0.3 mm, average 0.1 mm. Xenoblastic. Shape controlled by other minerals. Dark green colour, therefore spinel-hercynite composition. Altered in parts to brown amorphous material.

Phlogopite (10%): 0.2 to 0.6 mm, average 0.4 mm. Xenoblastic, platy. Occasional inclusions of magnetite and tremolite. Faintly

pleochroic,  $\alpha$  pale brown,  $\beta$  pale brown,  $\gamma$  colourless. 001129

Magnetite (10%): Up to 0.2 mm, average 0.05 mm. Xenoblastic, rounded.

Usually associated with spinel.

Sample 68.

Quartzite.

Texture: Granoblastic, approaching granuloblastic. Fine grained.

Quartz (80%): Up to 0.3 mm, average 0.1 mm. Xenoblastic, granular.

Poikiloblastic, contains very small inclusions of muscovite, rutile and magnetite.

Muscovite (18%): Up to 0.2 mm, average 0.1 mm. Xenoblastic, platy.

In parts occurs as very fine grained interstitial material.

Magnetite (1%): Less than 0.05 mm. Xenoblastic, rounded. Occurs almost entirely as inclusions in quartz.

Pyrite (1%): Up to 0.1 mm, average less than 0.05 mm. Idioblastic, square.

Rutile (trace): Less than 0.05 mm. Subidioblastic, rectangular. Occurs only as inclusions in quartz.

Sample 34.

Marble - C lens.

Texture: In parts granuloblastic, fine grained. In other parts coarser grained granoblastic.

Calcite/dolomite (75%): Up to 2 mm, average 0.4 mm. Xenoblastic.

Granular calcite about 0.3 mm. Irregular grains larger and poikiloblastic, contain inclusions of forsterite and magnetite.

Forsterite (15%): 0.05 to 0.3 mm, average 0.1 mm. Xenoblastic, granular, usually rounded. Distinguished from humite minerals by lack of colour and  $2V_{\gamma} \sim 80^{\circ}$ . Intergrowths form with calcite grains.

Magnetite (5%): Up to 0.1 mm, average less than 0.05 mm. Xenoblastic, rounded. Occurs mostly along fractures and between calcite grains. Some occurs as inclusions.

Xanthophyllite (3%): Up to 0.4 mm, average 0.1 mm. Xenoblastic to subidioblastic, platy. Colourless, non-pleochroic.

Diopside (2%): 0.05 to 0.3 mm, average 0.1 mm. Xenoblastic, granular to slightly prismatic, usually rounded.

Sample 259.

Marble - B lens.

Texture: Granoblastic, approaching granuloblastic. Medium grained.

Calcite/Dolomite (65%): 0.05 to 0.3 mm, average 0.2 mm. Xenoblastic, granular, often polygonal.

Clinohumite (20%): 0.05 to 0.3 mm, average 0.1 mm. Xenoblastic, granular, rounded. Distinctly pleochroic,  $\alpha$  golden yellow,  $\beta$  lemon yellow,  $\gamma$  pale yellow. Most abundant near fractures.

Spinel (10%): Up to 0.3 mm, average 0.1 mm. Xenoblastic, granular. Green colour, therefore spinel-pleonaste composition. Contains inclusions of magnetite. Most abundant near fractures.

Magnetite (5%): Up to 0.1 mm, average less than 0.05 mm. Xenoblastic. Most abundant near spinel.

Sample 51.

Pyroxene Garnet Hornfels.

Texture: Blastopsephitic, calcareous fragments in the original rock have been preserved as ovoids. Groundmass granoblastic, medium grained. Ovoids coarser grained with a more irregular texture.

Ovoids (15%): Up to 3 cm, average 1.5 cm. Percentages of constituent minerals below are given in relation to the ovoids and not total rock.

Quartz (40%): 1 to 10 mm, average 5 mm. Xenoblastic.

Poikiloblastic, contains inclusions of actinolite and pyroxene.

Calcite (25%): 1 to 10 mm, average 5 mm. Similar form to quartz.

Epidote (10%): 2 to 4 mm, average 3 mm. Subidioblastic, elongate. Very faintly pleochroic,  $\alpha$  colourless,  $\beta$  colourless,  $\gamma$  very pale yellow.

Cordierite (10%): 0.5 to 2 mm, average 1 mm. Xenoblastic, very irregular form. Lamellar twinning developed.

Vesuvianite (5%): Up to 0.5 mm, average 0.3 mm. Xenoblastic. Anomalous blue interference colours. Associated with cordierite.

Actinolite (5%): Up to 1 mm, average 0.3 mm. Subidioblastic, needle to fibrous form. Often occurs as inclusions in quartz and calcite.

Pyroxene (4%): Up to 0.6 mm, average 0.3 mm. Xenoblastic, granular. Occurs usually as inclusions in quartz and calcite.

Scheelite (1%): 0.1 to 0.3 mm, average 0.2 mm. Xenoblastic, granular, rounded.

Groundmass (85%): Percentages given in relation to groundmass.

Garnet (60%): Up to 1.5 mm, average 0.5 mm. Xenoblastic, granular. Pale brown colour, therefore predominantly grossularite. Poikiloblastic, contains numerous inclusions of clinopyroxene and quartz.

Clinopyroxene (30%): Up to 0.4 mm, average 0.2 mm. Xenoblastic, granular. Very pale green colour, therefore diopsidic. In parts grains occur in aggregates.

Quartz (10%): Up to 0.3 mm, average 0.1 mm. Xenoblastic. Interstitial to garnet.

#### Sample 56.

Banded Footwall Beds.

Texture: Compositionally banded with bands 0.5 to 1 cm thick. Most bands have a granoblastic texture with the marble and clinopyroxene bands approaching a granuloblastic texture. Pelitic hornfels bands have a typical hornfels texture.

#### Marble Bands:

Calcite (98%): 0.1 to 1 mm, average 0.3 mm. Xenoblastic, polygonal. Poikiloblastic, contains small inclusions of magnetite and clinopyroxene.

Clinopyroxene (1%): Up to 0.1 mm, average less than 0.05 mm.

Xenoblastic, granular. Pale green colour, therefore diopsidic.

Magnetite (1%): Up to 0.1 mm, average less than 0.05 mm.

Xenoblastic.

Melilite Bands:

Melilite (80%): Up to 4 mm, average 1 mm. Subidioblastic, prismatic. Some grains show wide lamellar twinning. Associated with calcite. Intergrowths with calcite occur. Calcite also occurs in fractures in the melilite. Refractive indices,  $\beta = 1.659$ , therefore composition is 34 mol% akermanite, 66 mol% gehlenite.

Calcite (15%): Xenoblastic.

Hydrogrossular (5%): Up to 2 mm, average 0.5 mm. Xenoblastic, granular. Identical to grossularite with uncrossed polars but under crossed polars shows a low birefringence and is uniaxial negative. Occurs near boundary of melilite and garnet bands.

Garnet Bands:

Rarely pure except occasionally in thin bands less than 1 mm thick. Bands usually consist of garnet and clinopyroxene. Grade into clinopyroxene bands.

Garnet: Up to 1 mm, average less than 0.05 mm. Xenoblastic, granular. Refractive index is 1.777, therefore composition is 72 mol% grossularite, 28 mol% andradite.

Clinopyroxene Bands:

Where garnet disappears completely the bands are very pure.

Clinopyroxene: Up to 1 mm, average 0.2 mm. Xenoblastic granular. Pale green colour, diopsidic composition.

Pelitic Hornfels Bands:

Very altered to iron oxides mainly. Only traces of biotite remains. Actinolite forms near the clinopyroxene band.

Sample 13.

Skarn - C lens.

Texture: Porphyroblastic. Smaller grains usually granoblastic.

Poikiloblastic textures common.

Garnet (50%): Up to 5 mm, average 2 mm. Xenoblastic to idioblastic, granular. Poikiloblastic, contains grains of all other minerals in the rock. Thin hydrogrossular rims around large idioblastic grains. Darker brown colour than garnet in pyroxene garnet hornfels, therefore richer in the andradite component.

Clinopyroxene (25%): Up to 1 mm, average 0.2 mm. Xenoblastic, granular and occasionally prismatic. Light green colour, non-pleochroic. Smaller grains occur as inclusions in garnet. Larger grains usually interstitial to garnet. Partly altered to iron-rich material.

Calcite (10%): Up to 3 mm, average 0.5 mm. Xenoblastic. Mainly interstitial to garnet grains.

Hornblende (5%): Up to 1 mm, average 0.2 mm. Xenoblastic to subidioblastic, prismatic. Strongly pleochroic,  $\alpha$  light green - brown,  $\beta$  olive green,  $\gamma$  deep blue green. Associated with the clinopyroxene from which it has formed. Partly altered to iron-rich material.

Quartz (4%): Up to 1 mm, average 0.3 mm. Xenoblastic. Similar form to calcite.

Scheelite (2%): 0.1 to 0.6 mm, average 0.2 mm. Xenoblastic, granular, rounded. Colourless, very high relief. Scattered through all parts of rock except interstitial calcite and quartz.

Opagues (2%): Up to 1 mm. Xenoblastic. Mainly pyrite with a little molybdenite (platy). Interstitial to garnet.

Actinolite (trace): Up to 1 mm, average 0.3 mm. Subidioblastic, needle and wedge forms. Completely enclosed in quartz interstitial to garnet.

Calcite (5%): Xenoblastic. Associated with garnet in the fractures.

Clinopyroxene (2%): Xenoblastic. Associated with garnet and usually enclosed in it. Partly altered to iron-rich material.

Hornblende (2%): Xenoblastic. Similar association as clinopyroxene.

Epidote (1%): Xenoblastic. Interstitial to garnet. Some occurs in the fractures.

Sample 32.

Skarn - C lens.

Similar to sample 13 but the garnet has been more extensively replaced by clinopyroxene. Also zonation is visible through the garnet grains as well as the hydrogrossular rim. In parts, replacement has taken place selectively along certain zones, mainly those richer in iron. Compositions of the major minerals were determined from refractive indices.

Clinopyroxene (45%):  $\beta = 1.713$ ,  $2V_x = 55^\circ$ , therefore composition in relation to the formula  $(Ca Fe Mg)_2 (SiAl)_2 O_6$  is Ca 0.42, Fe 0.31 and Mg 0.27.

Garnet (20%): R.I. = 1.842, therefore composition is 71 mol% andradite, 29 mol% grossularite.

Calcite (15%).

Hornblende (8%):  $\beta = 1.711$ , therefore  $Mg/Mg+Fe = 0.1$ , i.e. ferro-hastingsite.

Quartz (5%):

Scheelite (5%).

Opaques (2%).

Actinolite (trace).

Sample 20.

Skarn - C lens (siliceous).

Texture: Granoblastic, poikiloblastic. Very coarse grained.

Quartz (50%): Up to several cm across. Xenoblastic. Poikiloblastic, contains many well formed garnet grains. Otherwise very clean.

Garnet (10%): 0.1 to 3 mm, average 1 mm. Idioblastic. Zoning and hydrogrossular rim indistinct. Brown colour indicates a predominantly andradite composition as in other skarn described. Replaced to a small extent by clinopyroxene, hornblende and calcite. Well fractured in parts.

APPENDIX 3GEOCHEMICAL RESULTS.3.1 W AND Sn (ppm) IN GRASSY AND BOLD HEAD ADAMELLITES.

Analyses by author (X.R.F.)

<u>Sample No.</u>	<u>W</u>	<u>Sn</u>	<u>Sample No.</u>	<u>W</u>	<u>Sn</u>
72	3	7	184	5	5
74	6	5	185	4	5
101	5	4	186	2	4
114	6	5	191	6	5
125	3	3	194	3	4
143	7	5	195	2	5
169	5	10	304	5	9
180	3	7	305	5	10
181	9	6	306	10	15
182	0	6	324	1	4
183	2	3	327	4	5

3.2 PRELIMINARY SURVEY OF MINE SERIES OF No.1 OREBODY

Analyses by McPhar Geophysics Pty.Ltd.

<u>Sample No.</u>	<u>W</u>	<u>Mo</u>	<u>Sn</u>	<u>Ge</u>	<u>Mn</u>	<u>Pb%</u>
1	6800	360	190	90	3400	0.17
32	10600	540	110	100	2600	0.17
34	<20	<10	<20	<10	580	0.06
35	50	<10	<20	<10	600	0.38
38	40	<10	<20	<10	820	0.59
41	<20	<10	<20	<10	600	0.16
42	30	<10	<20	<10	2600	0.33
44	<20	<10	<20	<10	280	1.07
46	<20	<10	<20	<10	290	1.60
49	2400	150	120	80	3000	0.20
53	50	20	40	20	1200	1.08
62	<20	<10	<20	<10	270	1.54
64	<20	<10	<20	<10	190	1.72
66	<20	<10	<20	<10	780	0.48
67	<20	<10	<20	<10	160	0.15
68	<20	<10	<20	<10	220	0.17
69	<20	<10	<20	<10	60	0.19
70	<20	<10	<20	<10	120	0.20

<u>Sample No.</u>	<u>Ni</u>	<u>Cr</u>	<u>Co</u>	<u>Cu</u>	<u>Pb</u>	<u>Zn</u>
1	<10	70	90	60	50	15
32	<10	60	80	10	30	40
34	<10	30	<20	5	30	15
35	50	80	70	5	<20	80
38	20	40	40	70	<20	60
41	<10	30	<20	10	60	10
42	60	40	20	100	60	30
44	60	130	80	110	30	55
46	50	110	100	5	<20	60
49	<10	50	70	5	40	20
53	50	80	100	5	20	40
62	40	80	80	10	20	60
64	40	60	110	230	20	80
66	180	700	100	10	<20	10
67	190	2100	110	25	20	10
68	<10	100	<20	20	<20	30
69	10	70	<20	10	<20	10
70	10	100	<20	10	<20	30

3.3 DETAILED STUDY OF MINE SERIES OF No.1 OREBODY.

Analyses by McPhar Geophysics Pty.Ltd.

Volcanics:

<u>Sample No.</u>	<u>W</u>	<u>Zn</u>
200	< 20	100
221	< 20	20
236	< 20	30
254	< 20	30
255	< 20	25
256	< 20	15
257	320	20
272	< 20	30

Marble - B Lens:

<u>Sample No.</u>	<u>Zn</u>	<u>Mn</u>	<u>Ni</u>
205	20	3300	15
239	25	1300	20
259	10	2900	25
273	25	1300	20

Biotite Hornfels:

<u>Sample No.</u>	<u>Zn</u>	<u>Ti%</u>
202	95	1.26
223	70	0.27
242	95	1.12
262	90	1.16
275	85	1.00

Biotite Actinolite Hornfels:

<u>Sample No.</u>	<u>Zn</u>	<u>Ti%</u>
218	90	1.89
233	210	1.42
251	320	1.11
268	270	0.40
287	55	1.30
301	85	1.69

Pyroxene Garnet Hornfels:

<u>Sample No.</u>	<u>Sn</u>	<u>Ge</u>	<u>Cu</u>	<u>Zn</u>	<u>Mn</u>
208	50	45	10	100	4000
225	30	25	60	40	1700
244	< 20	20	10	70	1700
265	30	25	30	95	3600
278	20	30	30	55	3500
291	45	40	20	45	2400

Andradite Skarn - C lens:

<u>Sample No.</u>	<u>WO<sub>3</sub>%</u>	<u>Sn</u>	<u>Ge</u>	<u>Cu</u>	<u>Zn</u>	<u>Mn</u>
210	1.82	220	100	15	30	6800
211	0.80	170	80	10	25	5900
212	0.43	120	60	40	35	3900
227	0.35	250	50	40	55	7400
228	<0.05	130	65	35	35	9200
229	<0.05	110	55	340	55	7100
245	0.17	85	45	85	100	5300
246	1.90	350	80	10	20	6300
247	0.50	80	70	15	45	6800
269	0.04	110	55	340	55	7100
270	0.03	130	35	20	70	5300
271	0.04	50	25	10	60	1900
280	0.05	90	80	20	35	7900
281	1.48	290	110	10	15	7100
282	0.08	190	85	35	30	7600
293	0.80	200	75	15	15	6400
294	1.20	130	70	70	35	4200
295	1.00	170	70	20	50	4400

3.4 INVESTIGATOR 6 AREA.Volcanics:

<u>Sample No.</u>	<u>W.</u>	<u>Zn</u>
329	< 20	20
334	< 20	65

Marble:

<u>Sample No.</u>	<u>Zn</u>	<u>Mn</u>	<u>Ni</u>
317	25	240	15
322	15	180	20
331	10	900	30
341	15	1000	25
345	20	600	20

Biotite and Biotite Actinolite Hornfels:

<u>Sample No.</u>	<u>Zn</u>	<u>Ti%</u>
312	70	0.16
320	70	0.70
333	75	0.96
339	100	1.48
344	90	0.70

Skarn and Pyroxene Garnet Hornfels:

<u>Sample No.</u>	<u>Sn</u>	<u>Ge</u>	<u>Cu</u>	<u>Zn</u>	<u>Mn</u>
321	20	20	190	35	1100
335	30	15	10	50	2600
343	<20	<10	110	100	1000

3.5 METAMORPHOSED ROCKS:Volcanics:

<u>Sample No.</u>	<u>Ni</u>	<u>Cr</u>	<u>Co</u>	<u>Zn</u>
340	70	200	120	65
341	55	170	120	85
343	45	75	100	70

Sediments:

<u>Sample No.</u>	<u>W</u>	<u>Sn</u>	<u>Mn</u>	<u>Ti%</u>
353	<20	<20	380	0.83
354	<20	<20	870	0.43
356	<20	<20	260	0.60
357	<20	<20	1200	0.53

<u>Sample No.</u>	<u>Ni</u>	<u>Co</u>	<u>Zn</u>
353	60	65	130
354	65	65	95
356	65	85	120
357	40	70	80

Tilloid:

<u>Sample No.</u>	<u>W</u>	<u>Mn</u>	<u>Ni</u>	<u>Co</u>	<u>Zn</u>
345	<20	730	35	40	60
350	<20	760	60	95	100

3.6 McPHAR ANALYTICAL METHODS.

W, Mo, Sn, Ge, Ti, Ni, Cr and Co were analysed by X.R.F.

Cu, Pb, Zn and Mn were analysed by A.A.S. following hot concentrated HCl leaching and HCl/HNO<sub>3</sub> leaching in the latter stages for one hour of 0.25g of sample.

## APPENDIX 4

Ar<sup>40</sup>/Ar<sup>39</sup> METHOD OF AGE DETERMINATIONS.

The Ar<sup>40</sup>/Ar<sup>39</sup> method is described by Green (1973) and only a brief summary is given here.

The samples dated were subjected to neutron irradiation in the MIFAR reactor at Lucas Heights. The ratio of radiogenic Ar<sup>40</sup> (produced by decay of natural K<sup>40</sup>) to Ar<sup>39</sup> (produced in the fast neutron flux only by the reaction K<sup>39</sup> (n,p) Ar<sup>39</sup> ideally) for each sample was measured with a mass spectrometer. Comparison of these values with Ar<sup>40</sup>/Ar<sup>39</sup> ratios of samples of known ages subjected to identical irradiation enabled the ages of the unknown samples to be determined.

Assuming no interference from the Ca<sup>42</sup> (n,a) Ar<sup>39</sup> reaction and similar reactions, the age of a sample can be determined by the equation

$$t = 4.341 \times 10^9 \log [1 + J (\text{Ar}^{40^*}/\text{Ar}^{39})]$$

where J is a measure of the neutron absorption by K<sup>39</sup> and is given by

$$J = \frac{e^{t_{\text{std}}} - 1}{(\text{Ar}^{40^*}/\text{Ar}^{39})_{\text{std}}}$$

where t<sub>std</sub> is the age of the standard sample dated by conventional means, and T = (λ<sub>α</sub> + λ<sub>β</sub>)<sup>-1</sup> for K<sup>40</sup> decay.

The following table lists the results obtained in determining the ages of the samples.

Sample No.	Mineral	Measured Ratios			Ar <sup>40</sup> (rad)	Jx10 <sup>-3</sup>	Age (m.y.)
		Ar <sup>40</sup> /Ar <sup>39</sup>	Ar <sup>37</sup> /Ar <sup>39</sup>	Ar <sup>36</sup> /Ar <sup>39</sup>			
183	Biotite	158.77	0.017	0.034	93.5	1.453	368
183	Hornblende	157.41	8.81	0.102	80.6	1.718	376
195	Biotite	143.53	0.037	0.052	89.1	1.718	374
165	Hornblende	193.19	5.63	0.123	81.0	1.272	345

APPENDIX 5CATALOGUE OF SAMPLES.

Sample locations are shown on Maps 1 and 2 and the accompanying section. Their co-ordinates are based on the integrated survey grid system. Where a sample was collected from drill core the co-ordinates of the drill hole are given and also the number of the drill hole followed by the depth of the sample in meters. For the drill holes in the open cut however, the co-ordinates are not given.

Preparations:

- a. Thin section.
  - b. Mineral preparation.
  - c. Photomicrograph.
  - d. X-ray diffraction.
  - e. Major element analysis (X.R.F.)
  - f. Minor element analysis (X.R.F.)
  - g. Optical analysis of minerals.
  - h.  $Ar^{40}/Ar^{39}$  age determination.
- } by author.

All samples listed have been subjected to minor element analysis by McPhar Geophysics Pty.Ltd.

<u>Catalogue No.</u>	<u>Field No.</u>	<u>Name</u>	<u>Preparation</u>	<u>Locality.</u>
35055	100	Coarse grained porphyritic adamellite.	a b c g	563400N 219850E
35056	115	"	a c	563050N 219950E
35057	180	"	a b e f	563600N 219650E I8-1/64
35058	181	"	a b e f	562950N 218700E
35059	183	"	a b e f h	559800N 215650E
35060	142	Medium grained porphyritic adamellite.	a c	561000N 217750E
35061	155	"	a c	560250N 217200E
35062	182	"	a b e f	561600N 218550E

<u>Catalogue</u> <u>No.</u>	<u>Field</u> <u>No.</u>	<u>Name.</u>	<u>Preparation</u>	<u>Locality.</u>
35063	106	Biotite adamellite	a c	563250N 219900E
35064	122	" "	a	562250N 218700E
35065	128	Strongly porphyritic adamellite.	a	561850N 218750E
35066	114	Basic xenolith.	a b c f g	563000N 219950E
35067	143	" "	a b f	569950N 217850E
35068	169	" "	a b f	559900N 215950E
35069	304	Endoskarn.	a b c e f g	276/143
35070	307	"	a	276/148.5
35071	184	Microadamellite	a	406/259
35072	185	Porphyritic microadamellite	a c	406/261
35073	101	Quartz porphyry	a c f	563450N 219850E
35074	125	Aplite	a f	562000N 218800E
35075	175	"	a c	559350N 215350E
35076	191	Coarse grained porphyritic adamellite.	a b e f	567210N 220105E 247/65
35077	194	"	a b e f	567065N 220145E 303/154
35078	195	"	a b c e f g h	567210N 220035E 361/57
35079	75	Contaminated hornblende basalt.	a	564280N 219537E
35080	76	Contaminated lamprophyre	a c	564266N 219614E
35081	149	Lamprophyre	a	560600N 217700E
35082	165	"	a b c g h	559800N 216350E
35083	35	Metavolcanic	a	564070N 219940E
35084	237	"	a	125/29.5
35085	44	Biotite hornfels.	a	564163N 219501E
35086	62	Biotite actinolite hornfels	a	564307N 219497E
35087	66	Metavolcanic	a	564278N 219474E
35088	68	Quartzite	a	564256N 219898E
35089	34	Marble	a c	564204N 219525E
35090	42	"	a	564075N 219727E

<u>Catalogue</u> <u>No.</u>	<u>Field</u> <u>No.</u>	<u>Name.</u>	<u>Preparation.</u>	<u>Locality.</u>
35091	204	Marble	a d	106/42
35092	205	"	a c	106/42.5
35093	238	"	a d	125/59
35094	258	"	a d	174/82.5
35095	259	"	a c	174/85
35096	273	"	a d	207/31
35097	317	"	a	564390N 218910E 113/111
35098	322	"	a	564280N 218580E 127/110.5
35099	331	"	a	564290N 218395E 136/151.5
35100	50	Pyroxene garnet hornfels	a c	564170N 219567E
35101	51	" " "	a c	564146N 219662E
35102	53	" " "	a c	564075N 219898E
35103	54	" " "	a	564156N 219942E
35104	343	Hornblende hornfels	a	564475N 218665E I6-2/38
35105	56	Banded skarn	a b c g	564155N 219786E
35106	1	Andradite skarn	a c	564163N 219934E
35107	13	" "	a c	564092N 219854E
35108	32	" "	a b c d f g	564215N 219477E
35109	211	" "	a e	106/73
35110	228	" "	a e	112/130
35111	246	" "	a e	125/82.5
35112	270	" "	a	174/115
35113	281	" "	a	207/58
35114	294	" "	a	422/19.5
35115	2	Hydrogrossular skarn	a	564171N 219929E
35116	27	" "	a c	564195N 219543E
35117	20	Siliceous andradite skarn	a c	564178N 219704E

<u>Catalogue</u> <u>No.</u>	<u>Field</u> <u>No.</u>	<u>Name.</u>	<u>Preparation.</u>	<u>Locality.</u>
35118	31	Siliceous andradite skarn	a	564226N 219478E
35119	18	Banded aluminous skarn	a c	564138N 219783E
35120	33	" " "	a	564193N 219446E
35121	321	Andradite skarn	a	564280N 218580E 127/70
35122	335	" "	a	564365N 218590E 161/56

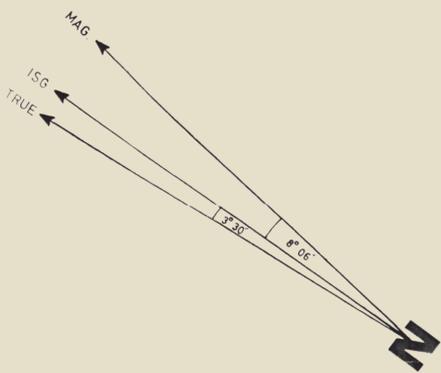
# GRASSY ADAMELLITE GEOLOGICAL TRAVERSE

(To accompany thesis by P.A. Haynes, 1973)

001146

## Map I

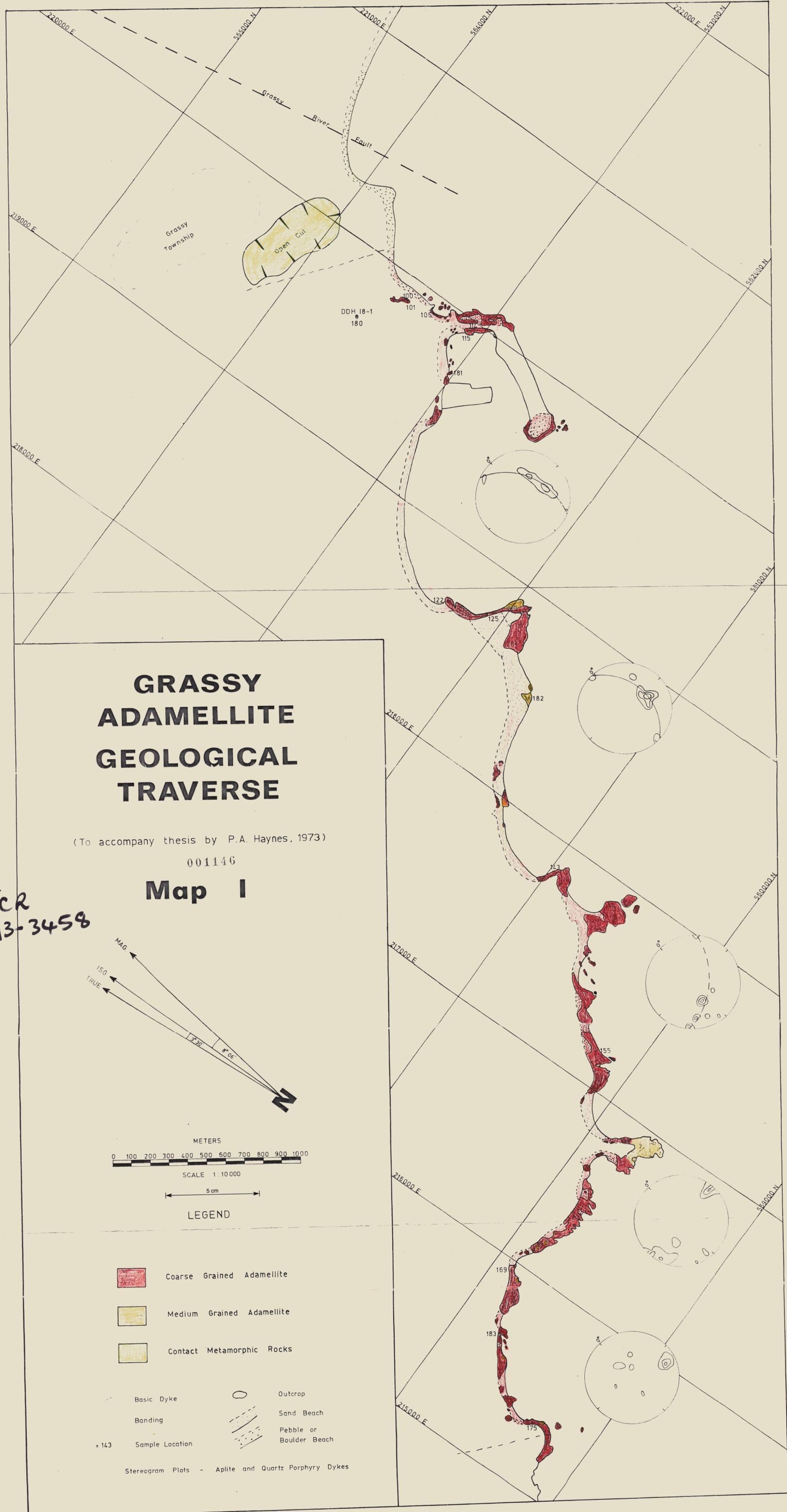
TCR  
93-3458



SCALE 1:10 000

### LEGEND

-  Coarse Grained Adamellite
-  Medium Grained Adamellite
-  Contact Metamorphic Rocks
-  Basic Dyke
-  Banding
-  x 143 Sample Location
-  Outcrop
-  Sand Beach
-  Pebble or Boulder Beach
-  Stereogram Plots - Aplite and Quartz Porphyry Dykes



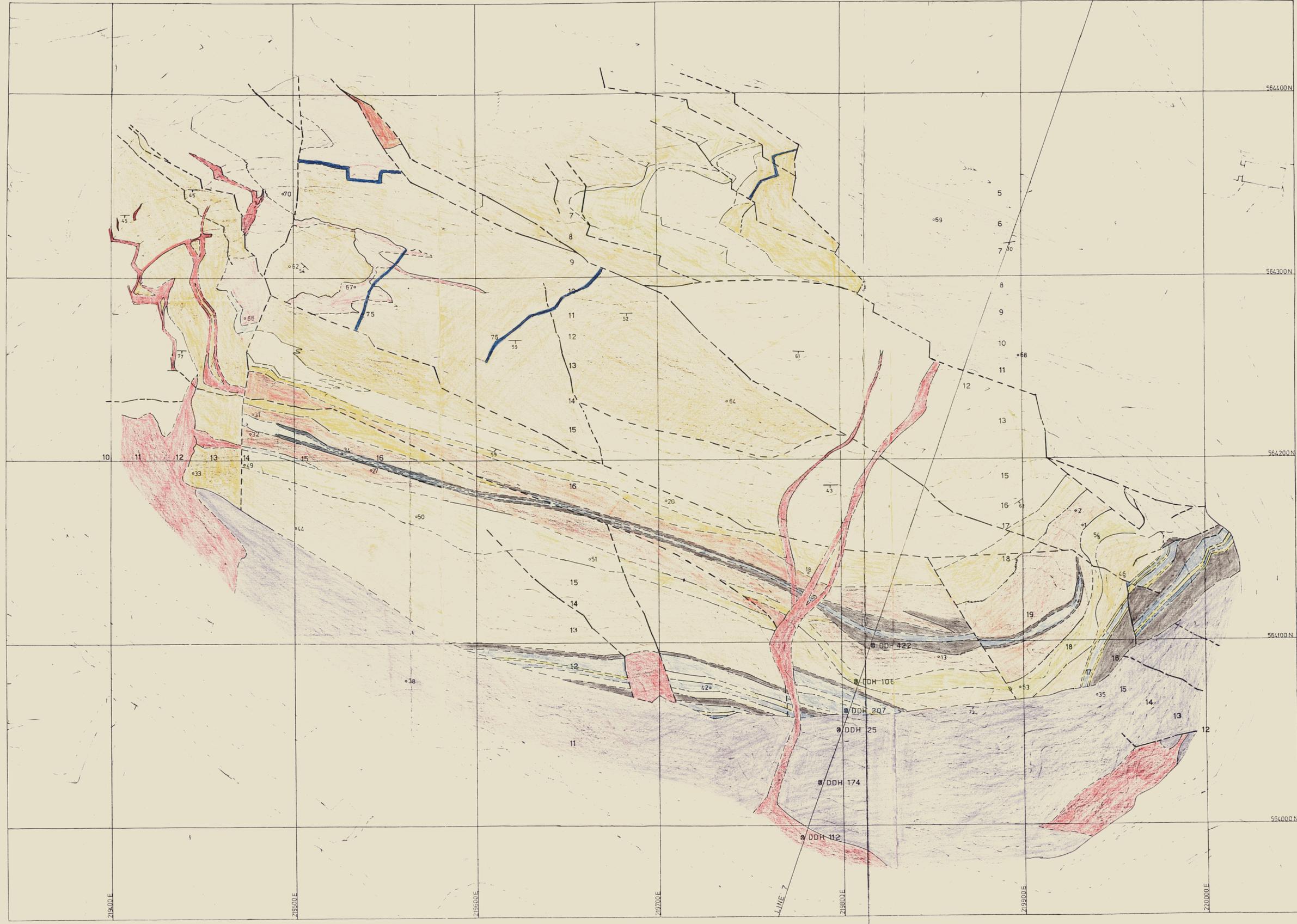
# No 1 OREBODY OPEN CUT GEOLOGICAL PLAN

(To accompany thesis by P.A. Haynes, 1973)

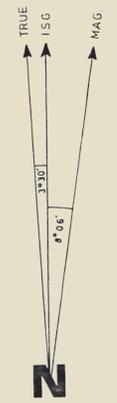
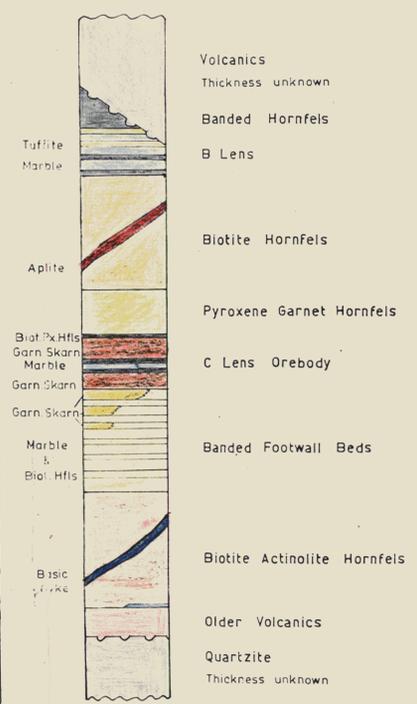
BENCH LEVELS AS AT MARCH, 1973

## Map 2

TCA  
93-3458



### STRATIGRAPHIC SUCCESSION To Scale



SCALE 1 1000



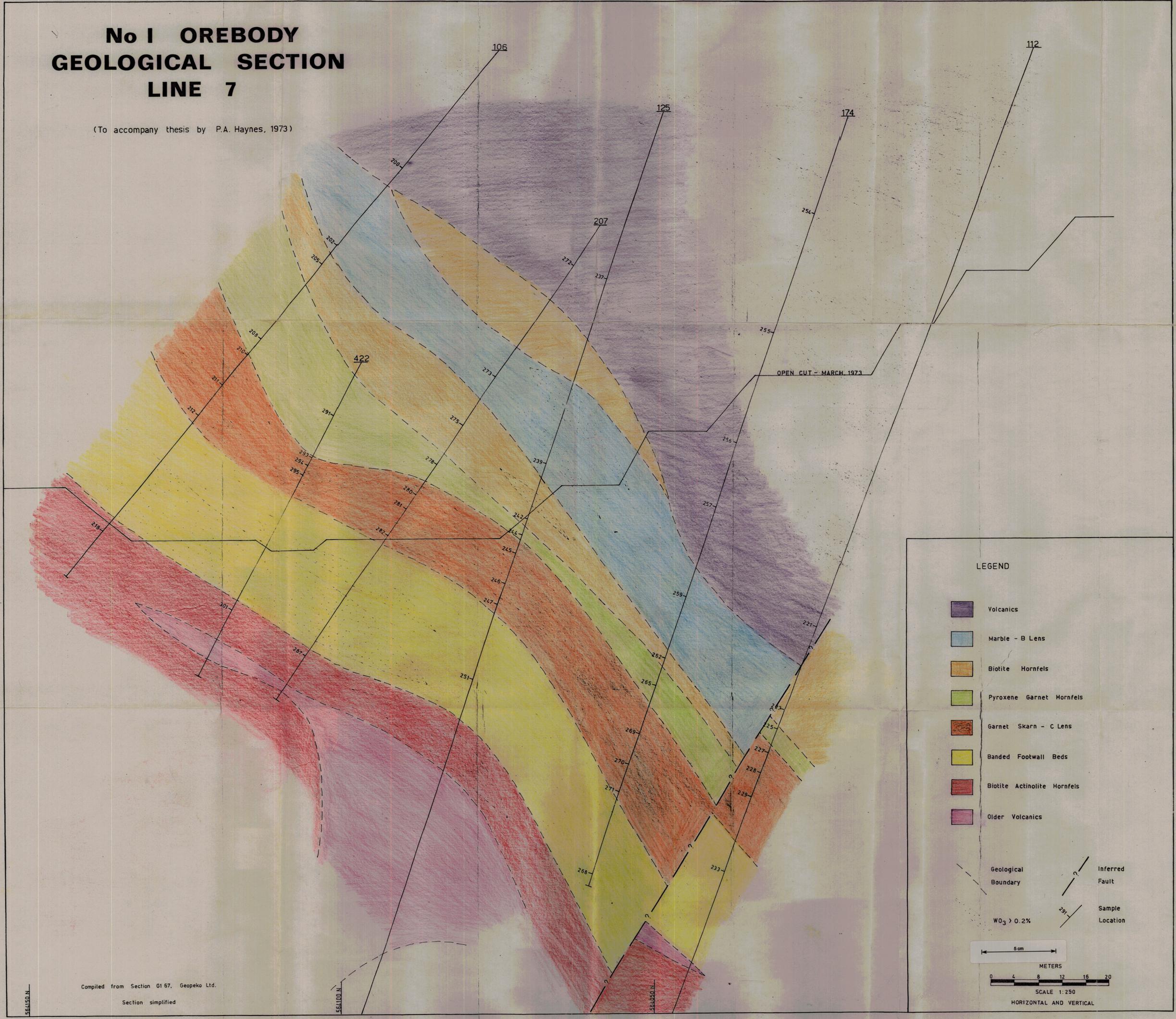
### SYMBOLS

- 20 Sample Location
- 16 Bench Level
- Accurate } Geological Units
- - - Approximate } Geological Units
- Strike and Dip
- Accurate } Fault
- - - Approximate } Fault

Co-ordinate System:  
Integrated Survey Grid  
Compiled from Map K91, Geopeko Ltd

# No 1 OREBODY GEOLOGICAL SECTION LINE 7

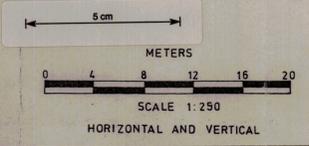
(To accompany thesis by P.A. Haynes, 1973)



### LEGEND

- Volcanics
- Marble - B Lens
- Biotite Hornfels
- Pyroxene Garnet Hornfels
- Garnet Skarn - C Lens
- Banded Footwall Beds
- Biotite Actinolite Hornfels
- Older Volcanics

- Geological Boundary
- $WO_3 > 0.2\%$
- Inferred Fault
- Sample Location



Compiled from Section G167, Geopko Ltd.  
Section simplified

564450 N

564450 N

564450 N