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JAMES COOK UNIVERSITY
AUSTRALIA

# GEOLOGY AND MINERALIZATION, UNITED NORTH AUSTRALIAN MINE, WATSONVILLE, NORTH QUEENSLAND.

By

Neil Fraser, B. Sc. (James Cook University)

December, 1972

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Presented in partial fulfilment for the degree of Bachelor of Science with Honours (Geology and Mineralogy) at James Cook University of North Queensland, Townsville.

*Note. This digital document was prepared from an original, poor quality, carbon copy typed in 1972. A number of changes have been made; correction of spelling mistakes, insertion of words inadvertently omitted from the text, correction of grammatical errors, renumbering of plates and figures, incorporation of plates into the body of the text, revision of punctuation, reformatting of text layout and tables. No changes have been made to the data, descriptions, discussions or interpretations presented in the original document. Neil Fraser, April 2015.*

# TABLE OF CONTENTS

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# ABSTRACT

The United North Australian Mine lies within a roof pendant of sedimentary rocks of Silurian-Devonian age. These sediments have been intruded by the Upper Carboniferous Elizabeth Creek Granite to the south and the Watsonville Granite to the north. High level sub-volcanic porphyries of the Slaughter Yard Creek Volcanics intrude the eastern part of the area.

A mineralised, partially cone shaped, porphyry which was derived from the Elizabeth Creek Granite has been recognised in the area. This body has been named the UNA Porphyry. This porphyry was intruded with a dissolved aqueous phase which separated during emplacement and crystallisation. The resultant hydrothermal fluid produced extensive sericitization and some silicification. Alteration and mineralization proceeded contemporaneously. The metals in the aqueous phase were deposited as disseminated and semi-massive mineralization throughout the porphyry. Massive sulphide bodies are localized within thicker portions of the porphyry such as the Two Treys Mine area.

The polymetallic sulphide assemblage in the Two Treys ore body formed between $334^{o}$ and $235^{o}$C, at pressures possibly as low as 500 bars, and at depths as shallow as 2,000 feet. All the ore minerals apparently formed simultaneously. Metal zoning in the ore body reflects gradients in oxygen and sulphur fugacities present within the hydrothermal fluid at the time of formation rather than paragenesis.

The sulphides have suffered deformation and annealing effects subsequent to their formation. A later stage of mineralization has been superimposed over this earlier stage producing indistinct zoning in the area.

# 1.0 INTRODUCTION

## 1.1 Introduction

This thesis presents the geology of the United North Australian Mine and its environs near Herberton, North Queensland. The project involved both detailed and regional mapping supported by laboratory investigations and was undertaken over a period of ten months. Field studies were carried out during January, February, May and August 1972. A two hundred foot grid laid out by Mareeba Mining and Exploration Pty. Ltd. provided a survey control for detailed mapping. A base map complied from aerial photographs was used for regional mapping. A detailed topographic map, an interpretation of the mine area, and a regional map were produced.

Laboratory studies were directed towards elucidating:

(i) The nature and origin of the massive sulphide mineralization in the mine area.
(ii) The chemical and mineralogical characteristics of the accompanying wall rock alteration.

Twenty-one polished sections were used to study the ore minerals. Twenty thin sections combined with fifteen whole rock analyses were used to study the wall rock alteration. X-ray determinations were also conducted on some of the minerals.

## 1.2 Location and Access

Herberton is 85 miles by road west of Cairns. The thesis area is located six miles west of Herberton on the western slopes of the Great Dividing Range, and includes the old copper and tin mines of the United North Australian Group of workings. The Herberton-Irvinebank road provides access to the area. The old mining settlement of Watsonville is situated just west of the area studied.

## 1.3 Climate

The Herberton district lies within the highlands of the Great Dividing Range. It has a monsoonal climate with dry winters and wet summers. The average annual rainfall varies from 45 inches on the eastern side of the Range to 30 inches on the west. Most rain falls in summer between December and March. The mean daily temperature ranges from 60° F in the winter to 75° F in the summer.

## 1.4 Physiology

The thesis area is more than 3,000 feet above sea level and the physiography is controlled by both lithology and elevation. The sediments in the centre of the area have deeply incised creeks and steep ridges which run westward from the top of the Great Dividing Range (Plate 1). The creek courses are controlled in some places by faulting and porphyry dykes.

The acid porphyry in the southeast of the area display a trellised drainage pattern controlled by jointing and porphyry dykes. To the northeast they have a steeply incised dendritic pattern.

The Watsonville Granite to the north has a subdued topography with gently rounded hills of granite boulders (Plate 8) separated by alluvial flats. To the south, the Elizabeth Creek Granite has moderately steep ridges which are more resistant to erosion due to siliceous alteration associated with tin mineralization.

The vegetation is tropical savannah woodland type on the flatter country, while the more rugged areas carry open forest.

*Plate 1. View of the thesis area looking north. The Herberton-Invinebank road runs across the centre of the photograph. Steep ridges and gullies of the Hodgkinson Formation are present in the centre of the area, north of the road.*

## 1.5 History and Previous Investigations

Cassiterite was first produced in this area in 1883 from the North Australian Mine. In 1890 the small independent mines in the area were amalgamated under the Irvinebank Mining Co. to become the United North Australian Group of Mines. The geology of these mines was first described by Jack (1883) and later by Skertchly (1897).

In 1902 a small high grade copper lode was discovered in the North Australian Mine. A battery to treat tin ores was erected beside Jamie creek in 1911 and further additions and alterations were made in 1917 to allow treatment of copper ores. Major mining operations ceased in 1919 due to problems of treating complex tin/copper ores, and lower grades encountered in the mines. Sporadic tribute mining and the treatment of dumps and stullings continued up to 1957. During this period A. J. Foley and Party worked the existing Ironclad and North Australian mines. The Two Treys ore body was discovered and worked during this period, the ore being sent to the Chillagoe smelters. The major mines worked up to 1919 included the Baal Gammon (Sn, Cu), Easter Monday (Sn, Cu), Crucible (Sn, Cu), Shaugraun (Sn, Cu), North Australian (Sn, Cu), Ironclad (Sn, Cu), Good Friday (Sn) and Grand Secret (Sn), (Maps 1, 2, 3). Total recorded production from the United North Australian Group of Mines has been 1,703 tons of tin concentrates, 292 tons of copper and 22,185 ounces of silver (Marlow, 1967).

In 1937-1938 a geophysical survey was carried out by the Aerial Geological and Geophysical Survey of Northern Australia (Wade, 1938; Jensen, 1938) and the geology of the Herberton district was described by Jensen (1939).

The first detailed exploration programme by a major mining company was carried out by Carpentaria Exploration Co. in 1962. Four diamond drill holes were completed but work was discontinued due to disappointing results (Syvret, 1962).

A further geophysical survey was carried out by the Bureau of Mineral Resources, Geology and Geophysics (BMR) in 1964 to relocate geophysical anomalies previously found in 1938-1938 (Sedmik, 1967). Following this survey a joint drilling programme was carried out by the BMR and the Queensland Department of Mines (Levingstone, 1968). Twelve diamond drill holes were completed and the results were sufficiently encouraging for Carpentaria Exploration Co. to carry out further percussion and diamond drilling in 1966 (Marlow, 1967).

The area was acquired by Great Northern Mining Corporation N.L. in 1969 and an exploration programme supervised by Hall Relph and Associates was carried out. Twenty-five percussion and diamond drill holes outlined a zone of massive sulphide mineralization in the Two Treys area.

Following geological reinterpretation, an option over the area was negotiated by Mareeba Mining and Exploration Pty. Ltd. In 1971. Further diamond and percussion drilling carried out in the Two Treys and other areas of the lease revealed a continuous dipping horizon of disseminated mineralization which contained massive sulphide zones, such as occurred in the Two Treys Mine area.

# 2.0 GEOLOGY OF THE HERBERTON DISTRICT

## 2.1 Regional Geology

The regional geology of the Herberton district is described by Blake (1968, 1970). Other studies have been made by Jensen (1923, 1939), White (1961), Best (1962) and de Keyser and Lucas (1968). Only units which occur within the Herberton district (Fig. 1) are described here.

The Herberton district is situated in the southern region of the Hodgkinson Basin, which forms part of the Palaeozoic geosyncline in eastern Australia. The Hodgkinson Basin has developed unconformably over the eastern margin of the Precambrian Georgetown Inlier which consists of granite intruded gneiss, schist and amphibolite.

Deposition was probably initiated during the late Silurian, when the Palmerville Fault system developed as a hinge zone (de Keyser and Lucas, 1969). To the west of this fault, near shore clastic and mixed clastic-carbonate sediments were deposited in an unstable shelf environment. They are represented by the Upper Silurian to Lower Devonian Chillagoe and Mount Garnet Formations. With accelerating subsidence from about the Middle Devonian onwards, the thick turbedite sequence of the Hodgkinson Formation was deposited, comprising rhythmically alternating sandstone, siltstone and graywacke, with minor intercalated beds of chert, volcanics and limestone.

The relationship between the older Chillagoe and Mount Garnet Formations and the Hodgkinson Formation is uncertain. According to recent work (de Keyser and Lucas, 1968), the Hodgkinson Formation unconformably overlies the older sediments in the south of the Hodgkinson Basin, although further north the relationship appears to be conformable.

The geosynclinal deposits were folded, faulted and regionally metamorphosed during the major Carboniferous orogeny. During the orogeny numerous granitic intrusions were emplaced which produced widespread thermal metamorphism. Extensive acid volcanics were extruded contemporaneously, often in ring complexes and cauldron subsidence areas (Branch, 1966). Widespread mineralization accompanied the igneous activity which continued from the Carboniferous into the Upper Permian.

Continental basalts were erupted over much of the uplifted region in the Cainozoic.

## 2.2 Geology of the Herberton District

The geology of the Herberton district is shown in Figure 1, together with those units which occur within the thesis area. The geology of the 1:63,360 Sheet which covers the Herberton district is described by Blake (1968).

### 2.2.1 Hodgkinson Formation.

The Hodgkinson Formation as described by Blake (1968) includes rocks mapped by Best (1962) and de Keyser and Lucas (1968) as Mount Garnet Formation, Hodgkinson Formation, Ringrose Formation and Montalbion Sandstone. Blake considers that these rocks form a single conformable sequence of similar lithological types, and classifies them as a single formation.

In the Herberton district the Hodgkinson Formation consists of alternating thin bedded sandstone, siltstone, shale, and thick-bedded to massive sandstone with minor conglomerate, limestone, chert and basalt. It has been strongly faulted and folded. The folding is about steeply dipping axial planes and some is probably isoclinal. Further north, Amos (1968) has recognised four separate phases of folding in the Hodgkinson Formation. Three of these phases were recognised in the Chillagoe Formation by Archibald (1971).

De Keyser and Lucas (1968) have compared the Hodgkinson Formation with a geosynclinal flysch facies and believe it is up to 30,000 feet thick in places.

The source area of the sediments is considered by White (1961) to have been the Precambrian Georgetown Inlier.

### 2.2.2 Carboniferous Volcanics

The Glen Gordon Volcanics occur to the southwest of Herberton and are composed of welded tuff sheets, acid lava flows, conglomerate, tuff, tuffaceous sandstone and siltstone. The volcanics are predominantly of rhyodacitic composition and are considered by Branch (1966) to be associated with cauldron subsidence areas. They are approximately 1,000 feet thick and probably of Middle or Upper Carboniferous age. They unconformably overlie the Hodgkinson Formation and are intruded and metamorphosed by both the Elizabeth Creek Granite and the Kalunga Granodiorite.

To the west the volcanics have been gently folded, probably as a result of volcano-tectonic activity related to the formation of the Glen Gordon Cauldron postulated by Branch (1966). In the Herberton district the eastern boundary of this cauldron is covered by Tertiary basalt while the western boundary is complicated by the intrusion of later granites.

The name Slaughter Yard Creek Volcanics was proposed by Blake (1966) for an irregular outcrop of acid volcanic rocks covering an area of about 6 square miles between Herberton and Watsonville. They were previously mapped as Glen Gordon Volcanics (Best, 1963; Branch, 1966).

Blake has described the volcanics as consisting of pale grey acid lavas in the northern part of the outcrop, and pink and grey intrusive rocks in the central and southern part. He indicates that the lava is several hundred feet thick and shows contorted flow banding. The intrusive rocks are thought to be contemporaneous with the lava, and form dykes, inclined sheets, and larger and more irregular bodies.

Field mapping during the course of this study has shown some of Blake’s observations to be erroneous, and these relationships are further discussed in Chapter 3.

These volcanics intrude the Hodgkinson Formation, the Upper Carboniferous Elizabeth Creek Granite and Kalunga Granodiorite, and are themselves intruded and thermally metamorphosed by the Lower Permian Watsonville Granite. Blake (1968) considers them to be Lowermost Permian in age.

### 2.2.3 The Permo-Carboniferous Plutonic Association

Granitic rocks cover large areas of the Herberton district and are probably related to an underlying batholith. The granites were originally divided into two main groups, the Herbert River Granite and the Elizabeth Creek Granite, by White (1961), Best (1962) and Branch (1966).

Detailed work in the Hodgkinson-Mount Garnet region by Blake (1968), has established at least ten different granitic units based on their intrusive relationships. However, a detailed study of revised Rb-Sr ages of granitic rocks from the region by Black and Richards (1972) indicates there were two distinct periods of intrusive activity, around 328 m.y. and 280 m.y. According to Harland et al (1964), these ages correspond to Upper Carboniferous and Lower Permian respectively. This suggests there may be two complex batholiths in the region, each of which consists of a number of granitic intrusions of slightly different ages.

In the Herberton district the Elizabeth Creek Granite (which belongs to the older group) intrudes the Kalunga Granodiorite, and is itself intruded by the Watsonville Granite (which belongs to the younger group) and an unnamed quartz diorite.

### 2.2.4 Cainozoic Basalt

Extensive outcrops of the Atherton Basalt overlie the Elizabeth Creek Granite and the Kalunga Granodiorite to the east of the Herberton district. Pyroclastic rocks are restricted to the immediate vicinity of cinder cones, while lavas erupted from shield volcanoes flowed down valleys to the south, west and east.

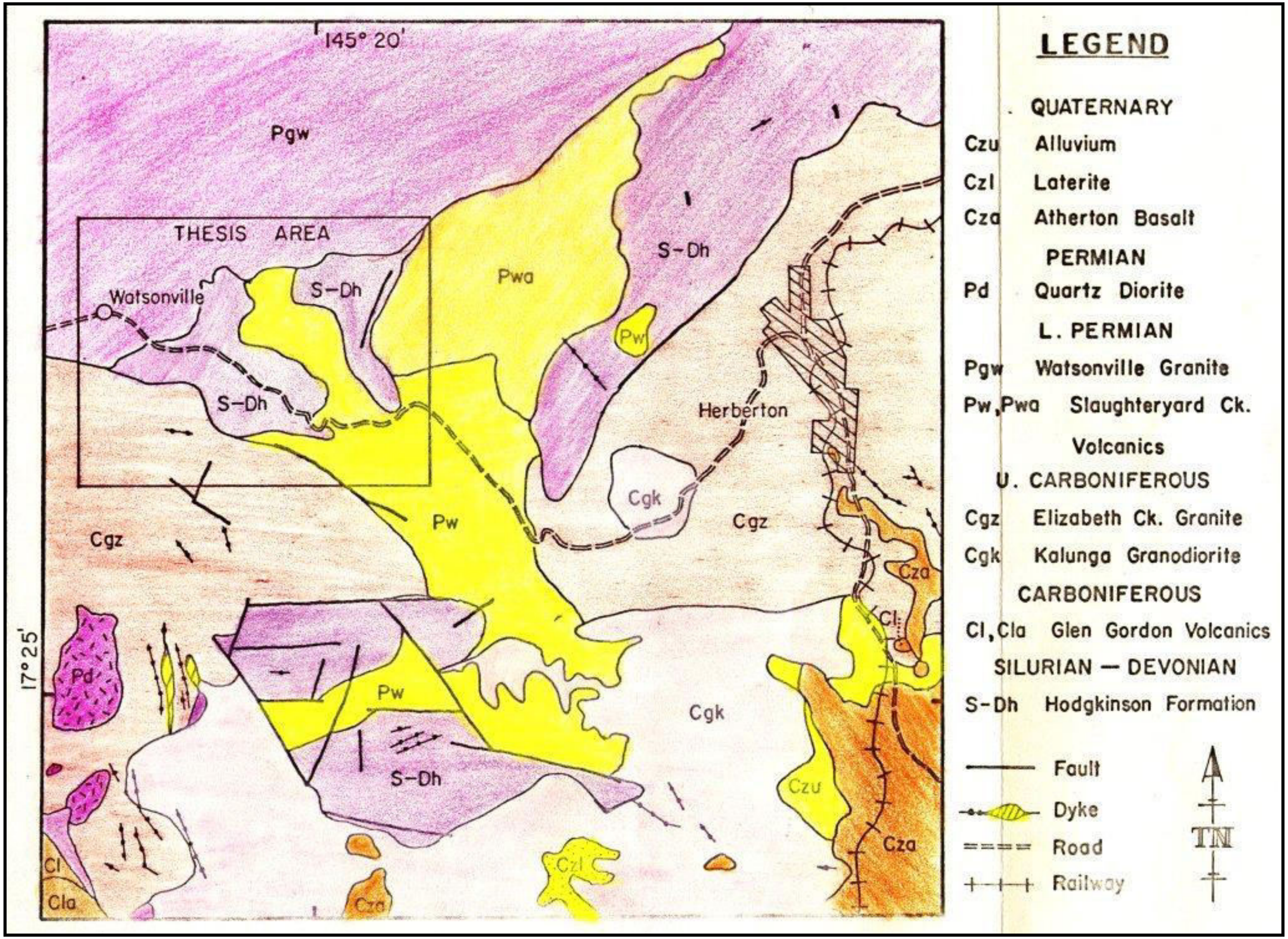

*Figure 1. Regional Geology of the Herberton District. (After Blake, 1968; scale 1:63,360)*

# 3.0 GEOLOGY OF THE THESIS AREA

## 3.1 Introduction

The geology of the thesis area is shown in Map 1. Here a roof pendant of sediments of the Hodgkinson Formation has been intruded by three major igneous units; the Elizabeth Creek Granite, the Slaughter Yard Creek Volcanics and the Watsonville Granite. The sediments have been mineralised, metamorphosed and structurally deformed during these periods of igneous activity.

## 3.2 Sediments

A roof pendant of sedimentary rocks occupies an area of about 1.5 square miles in the centre of the thesis area. These sediments are considered by Blake (1968) to be part of the Hodgkinson Formation. In the thesis area they appear to dip gently at $20^o$ to $30^o$ to the southwest.

Exposure of these sediments is very poor and is restricted to road cuttings, mine workings and occasionally creek beds. The rocks are generally pale to dark grey or greenish grey, but the true colour is often masked by pink or red-brown iron staining. Unweathered material was collected from diamond drill core for detailed examination (Samples 9841, 9842, 9843).

The sediments consist of alternating thin bedded and massive sandstone (Plate 2). Individual beds range in thickness from less than one inch up to a maximum of three feet. Bedding is impersistent with frequent lensing and intertonguing of individual units. The sandstones range from coarse to fine grained and are classified as subgraywacke or feldspathic graywacke and orthoquartzite (after Pettijohn, 1957, p.291). Poorly sorted, angular quartz grains make up from 60-70% of the rock. Feldspar and lithic fragments make up the remainder of the major constituents. The feldspar fragments includes albite, orthoclase, microcline and perthite, while the lithic fragments are porphyritic volcanic material.

The matrix is generally less than 15% and composed of fine grained sericite and quartz with lesser amounts of red-brown biotite, opaque minerals and red iron oxide. A few rounded zircon grains are also present.

A few poorly preserved sedimentary structures are present. The thin bedded sandstones are finely laminated and cross laminations are occasionally present, graded bedding is discernible occasionally, two poorly preserved load casts were seen, and worm burrows were noted in one locality.

Within the thesis area a regional variation in the nature of the sediments was noted. In the northeast the sandstones and quartzites are massive, coarse grained and contain little matrix while in the southwest they become increasingly thin bedded and laminated, finer grained and contain a higher percentage of matrix. This may possibly indicate that the sedimentary material was derived from a source to the east of the area.

The depositional environment of the Hodgkinson Formation has been interpreted by de Keyser and Wolf (1964), de Keyser and Lucas (1968) and Blake (1968) as being marine, with both shallow and deep water sediments formed largely by turbidity currents, and probably constitutes a flysch type environment. The sediments in the thesis area exhibit many of the features attributed to the Hodgkinson Formation by these authors and further support their interpretation.

*Plate 2. Sediments of the Hodgkinson Formation in road cutting near the Shaugraun workings. Fine grained laminated sandstone with a prominent parting parallel to the bedding planes overlie a massive sandstone band.*

### 3.3 Elizabeth Creek Granite

The Elizabeth Creek Granite intrudes the Hodgkinson Formation in the southern part of the thesis area. Blake (1968) has described it as being a pale pink and grey leucocratic adamellite. However, in the thesis area the granite is highly altered. This alteration is spatially related to cassiterite mineralization in the granite and fresh material does not outcrop.

The specimen described here was collected at Carrington Falls by Dr. R. G. Taylor. Here the granite appears unaltered and is some miles from the nearest mineralisation. An analysis of this specimen is presented in Table 1. According to the classification of Nockolds (1954), it is adamellite.

It consists of very coarsely crystalline pink alkali feldspar (40%), white plagioclase (20%), quartz (25%) and biotite (5%). Alkali feldspar is subhedral, very cloudy due to argillization, contains flakes of fine grained white mica and patches of carbonate, and is microperthite. Plagioclase (An28) are subhedral, cloudy with sericitized cores, although they are not apparently zoned. Quartz is anhedral, generally interstitial, and exhibits undulose extinction. A few biotite form tabular red-brown flakes which show slight alteration to chlorite around their margins. The remainder are totally altered to chlorite with spindle shaped stringers of brown epidote. The chlorite has been replaced by small patches of carbonate in places. Tabular grains of sphene are associated with aggregates of altered biotite, and smaller prismatic crystals and granular patches are widespread throughout the feldspars. Prismatic zircons and apatite are also present.

Samples of altered granite from the Glencairn tin mine in the Thesis area are salmon pink in colour and finer grained, although mineralogically similar to the adamellite (Sample 9856). All the feldspars are extensively argillized and have been considerably altered to fine grained white mica. Biotite is totally altered to dark, cloudy, green-brown secondary biotite and chlorite. Iron has been released and forms small opaque grains. Golden zircons with pronounced colourless haloes and purple fluorite are also present in the altered biotite.

With more intense alteration (Sample 9857), the feldspars become totally altered to an irregular mosaic of fine grained aggregates of sericite, green secondary biotite and chlorite. Tourmaline is also present. Silicon is released and deposited as quartz during this alteration process. Altered granite adjacent to the tin lodes (Sample 9860) consists entirely of green secondary biotite and sericite with large round clots of quartz.

A number of analyses of samples of Elizabeth Creek Granite are presented in Table 1.

The average analysis of 13 samples (Table 1, sample D), indicates that the average granite is far more similar to altered granite such as occurs at the Happy Jack Mine (Table 1, sample C) than to the adamellite from Carrington Falls. This adamellite could represent either an insitu differentiate of the Elizabeth Creek Granite or a separate phase unrelated to the mineralization.

The contact between the Hodgkinson Formation sediments and the Elizabeth Creek Granite in the thesis area is poorly exposed, but is quite sharp in samples of float material with obvious thermal metamorphism.

### 3.4 UNA Porphyry

The UNA Porphyry extends across the centre of the thesis area in a discontinuous arc with a total length of over 3,000 feet. The porphyry has a whitish-grey, bleached and pitted appearance and is frequently limonite stained (Plate 3). It was originally comprised of phenocrysts of alkali feldspar, plagioclase and quartz in a granophyric groundmass, but is almost totally altered due to hydrothermal activity associated with mineralization. The detailed petrology will be discussed in Chapter 4.

*Plate 3. Irregular top of strongly silicified and limonite stained UNA Porphyry intruding sediments of the Hodgkinson Formation. Road cutting on Herberton-Irvinebank Road.*

| Sample | 9756 | A | B | C | D | E | F |
|---|---|---|---|---|---|---|---|
| $SiO_2$% | 75.04 | 75.56 | 70.80 | 74.30 | 76.02 | 75.96 | 75.20 |
| $TiO_2$% | 0.14 | 0.12 | 0.25 | 0.20 | 0.10 | 0.14 | 0.05 |
| $Al_2O_3$% | 12.70 | 12.89 | 13.60 | 12.60 | 12.60 | 12.80 | 12.70 |
| $Fe_2O_3$% | 0.63 | 0.37 | 2.50* | 2.40* | 0.49 | 2.20* | 0.07 |
| FeO% | 1.52 | 1.60 | nd | nd | 0.86 | nd | 1.48 |
| MnO% | 0.11 | 0.01 | 0.03 | 0.03 | 0.02 | 0.08 | 0.04 |
| MgO% | 0.14 | 0.29 | 0.35 | 0.10 | 0.14 | 0.01 | 0.60 |
| CaO% | 0.25 | 0.88 | 3.00 | 1.40 | 0.98 | 1.18 | 1.34 |
| $Na_2O$% | 1.26 | 2.76 | 2.80 | 2.70 | 3.35 | 4.20 | 3.39 |
| $K_2O$% | 5.48 | 4.95 | 5.00 | 5.00 | 4.63 | 4.26 | 4.42 |
| $H_2O$+% | 1.34 | 0.53 | 0.95 | 0.60 | 0.51 | 0.30 | 0.44 |
| $H_2O$-% | 0.04 | 0.19 | nd | nd | 0.13 | nd | 0.05 |
| $P_2O_5$% | 0.02 | 0.07 | 0.06 | 0.05 | 0.04 | 0.02 | 0.10 |
| $CO_2$% | nd | nd | nd | nd | 0.09 | nd | nd |
| **Total %** | **98.75** | **100.22** | **99.39** | **99.41** | **99.96** | **101.15** | **99.91** |

* Total Fe determined as $Fe_2O_3$; nd - Not detrmined

Sample Detailes:

| | |
|---|---|
| 9756 | UNA Porphyry, Two Treys Mine, Mareeba Mining and Exploration Pty. Ltd., diamond drill hole DMU 25 |
| A | Elizabeth Creek Granite, Main Road 1 mile south of Herberton, from Blake (1968) |
| B | Elizabeth Creek Granite, Carrington Falls, collected by Dr. R. G. Taylor |
| C | Altered Elizabeth Creek Granite, Happy Jack Mine, Loloma Mining Corp., diamond drill hole HJ 1 |
| D | Average of 13 reported analyses of Elizabeth Creek Granite, compiled from de Keyser and Lucas (1968) |
| E | Watsonville Granite, Main Road 1/2 mile east of Watsonville, collected by Dr. R. G. Taylor |
| F | Watsonville Granite, Main Road 9 miles west of Herberton, from Blake (1968) |

*Table 1. Chemical Analyses of samples of Elizabeth Creek Granite and Watsonville Granite*

Chemically, the porphyry is similar to a rhyolite (Table 1, sample 9756) according to Nockolds (1954) and Joplin (1967). It is shown to be intrusive by the presence of thermally metamorphosed sediments with andalusite and albite in a restricted zone from 5 to 10 feet thick at the base. The porphyry has an average thickness of 50 feet, but varies from 30 to 120 feet.

The outcrop pattern of the porphyry reflects current topography, the original shape of the intrusion, faulting episodes subsequent to intrusion, and alteration and mineralization (Map 2).

In the Baal Gammon and Two Treys Mine areas, the porphyry dips at about $35^o$ slightly west of south, while towards the southeast the dip direction changes to west and the dip becomes steeper. This suggests that the porphyry was originally shaped like a sector of a cone.

Two episodes of faulting have produced considerable displacement of some sections of the porphyry.

The UNA Porphyry is believed to be similar in age to the Elizabeth Creek Granite. It is older than the porphyry dykes of the Slaughter Yard Creek Volcanics which intrude it and is considered to be contemporaneous with, or slightly younger than the Elizabeth Creek Granite. This is discussed further in section 4.9.

### 3.5 Slaughter Yard Creek Volcanics

Blake (1968) has described these volcanics as consisting of acid lavas in the north and intrusive porphyries in the south. He considers the two are contemporaneous. However, detailed field mapping during the study revealed three separate phases all of which are intrusive. In order of decreasing age these are porphyritic rhyodacite, porphyry dykes and intrusive rhyolite.

### 3.5.1 Porphyritic Rhyodacite

The southern and oldest phase is a pink and grey Porphyritic Rhyodacite with phenocrysts comprising nearly 50% of the rock. Approximately equal amounts of anhedral pink microcline (up to 1 cm long), creamy-white plagioclase and rounded quartz phenocrysts are present in a very fine grained groundmass of quartz, feldspar and red-brown decussate aggregates of secondary biotite. Small granules of apatite and prismatic zircons are also present (Sample 9848).

Primary biotite (5%) was originally present but has been totally altered to chlorite with stringers of brown epidote and radiating masses of clinozoisite. This has been replaced by carbonate in places.

Both alkali feldspars and plagioclase (An32) have been argillized and altered to fine grained white mica and carbonate in places. Quartz phenocrysts are occasionally embayed but frequently have frittered margins.

Blake (1968) has recorded sanidine as being present in these rocks but this could not be confirmed.

The contact of this intrusion with the sediments of the Hodgkinson Formation is very poorly exposed in the thesis area. Blake (1968) has interpreted an outcrop in a road cutting west of Herberton as representing the contact between “an irregular body of pale grey acid porphyry belonging to the Slaughter Yard Creek Volcanics” and the Hodgkinson Formation. However, detailed mapping has shown this to be the margin of a large porphyry dyke which intrudes both the Porphyritic Rhyodacite and the Hodgkinson Formation.

Near the margins of the Porphyritic Rhyodacite, a considerable decrease in the size and number of phenocrysts was noted. Flow banding at the margins is absent. This suggests the intrusion was emplaced passively.

### 3.5.2 Porphyry Dykes

The second phase of intrusive activity is represented by a number of porphyry dykes which intrude both the Porphyritic Rhyodacite and the sediments. They form an anastomosing dyke swarm which strikes northwest across the thesis area. The dykes have intruded along a series of faults and although most appear to be vertical, a few show variable dips (Plate 4).

There are two different types of dykes, a porphyritic microadamellite and a coarsely porphyritic rhyodacite. The Easter Monday Porphyry is an excellent example of a rhyodacite dyke while the Jamie Creek Porphyry is an example of a composite dyke of both types. The thickness of the dykes varies from 5 to 350 feet.

The age relationship between the two types of dykes is not apparent in the field. However, their intrusive relationships with other units and their occurrence together in composite dykes suggests they are of a similar age.

*Plate 4. Vertical intrusive contact of rhyodacite dyke (left) with intrusive rhyodacite (right) exposed in road cutting in Slaughter Yard Creek Volcanics on Herberton-Irvinebank Road. Note fine grained margin, flow banding and spherulitic structures in porphyry dyke.*

#### 3.5.2.1 Porphyritic Dykes

These originate from a wide porphyry dyke that intrudes the Porphyritic Rhyodacite near the top of the Great Dividing Range. The dykes are composed of up to 25% large phenocrysts (5-10 mm diameter) of alkali feldspar, quartz and albite, in a fine grained groundmass (Sample 9846).

The alkali feldspar is orthoclase and forms euhedral crystals which have been extensively altered to clay minerals and very fine grained white mica. Quartz phenocrysts are extensively embayed by vermiform intergrowths of fine grained quartz and white mica.

Slightly corroded albite phenocrysts are present with a thin impersistent alkali feldspar rim. Quartz, zircon, red-brown biotite and arfvedsonite are present within the phenocrysts which are extensively argillized.

The groundmass is a very fine grained irregular granophyric intergrowth of quartz and alkali feldspar. It contains irregular clots of red-brown secondary biotite which appear to be replacing strongly pleochroic decussate aggregates of arfvedsonite. Small zircon, epidote and opaque grains are also present. One perfectly developed cuneiform granophyric intergrowth was observed in the groundmass.

The margins of these types of dykes are fine grained and frequently show both flow banding and spherulitic structures. This suggests the dykes were intruded rapidly to very shallow depths and cooled quickly.

#### 3.5.2.2 Microadamellite Dykes

A wide microadamellite dyke has intruded along the contact between the Elizabeth Creek Granite and the Porphyritic Rhyodacite. Another forms part of the Jamie Creek Porphyry.

These dykes are a grey fine grained porphyry comprised of approximately equal amounts of small phenocrysts (1-2 mm diameter) of alkali feldspar, plagioclase (An37-An16) and quartz. The phenocrysts make up to 60% of the rock together with large corroded albite xenocrysts (1 mm diameter). They are present in a fine grained granophyric groundmass of quartz and alkali feldspar (Sample 9847).

Quartz phenocrysts are subhedral and rarely embayed. Alkali feldspars are cloudy due to argillization and contain fine grained white mica. Plagioclase crystals are zoned and cores are frequently extensively sericitized. The calcic cores (An37) are surrounded by more sodic zones whose composition changes from An27 to An16. A thin outermost rim of alkali feldspar is also present.

The xenocrysts are originally albite with an incomplete rim of alkali feldspar approximately 0.2 mm thick. The inside of the crystals have been extensively corroded to produce “islands” of albite which have rims of more calcic plagioclase (An35) deposited around their margins. This rim of plagioclase is itself zoned progressively outwards. The remaining cavities in the sieved structure have been filled by alkali feldspar, quartz, red-brown biotite and chlorite. This xenocryst appears to have been dissolved and sieved by coming into contact with a more calcic magma.

Plagioclase, having the same composition as phenocrysts crystallizing simultaneously in the magma, was then deposited around the remains of the crystal. Blake (1968) has described similar sieved xenocrysts from dykes in this region which occur between Silver Valley and Watsonville, and east of Brownville. He believes that they may be partially melted inclusions derived from the adjacent Elizabeth Creek Granite. No evidence which substantiated or disproved this belief was found in this study.

In the groundmass of the rock, radiating granophyric intergrowths of quartz and alkali feldspar are developed around the margins of the phenocrysts, but have a pronounced preference for plagioclase. The phenocrysts frequently have corroded margins as a result. A few well developed cuneiform intergrowths are also present.

The interstices between the radiating intergrowths are irregular granophyric intergrowths and drusy cavities. Clots of red-brown biotite, partially replaced by chlorite, and opaque grains occupy these cavities. Small prismatic zircons and apatite are also present throughout the groundmass.

These dykes have fine grained margins and flow banding and alignment of fragments is absent. This suggest that they were intruded passively.

### 3.5.3 Intrusive Rhyolite

The third phase of the Slaughter Yard Creek Volcanics is an intrusive rhyolite which occupies the northeast part of the area. This cream-brown rock consists of small phenocrysts of quartz, alkali feldspar and plagioclase 1-2 mm diameter. The phenocrysts comprise 10% of the rock and occur in an extremely fine grained groundmass (Sample 9849).

The quartz phenocrysts are subhedral to anhedral. Many are embayed by the groundmass, while a few appear to have been extensively resorbed and are anhedral with highly frittered margins.

The alkali feldspar is cloudy microcline while the plagioclase is unzoned andesine (An33). Both the alkali feldspar and the plagioclase are partially altered to fine grained red-brown biotite. In some instances the feldspars are totally altered.

The groundmass is extremely fine grained quartz and probably feldspar, with occasional fine grained aggregates of red-brown biotite.

Blake (1968) has described these rocks as pale grey acid lavas several hundred feet thick, showing contorted flow banding. However, detailed mapping during the course of this study revealed that the flow banding was vertical and parallel to the contact of an intrusive rhyolite. It disappears completely within a few hundred feet of the contact as the rocks become more massive. Rotated quartz phenocrysts and fragments of the intruded quartzite and porphyritic rhyodacite are also present within the flow banded rhyolite close to the contact (Plate 5).

The emplacement of this intrusion was fault controlled along part of its western margin. Here a linear zone of brecciated quartzite has been intruded by the rhyolite. Angular quartzite fragments comprise up to 50% of the rhyolite in a narrow zone close to the contact (Plate 6).

The intrusion is interpreted as being a volcanic plug. It appears to have been intruded rapidly to very shallow depths in a highly viscous state and cooled quickly. The near surface wall rocks behaved in a brittle manner and numerous fragments were plucked from them by the rapidly moving highly viscous magma.

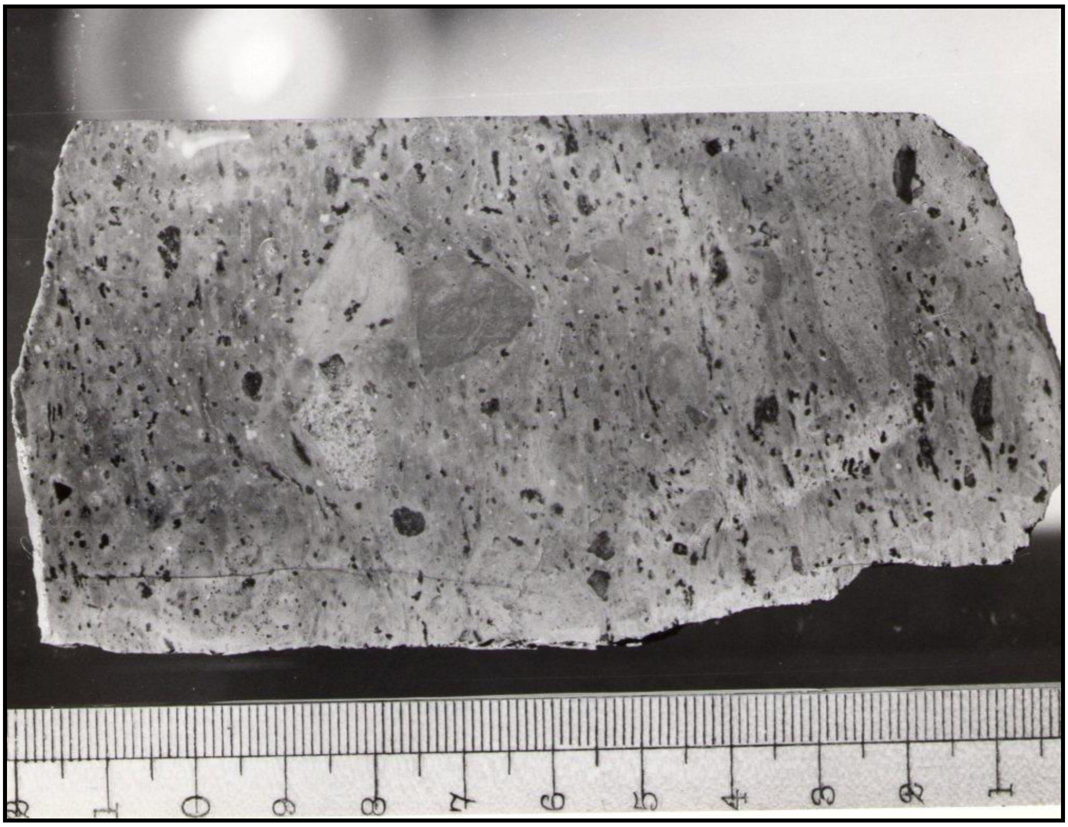

*Plate 5. Flow banded porphyry from the margin of the intrusive rhyolite, Slaughter Yard Creek Volcanics, with fragments of porphyry (white), sediment (grey) and round quartz phenocrysts (black). (Sample 9854).*

It is suggested here that the rhyolite may be an intrusive equivalent of the Walsh Bluff Volcanics which occur a few miles north of the thesis area. The intrusive rhyolite and the Walsh Bluff Volcanics have identical intrusive relationships with other rocks in the area. Both intrude the Elizabeth Creek Granite and both are intruded by the Watsonville Granite (Blake, 1968).

The Walsh Bluff Volcanics consist of subhedral, porphyritic, acid lavas, welded tuff sheets and minor agglomerate and tuff. The presence of features in the rhyolite indicating rapid intrusion at shallow depths make it highly likely that subaerial and pyroclastic extrusive lavas could have been produced. These could have been removed by erosion or intrusion of the Watsonville Granite.

### 3.6 Intrusive Breccias

Two small intrusive brecciated bodies occur in the southern part of the thesis area (Map 1). They are roughly circular in shape and occur partially within rhyodacite dykes of the Slaughter Yard Creek Volcanics, at the contact of the Elizabeth Creek Granite with sediments of the Hodgkinson Formation (Plate 7).

The breccias contain numerous fragments of the fine grained porphyry and arenaceous sedimentary material, which vary from less than 1 mm to more than 5 cm diameter. The larger fragments tend to be more rounded than the smaller angular to subangular fragments. The degree of brecciation within the bodies is variable. The smaller more westerly body is only brecciated in the centre, while the larger body has an intensely brecciated southern portion. The northern portion of this breccia shows intensely contorted flow banding with only occasional fragments.

Most of the porphyry fragments in the breccia exhibit flow banding (Samples 9851, 9852). They contain phenocrysts of plagioclase, alkali feldspar and quartz. The quartz has been extensively resorbed and the feldspars are highly argillized. The groundmass is very strongly recrystallized and now consist of quartz and fine grained argillaceous alteration products.

The intrusive material is a creamy-brown rock, rhyolitic in appearance, with phenocrysts of unzoned plagioclase (An37), alkali feldspar and strongly resorbed quartz. The feldspars are extensively argillized and in some instances totally altered to fire grained aggregates of quartz and argillaceous material. The groundmass consist of highly recrystallized quartz and possibly altered feldspars, plus small fine grained aggregates of carbonate, epidote and green biotite. Prismatic apatite and zircon are also present. Green biotite aggregates are aligned parallel to flow banding in the rhyolitic material.

Although the brecciation post-dates the intrusion of the rhyodacite porphyry dykes, it appears to have formed from flow foliated material from the margins of these dykes. The plagioclase in this intrusion is the same composition as that in the rhyodacite dykes.

Thus it appears that both the rhyodacite dykes and the breccias may have originated from the same magma. The brecciation occurred relatively soon after the intrusion of the rhyodacite and probably before complete crystallization.

The larger breccia also appears to intrude the microadamellite dyke which suggest these dykes may have been emplaced before the rhyodacitic variety.

Porphyry dykes forming intrusive breccias have also been described nearby in Sliver Valley by Blake (1968). He has interpreted these as vent or pipe breccias with the dykes occupying the site of an eruptive fissure. This is probably true in the thesis area also, but the extruded lavas have been totally removed by subsequent weathering.

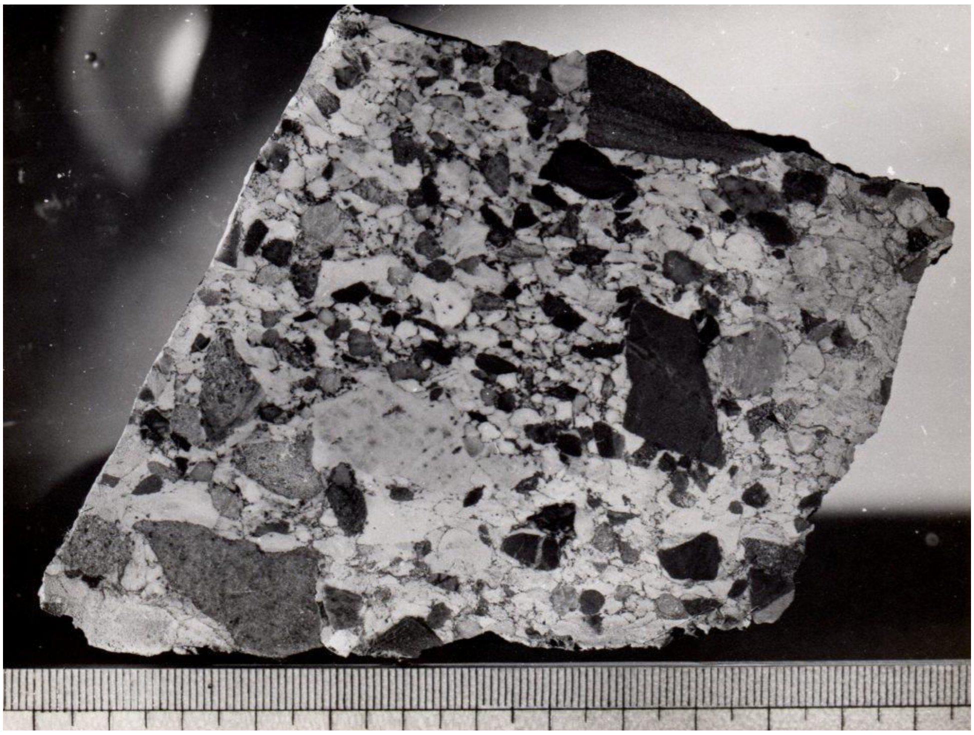

*Plate 6. Intruded fault breccia from western contact of intrusive rhyolite, Slaughter Yard Creek Volcanics. Dark angular fragments are intruded quartzite, lighter coloured fragments are porphyritic rhyolite. (Sample 9854).*

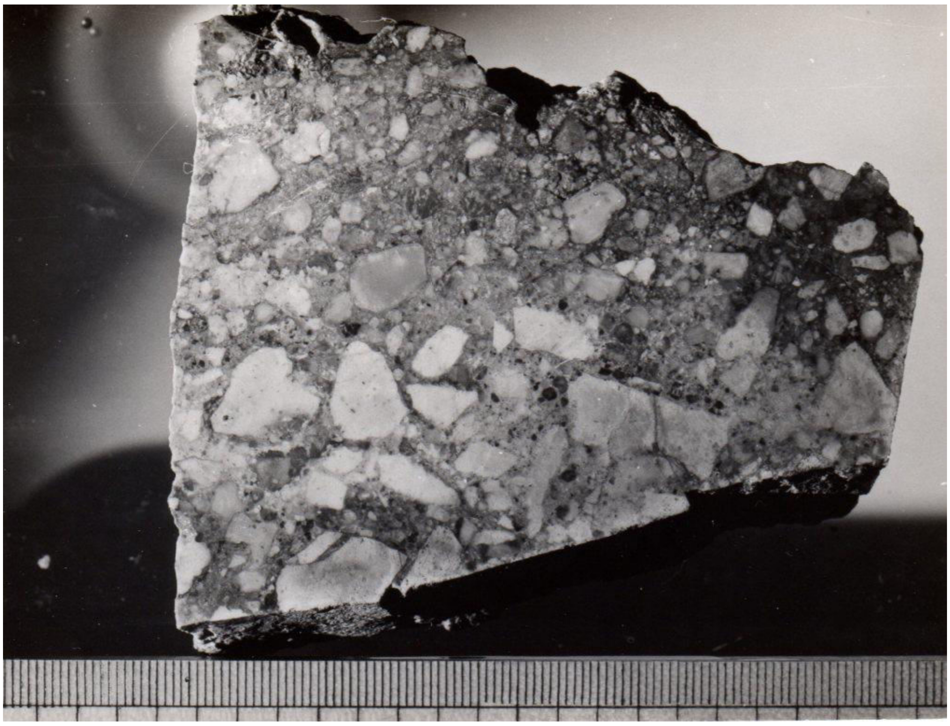

*Plate 7. Intrusive breccia with sub-rounded fragments of porphyry (white) and sediment (dark). (Sample 9851).*

## 3.7 Watsonville Granite

In the northern part of the thesis area the Watsonville Granite intruded and thermally metamorphosed the sediments of the Hodgkinson Formation, as well as the porphyry dykes and intrusive rhyolite of the Slaughter Yard Creek Volcanics.

The Watsonville Granite is a coarse grained orangey-grey biotite adamellite (Sample 9855) which characteristically shows well developed spherical weathering (Plate 8). Two chemical analyses are presented in Table 1, samples E and F. The major components are quartz (20-25%), alkali feldspar (50-60%), plagioclase (15%) and biotite (5-10%). Quartz is interstitial, anhedral and shows undulose extinction. Alkali feldspar is microperthite and forms turbid subhedral crystals which are extensively argillized. Plagioclase forms euhedral crystals some of which are zoned with composition varying from An35 to An20. Myrmekitic intergrowths of quartz and plagioclase are present in places. Biotite forms brown subhedral tabular crystals which are partially altered to chlorite. Zircons with pleochroic haloes and opaque grains form inclusions in the biotite. Small Interstitial clusters of fibrous fine grained white mica are also present.

Sporadic xenoliths of sediment and porphyry are present within the granite close to the southern boundary.

*Plate 8. Watsonville Granite exhibiting large exfoliated boulders.*

### 3.8 Contact Metamorphism

Blake (1968) has recorded widespread contact metamorphism within the thermal aureoles associated with the Upper Palaeozoic granites, particularly the Elizabeth Creek Granite. Blake has recorded the affected rocks as belonging to the albite-epidote-hornfels facies and hornblende-hornfels facies of contact metamorphism.

All samples of sediments examined in the thesis area show pervasive contact metamorphism. The groundmass of the metamorphosed sediments consists of quartz and albite with decussate aggregates of red-brown biotite, numerous minute flakes of white mica and occasional chlorite and muscovite flakes. The margins of the large quartz grains are minutely corroded and are often surrounded by a rim of fine grained flakes of white mica.

The intrusion of the UNA Porphyry also has associated contact metamorphism and porphyroblasts of andalusite and albite have been produced in intruded sediments. The groundmass consist almost entirely of red-brown biotite plus minute flakes of white mica and occasional flakes of muscovite and chlorite (Samples 9775, 9778).

Andalusite bearing hornfels is also very well developed around the contact of the Watsonville Granite and variations in the nature of the thermal metamorphism strongly reflects variations in the nature of the sediments.

In the thin bedded finely laminated sandstones, the thin silty layers are now occupied by small poikilitic andalusite and poikiloblasts of albite (Sample 9780). The andalusite has grown randomly in the planes of the bedding. The quartz rich layers are occupied by strongly recrystallized, polygonal quartz and clots of biotite with minor chlorite. The biotite clots are elongate in, and parallel to the bedding planes, but the individual grains are randomly oriented.

The massive sandstones have large prismatic andalusite needles up to 1 cm long developed randomly throughout the rock (Sample 9781). The andalusites are strongly poikiloblastic with inclusions mainly of quartz. The groundmass consists of poikilitic polygonal quartz plus occasional flakes of muscovite and small andalusite grains.

The quartzites have been strongly recrystallized with coarse grained granoblastic polygonal quartz in a groundmass of fine grained white mica, quartz and muscovite flakes. Small amounts of iron oxide and opaque grains are also present.

All the metamorphosed rocks in the thesis area belong to the albite-epidote-hornfels facies of contact metamorphism (Turner, 1968, p. 192).

### 3.9 Structural Geology

Structural interpretation of the sediments in the thesis area was very difficult due to their weathered and highly broken nature. The most prominent feature present is a fracture which is parallel to the bedding planes. This fracture was shown to be present throughout the area and dip between $20^{o}$ and $30^{o}$ to the southwest. The fracture may represent a cleavage produced by isoclinal folding but no conclusive evidence for the existence of such folding could be obtained.

A variety of facing structures show that in some areas the bedding is overturned. However, they failed to provide any consistent pattern of overturing.

One small scale fold was located and was examined in detail in the laboratory (Sample 9858). In thin section the fold showed no development of axial plane structures or preferred orientation of micaceous minerals, no attenuation of the alternating argillaceous or arenaceous bands, and no deformation of competent grains. This suggest that the folding was produced prior to the consolidation of the sediments, probably by slumping.

Amos (1968) and Archibald (1971) have distinguished up to four phases of folding in the Hodgkinson and Chillagoe Formations further north, while Blake (1968) has mapped large scale folding in the Irvinebank and Mount Garnet areas. Some of the folds recognised by Blake may be isoclinal. It would therefore, be quite reasonable to expect some type of deformation due to folding in the thesis area. However, the intrusion of the granite plutons and a suite of level sub-volcanics, together with the accompanying contact metamorphism and extensive small scale fracturing, faulting and jointing could have destroyed any evidence of this.

It is also possible that the intense small scale fracturing, faulting and jointing, is in fact the deformation produced in this area by the Lower Carboniferous orogeny and subsequent intrusion of the Elizabeth Creek Granite. If, as suggested by Branch (1966), the granite is a high level intrusion, the near surface wall rocks would tend to deform in a brittle manner. This deformation is a pre-Elizabeth Creek Granite effect, because these structures have acted as controls for the later tin lodes.

Two phases of faulting are present in the area. These faults are rarely seen in the field and can usually only be interpreted from outcrop patterns. The fault exposed in the western Baal Gammon open cut is an exception (Plate 9). The oldest and most pronounced faults strike northwest across the area.

*Plate 9. Vertical fault surface of a second phase fault exposed in the Western Baal Gammon open cut.*

They have produced considerable displacement of the UNA Porphyry. Many of these faults have been intruded by porphyry dykes of the Slaughter Yard Creek Volcanics. The attitude of these dykes is variable and suggest some may be reverse faults while others may be normal (Cross section 1).

The second phase of faulting strike north-south and truncate the first phase. These faults have displaced both the UNA Porphyry and the porphyry dykes and are only apparent in the mine area. The fault exposed in the western Baal Gammon open cut belongs to this second phase (Plate 9).

A northwest trending fault is present along the western margin of the intrusive rhyolite phase of the Slaughter Yard Creek Volcanics. The relationship of this fault to the other two phases is uncertain, but its orientation and relationship to the igneous units suggests it belongs to the same phase of faulting. The attitude of the second phase faults is uncertain but where it can been seen, it is vertical.

Insufficient data was available to determine whether the relative directions of movement along the faults was vertical, horizontal or a combination of both. However, the trends of faults observed in the thesis area agree with regional observations of Blake (1968) who described a pronounced northwest trend and a lesser northeast trend.

## 3.10 Conclusions

### 3.10.1 Geological History

Reconnaissance mapping during this study provided a great deal of additional information on the regional geology of this area. The geological history has now been shown to be far more complex than previously indicated by Blake (1968), especially with regard to the igneous activity. Blake recognised three separate episodes of igneous activity and four different igneous units in this area. During the present study, at least six different episodes of igneous activity and eight different units have been recognised. The conclusions of Blake (1968) and those from this study are summarised and compared in Table 2.

| Blake (1968) | This Study | Indicated Age |
|---|---|---|
| Watsonville Granite | Watsonville Granite | Lower Permian<br>(Rb/Sr 280 m.y.) |
| Slaughter Yard Creek Volcanics (Acid lavas and intrusive porphyries) | Intrusive Rhyolite | Upper Carboniferous<br>(This study) |
| | Second Phase of Faulting | |
| | Intrusive Breccias | |
| | Rhyodacite Dykes | |
| | Microadamellite Dykes | |
| | First Phase of Faulting | |
| | Intrusive Rhyodacite | |
| | UNA Porphyry | Upper Carboniferous<br>(This study) |
| Elizabeth Creek Granite | Elizabeth Creek Granite | Upper Carboniferous<br>(Rb/Sr 328 m.y.) |
| | ? Small scale faulting, fracturing and jointing | |
| Orogeny | Orogeny | Lower Carboniferous |
| Hodgkinson Formation | Hodgkinson Formation | Silurian-Devonian |

*Table 2, Comparative summary of geological history.*

### 3.10.2 Plutonic Environment

Branch (1966) has indicated that the granitic rocks in this region are high level varieties because of the presence of ring dykes and cauldron subsidence structures. He has estimated the depth of intrusion of the Elizabeth Creek Granite at between 1,000 and 2,000 feet. This conclusion is based on the erosional history and present day thickness of the intruded volcanic rocks, and on the assumption there has been no more than 1,000 feet of erosion from the Upper Palaeozoic to Cretaceous time.

Although these assumptions have been shown to be invalid for the Almaden Granite by Paverd (1971), there is considerable evidence which suggest reasonably shallow conditions of emplacement in the thesis area. The presence of a rhyolite plug together with dykes and possible vent breccias suggest that some units of the Slaughter Yard creek Volcanics are the sub-volcanic equivalents of extrusive rocks which have since been eroded away.

The brittle behaviour of the sediments during intrusion of these sub-volcanic units and the Elizabeth Creek Granite gives a further indication of the shallow conditions prevailing at the time. It may also explain the lack of conclusive evidence for deformation due to folding in the thesis area.

Branch (1966) believes the lower surface of the Upper Palaeozoic pyroclastic flow sheets corresponds with the Upper Carboniferous land surface. This is not the case in the thesis area and there is evidence to suggest that the presently exposed surface of the Elizabeth Creek Granite corresponds closely to the original top of the intrusion.

The locus of mineralisation throughout the Watsonville area is a high ridge of silicified granite which has cassiterite lodes restricted to its top and flanks. Hocking (1965) has shown that emanative centres such as this are granite cusps or ridges which represent the highest point of penetration of a tin bearing granite. The extrusive material of the Slaughter Yard Creek Volcanics has presumably protected the granite from erosion up until recent times. This suggests that these volcanics may be Upper Carboniferous, rather than Lower Permian as proposed by Blake (1968). Elsewhere (e.g. Walsh's Bluff) the granite was exposed by Lower Permian.

To the south of the area the intrusive contact of the Elizabeth Creek Granite with the flat lying Glen Gordon Volcanics has been preserved. Branch (1966) believes these volcanics were little more than 1,000 feet thick.

Thus there are many features throughout the area which indicate the granite rocks are high level intrusions and may have intruded to depths as shallow as 1,000 or 2,000 feet.

# 4.0 PETROLOGY AND GEOCHEMISTRY OF THE UNA PORPHYRY

## 4.1 Introduction

The detailed petrology of the UNA Porphyry is discussed in this section together with chemical and mineralogical aspects of the hydrothermal alteration. The origin of the porphyry together with the relationship of the alteration and mineralization will also be examined. This porphyry was first recognised by Mr. A. C. Day (Mareeba Mining and Exploration Pty. Ltd.) in 1971 and no previous investigations have been carried out prior to this study.

This discussion will be based on a study of a single diamond drill hole, DMU 25 which was drilled through the porphyry in the Two Treys Mine area. The drill core from this hole shows several feet of "unaltered" porphyry. This is the only fresh material of this unit observed by the author during examination of approximately 10,000 feet of diamond and percussion drilling samples from the area.

## 4.2 Petrology

The unaltered UNA Porphyry comprises phenocrysts of quartz (25%), alkali feldspar (10%) and plagioclase (5%) which vary from 2-7 mm diameter. The phenocrysts are present in a well-developed granophyric groundmass. Radiating granophyric intergrowths of quartz and alkali feldspar surround the phenocrysts and frequently corrode them. Several well developed cuneiform intergrowths are also present (Plate 10). Small crystals of corroded plagioclase and alkali feldspar are also present within the groundmass, together with occasional prismatic zircons and tabular apatite.

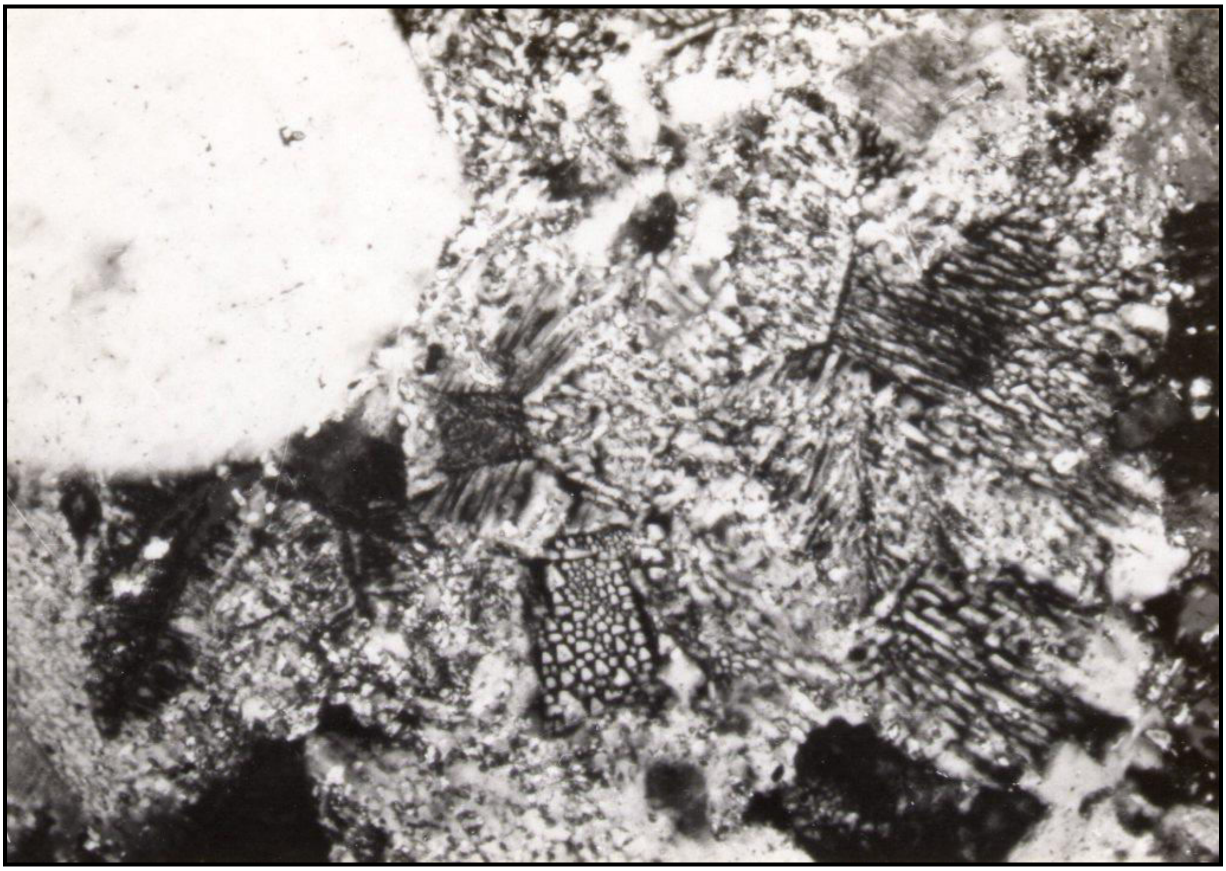

*Plate 10. Granophyric intergrowths of quartz and alkali feldspar (slightly sericitized) forming matrix of UNA Porphyry. Slightly corroded quartz phenocryst (white) upper left. (Crossed nicols, sample 9759).*

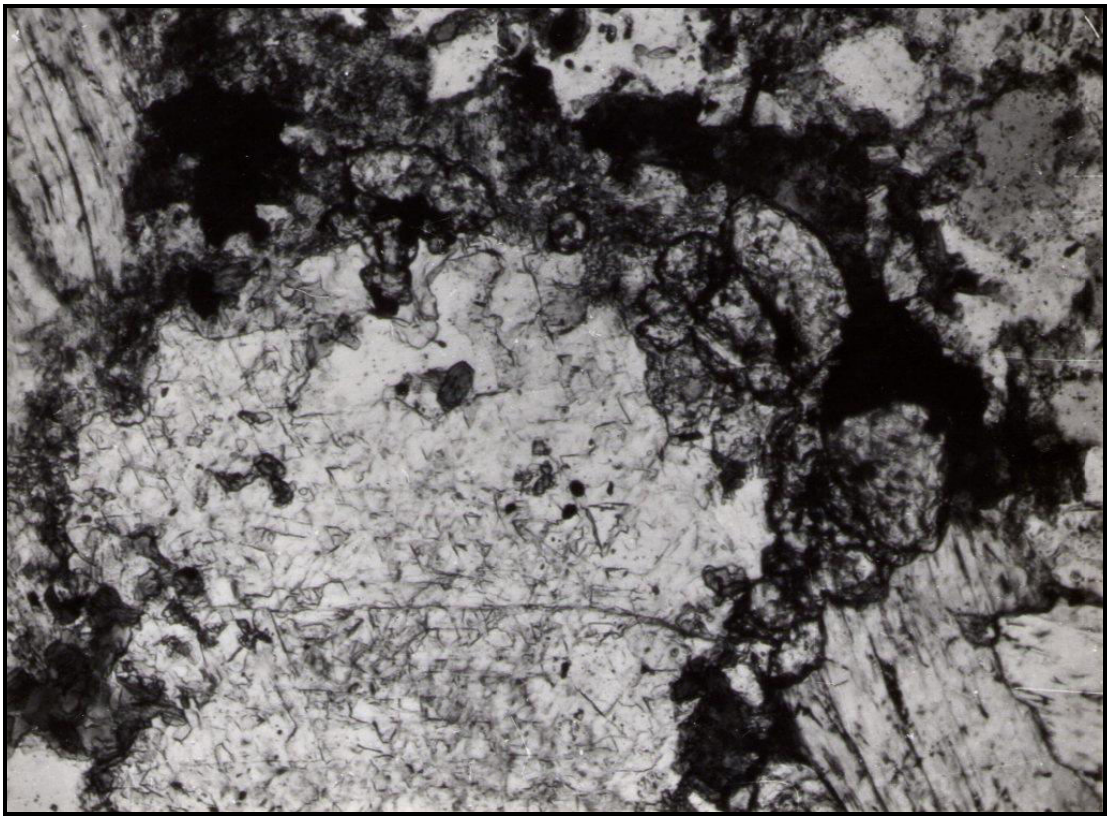

*Plate 11. Drusy cavity with fluorite (centre), surrounded by garnet (grey, high relief), biotite (dark grey), sulphides (black), and muscovite and quartz. (Transmitted light, sample 9759).*

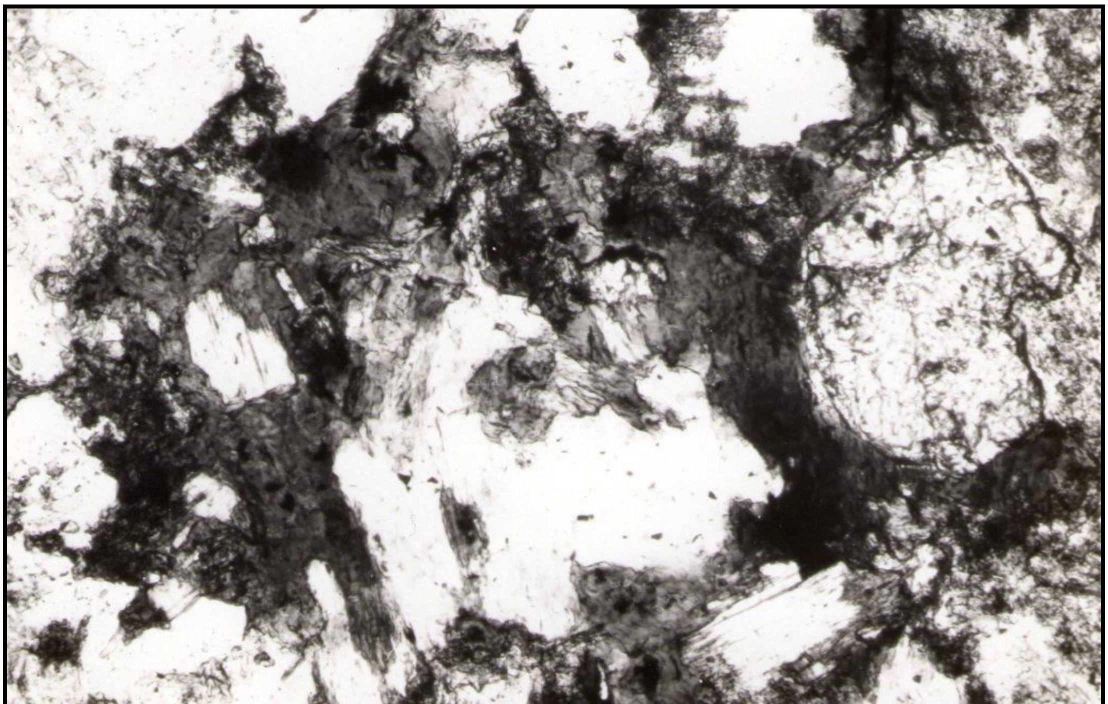

*Plate 12. Drusy cavity originally filled with biotite (dark grey) and garnet (high relief, right), surrounded by quartz (white). Biotite is being altered to sericite (white centre) and released iron is forming sulphides (black). (Transmitted light, sample 9759).*

Numerous drusy cavities are present. Each of these is surrounded by a rim of euhedral quartz crystals. A variety of secondary minerals are present within these cavities including sericite, muscovite, biotite, fluorite, carbonate, sulphides, cassiterite, topaz and iron oxides (Plate 11, Plate 12).

Chemically, the porphyry is very similar to a rhyolite (Table 3, sample 9756). However, at the base of the porphyry (Table 3, sample 9773) silicon has decreased slightly, while titanium, aluminium and magnesium have increased suggesting a slightly less felsic margin is present.

The number and size of phenocrysts decreases markedly near the base of the porphyry where the granophyric matrix is poorly developed and slightly more irregular. No flow banding is present near the margin. These facts suggest the porphyry was intruded passively.

## 4.3 Mineralogical Data from the UNA Porphyry

### 4.3.1 Quartz

Primary quartz is present as subhedral rounded phenocrysts 2-7 mm diameter. The phenocrysts are often fractured, show strain extinction effects and are slightly embayed in places by fine grained intergrowths of quartz and sericite. Most grains have corroded margins and a few have been strongly resorbed.

Quartz also occurs as elongate triangular rods forming granophyric intergrowths with alkali feldspar and as subhedral grains around the margins of drusy cavities.

### 4.3.2 Alkali Feldspar

The alkali feldspar from euhedral phenocrysts 5-7 mm length, which show polysynthetic twinning. They are always very cloudy due to their partial argillization and much of the twinning has been destroyed. Refractive index determination gave the following values of β:

1.525 ± 0.002

1.522 ± 0.002

Measurement of the optical axial angles gave values of 2Vα ranging from $80^{\circ}$ to $85^{\circ}$. These results suggest the alkali feldspar belongs to the low albite microcline series (Deer et al, 1966, p.308-309).

### 4.3.3 Plagioclase

Plagioclase forms subhedral phenocrysts 2-3 mm diameter, all of which are being altered to fine grained intergrowths of quartz and sericite. Using the feldspar determination curves of Deer et al (1966, p. 33) optical composition determinations gave the following results:

An33 (albite twin)

An35 (albite twin)

An38 (pericline twin)

### 4.3.4 Biotite

Two different forms of biotite are present. Extremely fine grained green aggregates occur where it has replaced alkali feldspar. Individual grains could not be distinguished under the microscope and identification was confirmed by X-ray diffraction. This biotite exhibits weak pleochroism and little variation in absorption colours.

Aggregates of large flakes are also present which are strongly pleochroic and have the following absorption colours:

$\alpha$ = pale yellow

$\beta$= brown

$\gamma$ = brown green

Refractive Index determinations gave the following values of $\beta$:

1.661 ± 0.002

1.665 ± 0.002

Measure of optic axial angles gave values of $2V\alpha$ ranging from $0^o$ to $5^o$. These biotites have been extensively altered to chlorite in places.

### 4.3.5 Chlorite

Some aggregates of biotite exhibit extensive alteration to chlorite. The chlorites show strong pleochroism and their absorption colours are:

$\alpha$ = pale yellow

$\beta$= dark green

$\gamma$ = dark green

This suggest the chlorite is an iron rich variety.

### 4.3.6 Garnet

Pink garnets occur in the drusy cavities. They also occur together with fine grained aggregates of biotite replacing alkali feldspar. The garnets in the drusy cavities are subhedral, contain few inclusions and are relatively clear. The garnets replacing alkali feldspar are rounded, have scalloped margins and faint anisotropism. They are cloudy, have numerous minute inclusions and frequent opaque grains.

Refractive index determination gave the following values of n:

1.830 ± 0.002

1.832 ± 0.002

A cell size of $11.62A^o$ was calculated from an X-ray diffraction trace. In the absence of an accurate specific gravity determination, no estimation of the composition could be made. However the manganese content of the garnet bearing samples (Table 3 and Figure 1, samples 9760B, 9761, 9762), together with the cell sizes for natural spessartine and synthetic spessartine ($11.60A^o$, $11.63A^o$), (A.S.T.M. Card Nos. 2-0992, 10-354), suggest that these are manganiferous garnets.

### 4.3.7 Muscovite

Muscovite occurs as large tabular flakes within drusy cavities and as ragged flakes replacing aggregates of fine grained sericite. Determination of refractive indices gave the following values:

B = 1.590 ± 0.002

$$\gamma = 1.595 \pm 0.002$$

Measurement of optic axial angles gave values of $2V\alpha$ ranging from $15^o$ to $20^o$.

### 4.3.8 Hydrated Calcium Silicates

These mineral are present in veins of gangue which cut the massive sulphides, together with fluorite, siderite and amorphous silica (Plates 13, 14). They are also present as a ground mass of gangue enclosing isolated patches of sulphide mineralisation and can be seen to be actively replacing quartz phenocrysts (Plate 15).

Most frequently they form massive, fine grained, fibrous intergrowths but in some instances, well develop crystals have formed (Plate 16). Here, strongly euhedral, radiating, prismatic crystals are present which have two cleavages at right angles, parallel to the margins of the crystals. In cross section they are rhombic. The crystals display high relief, parallel extinction and are length slow. They are biaxial positive. Measurement of axial optical angles gave values of $2V\alpha$ ranging from $40^o$ to $50^o$. Refractive index determinations gave the following values of $\beta$:

$$1.625 \pm 0.002$$

$$1.620 \pm 0.002$$

An X-ray diffraction trace and a powder photograph revealed numerous reflections with the greatest intensities being recorded at $9.58A^o$ and $3.29A^o$ respectively. These reflections are characteristic of a large range of hydrated calcium silicate minerals and it is probable that the material X-rayed contained a number of different minerals of this type. The only one that could be tentatively identified was a hydrated calcium aluminium silicate with the formula $CaAl_2Si_4O_{12}.4H_2O$.

## 4.4 Wall Rock Alteration

The following account of the alteration of the UNA Porphyry is based on a study of diamond drill hole DMU 25 from the Two Treys Mine area. The drill core from this hole shows a sequence passing from the original unaltered porphyry at the top, through altered porphyry with disseminated sulphides into a massive sulphide zone. This drill hole was divided into 6 zones and representative samples from each were selected for chemical analysis. The mineral assemblages within these zones are considered to be representative of all types of hydrothermal alteration occurring within this porphyry throughput the thesis area.

The partial chemical analyses of these samples are shown in Table 3 and the relationship of the samples to the various zones is shown in Figure 2 and Figure 3. These six zones have been selected on purely mineralogical grounds and do not necessarily represent particular types of alteration as defined by Meyer and Hemley (1967). The distribution of the mineral components throughout these zones is shown in Figure 3. To illustrate more precisely the variation in the amounts of the chemical elements present, the chemical analyses have been expressed as gram equivalents per 1,000 cubic centimetres of rock (Table 4). The variation in this quantity for each of the elements throughput the six zones is shown in Figure 2.

Although it is improbable that material is added to or subtracted from the unit volume of rock in the form of oxides, the chemical analyses are presented in this form to facilitate comparison with similar studies. In the following discussion of the various alteration zones, variation in the gram equivalents of elements (Figure 2) will only be discussed in relation to mineralogical variations (Figure 3).

*Plate 13. Gangue vein of amorphous silica (mottled, centre), hydrated calcium silicate (radiating fibrous), siderite (dark grey, high relief), and fluorite (white, high relief, left), cutting massive sulphide (black). (Transmitted light, sample 9765).*

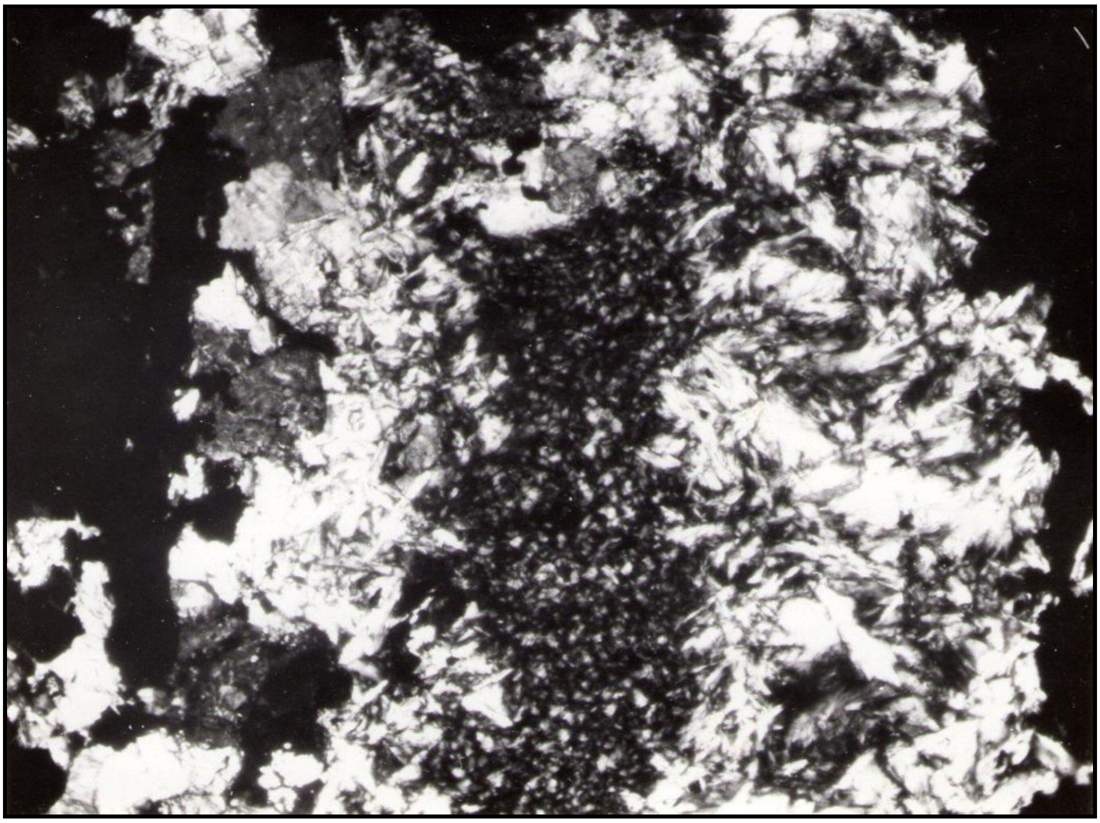

*Plate 14. As for Plate 13. (Crossed nicols, sample 9765).*

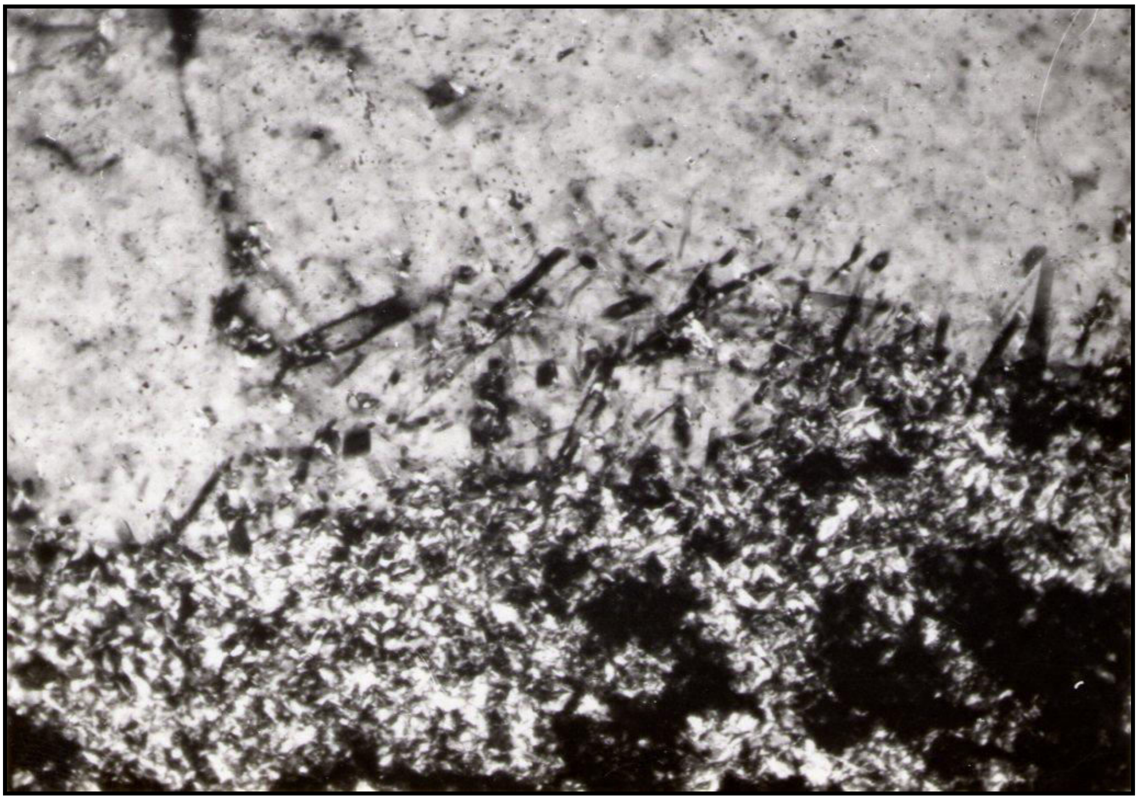

*Plate 15. Fine grained prismatic hydrated calcium silicates replacing quartz phenocrysts. (Crossed nicols, sample 9767).*

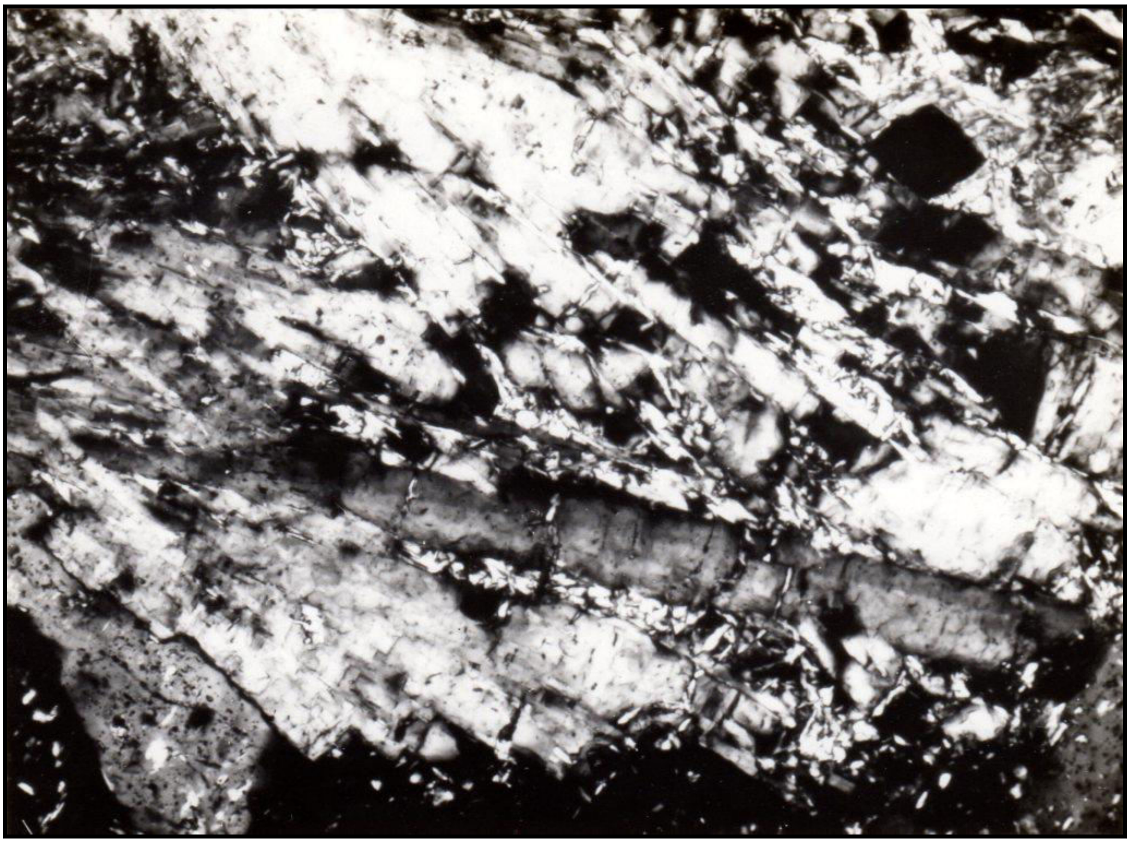

*Plate 16. Well-developed prismatic needles of hydrated calcium silicate. (Crossed nicols, sample 9766).*

| Sample | 9756 | 9759 | 9760A | 9760B | 9761 | 9762 | 9764 | 9765 | 9766 | 9768 | 9770 | 9771 | 9773 | 9774 | 9775 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$% | 75.04 | 74.50 | 75.75 | 73.75 | 75.75 | 73.75 | 77.00 | 3.50 | 71.60 | 74.50 | 71.80 | 69.75 | 69.75 | 53.25 | 53.00 |
| $TiO_2$% | 0.14 | 0.04 | 0.09 | 0.07 | 0.11 | 0.11 | 0.11 | 0.04 | 0.07 | 0.07 | 0.13 | 0.14 | 0.43 | 1.26 | 1.30 |
| $Al_2O_3$% | 12.70 | 12.45 | 12.20 | 11.70 | 11.65 | 11.70 | 10.70 | 1.50 | 4.80 | 4.90 | 11.60 | 11.70 | 14.10 | 16.90 | 17.70 |
| $Fe_2O_3$% | 0.63 | 0.38 | 0.92 | 1.09 | 1.05 | 1.49 | 2.19 | 44.32 | 3.14 | 5.35 | 0.96 | 3.14 | 0.88 | 0.51 | 2.48 |
| FeO% | 1.52 | 1.41 | 1.47 | 4.94 | 1.91 | 2.52 | 1.12 | nd | 0.77 | 1.52 | 6.34 | 7.48 | 4.59 | 10.65 | 7.40 |
| MnO% | 0.11 | 0.09 | 0.11 | 0.46 | 0.34 | 0.14 | 0.03 | 0.03 | 0.01 | 0.01 | 0.11 | 0.18 | 0.21 | 0.20 | 0.17 |
| MgO% | 0.14 | 0.07 | 0.12 | 0.20 | 0.20 | 0.11 | 0.13 | 0.03 | 0.04 | 0.05 | 0.17 | 0.31 | 1.83 | 5.84 | 5.27 |
| CaO% | 0.25 | 0.15 | 0.42 | 0.30 | 0.42 | 0.40 | 0.40 | 0.80 | 0.92 | 0.92 | 0.05 | 0.05 | 1.22 | 3.25 | 6.37 |
| $Na_2O$% | 1.26 | 1.77 | 0.45 | 0.01 | 0.01 | 0.01 | 0.18 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.51 | 1.18 | 0.66 |
| $K_2O$% | 5.48 | 5.83 | 4.69 | 3.10 | 3.65 | 3.39 | 3.13 | 0.32 | 1.33 | 1.40 | 2.45 | 3.35 | 3.68 | 4.18 | 3.10 |
| $H_2O$+% | 1.34 | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd |
| $H_2O$-% | 0.04 | 0.03 | 0.03 | 0.03 | 0.02 | 0.03 | 0.03 | 0.10 | 0.03 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 |
| $P_2O_5$% | 0.02 | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd |
| Cu% | 0.07 | 0.03 | 0.08 | 0.02 | 0.05 | 0.05 | 0.08 | 8.50 | 0.19 | 0.24 | 0.05 | 0.01 | 0.01 | 0.01 | 0.01 |
| Pb% | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.48 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Zn% | 0.09 | 0.02 | 0.02 | 0.02 | 0.01 | 0.10 | 0.04 | 1.50 | 0.06 | 0.21 | 0.04 | 0.03 | 0.01 | 0.01 | 0.02 |
| **Total** | **98.84** | **96.78** | **96.36** | **95.70** | **95.18** | **93.82** | **95.16** | **61.13** | **82.99** | **89.21** | **93.73** | **96.18** | **97.25** | **97.27** | **97.51** |

nd - Not determined

| **Trace Elements** | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ba ppm | 725 | 403 | 434 | 228 | 157 | 184 | 296 | 31 | 107 | 76 | 112 | 134 | 206 | 367 | 358 |
| Sr ppm | 58 | 56 | 24 | 10 | 7 | 7 | 15 | 7 | 17 | 15 | 7 | 8 | 44 | 217 | 262 |
| Sn ppm | 250 | 80 | 150 | 350 | 90 | 250 | 250 | 6300 | 300 | 180 | 500 | 110 | 130 | 950 | 10 |

| **Specific Gravity** | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SG g/cc | 2.77 | 2.82 | 2.96 | 3.05 | 3.00 | 2.87 | 3.02 | 3.86 | 2.90 | 2.77 | 3.00 | 3.04 | 2.89 | 3.08 | 2.88 |

*Table 3, Chemical analyses of samples of UNA Porphyry from diamond drill hole DMU 25, Two Treys Mine.*

### 4.4.1 Zone 1

This zone is represented by the original porphyry. Material which could be considered to be totally unaltered was not found. Some of the plagioclase in this zone is slightly altered to sericite[1] and quartz around the margin (Plate 17). Alkali feldspar is not hydrothermally altered but is cloudy due to argillization. This is probably a supergene effect. The granophyric intergrowths are unaltered.

The drusy cavities in this area are mostly filled with a dirty green brown biotite which is replaced by sericite through an intermediate chlorite stage. Iron is released in this process producing the dark cloudiness in the biotite. Concurrent sulphidization has produced pyrite and chalcopyrite. Pink garnets and cassiterite grains are also present within the drusy cavities.

Thus it is probable that some calcium has been removed from this rock by partial alteration of plagioclase, while iron, manganese and potassium have bene introduced. The iron and manganese have been incorporated in the garnets, and the potassium in the sericite.

### 4.4.2 Zone 2

In this zone plagioclase has been totally replaced by a fine grained intergrowth of sericite and quartz. Initially fine grained sericite is developed along the cleavage in the plagioclase and becomes increasingly coarse with more intense alteration. Some of the sericite has a well-developed radiating fibrous appearance, while other areas are being replaced by muscovite (Plate 18). The biotite in the drusy cavities is increasingly sulphidized and altered to sericite.

There is no distinct boundary between Zone 1 and zone 2 and there is little variation between most elements. The increase in potassium and sodium between samples 9756 and 9759 reflects the incorporation of these element into sericite.

The decrease of these elements from sample 9759 through to 9760A reflects the initiation of the breakdown of alkali feldspar to form quartz and sericite (Plate 19). A minor decrease in calcium between sample 9756 and 9759 reflects the low anorthite content of the plagioclase, while a slight increase in sample 9760A is due to increasing amounts of fluorite in the drusy cavities. The barium appears to have been incorporated in the plagioclase (Table 3).

### 4.4.3 Zone 3

Alkali feldspar is totally broken down to sericite and quartz in this zone. Alteration is initiated along fractures, cleavages and around the margins, while minute green biotites start to develop within the phenocrysts. The alkali feldspar in the granophyric groundmass is broken down simultaneously. Green secondary biotite and pink garnets are also formed at the expense of alkali feldspar (Plate 20).

The contact between Zone 2 and Zone 3 is very sharp and can be traced across individual alkali feldspar phenocrysts. A rapid decrease of sodium and potassium in this zone corresponds to the destruction of alkali feldspar. However a considerable amount of potassium is retained by incorporation in the sericite.

The increasing amounts of divalent iron and manganese are incorporated in the garnet and secondary biotite which reach a maximum in samples 9760B and 9761.

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[1] The term “sericite” is used here to describe a fine grained mica like mineral which is produced during the alteration of some other silicate phases, such as feldspar and biotite.

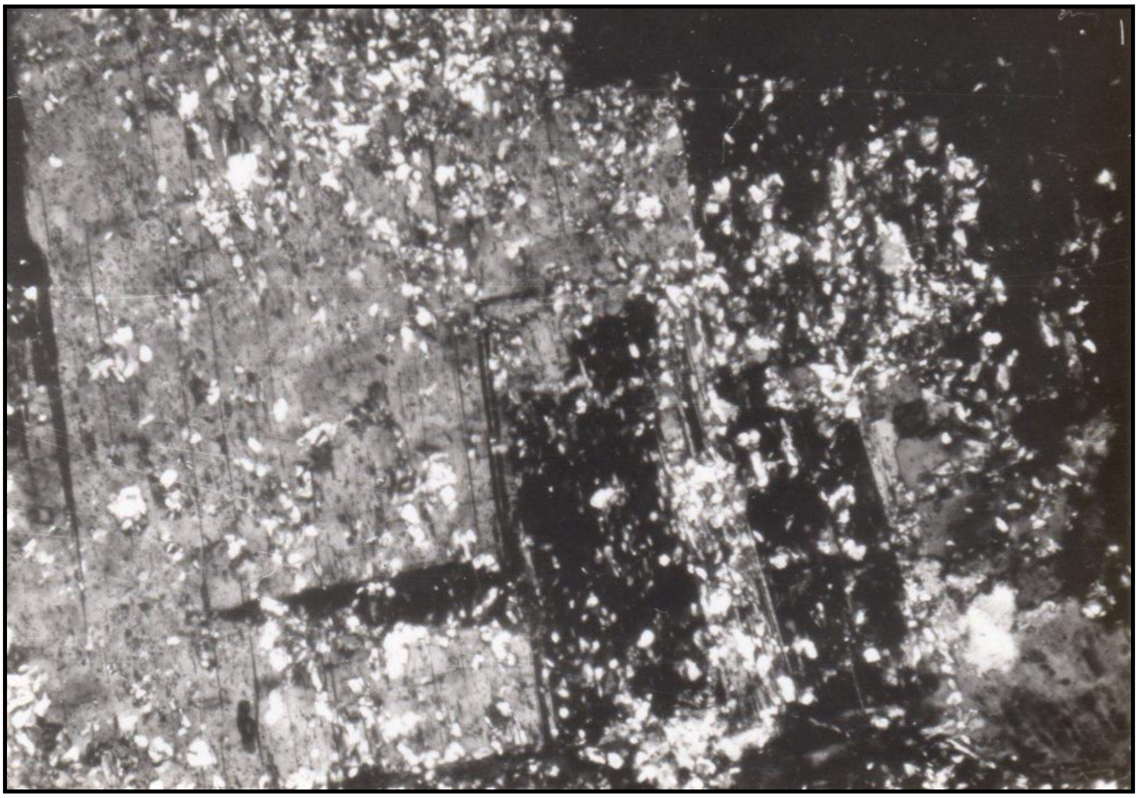

*Plate 17. Plagioclase from Zone 1 showing initial stages of alteration to sericite and quartz. (Crossed nicols, sample 9756).*

*Plate 18. Fine grained sericite being replaced by coarse ragged muscovite. (Crossed nicols, sample 9762)*

Both the biotite and garnet appear unstable, with the garnet breaking down to produce biotite, and biotite being sulphidized and altered to sericite. The garnets also appear to contain fine grained clay minerals which may have been derived from the initial argillization of the alkali feldspars. A steady decrease in ferric iron and manganese coincides with the removal of these minerals (Figure 2 and Table 3).

The sericite is continuously replaced by muscovite in this zone until it becomes a major phase in Sample 9764 (Figure 3). Silicon is also stabilized throughout this zone and shows a slight but continual increase from the amount initially present in Sample 9765. This corresponds to a slight decrease in aluminium and may represent the substitution of silicon for tetrahedral aluminium in sericite and muscovite.

The alteration in this zone exhibits the mineralogical and chemical features of sericite alteration as defined by Meyer and Hemley (1967). This is the most widespread type of alteration throughout the area. The original texture of the rock has been almost totally destroyed and the only feature which indicates the rock was originally a porphyry are the quartz phenocrysts.

### 4.4.4 Zone 4

Nearly all the silicate minerals have been destroyed in this zone which consists principally of quartz and sulphides. A massive sulphide zone is present in Sample 9765 while the remainder of the zone is quartz, sulphides, minor sericite and muscovite, and gangue minerals. The massive sulphide zone here is very narrow and silicification is of limited extent. However, silicification is very intensive around the pyrrhotite-chalcopyrite zone of the Two Treys ore body where surrounding zones of from 50-80% quartz are present.

Some of the muscovite and sericite here is enclosed within the massive sulphides and it appears as though the sulphides and silicates formed simultaneously.

The gangue minerals present include fluorite, siderite, hydrated calcium silicates and amorphous silica. These occur in veins cross cutting the massive sulphides (Plate 13, Plate 14). The hydrated calcium silicates also occur as irregular masses surrounding patches of sulphides, and are actively replacing quartz phenocrysts in some instances (Plate 15).

Potassium and aluminium are highly depleted in this zone due to the destruction of sericite and muscovite. However, silicon does not appear to have been removed although it is largely absent from the massive sulphide zone. Calcium shows a significant increase here due to its introduction in the form of gangue minerals.

This zone can be considered as a type of sericite alteration, as the silicification involves changes in the relative proportions of elements present, rather than change in the type of mineralogy.

### 4.4.5 Zone 5

This zone is basically identical to the sericite alteration of Zone 3. However, a considerable amount of metastable biotite is present. This biotite is being actively sulphidized and altered to sericite through an intermediate chlorite. The large increase in ferric iron reflects the increasing amount of biotite present.

Fluorite is absent in this zone and instead the fluorine is present in topaz. As a result of this there is a complete lack of calcium in this zone (Figure 2).

| **Sample** | **9756** | **9759** | **9760A** | **9760B** | **9761** | **9762** | **9764** | **9765** | **9766** | **9768** | **9770** | **9771** | **9773** | **9774** | **9775** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 34.61 | 34.98 | 37.34 | 37.41 | 37.77 | 35.17 | 38.64 | 2.25 | 34.54 | 34.32 | 35.87 | 35.33 | 33.51 | 27.26 | 25.40 |
| $TiO_2$ | 0.05 | 0.01 | 0.03 | 0.02 | 0.04 | 0.04 | 0.04 | 0.02 | 0.02 | 0.02 | 0.05 | 0.05 | 0.16 | 0.49 | 0.47 |
| $Al_2O_3$ | 6.90 | 6.89 | 7.09 | 7.00 | 6.85 | 6.58 | 6.33 | 1.14 | 2.73 | 2.66 | 6.83 | 6.99 | 7.98 | 10.20 | 10.00 |
| $Fe_2O_3$ | 0.22 | 0.13 | 0.34 | 0.42 | 0.39 | 0.53 | 0.83 | nd | 7.28 | 1.85 | 0.36 | 1.20 | 0.32 | 0.20 | 0.89 |
| FeO | 0.59 | 0.55 | 0.61 | 2.10 | 0.80 | 1.01 | 0.47 | nd | 0.31 | 0.59 | 2.65 | 3.17 | 1.84 | 4.52 | 2.97 |
| MnO | 0.04 | 0.04 | 0.05 | 0.20 | 0.14 | 0.06 | 0.01 | 0.02 | 0.01 | 0.01 | 0.05 | 0.08 | 0.09 | 0.09 | 0.07 |
| MgO | 0.10 | 0.05 | 0.09 | 0.15 | 0.15 | 0.08 | 0.10 | 0.05 | 0.03 | 0.03 | 0.13 | 0.47 | 1.31 | 4.47 | 3.77 |
| CaO | 0.10 | 0.08 | 0.22 | 0.16 | 0.22 | 0.20 | 0.22 | 0.55 | 0.48 | 0.45 | 0.03 | 0.03 | 0.63 | 1.78 | 3.27 |
| $Na_2O$ | 1.13 | 1.61 | 0.43 | 0.01 | 0.01 | 0.01 | 0.08 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.48 | 1.17 | 0.61 |
| $K_2O$ | 3.22 | 3.49 | 2.95 | 2.01 | 2.32 | 2.06 | 2.00 | 0.26 | 0.82 | 0.82 | 1.56 | 2.16 | 2.26 | 2.73 | 1.50 |

nd - Not determined

*Table 4, Major element analyses of samples of UNA Porphyry from Two Treys Mine, expressed as gram equivalents per 1,000 cc.*

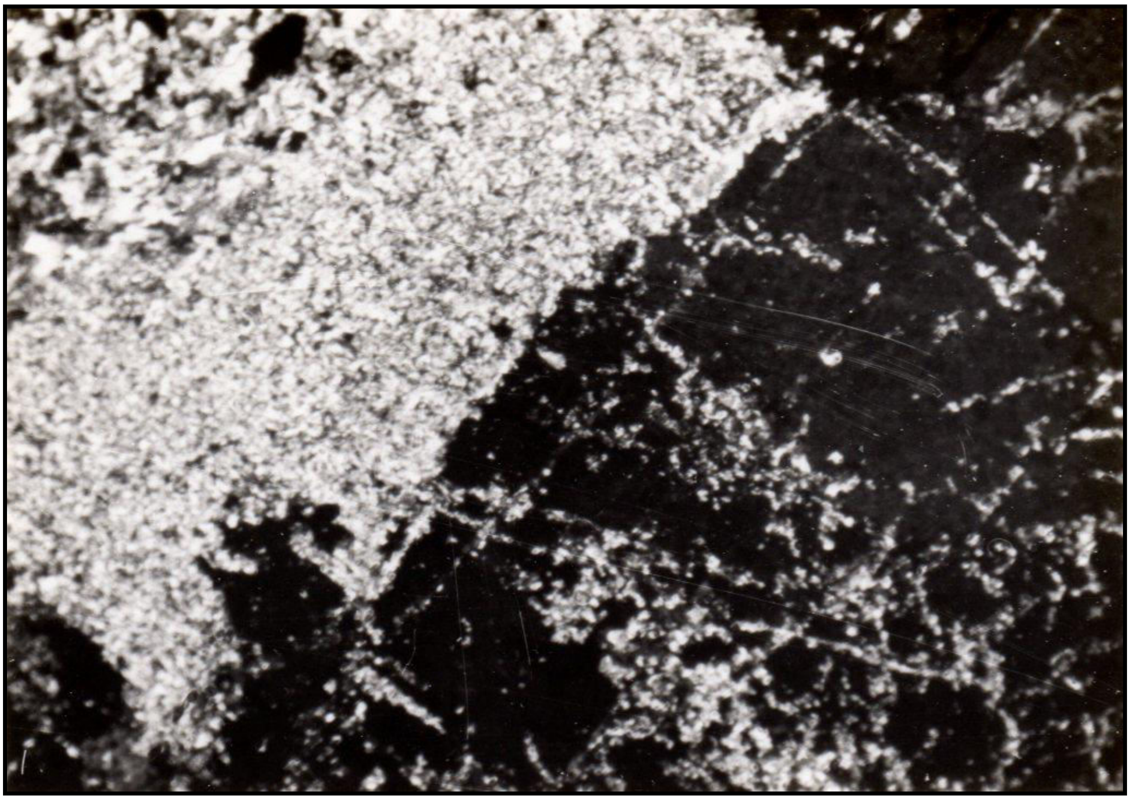

*Plate 19. Alkali feldspar (black) being replaced by fine grained sericite. (Crossed nicols, sample 9760).*

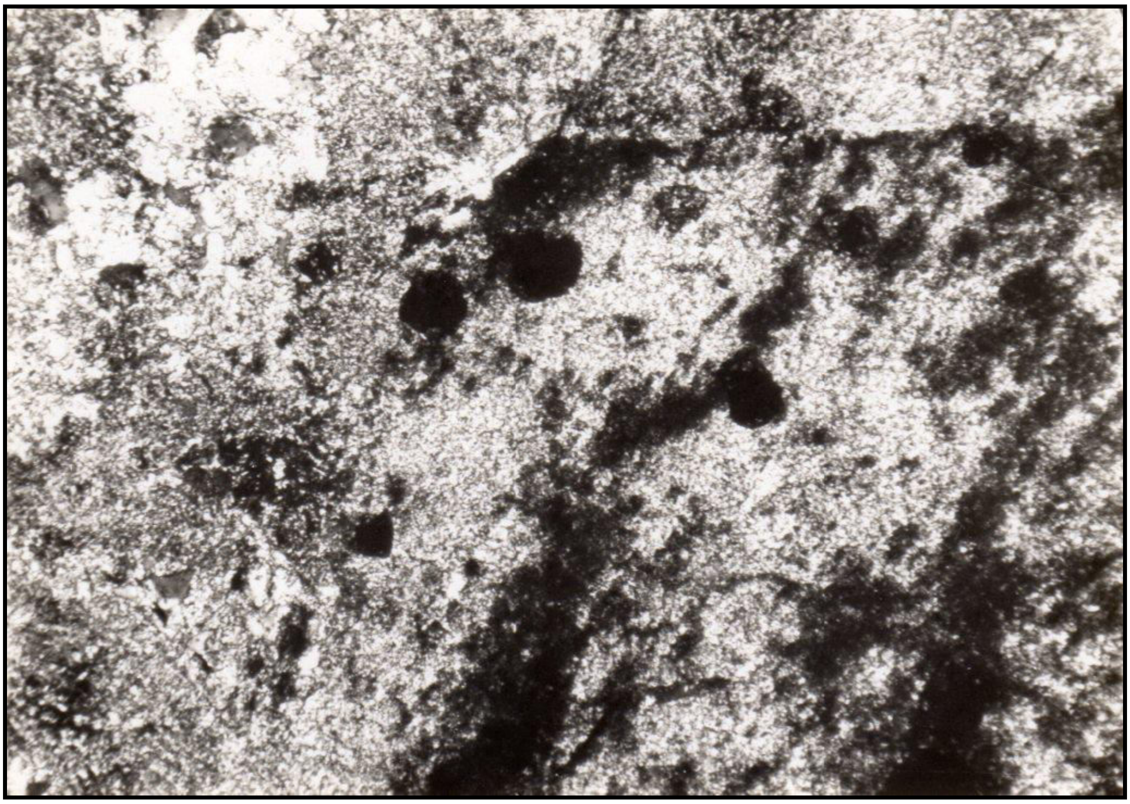

*Plate 20. Fine grained biotite (dark grey) and garnets (black, round), partially pseudo morphing alkali feldspar. Other alteration products are fine grained sericite and quartz. (Crossed nicols, sample 9761).*

The less felsic base of the porphyry is responsible for an increase in titanium, manganese, aluminium, magnesium and a slight decrease in silicon (Sample 5773).

### 4.4.6 Zone 6

This zone consists of altered sediments at the base of the porphyry. The main minerals present are biotite, quartz and feldspar. Both plagioclase and alkali feldspar are present and form porphyroblasts which appear to be unaltered. The biotite co-exists with numerous small grains of arsenopyrite and is not apparently being sericitized or sulphidized.

The sodium, calcium and potassium in this zone were introduced from the overlying porphyry during sericitization and formed feldspars. Some of the ferric iron in the biotite was also probably introduced. A simultaneous increase in barium and strontium is also present in this zone and the behaviour of these elements appear to reflect that of sodium and potassium. However it is also quite likely that some of the alkali and alkali earth elements were already present in the sediment as detrital feldspar and their weathering products.

## 4.5 Discussion

The four major processes which are involved in wall rock alteration by hydrothermal fluids are hydration or dehydration, cation metasomatism, anion metasomatism and electron metasomatism. The phases produced by these processes during alteration of rocks of granitic composition depend on temperature, pressure and the activities of the ionic species present in the fluid. The three chemical parameters which characterize the hydrothermal fluid are oxygen fugacity ($fO_2$), sulphur fugacity ($fS_2$) and pH. These can be used to relate the sulphide assemblage and oxide phases to the nature of the wall rock alteration.

However, it is difficult to present a quantitative discussion of the chemical changes during alteration due to the difficulty of accurately evaluating these parameters in highly complex mineral systems. Instead, only broad qualitative generalizations of physical and chemical conditions can be made.

In the following discussion some of the more important alteration products will be considered in relation to the chemical parameters of the hydrothermal fluid.

### 4.5.1 Alteration of Feldspars

The alteration of alkali feldspars has been studied experimentally in four component systems by Hemley (1959) and Hemley, Meyer and Richter (1961). Hydrolysis equilibria have been established for various temperatures, pressures and ionic activity ratios. Meyer and Hemley (1967) have combined these four component systems to produce an equilibrium diagram for the system $K_2O$-$Na_2O$-$Al_2O_3$-$H_2O$ at $400^oC$ and 15,000 psi. This system is representative of the hydrolysis equilibria of most rocks of a granitic composition undergoing alteration. The plagioclase in the UNA Porphyry has a reasonably low anorthite content and its behaviour during alteration can probably be approximated by that of albite.

In Zone 1, plagioclase is only slightly altered to sericite and alkali feldspar is stable. Alteration, therefore must take place close to the triple point for the assemblage albite-Kfeldspar-Kmica (Meyer and Hemley, 1967; Fig 6.7). At this point the $Na^+/H^+$ ratio of the fluid only slightly exceeds the $K^+/H^+$ ratio. As the plagioclase becomes totally altered to sericite and quartz in Zone 2, $H^+$ ions and $K^+$ ions are depleted from the fluid and $Na^+$ and $Ca^+$ ions are added. This will produce an increase in the $Na^+/H^+$ ratio and a decrease of the $K^+/H^+$ ratio of the fluid.

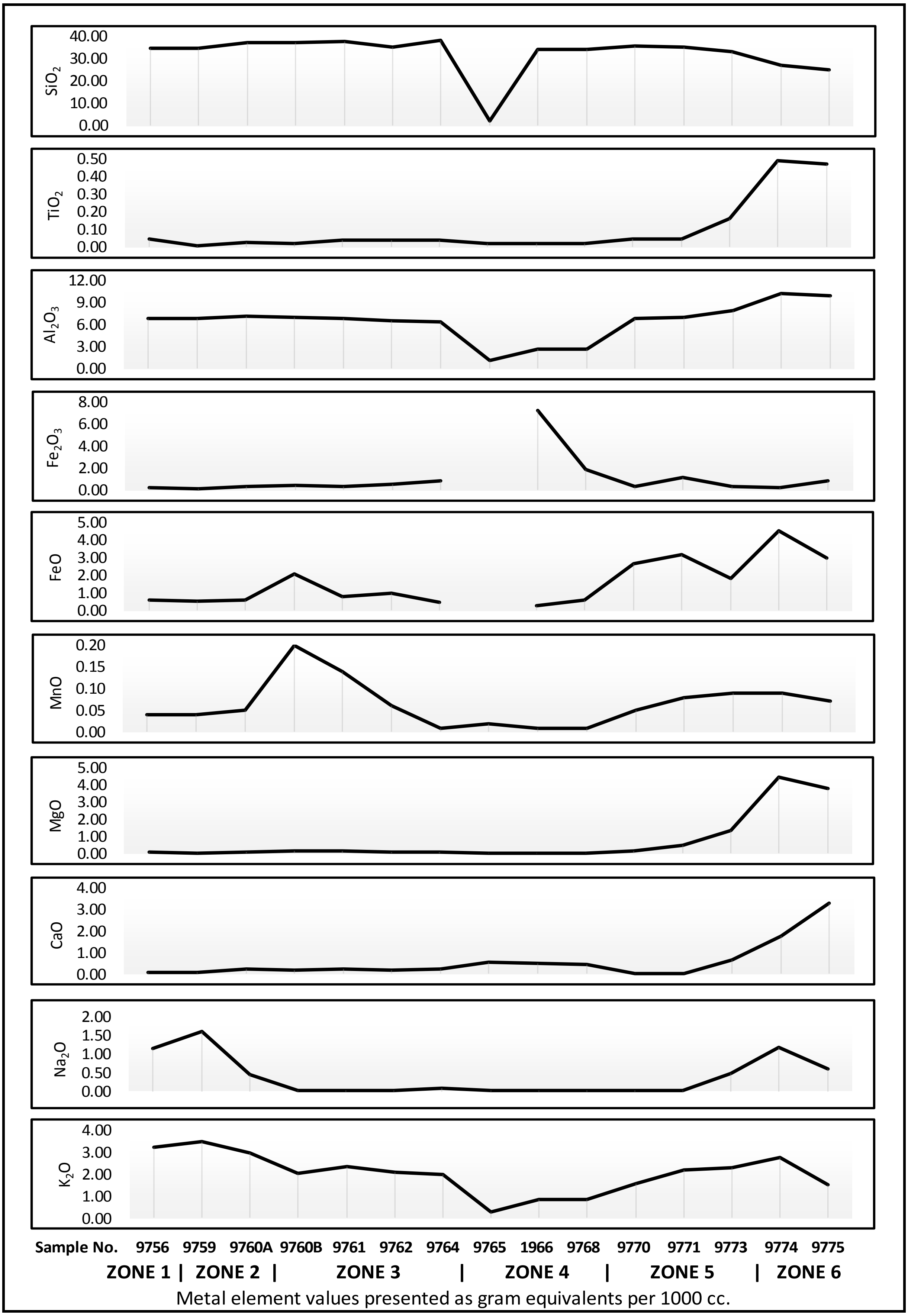

*Figure 2. Variation of gram equivalents per 1,000 cc for major element analyses of samples of UNA Porphyry from diamond drill hole DMU 25, Two Treys Mine.*

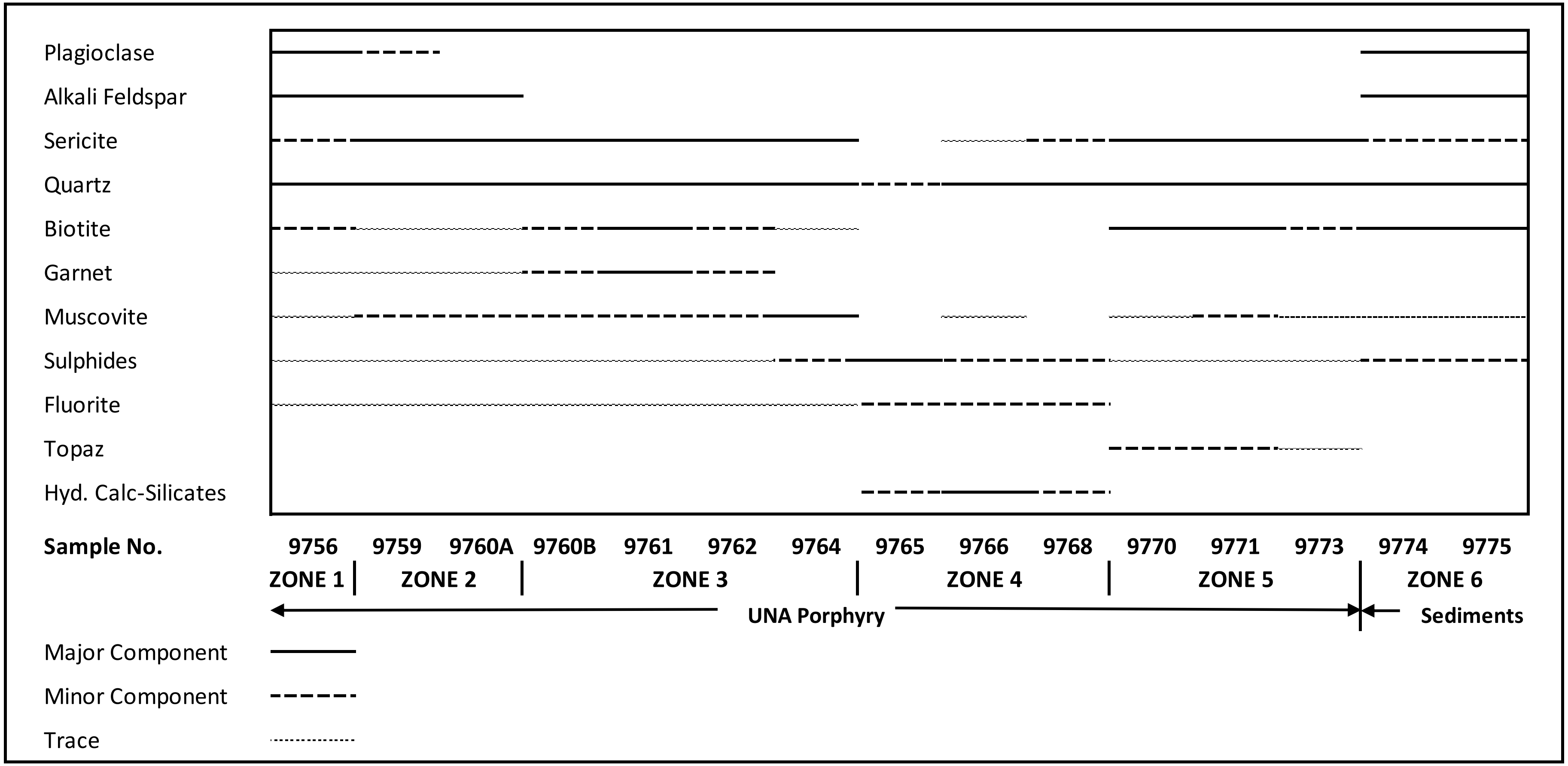

*Figure 3. Variation of mineral components from samples of UNA Porphyry from diamond drill hole DMU 25, Two Treys Mine.*

The concentration of sodium cannot exceed that of potassium by more than approximately five times as albite would tend to be stabilized (Orville, 1963).

The decrease in the $K^+/H^+$ ratio of the fluid will then cause alkali feldspar to become unstable and it will alter to sericite and quartz in Zone 3. This will cause $H^+$ ions to be depleted from the fluid and $Na^+$ ions and some $K^+$ ions to be added. A proportion of the $K^+$ ions are retained in the sericite formed by alteration of the alkali feldspar. The resultant fluid will then have $Na^+/H^+$ and $K^+/H^+$ ratios which will be higher than the initial ratios, with the $Na^+/H^+$ ratio increasing considerably more than the $K^+/H^+$ ratio.

The three zones (1-3) thus constitute an activity gradient of $H^+$ which decreases progressively with the increasing intensity of alteration. Although these alteration processes have been described separately in the occurrences studied here, it is quite probable that they are interdependent and occurred simultaneously.

### 4.5.2 Formation of Manganiferous Garnet

For manganiferous garnets to have formed as an alteration product the hydrothermal fluid would have to be enriched in both iron and manganese. Muller (1971) and Muller and Schneider (1971) have both shown that where both iron and manganese are present in a system it is necessary for the activity of $Fe^{2+}$ to be low or almandine garnet would form instead of spessartine. This can be achieved where $fO_2$ is high and most of the iron is present at $Fe^{3+}$. The activity of $Mn^{2+}$ is much less influenced by high $fO_2$ and spessartine garnet will form.

Muller (1971) has further shown that the $fO_2$ of a magma is controlled by the $H_2O/H_2$ activity ratio of the dissolved fluid. Therefore the hydrothermal fluid derived from a water rich magma will have highly oxidizing conditions and most of the iron in the fluid will be present as $Fe^{3+}$.

Thus a high $fO_2$ is indicated for the initial hydrothermal fluids that produced alteration in the UNA Porphyry

### 4.5.3 Replacement of Sericite by Muscovite

This phenomenon does not appear to have been previously described in this type of alteration and it is difficult to understand why this should occur. It has already been suggested that some sodium released during the break down of plagioclase was incorporated in the sericite along with potassium. Sodium and potassium have ionic radii of 0.99A$^o$ and 1.334A$^o$ respectively and this difference is likely to produce a highly disorganised structure in the sericite. It is suggested that the replacement of this sodium by potassium has produced the more ordered muscovite.

### 4.5.4 Sulphidization of Biotite

Sulphidization of biotite proceeds throughout all the zones but is most apparent in the sericite zones (2, 3 and 5). The garnets are also metastable in these zones and appear to be breaking down to from biotite. This suggest that the high fO2 conditions necessary for their formation no longer exist in the sericite zones.

Raymahashay and Holland (1969) have shown that strong hydrogen metasomatism occurs where the $fS_2/fO_2$ ratio is high. As sericite alteration represents the highest degree of hydrogen metasomatism in this instance, it is implied that more reducing conditions are present within these zones. Holland (1972) has pointed out the importance of the need for sulphur to be in a reduced state for sulphidization to occur.

It is probably these reducing conditions and the presence of $Fe_2^+$ which are responsible for the metastability of biotite in the sericite zone. A considerable change in the alteration conditions is therefore indicated from those which produced the garnets. The initially strongly oxidizing fluid became more reducing as the alteration became increasingly intense.

### 4.5.5 Formation of Gangue Minerals

The gangue minerals are present in veins which cross cut the massive sulphides (Plates 13, 14). In order of deposition the minerals are fluorite, siderite, hydrated calcium silicates and amorphous silica. These minerals were deposited from the residual hydrothermal fluid which was slightly alkaline in order to stabilize these minerals. The sequence of deposition also probably reflects decreasing temperature during the late stage activity. The temperature of formation of the hydrated calcium silicates is probably between 200°C and 300°C under these conditions (J. D. Bernal, pers. com.).

These fluids have introduced calcium, fluorine, iron, silicon and carbonate into zone 4.

## 4.6 Nature of the Hydrothermal Fluid

The initial hydrothermal fluid was shown to be rich in $Na^+$, $K^+$, $Fe^{2+}$, $Mn^{2+}$ and $H^+$ and to be strongly oxidizing with high $fO_2$. Burnham (1967) showed that partition coefficients in granitic magmas at the end magmatic stage favour the production of an initially chloride rich solution which is strongly acidic and has high $Na^+$, $Ca^+$, $K^+$ and $H^+$. The presence of $Cl^-$ enhances alkali metasomatism especially at low pressures.

Garnets were formed before and contemporaneously with the alteration of the feldspars. As sericitic alteration proceeded the intensity of hydrogen metasomatism increased. The loss of $H^+$ caused the fluid to become more dilute and slightly reducing. According to Burnham (1967), these fluids have less $Cl^-$ and tend to favour silicification and the removal of alumina.

Sulphide minerals were formed simultaneously with sericitization and silicification as the $fS_2/fO_2$ ratio increased, and reduced sulphur became available. This is evident in the sulphidization of biotite altering to sericite. Burnham (1967) showed that under these conditions the normative quartz/albite+orthoclase ratio is inversely proportional to pressure. This indicates that silicification must essentially be a low pressure phenomenon.

The final stage of hydrothermal fluids were alkaline and deposited the gangue minerals. Minor amounts of calcium, fluorine, silicon and carbonate were introduced. The transfer of calcium, potassium, sodium and iron from the porphyry into the underlying sediments probably occurred as a result of migration across a temperature gradient which existed between the two while the porphyry was being altered.

Thus the main elements removed during alteration were sodium, potassium, calcium and magnesium while the main elements introduced were $H^+$, sulphur, iron, manganese and other metals.

## 4.7 Temperature and Pressure During Alteration

Creasey (1966) indicated that sericite alteration in porphyry copper deposits took place at a temperature less than 625°C which is the dehydration temperature of muscovite at 1 kbar. However, to establish the temperature and pressure during the alteration of the UNA Porphyry without quantitative information is very difficult.

The fact that the porphyry has a granophyric groundmass provides some useful information on its conditions of formation. According to Dunham (1965) the granophyric texture originates by the simultaneously crystallization of quartz and feldspar when the groundmass had a bulk composition lying on the cotectic minimum of the Or-Ab-$SiO_2$-$H_2O$ system at the particular water vapour pressure. The liquid was supercooled to this region where the rate of nucleation is high but the rate of crystal growth is not at a maximum. The rate of supercooling is controlled by the rate of heat flow away from the magma. If the volatiles had been lost the magma would have formed a felsite.

This indicates that the UNA Porphyry cooled and crystallized rapidly, while retaining its volatiles. Luth, Jahns and Tuttle (1964) have shown that the vapour pressure of water in a magma can considerably lower the temperature of crystallization, particularly if its composition lies on the cotectic minimum. As the UNA Porphyry crystallized it would have released dissolved water, increasing the water vapour pressure, and therefore further lowering the temperature of crystallization of the remaining melt.

It has already been indicated that the plutonic environment in the thesis area was relatively shallow. This is further enhanced by the observation of Buddington (1959) who reported granophyres as occurring only within the epizone. This is the shallowest zone of igneous intrusion recognized by Buddington. However, if the UNA Porphyry was intruded to depths of 1,000 to 2,000 feet as advocated by Branch (1966) for the Elizabeth Creek Granite, it is difficult to explain how sufficient quantities of water remain dissolved in the magma to produce the observed alteration and mineralization.

Koster van Groose and Wyllie (1965), showed that water solubility in magmas was promoted by large concentrations of alkali halides. Strong alkali metasomatism had already been demonstrated in the UNA Porphyry and indicates that a high chloride concentration was present at the time. High chloride concentrations frequently occur in fluid inclusions in ore deposits (Roedder, 1971) and are present in natural brines. Koster van Groose and Whyllie (1969) have further suggested that isobaric crystallization of a melt at low pressure, produces an equilibrium assemblage of aqueous and saline fluid phases.

However, these ideas must be treated with some caution as experimental work by Burnham (1967) indicates that appreciable amounts of chloride do not significantly increase the amount of water that can be dissolved in a magma. Further, high chloride concentrations have not been recorded in naturally occurring felsic or mafic magmas.

Although no quantitative estimate of temperature during alteration can be made, it is highly probable that it was considerably lower than the maximum proposed by Creasey (1966). This is due to the rapid cooling and crystallization of the melt on the cotectic minimum of the Or-Ab-$SiO_2$-$H_2O$ system at increasing water vapour pressure. A moderately high water vapour pressure was probably enhanced by the chloride content of the fluid.

### 4.8 Origin of the Hydrothermal Fluid

The hydrothermal fluids which have altered the UNA Porphyry can only have been introduced either simultaneously with intrusion of the porphyry, or at some later stage. If the latter suggestion is true, then one would expect to see veins of sulphide plus gangue cross-cutting both the porphyry and the sediments. The associated alteration would be restricted to a zone adjacent to the vein.

This has been observed for mineralised porphyries at the Conrad Lode (Edwards and Wade, 1953), at the South Crofty Mine (Taylor, 1963) and at the Wheal Jane Mine (Raymond, Davis and Wilson, 1971). In these cases the mineralization has been shown to post-date the porphyries. However, cross-cutting veins observed in the UNA Porphyry post-date the alteration which is ubiquitous throughout the porphyry. Further, there are no obvious sulphides veins with attendant alteration cutting the sediments.

Within the porphyry itself, there are numerous drusy cavities which indicate that crystallization had proceeded in a magma which was rich in volatile components. Thus it is apparent that the only plausible explanation of the extent of alteration, the presence of drusy cavities and the lack of cross-cutting gangue sulphide relationships within the porphyry, is that the hydrothermal fluid was intruded simultaneously with the intrusion of the porphyry.

### 4.9 Age and Origin of the UNA Porphyry

At this stage it is critical to establish the age of the UNA Porphyry and its relationships to other igneous units in the area. It has already been shown to be older than the porphyry dykes of the Slaughter Yard Creek Volcanics. The porphyry cannot be seen to intrude the Elizabeth Creek Granite, and the granite does not appear to intrude the porphyry.

The porphyry is however, cut by quartz, tourmaline, cassiterite veins and is therefore older than the dominant phase of the mineralization in the area. This tin phase is also seen cutting the Elizabeth Creek Granite.

It has already been shown that the porphyry was intruded along with a metal and sulphur rich volatile phase, the composition of which is typical of hydrothermal fluids at the end magmatic stage (Burnham, 1967). This then indicates that the UNA Porphyry must have been derived from a parent body with similar characteristics. The only igneous unit that could fulfil these requirements in the area is the Elizabeth Creek Granite. This granite has been shown to have a strong spatial relationship with mineralization in this area by Blake (1968, 1970), Blake and Smith (1970), Taylor (1971) and Taylor and Steveson (in press).

The UNA Porphyry is also chemically very similar to the Elizabeth Creek Granite (Table 1). Further, the porphyry is partially cone shaped and dips towards the Elizabeth Creek Granite in a similar manner to most granophyres derived from high level granitic intrusions.

Therefore, although it is difficult to pin-point an exact age relationship for the UNA Porphyry, the evidence is not incompatible with it having been derived from, and being the same age as the Elizabeth Creek Granite.

### 4.10 Summary

(i) The UNA Porphyry was probably derived from the Elizabeth Creek Granite and was intruded to shallow depths
(ii) The hydrothermal fluid was introduced simultaneously with the intrusion of the porphyry.
(iii) The porphyry cooled quickly and the groundmass crystallized at the cotectic minimum of the Or-Ab-$SiO_2$-$H_2O$ system.
(iv) The composition of the fluid was similar to that proposed for fluids derived from granitic magmas at the end magmatic phase (Burnham, 1967). The composition changed continually from initially strongly acidic to finally alkaline.
(v) Sericite alteration, silicification and sulphide mineralization occurred contemporaneously.
(vi) The main elements removed from the porphyry during alteration were sodium, potassium, calcium, and magnesium, while $H^+$, sulphur, iron, manganese and other metals were added.

(vii) The temperature of alteration was considerably less than 625$^{o}$C. The pressure was controlled by the amount of water vapour present in the hydrothermal fluid.

# 5.0 OPAQUE MINERALOGY OF THE TWO TREYS ORE BODY

## 5.1 Introduction

In the Herberton district both sulphide and oxide ore minerals have a wide distribution and show a strong spatial relationship to the Elizabeth Creek Granite. Blake (1968, 1970) and Blake and Smith (1970) have proposed a broad district zonation in the Herberton-Mount Garnet area related to the Elizabeth Creek Granite and its metamorphic aureoles. They have distinguished four zones in the area characterized by (i) tungsten, (ii) tin, (iii) copper and (iv) lead mineralization. The innermost tungsten zone passes outwards into the tin zone which gives way to the copper zone. The outermost zone is characterized by lead mineralization.

However, Taylor (1971) and Taylor and Steveson (in press) have shown that mineral zoning is restricted to the immediate vicinity of a number of separate emanative centres around the margins of the granite, rather than encompassing the whole region. The Watsonville area is one of these emanative centres recognized by Taylor and Steveson. Local zoning is reflected here in the change from tungsten and tin mineralization in and around the margins of the Elizabeth Creek Granite, to copper and tin mineralization throughout the United North Australian Mine area in the sediments to the north. As tin mineralization is present throughout the mine area there is no distinct boundary between these two zones. There is also a distinct absence of lead and zinc mineralization. The tin deposits in the granite are mostly quartz-chlorite lodes which occupy joints and shears. The lodes are restricted to the top and flanks of a ridge of highly silicified granite.

The lode material, known locally as “black rock”, consists of chlorite, secondary biotite, sericite and veins and blebs of quartz. The main ore mineral is cassiterite. Wolframite is nearly always present as well as fluorite, topaz and minor sulphides.

In the United North Australian Mine area tin occurs in quartz, tourmaline cassiterite lodes and complex tin-sulphide lodes. The quartz, tourmaline, cassiterite lodes often contain topaz and fluorite, and are localized by a complex series of faults, fractures and joints which are known locally as “heads”. Some of these lodes such as the North Australian and Ironclad, pass into complex tin-sulphide lodes at depth. Where the complex tin-sulphide lodes occur in the sediments they consist mainly of pyrrhotite, chalcopyrite and arsenopyrite with tin being present as both stannite and cassiterite. Lodes of this type were worked in the Shaugraun, Easter Monday, Crucible, North Australian and Ironclad mines.

The mineralization in the UNA Porphyry is of three characteristic types, disseminated, semi-massive and massive. Disseminated sulphides occur throughout the porphyry mainly as pyrrhotite, chalcopyrite and arsenopyrite. However, in the Baal Gammon area, the porphyry has been extensively mined by open cut methods for disseminated cassiterite.

Within the centre of this porphyry a concordant impersistent mineralized zone is often present which consists of between 2% and 10% total sulphides with a thickness from 5-10 feet. Pyrrhotite, chalcopyrite and arsenopyrite are again the main constituents. Two bodies of complex massive sulphides are known to be present within the Baal Gammon and Two Treys Mine areas. These bodies occur within the UNA Porphyry. The detailed opaque mineralogy of the Two Treys ore body will be the major subject discussed in this chapter.

Data for this section was obtained from systematic visual estimation of the mineral components of drill core samples, and petrological study of a representative suite of polished sections of samples from the Two Treys Mine area.

## 5.2 Two Treys Mine

The Two Treys Mine area was selected for detailed study because of the large amount of information available from diamond drill core. The data used included detailed lithology and mineralogy, and chemical analyses from 33 drill holes. The location of the drill holes is shown in Figure 4. The massive sulphide lode present within the porphyry in this area plunges 20$^{o}$ to the southeast and dips 35$^{o}$ to the southwest. It forms an impersistent, elongate lense which is elliptical in cross section (Figures 5, 6, 7). True thickness varies from less than one foot to 35 feet, while mining and drilling operations indicate the length could exceed 300 feet. The true thickness of the porphyry in the mine area varied from 30 feet to 120 feet. This variation in thickness produces an elongate bulge in the upper surface of the porphyry (Figure 4). The massive sulphide lense is located below the bulge.

## 5.3 Mineral Zoning

A pronounced spatial zonation of sulphide minerals is evident within the Two Treys Mine area. This is shown in the contour diagrams in Figures 5, 6 and 7. These contour diagrams were prepared from visual estimates of the amount of each phase present over five foot intervals of diamond drill core. The exceptions to this are the diagrams for tin which are prepared from assay figures. These diagrams indicate that there are three pronounced mineralogical zones within the Two Treys ore body. These are (i) pyrite zone, (ii) arsenopyrite zone and (iii) pyrrhotite-chalcopyrite zone.

### 5.3.1 Pyrite Zone

Pyrite constitutes the major phase in the outermost zone together with lesser amounts of chalcopyrite. This zone forms a lateral impersistent shell which partially encloses the inner zones (Figures 5A, 6A, 7A). The pyrite and chalcopyrite rarely constitute more than 20% of the rock in this zone.

### 5.3.2 Arsenopyrite Zone

This zone consists of massive and disseminated arsenopyrite which forms an impersistent shell around the innermost pyrrhotite-chalcopyrite zone. The arsenopyrite usually forms a cap above this zone (Figures 6B, 7B) but occasionally it is present above and below (Figure 5D).

### 5.3.3 Pyrrhotite-Chalcopyrite Zone

Massive pyrrhotite and chalcopyrite are present within an innermost zone (Figures 5B, 5D, 6B, 7B). Here pyrrhotite constitutes the major and most widespread phase while chalcopyrite occurs as small massive pods within the pyrrhotite. Usually the pyrrhotite overlies the chalcopyrite but in Figures 5B and 5D the chalcopyrite is totally enclosed by massive pyrrhotite.

Tin is present as cassiterite and stannite but the contours of assay values do not distinguish between the species. In Figures 5A, 6A and 7B the maximum tin concentration usually coincides with zones of maximum total sulphides but in some cases (Figure 5A) the high tin values correspond with the lateral pyrite zones.

This zoning cannot be explained in terms of established paragenetic sequences. However, a notable feature is the steady decrease in the mole percent of FeS present in sulphide minerals from the outer zone through to the inner. An explanation of this phenomenon will be proposed in Section 6.

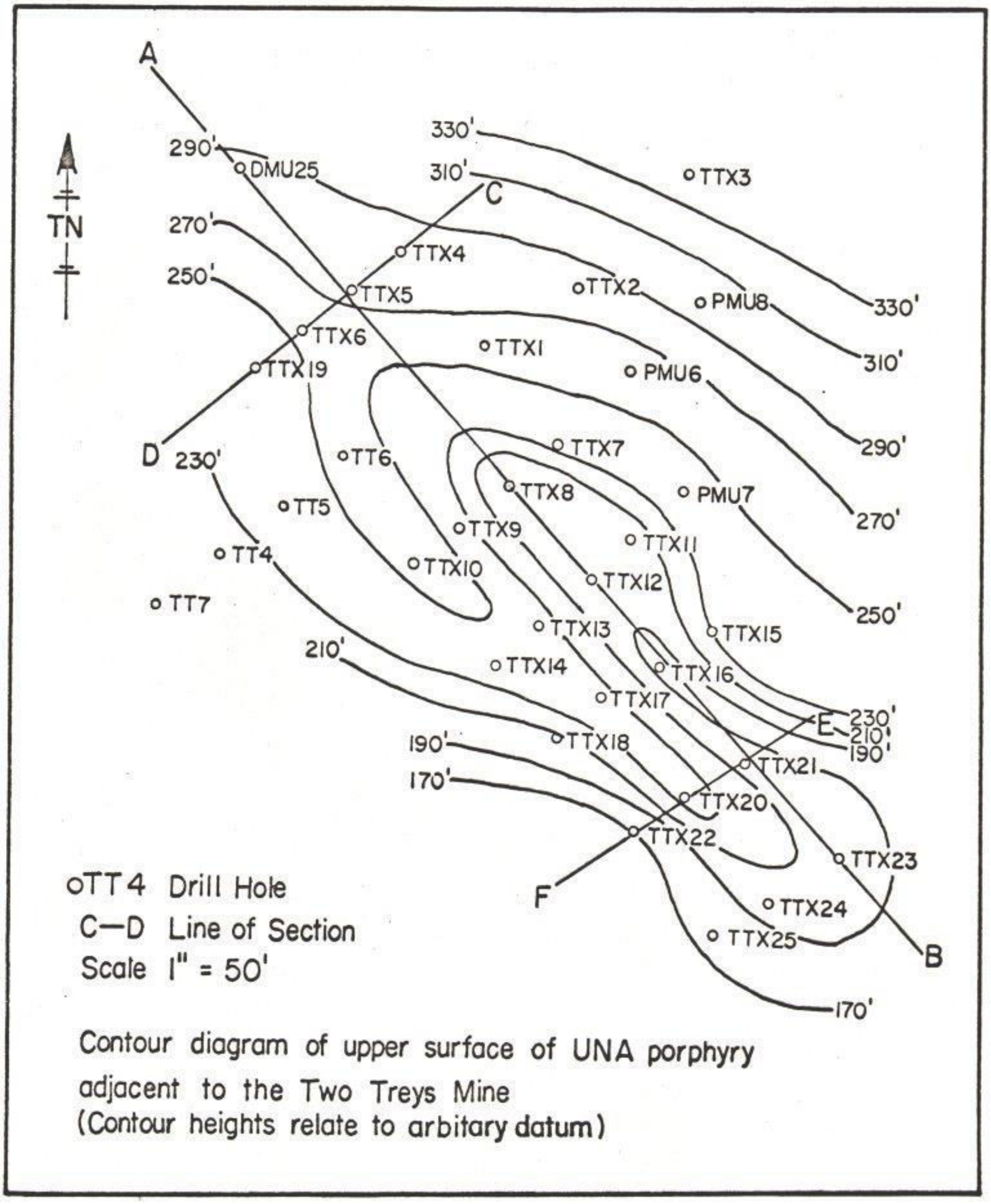

*Figure 4. Structure contour, upper surface of UNA Porphyry, Two Treys Mine, and location of drill holes and section lines through mine area.*

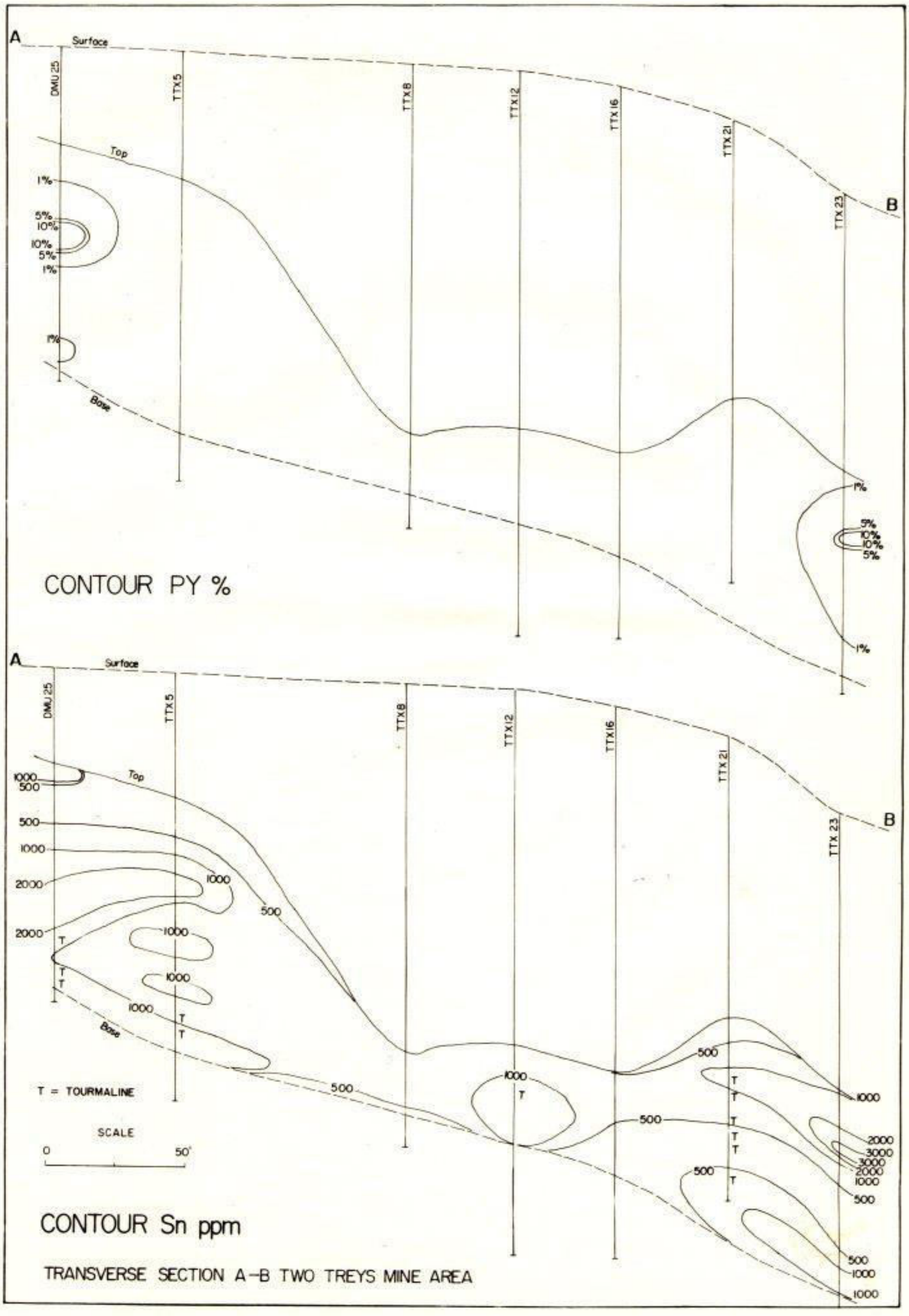

*Figure 5A. Transverse section A-B through Two Treys Mine, UNA Porphyry, with contoured pyrite (PY) percent estimated from diamond drill samples and tin (Sn) ppm from chemical analyses. The presence of tourmaline is also notated.*

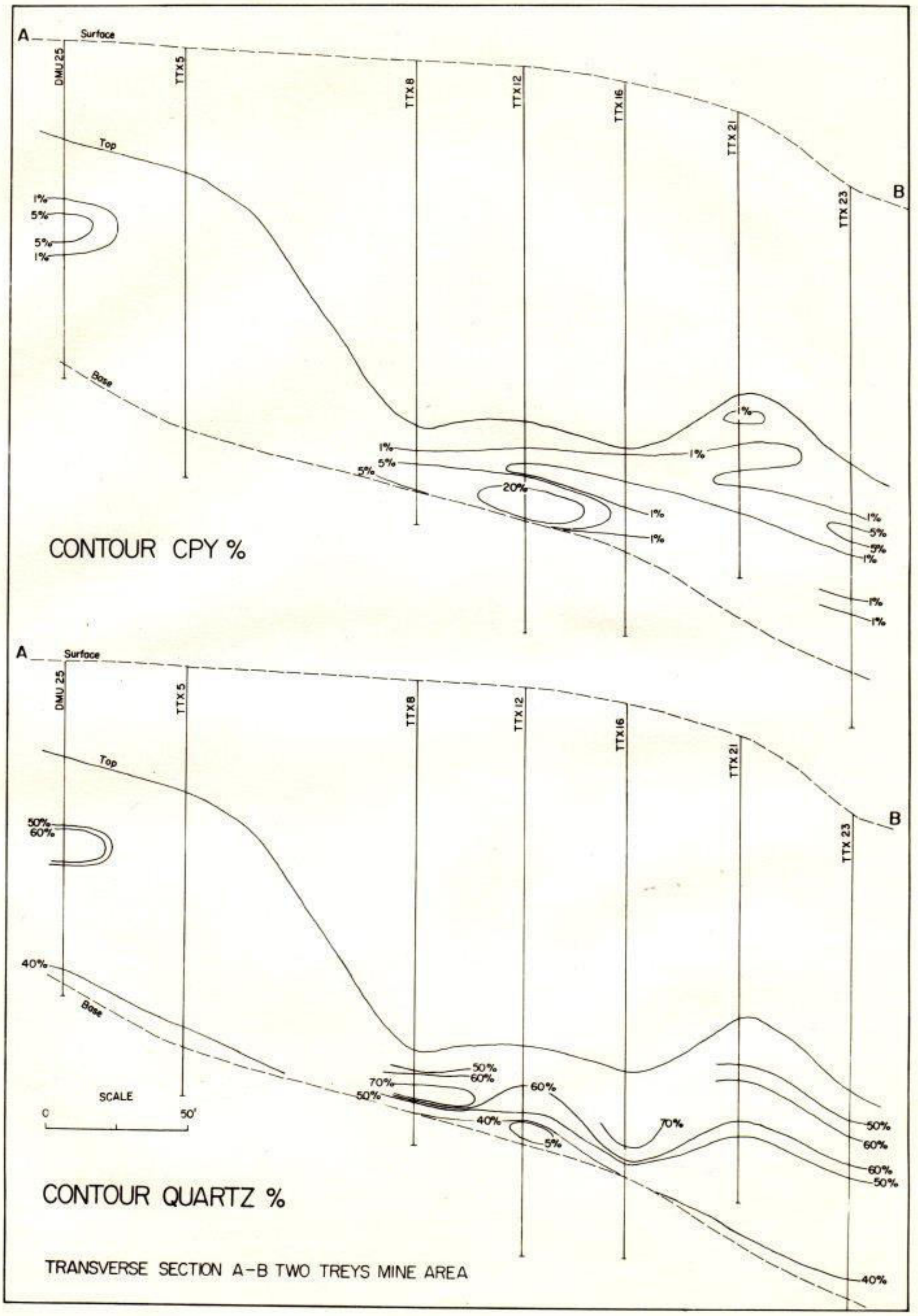

*Figure 5B. Transverse section A-B through Two Treys Mine, UNA Porphyry, with contoured chalcopyrite (CPY) and quartz percentages estimated from diamond drill samples.*

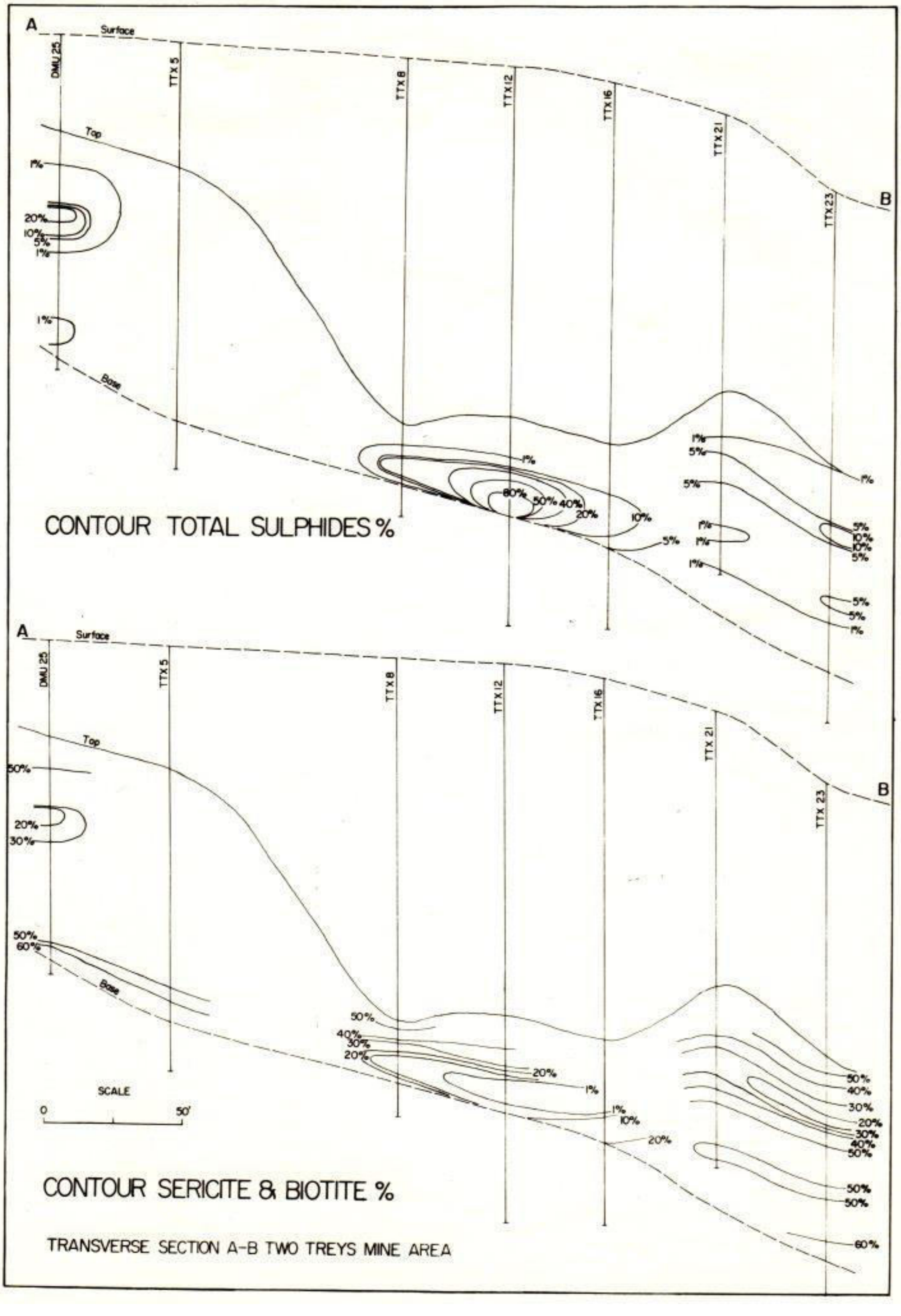

*Figure 5C. Transverse section A-B through Two Treys Mine, UNA Porphyry, with contoured total sulphides and sericite + biotite percentages estimated from diamond drill samples.*

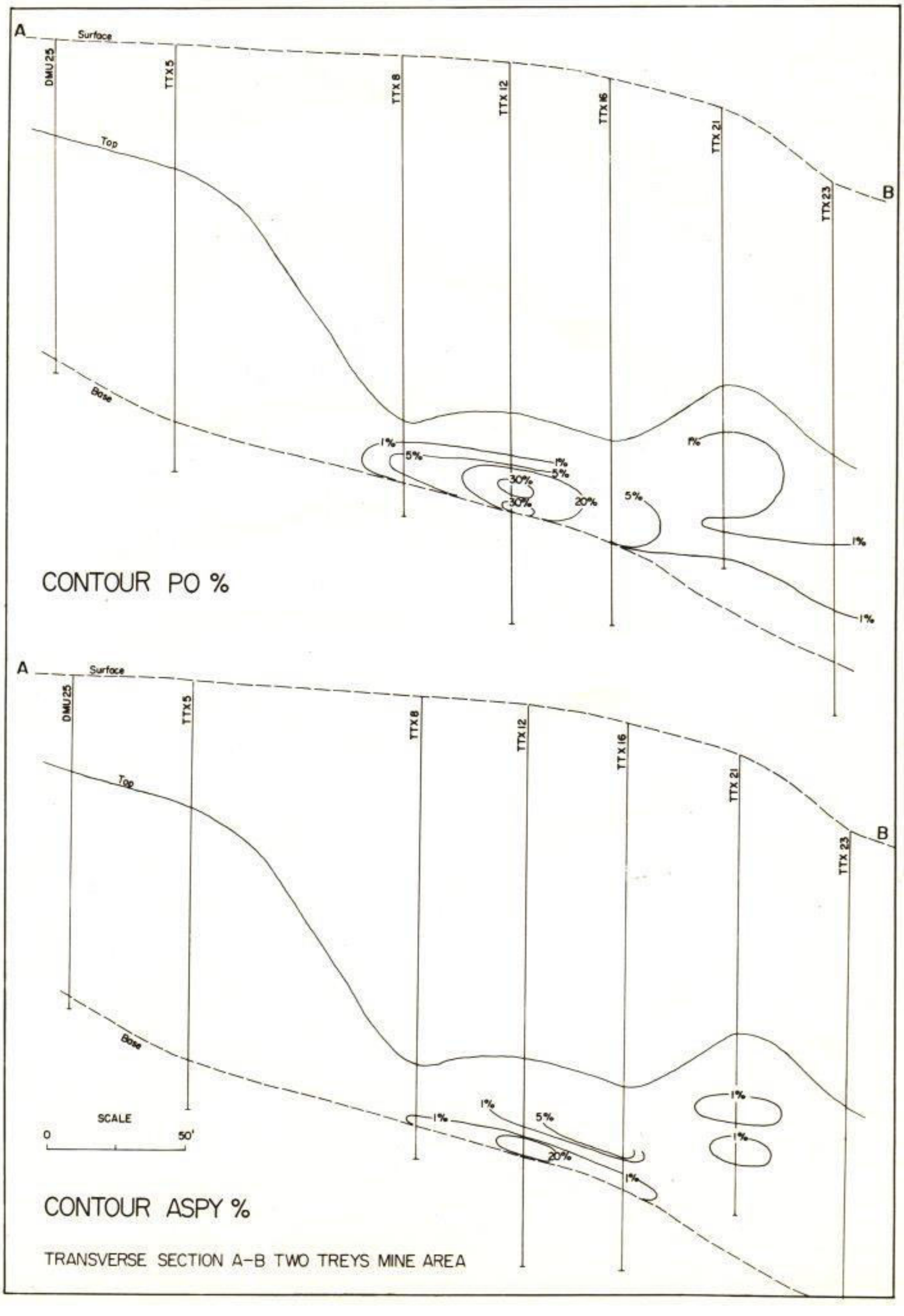

*Figure 5D. Transverse section A-B through Two Treys Mine, UNA Porphyry, with contoured pyrrhotite (PO) and arsenopyrite (ASPY) percentages estimated from diamond drill samples.*

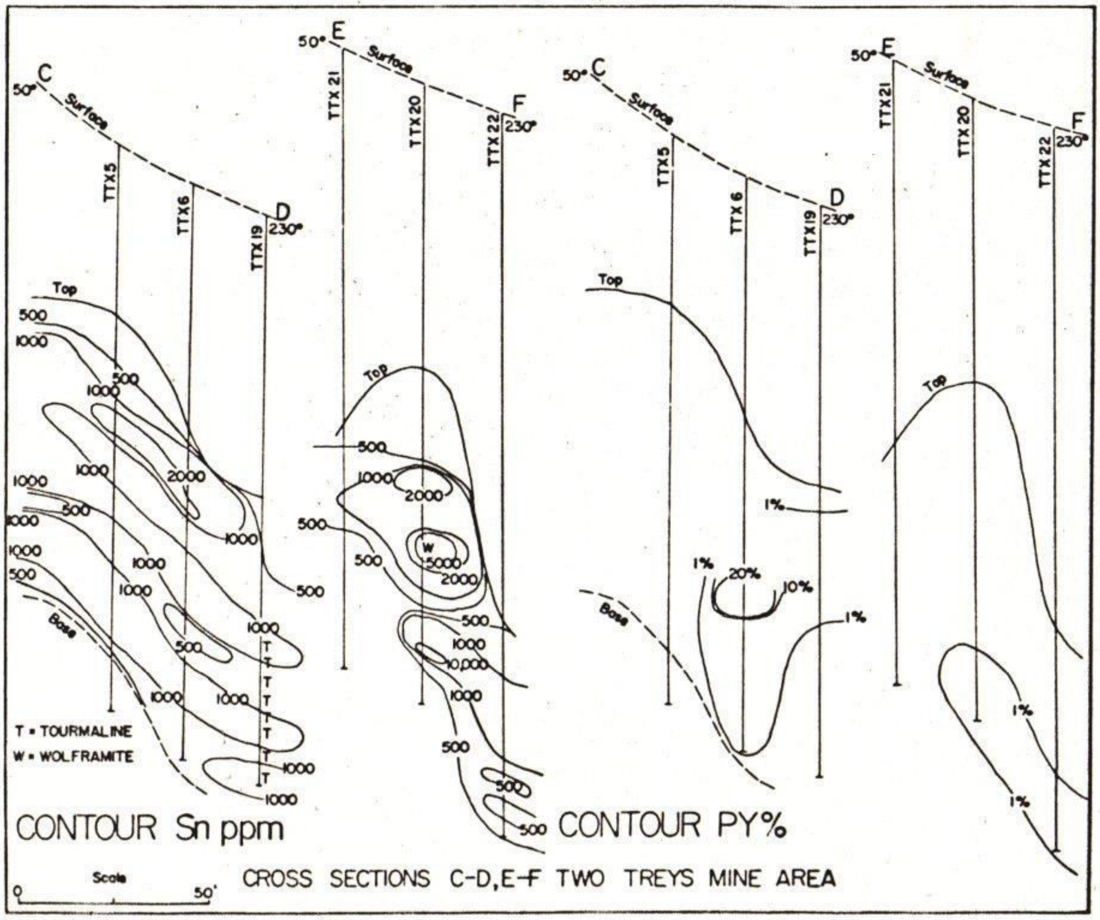

*Figure 6A. Cross sections C-D and E-F through Two Treys Mine, UNA Porphyry, with contoured tin (Sn) ppm from chemical analyses and pyrite (PY) percent estimated from diamond drill samples. The presence of tourmaline and wolframite is also notated.*

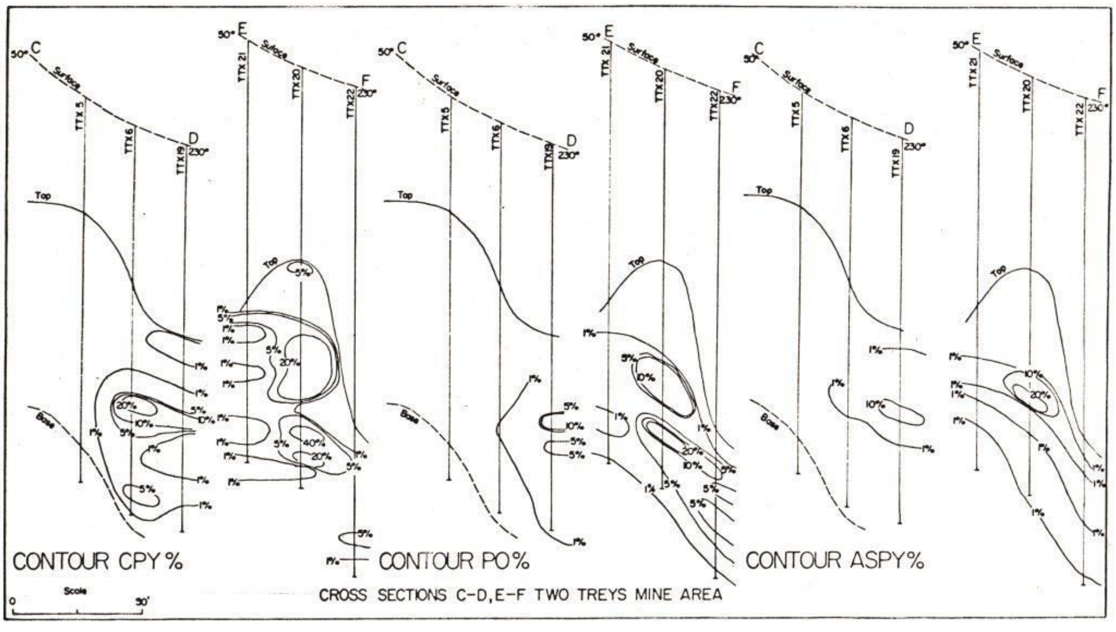

*Figure 6B. Cross sections C-D and E-F through Two Treys Mine, UNA Porphyry, with contoured chalcopyrite (CPY), pyrrhotite (PO) and arsenopyrite (ASPY) percentages estimated from diamond drill samples.*

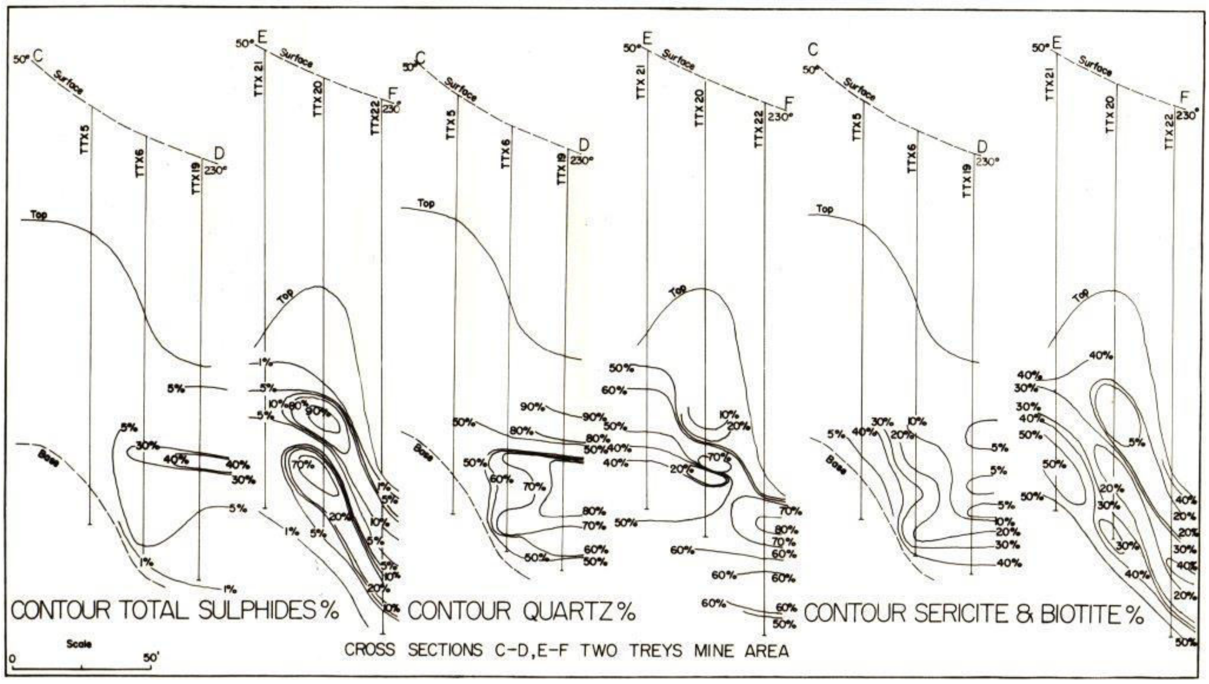

*Figure 6C. Cross sections C-D and E-F through Two Treys Mine, UNA Porphyry, with contoured total sulphides, quartz and sericite + biotite percentages estimated from diamond drill samples.*

## 5.4 Textural Studies

The textures displayed by ore minerals have traditionally been used as a basis for determining both the sequence of deposition and temperature of formation of ore deposits. The criteria proposed by Edwards (1959), Ramdohr (1969) and Schwartz (1951) for interpreting textures have received widespread acceptance. However, in recent years the reliability of paragenetic interpretation based on these textural criteria have been increasingly questioned. Brett (1964) in a study of sub-solidus phase relationships in the system Cu-Fe-S demonstrated that many so-called replacement textures could be produced by exsolution of one phase from another during cooling. He also has shown that the type of texture produced is dependent on the degree of supersaturation of one phase in the other, rather than rate of cooling.

A different approach was used by Stanton (1964) and Stanton and Gorman (1968) who demonstrated that textures exhibited by stratiform ores do not reflect age differences of the phases present, but rather minimum surface free energy grain boundary arrangements. Through a study of grain boundary relationships in natural and artificially annealed sulphide assemblages, these authors were able to demonstrate that annealing could produce grain growth, twinning and preferential recrystallization of some already deformed phases.

Similarly Gill (1969, 1970) and Graf and Skinner (1970) have studied the textures produced by experimental deformation of sulphide assemblages. Gill found that at a total pressure of 550 bars and a temperature of 440°C galena flows plastically into cracks in pyrite, sphalerite, chalcopyrite and pyrrhotite, while galena, pyrrhotite and chalcopyrite can penetrate pyrite and sphalerite. At higher temperatures all textural evidence of plastic flow is obliterated by recrystallization of the phases. Graf and Skinner have demonstrated that pyrite exhibits brittle behaviour within the full range of temperatures and pressures expected within the earth's crust, whereas pyrrhotite deforms plastically at temperatures as low as 100°C and is probably ductile under all conditions.

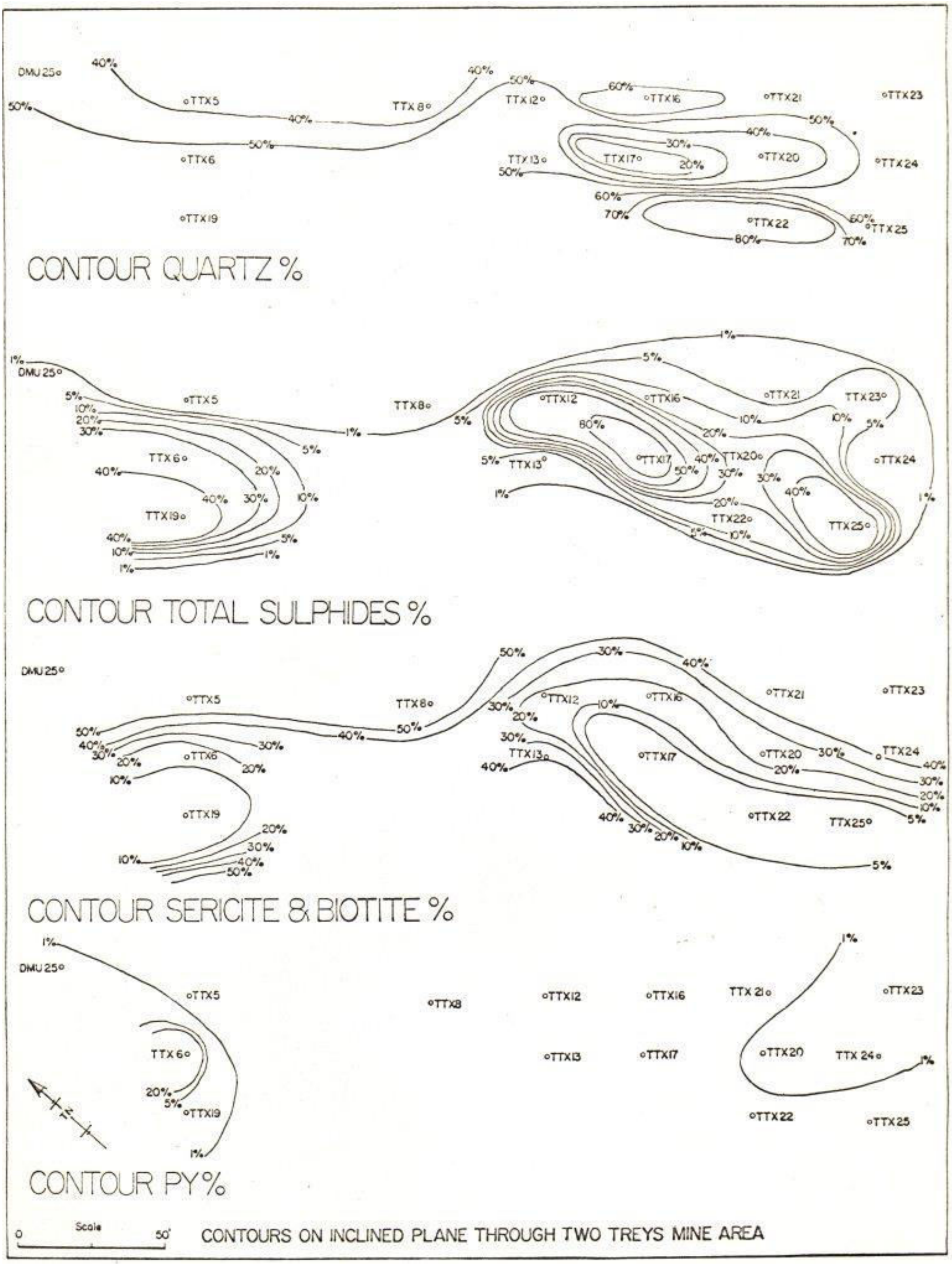

*Figure 7A. Inclined plane through Two Treys Mine, UNA Porphyry, with contoured quartz, total sulphides, sericite + biotite and pyrite (PY) percentages estimated from diamond drill samples.*

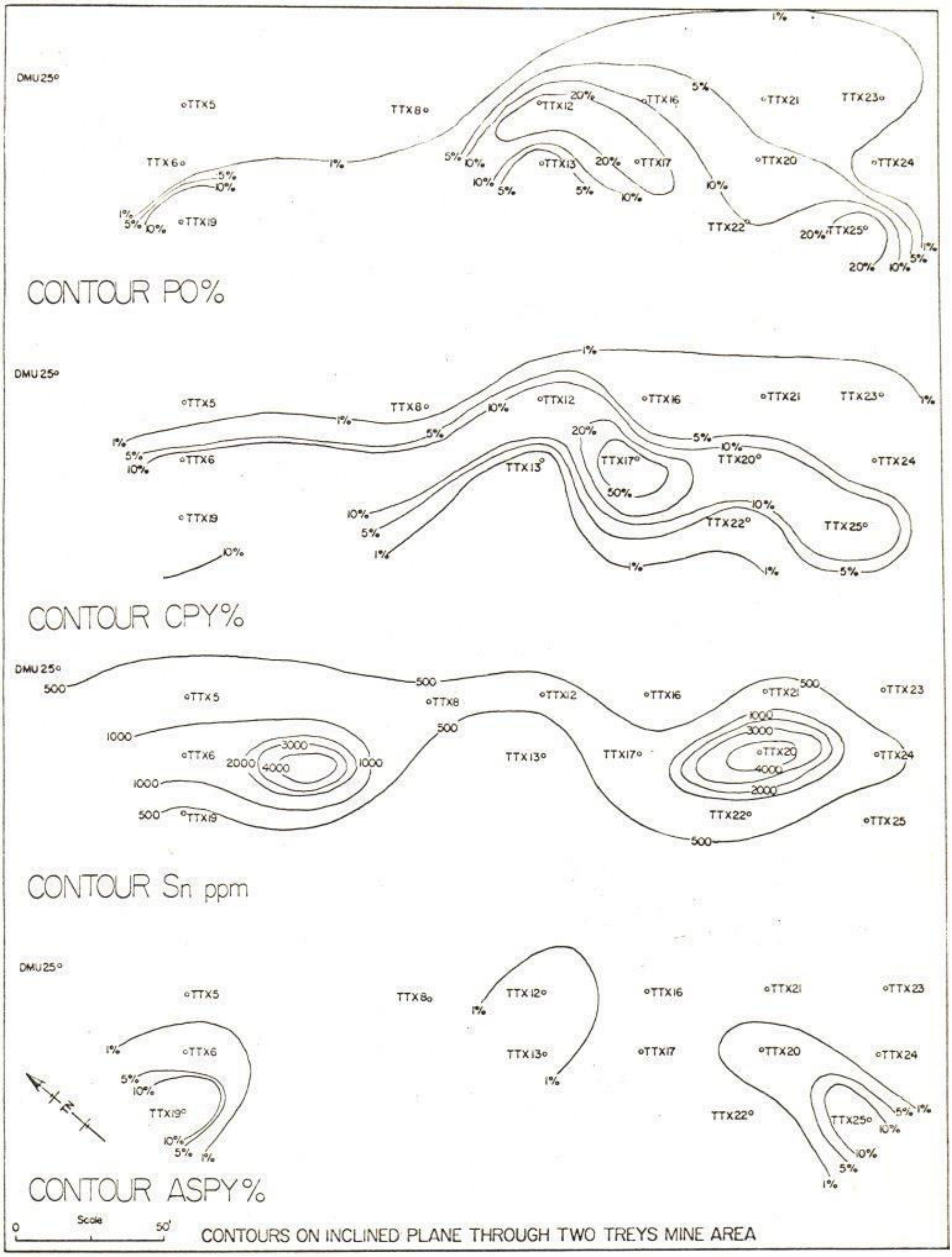

*Figure 7B. Inclined plane through Two Treys Mine, UNA Porphyry, with contoured pyrrhotite (PO), chalcopyrite (CPY) and arsenopyrite (ASPY) percentages estimated from diamond drill samples and tin (Sn) ppm from chemical analyses.*

It is evident therefore that paragenetic sequences based on textural criteria alone should be viewed with extreme caution. In the following study of ore minerals from the Two Treys Mine area, an attempt has been made to apply some of the criteria for recognition and interpretation of deformation and annealing textures proposed by Stanton (1964), Stanton and Gorman (1968) and Stanton (1971). Unambiguous cross cutting relationships provided by intersecting gangue sulphide veins have also been used where applicable.

### 5.4.1 Pyrite

Pyrite is restricted to the outer pyritic shell of the Two Treys ore body where it occurs mainly with chalcopyrite and leaser amounts of pyrrhotite and arsenopyrite. The pyrite is present in large, vuggy, pitted masses and rafted aggregates of well-formed idiomorphic grains which vary from 0.05-0.20 mm diameter.

The massive pyrite is fractured and has been intruded by veins of chalcopyrite and pyrrhotite. It has also been cut by veins of gangue. The pyrite adjacent to these veins exhibits an irregular, jagged and toothed appearance where it has obviously been fractured. Small angular grains of pyrite trapped in the vein, as well as a few small patches adjacent to the vein, have been altered to marcasite (Plate 21). The marcasite has numerous elongate pits which have a radiating appearance in places.

The rafts of pyrite have irregular margins and are enclosed entirely by chalcopyrite and pyrrhotite. In some instances the chalcopyrite may have replaced the pyrite to some extent.

Two types of textures are present in the pyrite. A semi-regular banding of small brown inclusions occurs in large patches of pyrite which are comparatively free of vugs. This may be a type of growth structure (Plate 22). “Birdseye” textures have also developed where several concentric growths of pyrite are present within areas of massive pyrite (Plate 23). Similar structures in pyrite have been described by Edwards (1954), Both and Williams (1968), Kelly and Turneaure (1970) and Paverd (1971), where it is formed in the initial stages of the low temperature alteration of pyrrhotite to pyrite and marcasite. The vuggy appearance of pyrite is also characteristic in this type of occurrence. However, the only marcasite observed occurring with pyrite in this study was produced by inversion of pyrite. There is no evidence to suggest that pyrite has formed by the alteration of pyrrhotite.

Pyrite exhibits mutual boundary relationships with arsenopyrite, and according to Stanton (1959 and 1964) this suggests the two formed contemporaneously due to their high surface free energies.

A maximum temperature of formation of pyrite is indicated by the assemblage pyrite-arsenopyrite which has been shown by Barton (1969) to be unstable above $491 \pm 12^{\circ}$C. The alteration of pyrite to marcasite is obviously a much later phenomenon. Stanton (1971) indicates that this occurs at low temperature and under strongly acid conditions, but Kullerud (1967) has shown that this cannot occur below $432 \pm 3^{\circ}$C at one atmosphere.

### 5.4.2 Arsenopyrite

Arsenopyrite forms large massive pods which partially surround the chalcopyrite-pyrrhotite zone. It is also present as aggregates or single idiomorphic grains throughout the chalcopyrite-pyrrhotite zone. The massive arsenopyrite has been extensively fractured, often into single diamond shaped crystals, and is intruded by veins of chalcopyrite and pyrrhotite. The rafted aggregates have been fractured and extensively replaced by chalcopyrite producing an extensive skeletal arrangement in places. Some individual grains have had their centres preferentially replaced by chalcopyrite producing atoll textures (Plate 24).

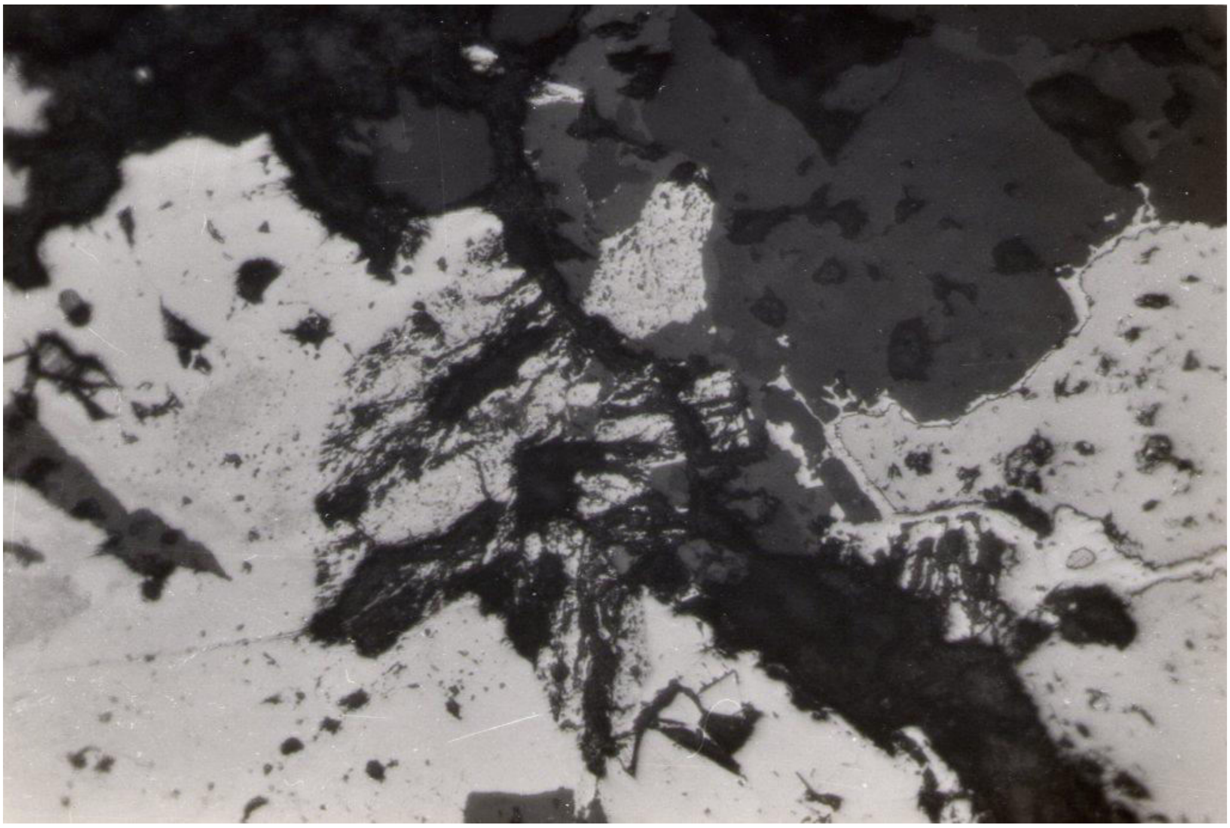

*Plate 21. Marcasite (centre) with elongate radiating pits replacing pyrite (light grey) adjacent to gangue vein (black, dark grey). (Reflected light, sample 9750).*

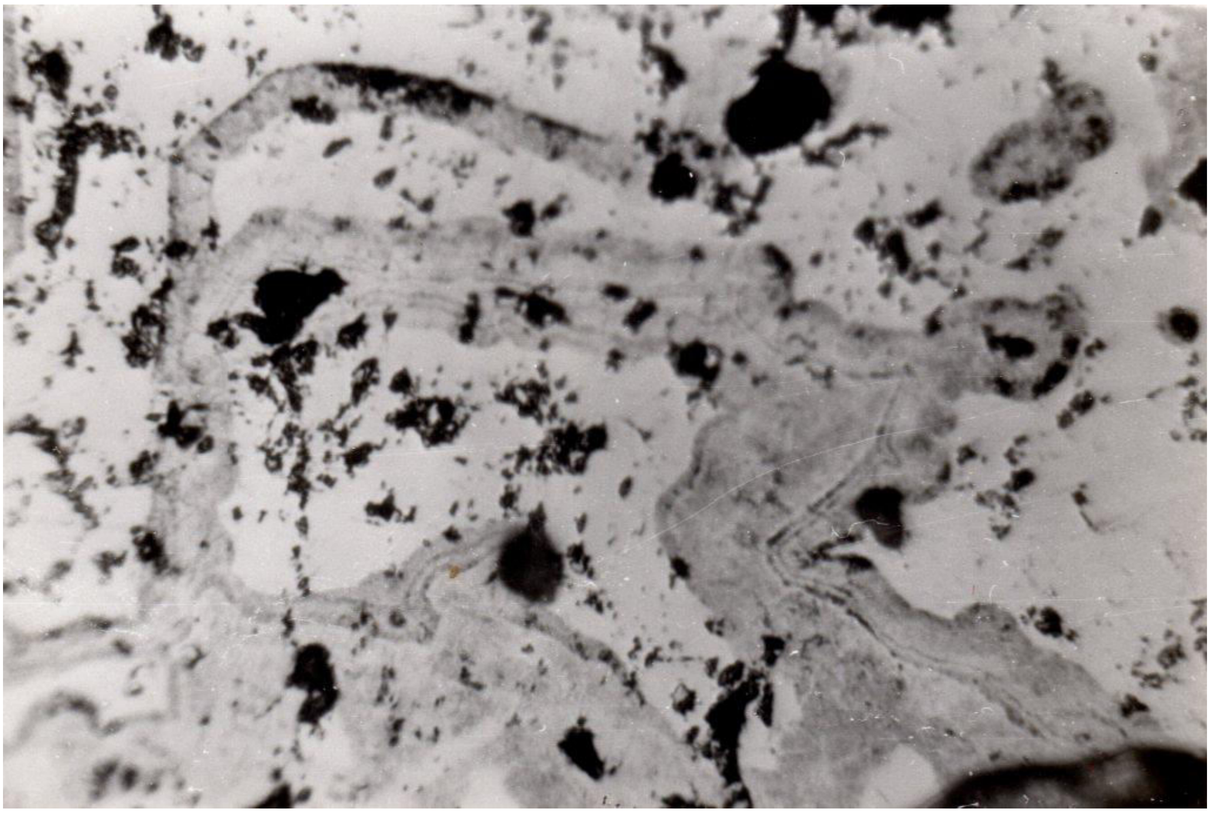

*Plate 22. Colloform growth banding in pyrite. (Reflected light, sample 9750).*

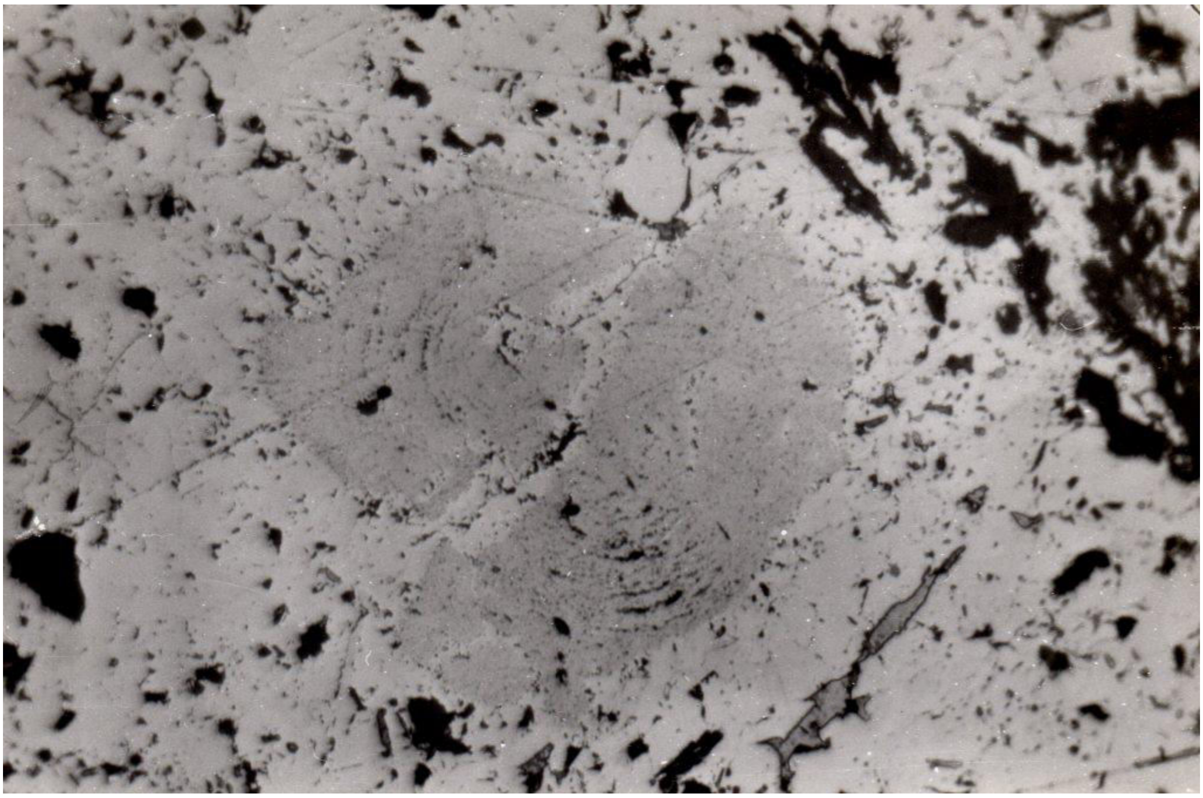

*Plate 23. Birdseye growth banding in pyrite. (Reflected light, sample 9750).*

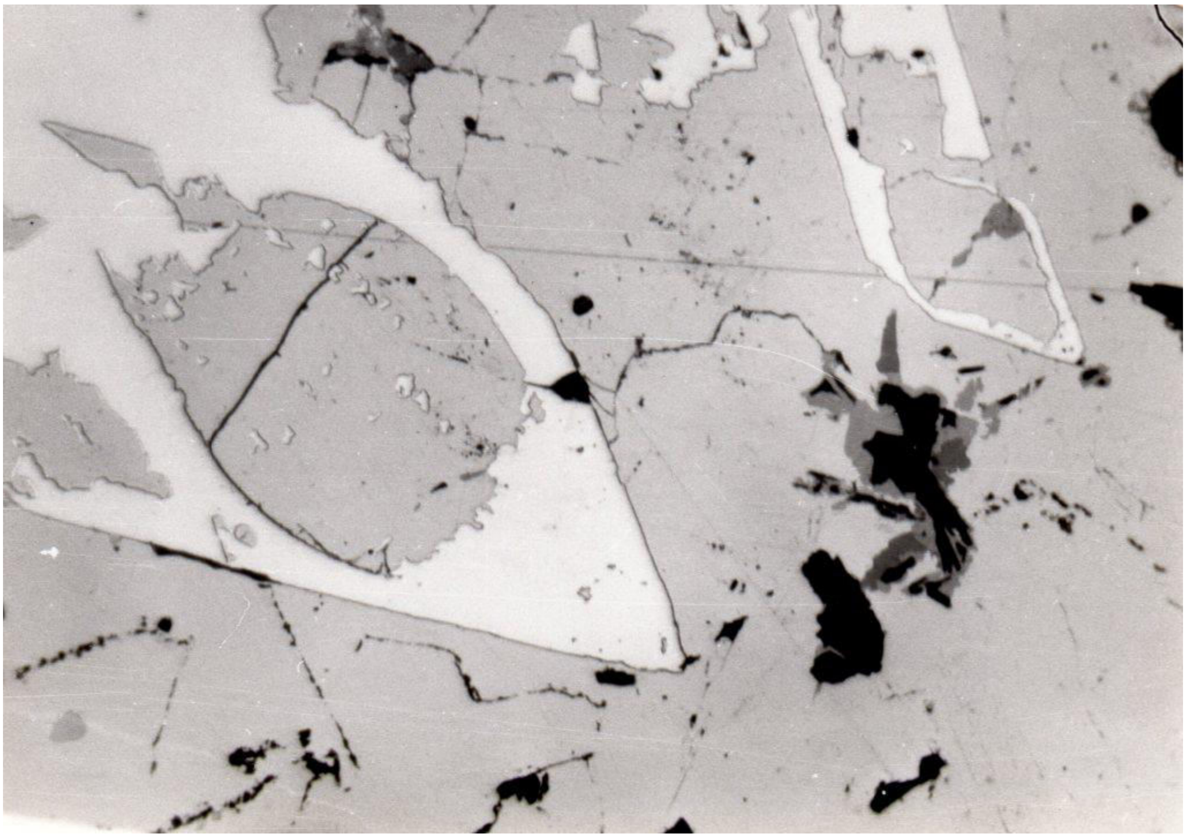

Plate 24. Atolls of arsenopyrite (white) produced by preferential replacement of cores of arsenopyrite crystals by chalcopyrite. (Reflected light, sample 9746).

This may possibly be due to compositional zoning within the arsenopyrite crystals. However, this could not be detected optically in the specimens examined.

Arsenopyrite exhibits mutual boundary relationships with both pyrite and wolframite, the three minerals having apparently formed contemporaneously.

Although no experimental studies on deformation of arsenopyrite and wolframite have been carried out under various conditions, it is quite obvious that these minerals exhibit brittle behaviour similar to that of pyrite during deformation of these ores. The maximum temperature of formation of the pyrite-arsenopyrite assemblage has already been stated as 491 ± 12°C (Barton, 1969).

### 5.4.3 Wolframite

Wolframite was noted in two localities in drill holes from the Two Treys Mine area where it forms long, bladed laths up to 1.5 cm long in the arsenopyrite and chalcopyrite-pyrrhotite zones. Some of the crystals are twinned and have been fractured crosswise, and in some instance displaced (Plate 25). They have been intruded by pyrrhotite and chalcopyrite.

The wolframite shows mutual boundary relationships with arsenopyrite (Plate 26) and presumably formed contemporaneously.

Temperature of formation of wolframite can only be estimated from fluid inclusion studies of related gangue minerals and cassiterite. Kelly and Turneaure (1970, p. 666-667) recorded temperatures from inclusions in quartz and cassiterite associated with wolframite in the Bolivian Tin Province varying from 192°C to 464°C. Studies of inclusions from wolframite deposits in Tasmania by Little (1960), Groves and Solomon (1969) and Groves, Solomon and Rafter (1970) indicate the temperature range of minerals deposited synchronously with the wolframite was 200°C to 400°C.

The maximum temperature of formation of wolframite therefore, probably lies below the experimentally determined upper stability limit of 491 ± 12°C for the pyrite-arsenopyrite assemblage.

### 5.4.4 Pyrrhotite

Pyrrhotite forms massive bodies within the pyrrhotite-chalcopyrite zone and also occurs as aggregates or individual grains in areas of massive chalcopyrite. It is coarsely crystalline and generally forms subhedral to rounded grains with individual crystals as much as 1 mm diameter. More irregular masses occur where it is present within veins which intrude fractures in the brittle minerals pyrite, arsenopyrite and wolframite. It is also present as veins in chalcopyrite.

The massive areas of pyrrhotite are free from other included grains but elsewhere it frequently contains small elongate or irregular blobs of chalcopyrite, stannite, bismuthinite, native bismuth (Plates 27, 28) and small grains of arsenopyrite and sphalerite. Often pyrrhotite appears to be replacing chalcopyrite, especially around grains of gangue which occur in the massive chalcopyrite. Here pyrrhotite forms a complete rim around the gangue grains. One polished section of pyrrhotite was etched with saturated chromic acid (Arnold, 1966) and examined for two phase assemblages under the microscope. Haynes and Hill (1970) distinguish two types of pyrrhotite by their reflectivity. The lightly etched highly reflective areas are hexagonal pyrrhotite, and the darker reflective areas are monoclinic (Plate 29).

The majority of the etched grains were hexagonal pyrrhotite which contain intergrown lamellae and elongate patches of monoclinic pyrrhotite. A few grains were apparently composed of monoclinic pyrrhotite with hexagonal lamellae.

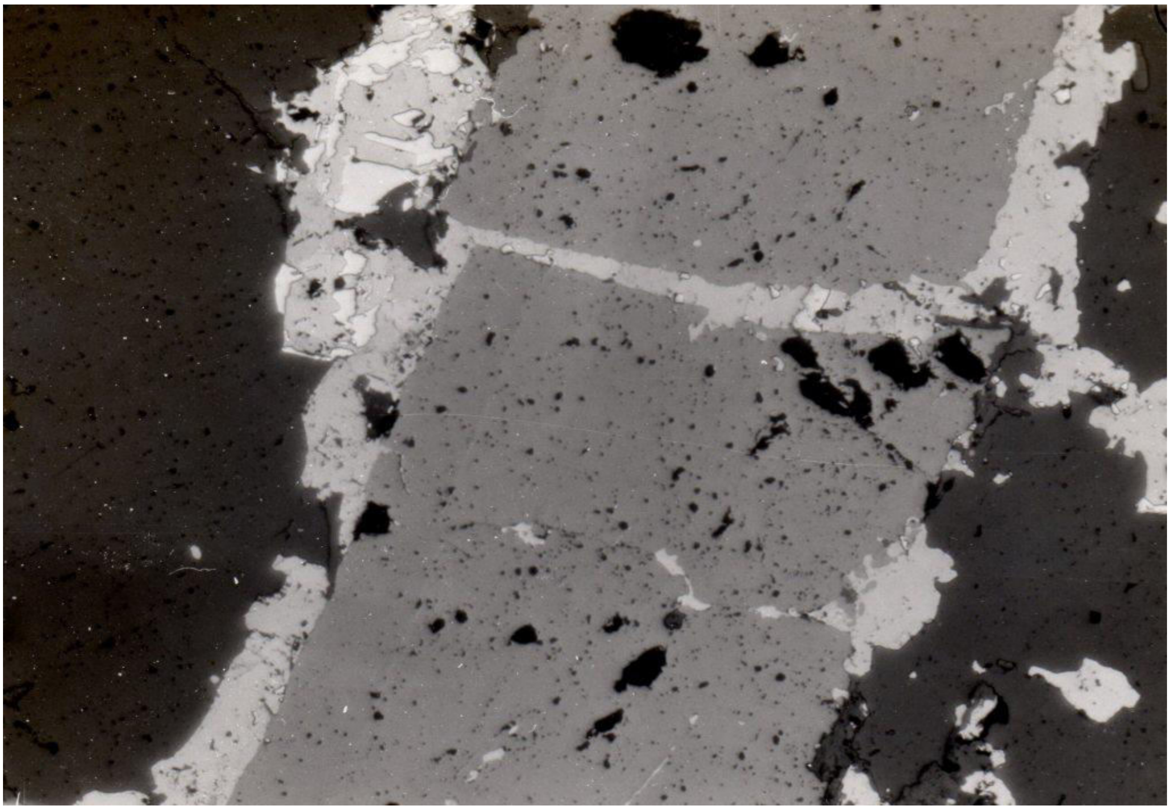

*Plate 25. Twinned wolframite blade (grey, centre) showing mutual boundary with gangue (dark grey), fractured, displaced and intruded by chalcopyrite (light grey). (Reflected light, sample 9746).*

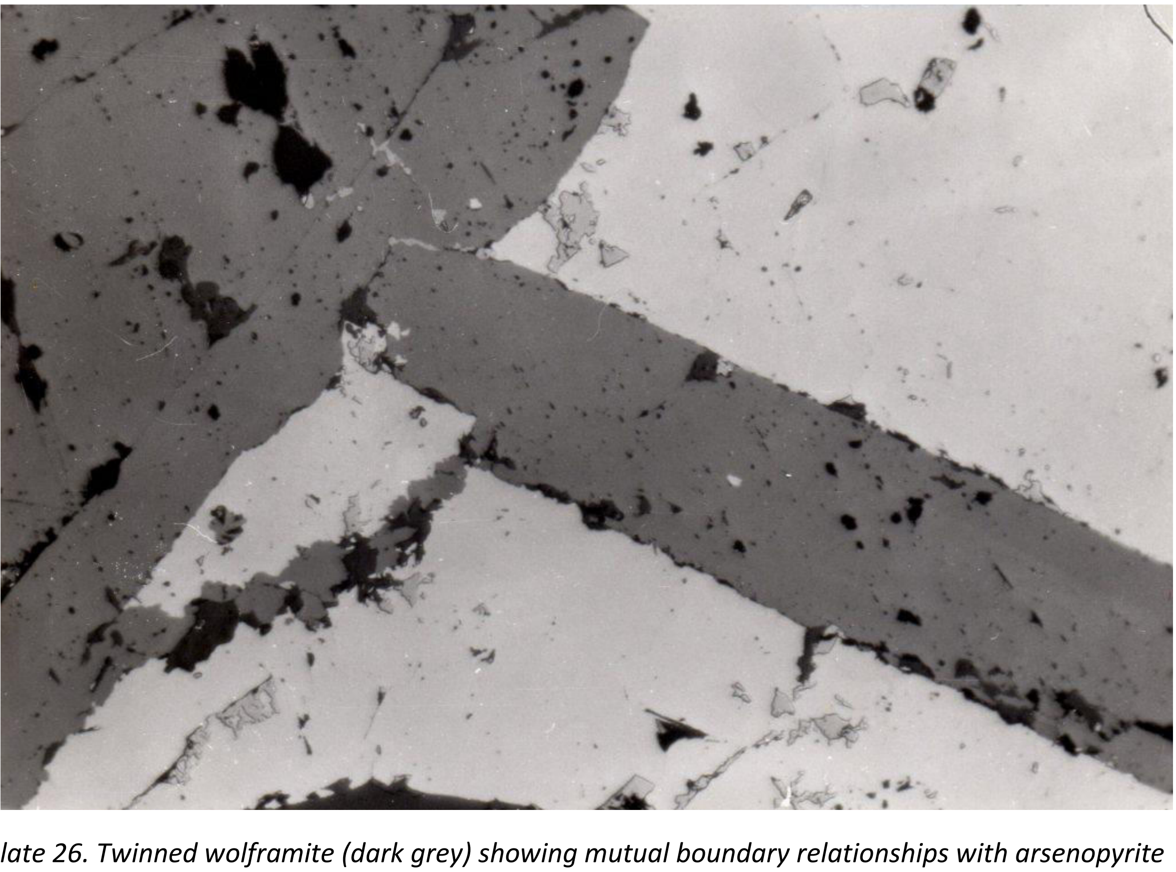

*Plate 26. Twinned wolframite (dark grey) showing mutual boundary relationships with arsenopyrite (light grey). (Reflected light, sample 9746).*

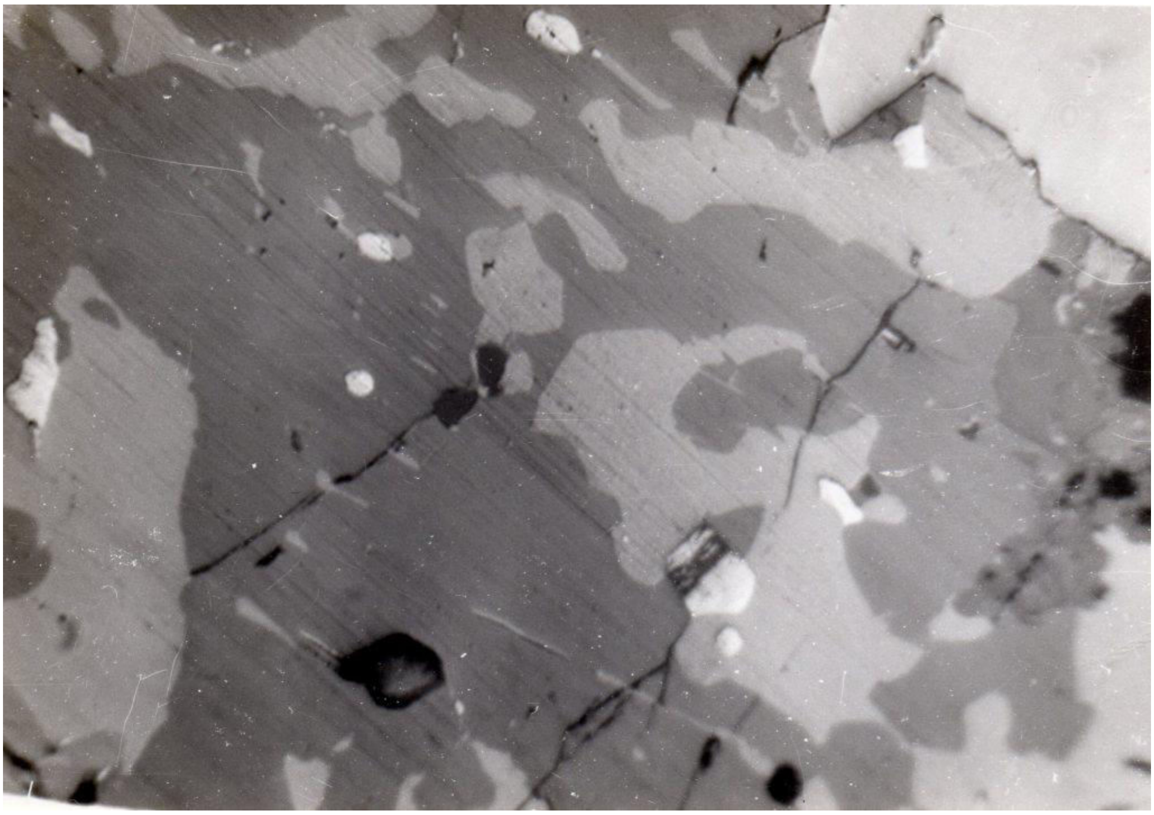

*Plate 27. Bismuthinite (light grey) in pyrrhotite (dark grey) with grains of native bismuth (white). Fractured arsenopyrite fragment upper right. (Reflected light, sample 9753).*

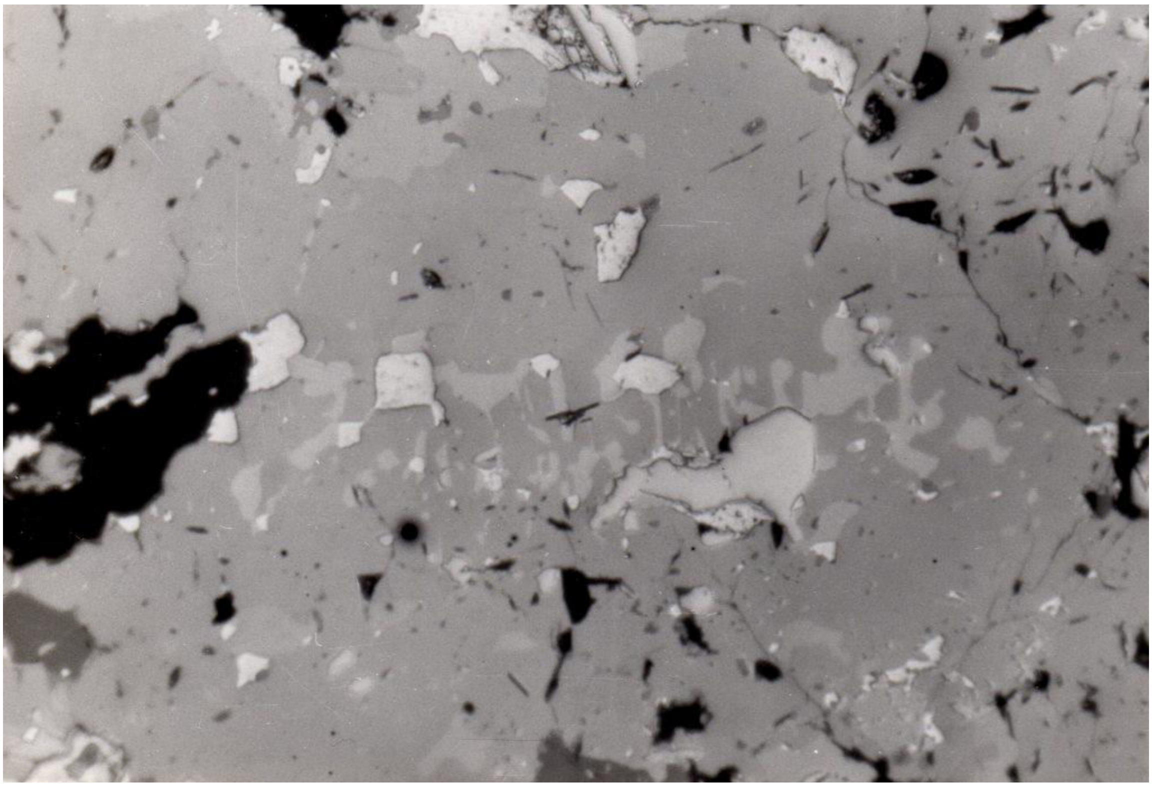

*Plate 28. Bismuthinite (light grey, centre) in pyrrhotite (darker grey) with grains of native bismuth (white). (Reflected light, sample 9750).*

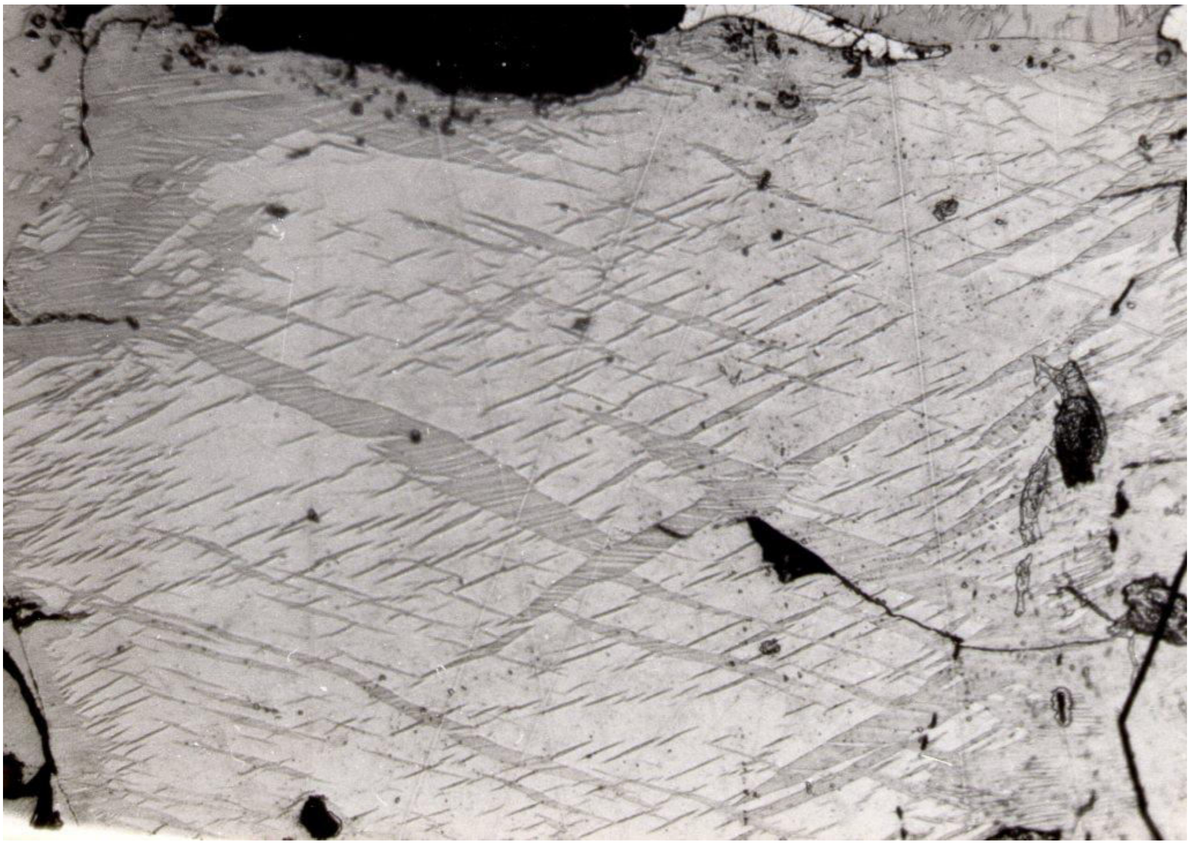

*Plate 29. Lamellae of monoclinic pyrrhotite (grey) in hexagonal pyrrhotite (light grey). (Chromic acid etched, reflected light, sample 9749).*

The hexagonal pyrrhotite frequently has a rim of monoclinic pyrrhotite around the margin of the grains which give the appearance of replacing the hexagonal type. The lamellar intergrowths are consistently arranged in two directions at 30-50° to each other, suggesting a crystallographically controlled orientation within their hosts, possibly resulting from exsolution (Haynes and Hill, 1970).

Experimental studies performed on natural and synthetic pyrrhotite by Desborough and Carpenter (1965), Clark (1966), Arnold (1966, 1969) and Yund and Hall (1969) have shown that hexagonal pyrrhotite has a composition of 46.1-47.5% Fe and is stable over a wide range of temperatures above and below 304°C. Monoclinic pyrrhotite, however, is stable only below 304°C and its composition varies with temperature from a maximum of 46.7% Fe at 304°C to increasingly sulphur rich composition at lower temperatures. When a mixture of monoclinic and hexagonal pyrrhotite are heated above 304°C the mixture inverts to an unstable hexagonal pyrrhotite which un-mixes slowly on cooling below 304°C.

The association of monoclinic and hexagonal pyrrhotite, therefore, probably indicates a maximum temperature of formation of 304 ± 6°C, under sulphur rich and/or iron deficient conditions.

Triple point angles of the etched pyrrhotite grains were measured in an attempt to quantitatively evaluate the extent to which pyrrhotite has been annealed. A standard deviation of ± 10.3 was determined from 330 measurements. Quantitative experiments on annealing of pyrrhotite do not appear to have been performed, but the data from triple point angles reported in Stanton (1964, p. 59) was used to calculate standard deviation for comparison. A natural pyrrhotite gave a standard deviation of ± 13.65 from 200 measured angles, while a synthetically and fully annealed sample gave a standard deviation of ± 10.87 from 100 measurements.

It appears therefore, that the pyrrhotite examined in this study has been extensively, if not fully annealed, providing the criteria used here are a valid indication of the extent of annealing.

This is not surprising considering that pyrrhotite is probably ductile under all geological conditions (Graf and Skinner, 1970). The veins of pyrrhotite intruded into the brittle minerals are quite likely to be the result of plastic flow in response to deformation.

It is tempting to postulate here that the rim of monoclinic pyrrhotite around the margin of hexagonal pyrrhotite grains may have been produced by grain boundary migration during deformation. The release of copper and bismuth, held in solid solution, from the margins of the grains during deformation could produce both the sulphur rich rim of monoclinic pyrrhotite and the included blebs of chalcopyrite, bismuth and bismuthinite. The conversion of hexagonal pyrrhotite to the monoclinic form during annealing has been demonstrated experimentally by Sugaki and Shima (1966).

### 5.4.5 Chalcopyrite

Chalcopyrite occurs as large anhedral grains up to 1 mm diameter which form massive aggregates in the centre of the pyrrhotite-chalcopyrite zone, and with pyrite in the pyritic shell. It also occurs as minute blebs and occasionally lamellae in sphalerite and stannite grains, and forms small irregular masses in pyrrhotite. Veins of irregular masses of pyrrhotite and chalcopyrite intrude fractures in the brittle minerals. Chalcopyrite is present in the arsenopyrite zone where it sometimes replaces the arsenopyrite.

Although pyrrhotite appears to be replacing chalcopyrite in some instances, the mutual boundary relationships of large individual grains and the inclusion of blebs and irregular masses of each in the other suggests the two formed largely contemporaneously.

Two types of lamellar twins are present throughout the individual chalcopyrite grains. Most commonly they are spindle shaped and do not extend right across grain but taper off within it (Plate 30). Stanton (1972) indicates these are deformation twins. The other variety are lath shaped, are more regular than spindle twins, and extend right across a particular grain. According to Stanton (1972) these are annealing twins. Triple angle measurements were not determined for chalcopyrite but its observed similarity of occurrence and behaviour to pyrrhotite suggests it is most likely annealed to some extent. The studies of Gill (1969, 1970) and Stanton and Gorman (1968) illustrate the ease with which chalcopyrite can be deformed. It has probably flowed plastically together with pyrrhotite into the fractures in the brittle minerals.

Yund and Kullerud (1966) have shown experimentally that chalcopyrite-pyrrhotite do not form a stable pair above $334 \pm 17^{o}C$, the stable phase above this temperature being pyrite-cubanite. No cubanite was observed during examination of these polished sections. This suggests that either chalcopyrite, or pyrrhotite, or both minerals formed below $334^{o}C$. This temperature is in close agreement with the maximum temperature of formation of the coexisting pyrrhotite phases.

### 5.4.6 Sphalerite

A few small discrete grains of sphalerite occur in the interstices between chalcopyrite grains and to a lesser extent, between pyrrhotite grains. Some of the pyrrhotite and gangue grains which occur in the chalcopyrite are surrounded by a complete rim of sphalerite. It also occurs as irregular blebs and discrete grains around the margins and sometimes within stannite grains.

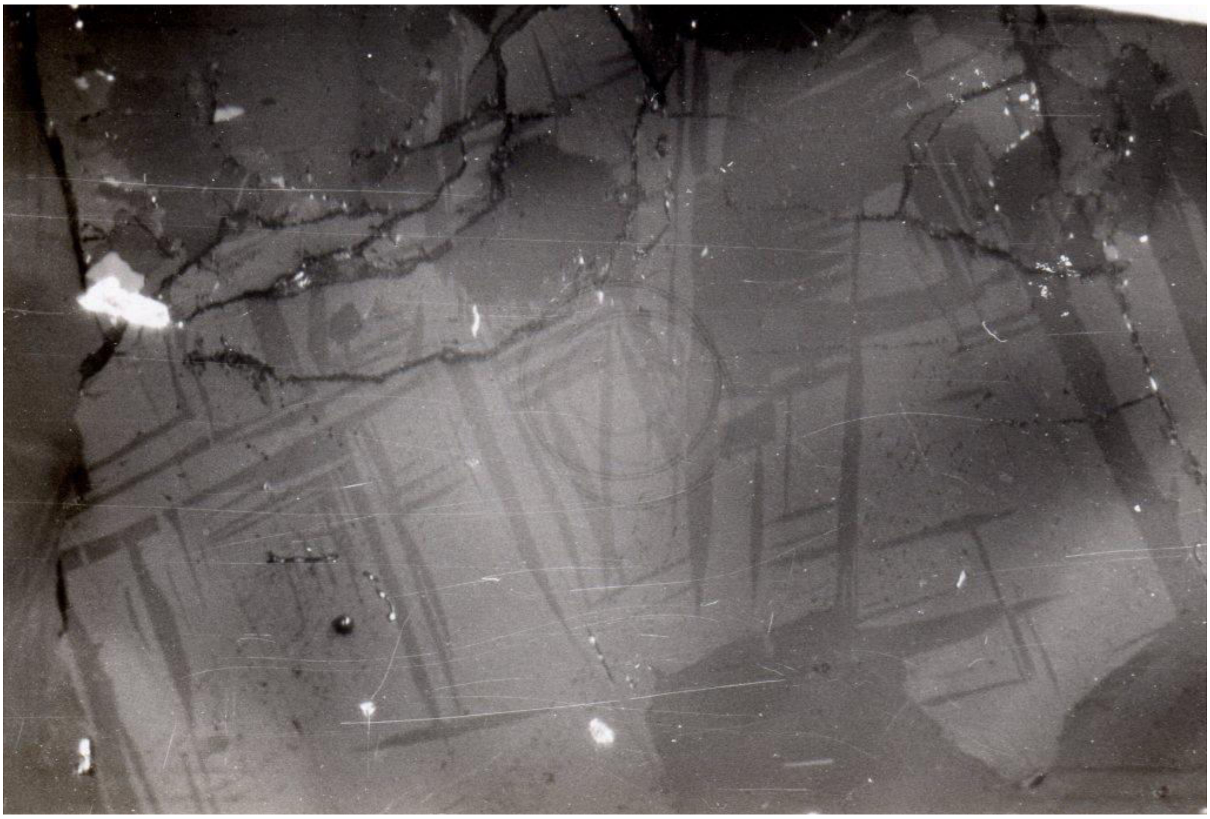

*Plate 30. Spindle twins (dark grey) in chalcopyrite (light grey). (Crossed nicols, sample 9745).*

Small elongate exsolution lamellae are occasionally present within larger grains. These define two regular directions which appear to be crystallographically controlled. The massive chalcopyrite has widespread minute exsolution bodies of sphalerite which are mostly long, thin discontinuous rods lying along cleavage plains. Where these rods intersect a variety of exsolution stars are formed (Plate 31). These include three and four armed stars and dumbbell shaped structures formed by the coalescing of two three armed stars.

These textural features indicate that sphalerite probably formed contemporaneously with chalcopyrite, pyrrhotite and stannite.

Two samples of massive sphalerite were etched with a 30% solution of hydroiodic acid and acetic acid to reveal the twinning present. As massive sphalerite is not present within the Two Treys ore body, samples were collected from drill holes which had intersected suitable material in the sediments above the UNA Porphyry (Samples 9734, 9735). This sphalerite is probably co-genetic with the material occurring within the Two Treys ore body and will have suffered the same deformation history.

The twins revealed by etching form regular parallel laths across the grains (Plate 32). Stanton (1972) indicated that these twins form as a result of deformation. Triple point angles were measured and the standard deviations calculated. These were then compared with those experimentally determined by Stanton and Gorman (1968) for natural and artificially annealed ores. These authors showed that sphalerite with an initial standard deviation of between ± 16 and ± 24 become fully annealed within 60 days at a temperature of 100$^{o}$C. At higher temperatures this was produced within 20 days. The standard deviation of fully annealed material varied between ± 10 and ± 12.

*Plate 31. Sphalerite exsolution structures in chalcopyrite, three and four armed stars, dumbbell structures and rods. (Reflected light, sample 9745).*

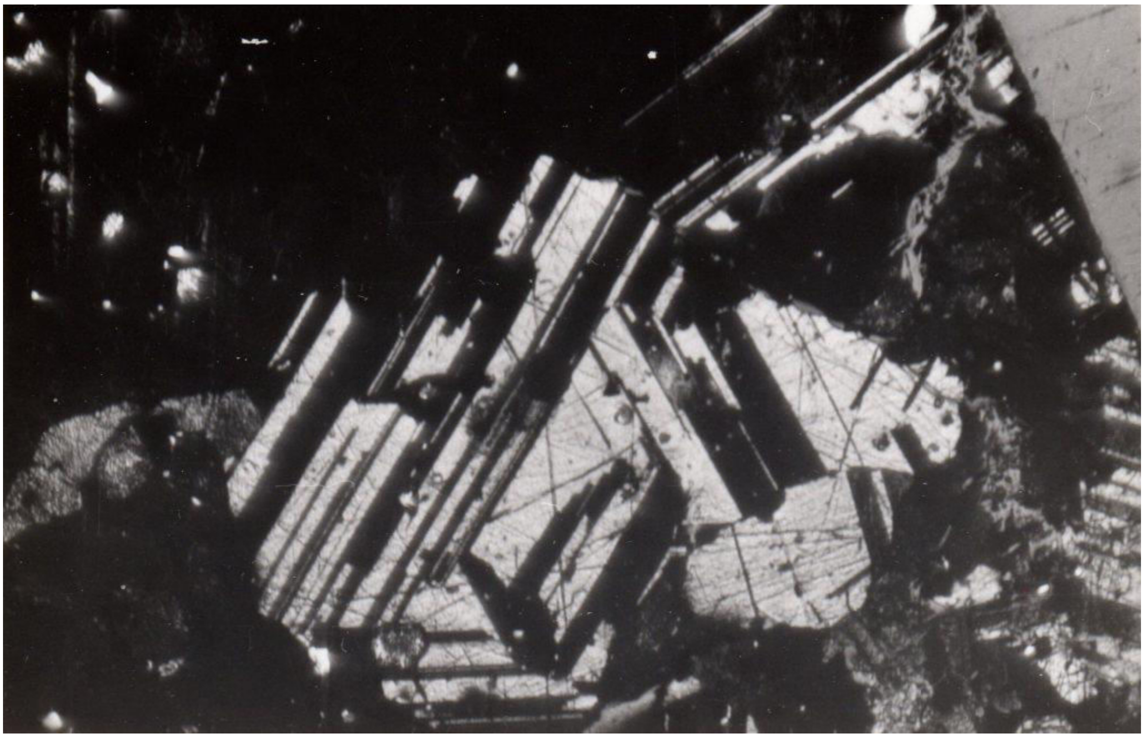

*Plate 32. Twins in sphalerite. Note discontinuous nature of some twins. (Hydroiodic acid and acetic acid etched, reflected light, sample 9735).*

The samples used in this study gave standard deviations of ± 15.0 from 205 measurements and ± 18.7 from 254 measurements respectively. Therefore, according to Stanton and Gorman's criteria these sphalerite samples show little if any annealing effects. This is quite surprising when one considers that the temperature of formation of sphalerite and the geological time for cooling in most hydrothermal circumstances would necessitate that all sphalerite would be fully annealed.

This suggests that other parameters play an important part in determining the extent to which annealing occurs. One of these is undoubtedly grain size. The samples used by Stanton and Gorman for their experiments had an initial grain size of 0.01 mm. Many of the grains in the material examined in this study was as coarse as 0.5 mm. If annealing by grain boundary migration is to occur it is obvious that it will proceed far more readily in finer grained material due to the shorter distance over which triple point adjustments have to take place.

Pressure undoubtedly will also play a part in this process. Stanton and Willey (1970) have shown that ores which are already deformed will anneal far more readily than undeformed ores. It has been shown that in this case very shallow conditions were present and pressure effects were probably negligible.

Subtle differences in the nature of the twinning in the sphalerite may also reflect the extent of annealing. Stanton and Gorman (1968) state that annealing twins "exhibit a high degree of coherency and extend right across the grains concerned." Detailed examination of the twinning in samples studied here reveal that many of the twins terminate abruptly within individual grains. Burns (1971) in a study of "apparently" deformed ores from Nicaragua recorded high standard deviation (± 19) calculated from triple point angles of sphalerite, indicating that the ores were apparently annealed. The sphalerite illustrated by Burns (Plate 3, p. B117) show discontinuous twins similar to those in this study. Therefore, it is suggested here that these incoherent, discontinuous twins represent deformation effects, while coherent twins which extend right across the grain are produced by annealing.

The approximate iron content of the sphalerite was determined using an iron sensitive stain (Einaudi, 1970). This revealed that all sphalerite samples had high iron content (approx. 25 mole % FeS) and were all of uniform composition throughout.

Scott and Burns (1971) have shown that the addition of pyrite to the system of sphalerite + pyrrhotite restricts sphalerite composition to a constant value of 20.7 ± 0.6 mole % FeS below 550$^{o}$C. Thus the iron content of sphalerite cannot be used as a geothermometer. However, the pressure effect of the FeS content of sphalerite is large, making sphalerite a useful geobarometer when in equilibrium with pyrite and hexagonal pyrrhotite. Using the calibration curves of Scott and Barnes (1971, p. 663) it is apparent that at temperatures up to 550$^{o}$C any sphalerite with more than 20 mole % FeS, should form at pressure less than 500 bars.

This provides further evidence of shallow, low pressure conditions of formation for these ores.

### 5.4.7 Cassiterite

Cassiterite occurs as small discrete rounded grains which vary from 0.05 to 1.0 mm in diameter. They occur throughout the pyrrhotite-chalcopyrite and pyrite zones. The grains frequently occur in clusters and often have rims of stannite. These clusters of cassiterite are most common in the massive chalcopyrite. The grains that occur in the pyrrhotite are usually larger but are far less common. Many cassiterite grains are twinned. Some have been fractured where they are cut by veins of carbonate gangue (Plate 33).

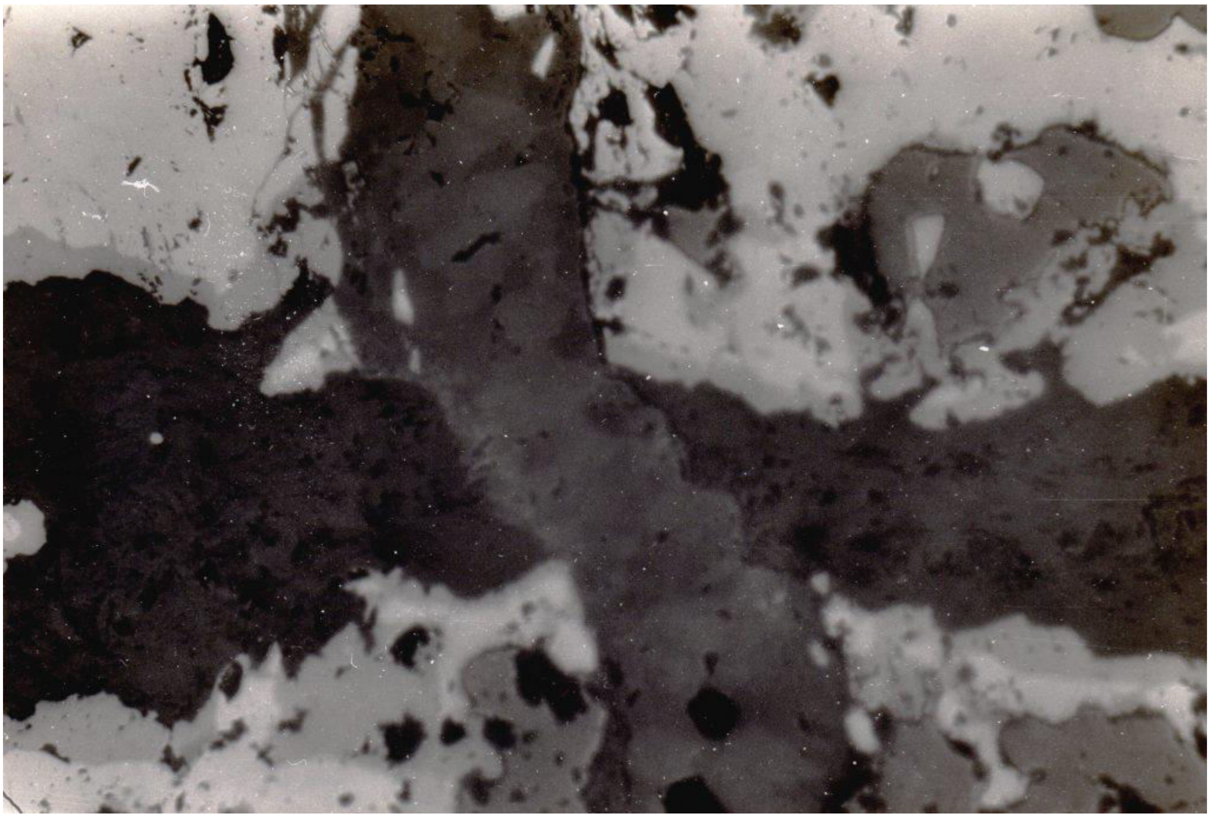

*Plate 33. Carbonate vein (north-south) cutting hydrated calcium silicate vein (east-west). Note thin rim of stannite adjacent to the east-west vein. Stannite is replacing chalcopyrite (light grey). Cassiterite with stannite rims are also present above and below east-west vein to right of plate. (Reflected light, sample 9752).*

Some of the cassiterite has the appearance of being corroded (Plates 34, 35). Here a number of small elongate semi-parallel patches of cassiterite occur within stannite grains. The elongate cassiterites have a much pitted, poorly reflective surfaces and in some instances they are quite similar to needle cassiterite.

Numerous occurrences of corroded cassiterite grains surrounded by a rim of stannite have been reported by Edwards (1951, 1954), Hosking (1969), Ramdohr (1969) and Daggar (1972). These authors have interpreted these textures as replacement. If this is so, cassiterite grains which only show partial corrosion by stannite around their margins should also be present in samples examined in this study. As this is not the case, it is suggested here that the textures of these cassiterites are a primary feature produced by fluctuations in the amount of tin available during simultaneous deposition of copper and tin bearing phases. Cassiterite and stannite are produced alternately. It is noteworthy that this type of cassiterite is confined to the area of massive chalcopyrite.

Temperatures of formation of cassiterite have been deduced by measuring filling temperatures of fluid inclusions of gangue minerals that formed contemporaneously with the cassiterite. This includes quartz, fluorite, topaz and in some instances cassiterite itself. Studies by Little (1960), Sawkins (1966), Bradshaw and Stoyel (1968), Groves and Solomon (1969, Groves, Solomon and Rafter (1970) and Turneaure (1971) indicate that hydrothermal tin deposition occurs in the range 200-530°C.

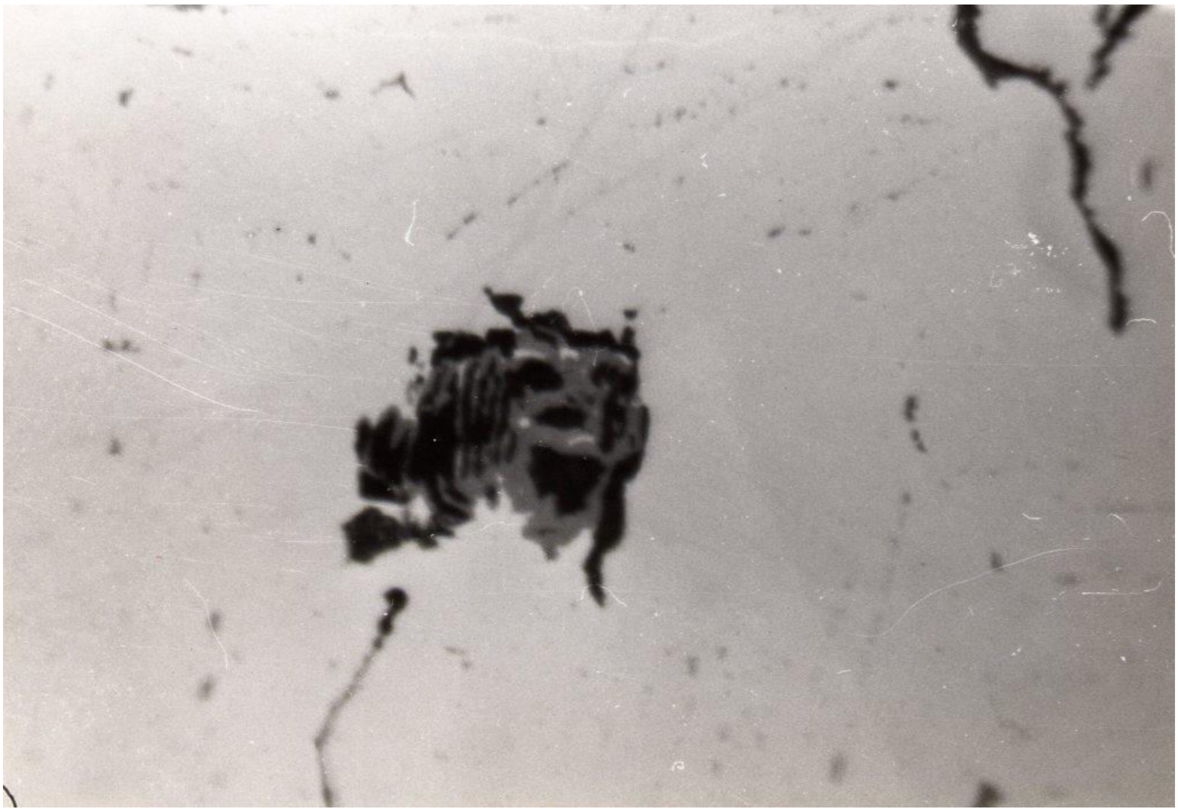

*Plate 34. "Corroded" (Growth zoned?) cassiterite (black) surrounded by a rim of stannite (dark grey) in chalcopyrite (light grey). (Reflected light, sample 9745).*

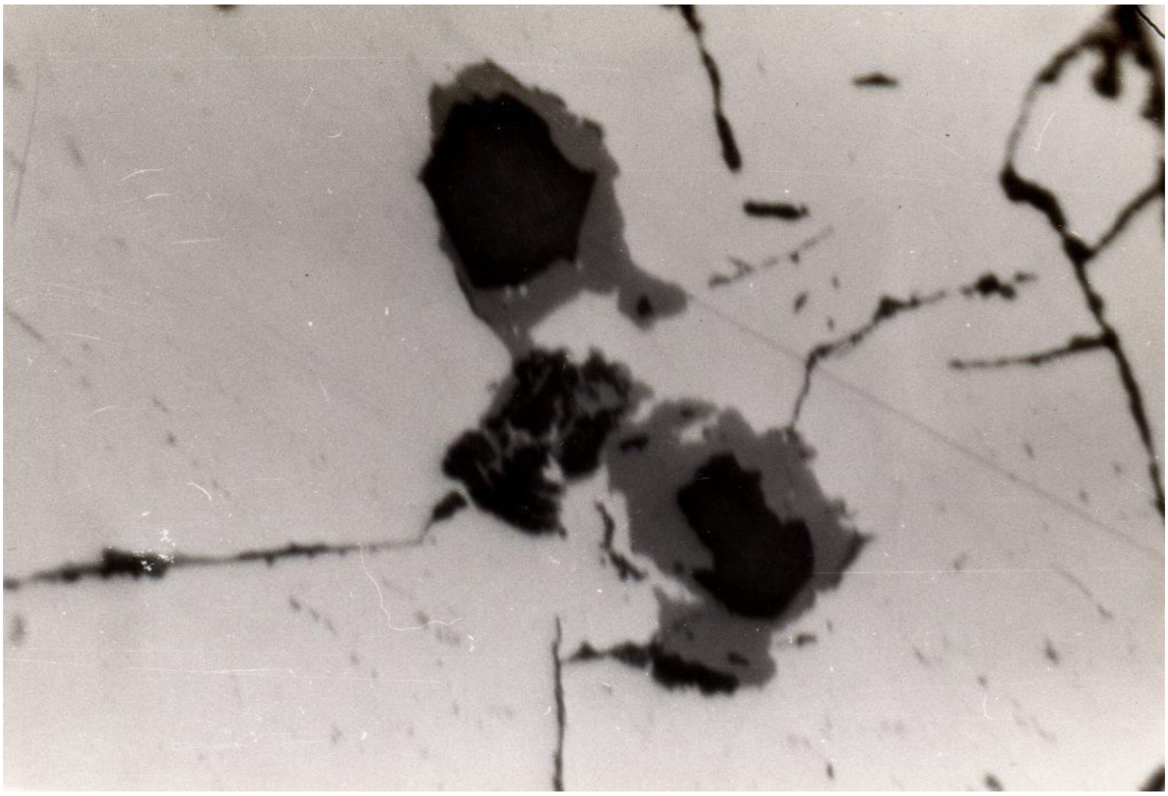

*Plate 35. "Corroded" cassiterite (centre) as for Plate 34. Compare with "un-corroded" cassiterite grains with stannite rims above and below. (Reflected light, sample 9745).*

### 5.4.8 Stannite

Stannite occurs as small irregular masses forming rims around grains of cassiterite and sphalerite (Plates 34, 35). It also occurs along cracks between grains of chalcopyrite and pyrrhotite and is often present as small blebs and irregular masses within the margins of pyrrhotite grains which exhibit mutual contact relationships with chalcopyrite. The larger bodies of stannite contain occasional well rounded blebs of chalcopyrite which may be exsolution bodies. All the stannite observed is the normal olive green-brown variety described by Ramdohr (1969).

The contemporaneity of the formation of cassiterite, stannite and chalcopyrite has already been discussed, and this also appears to be the case with pyrrhotite.

### 5.4.9 Bismuth and Bismuthinite

Bismuth and bismuthinite are present as irregular grains and inclusions which show a strong spatial relationship to pyrrhotite (Plates 27, 28). Individual grains rarely exceed 0.02 mm. However, they are only present in pyrrhotite where it has been deformed and forms complex intergrowths with chalcopyrite or has been intruded into brittle minerals. The areas of massive pyrrhotite and chalcopyrite are free of bismuth minerals.

Bismuthinite forms blebs and sometimes lobate masses which always occur within pyrrhotite grains. Bismuth forms discrete subhedral grains which occur within or along the margins of pyrrhotite grains, and occasionally within chalcopyrite where it is adjacent to pyrrhotite. These bismuth minerals are both very soft and probably exhibit ductile behaviour quite readily during deformation. Under crossed nicols native bismuth shows numerous acicular spindle shaped twins which terminate within the grain. Ramdohr (1969) believes these to be the result of deformation.

The close spatial association of the bismuth minerals with pyrrhotite suggests they formed contemporaneously with both pyrrhotite and chalcopyrite.

A minimum temperature of formation is provided by the pair bismuthinite-pyrrhotite which have been shown by Barton and Skinner (1967) to be part of an invariant assemblage of pyrrhotite-pyrite-bismuthinite-native bismuth at 235$^{o}$C. The assemblage pyrite-native bismuth, stable below 235$^{o}$C, was not recorded in this study. Native bismuth melts at 271.5$^{o}$C (Klement et al, 1963). Kelly and Turneaure (1970) showed that when ores containing native bismuth were heated above this temperature, tiny spherical beads of bismuth were sweated out, but there were no other discernible changes in the form, distribution or associations of the native bismuth. Thus liquid bismuth could have been present at temperatures above 271.5$^{o}$C and still have produced the observed natural textures.

## 5.5 Cross Cutting Gangue-Sulphide Vein relationships

Two types of veins are present within the UNA Porphyry. These are quartz-tourmaline-cassiterite veins and fluorite-siderite-hydrated calcium silicate-amorphous silica veins.

The quartz-tourmaline-cassiterite veins were observed cutting the altered porphyry (Plate 36), the massive sulphide zone (Plate 37), and the thermally metamorphosed sediments at the base of the porphyry. These veins vary in width from 2 mm to 5 cm. In Plate 36, a later sulphide phase has intruded the quartz-tourmaline-cassiterite vein by reactivation of the original fracture. The chalcopyrite and pyrite in these veins constitute relatively minor amounts of sulphide mineralization. This type of vein is typical of the major episode of tin mineralization in the United North Australian Mine area.

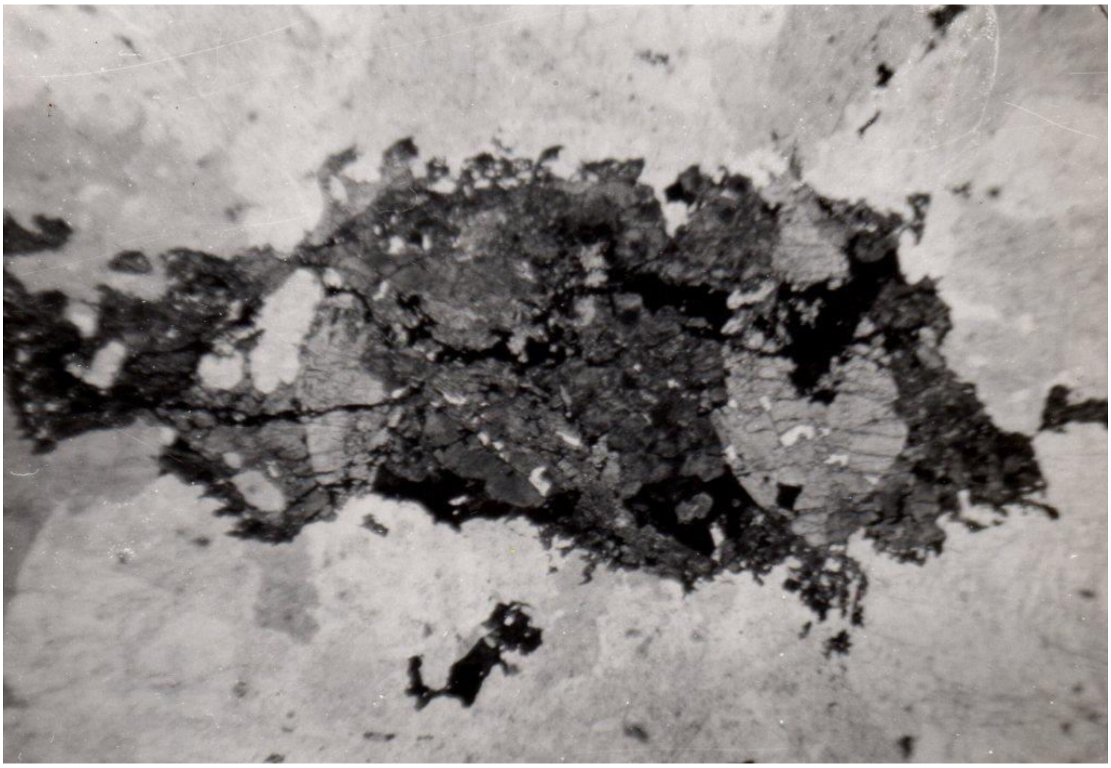

*Plate 36. Quartz (light grey)-tourmaline-cassiterite (dark grey) vein fractured and intruded by later suphides (black). (Reflected light, sample 9777).*

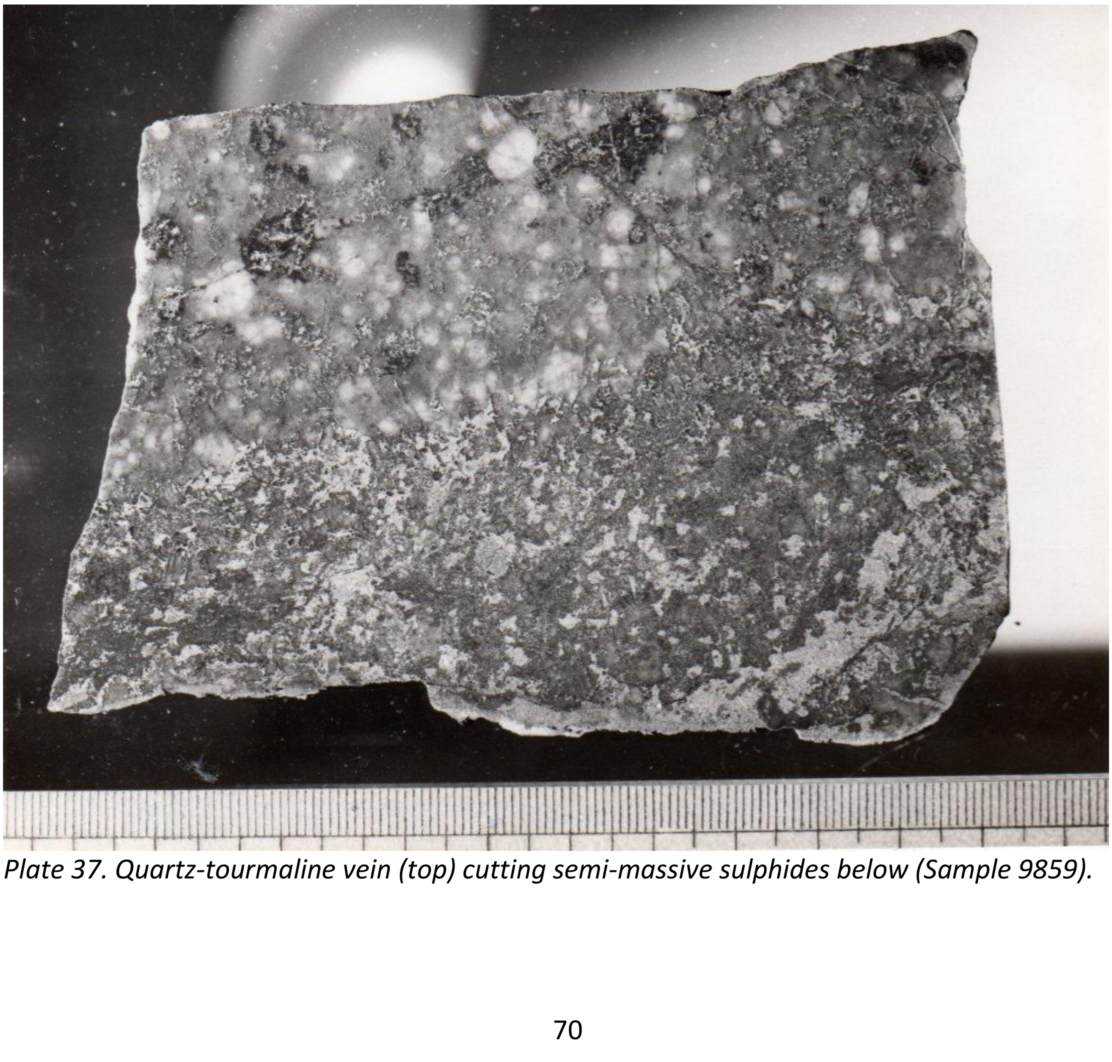

*Plate 37. Quartz-tourmaline vein (top) cutting semi-massive sulphides below (Sample 9859).*

The second type of vein was only observed cutting the massive sulphides (Plates 13, 14). The sequence of deposition of minerals within the vein was fluorite, siderite, hydrated calcium silicate and amorphous silica.

The relationships of gangue and sulphide minerals within both of these types of veins represent examples of poly-ascending zoning as described as Kutina (1965).

Some of the hydrated calcium silicate veins cutting the massive sulphide zone appear to have introduced tin which formed stannite and replaced chalcopyrite and pyrrhotite around the margins of the vein (Plate 33). A later carbonate vein is present cutting one of these veins in Plate 33.

These episodes of tin mineralization which postdate the major massive sulphide mineralization are responsible for the lack of distinct tin and copper zones around the emanative centre in the Watsonville area.

### 5.6 Discussion of Paragenesis

Before any discussion of paragenesis of an ore body can be undertaken it is important that its history of deformation is known. Since the formation of the Two Treys ore body the area has been intruded by at least three phases of the Slaughter Yard Creek Volcanics and the Watsonville Granite. It has also been subjected to two phases of faulting. Therefore, it would not be at all surprising to find evidence of deformation and annealing in the sulphides.

During this study of ore minerals from the Two Treys ore body the following deformation features were observed:

(i) Brittle fracturing of pyrite, arsenopyrite, wolframite and cassiterite.
(ii) Deformation twinning in sphalerite, chalcopyrite and bismuth.

Annealing features present include:

(i) Low standard deviations of triple point angles in massive pyrrhotite.
(ii) Apparent plastic flow of pyrrhotite and chalcopyrite into fractures in the brittle minerals.

The deformation and annealing were probably the result of both pressure and temperature effects. Conditions during formation of these ores have already been shown to be shallow and this would tend to enhance the brittle behaviour of the minerals. The role of temperature and the extent of its effects in producing annealing is difficult to evaluate. Rapid cooling would be expected under these shallow conditions. The porphyry dykes of the Slaughter Yard Creek Volcanics emplaced along the southern and north-eastern margin of the ore body have probably been responsible for some thermal effects. The sample of arsenopyrite used for tripe point measurements came from a drill hole close to the southern porphyry. However, the ease with which pyrrhotite can display ductile behaviour, indicates that sustained high temperatures are not necessary for annealing to occur.

Although the ores are deformed and partially annealed, the brittle minerals have suffered only slight displacement and there is no evidence of large scale remobilization. This indicates that the present mineral assemblage strongly reflects that which was originally formed. Further, the lack of both cross cutting veins of different sulphides and replacement phenomenon, together with textures indicating contemporaneous deposition, strongly implies that all of the ore minerals in the Two Treys ore body were deposited simultaneously. The notable exception to this is the replacement of arsenopyrite by chalcopyrite. This phenomenon is restricted to the boundary between the arsenopyrite and the pyrrhotite-chalcopyrite zones. However, this replacement appears to have occurred during or after deformation of the arsenopyrite and is therefore likely to be a post depositional effect.

From experiment studies of sulphide systems, maximum and minimum temperatures of formation can be obtained for the assemblages present. The assemblage pyrrhotite-pyrite-bismuthinite-native bismuth provides a minimum temperature of formation of 235$^{o}$C (Barton and Skinner, 1967), while the assemblage pyrrhotite-chalcopyrite provides a maximum temperature of formation of 334 ± 17$^{o}$C (Yund and Kellerud, 1966). All other mineral and mineral assemblages are stable or can be formed within this temperature range.

Therefore, the Two Treys ore body is a polymetallic deposit formed by simultaneously deposition of the ore minerals, under shallow conditions and at temperatures between 334$^{o}$C and 235$^{o}$C.

### 5.7 Comparison with Similar Deposits

The Two Treys ore body has many features in common with Xenothermal ore deposits. Ridge (1958) indicates that Xenothermal deposits form by rapid loss of heat and pressure between 300$^{o}$C and 500$^{o}$C, at low to moderate pressure (75-700 bars) and shallow to medium depths (1,000-4,000 feet). These deposits form under steep temperature and pressure gradients. Deposition occurs over a short period and confused parageneses results. High temperature minerals are not in equilibrium with lower temperature minerals and are frequently altered during later mineralization. Telescoped polyascendant zoning is common. Well studied examples of these type of deposits occur in the Potosi district of Bolivia and the Ikuno-Akenobe and Ashio districts of Japan.

In the Potosi district, Pliocene subvolcanic deposits are associated with porphyritic quartz latite and dacite stocks and dykes. Cassiterite, base metal sulphides and a variety of sulpha-salts are present in the veins which cut the porphyries and the intruded sediments. Kelly and Turneaure (1970) suggest the ores formed at depths of 350 to 2,000 metres and at total pressures of 30 to 500 bars. They recognize four districts stages of vein growth:

(i) Early Vein Stage. Quartz, tourmaline, arsenopyrite, cassiterite, wolframite, scheelite, bismuthinite and apatite. Temperatures rise from 300$^{o}$C to 530$^{o}$C then drop to 400$^{o}$C.
(ii) Base Metal Sulphide Stage. Pyrrhotite, base metal sulphides, minor teallite and franckeite. Some early fluorite. Temperature from 400$^{o}$C to 260$^{o}$C.
(iii) Pyrite-Marcasite-Siderite Stage. Hypogene alteration of pyrrhotite to form pyrite-marcasite-siderite aggregates. Minor replacement of franckeite. Temperature from 260$^{o}$C to 200$^{o}$C.
(iv) Late Veinlets and Crustifications.
    (a) Siderite, late fluorite, sphalerite, minor sulphides. Temperature 200$^{o}$C to 135$^{o}$C
    (b) Wavellite, vivianite and other hydrous phosphates. Temperature below 70$^{o}$C.

Sericite, chlorite, alunite and kaolinite are the main alteration products.

The deposits in the Ikuno-Akenobe and Ashio districts of Japan occur in subvolcanic Tertiary rhyolites and underlying sediments. The deposits consist of polymetallic veins and massive replacement deposits. Shallow near surface conditions are indicated and temperatures range from 330$^{o}$C to 160$^{o}$C. Local zoning and four or five stages of mineralization are recognized in all the deposits. Nakamura (1970) has recognized four stages in the Ashio Mine:

(i) Early cassiterite, wolframite, bismuth, bismuthinite, chalcopyrite stage.
(ii) Intermediate chalcopyrite, arsenopyrite, pyrrhotite stage.
(iii) Later sphalerite, galena, chalcopyrite stage.

(iv) Barren stage.

Zonal alteration is also present around the veins.

(i) Inner silicified zone.
(ii) Intermediate sericitized and silicified zone.
(iii) Outer chloritized and sericitized zone.

There are strong similarities of mineralogy, temperatures, pressures and depths of formation between these deposits and the Two Treys ore body. However, there are also a number of significant differences. The similarities include simultaneous formation of ore minerals, lack of open fissure textures and zoning which does not reflect a paragenetic sequence. The major difference however, is in the relationship of the mineralization to the host rocks. The Bolivian and Japanese deposits are epigenetic and are younger than the host rocks. The Two Treys ore body is syngenetic in that it was formed at the same time as the host rocks.

### 5.8 Summary

(i) All the ore minerals in the Two Treys ore body formed simultaneously.
(ii) Both deformation and annealing effects are present but original textural relationships have largely been preserved.
(iii) The temperature of formation was between 334°C and 235°C.
(iv) The depth of formation was very shallow, possibly as little as 2,000 feet.
(v) The pressure of formation may have been as low as 500 bars.
(vi) The zoning in the ore body does not reflect a paragenetic sequence.
(vii) Local zoning is complicated by a later cross cutting quartz, tourmaline, cassiterite phase.

# 6.0 ORIGIN OF THE TWO TREYS ORE BODY

## 6.1 Introduction

In the following chapter a model will be outlined which proposes an origin for the Two Treys ore body and various associated features of the UNA Porphyry. This model will attempt to incorporate and explain the following facts:

(i) The derivation of the UNA Porphyry from the Elizabeth Creek Granite and its intrusion to shallow depths.
(ii) The presence of a volatile phase in the porphyry magma rich in $H^+$, $Na^+$, $K^+$, iron, manganese and other base metal elements at the time of intrusion.
(iii) The separation of this volatile phase from the porphyry magma to produce a hydrothermal fluid.
(iv) The ubiquitous alteration of the porphyry.
(v) The contemporaneity of alteration and mineralization.
(vi) The formation of disseminated sulphides throughout the porphyry and the localization of a massive sulphide body within the Two Treys Mine area.
(vii) The type of sulphide assemblage produced in the Two Treys ore body.
(viii) The origin of the zoning in the Two Treys ore body.
(ix) The change in conditions and nature of the hydrothermal fluid during alteration and sulphide deposition.
(x) The indistinct zonation of tin and copper mineralization throughout the area.
(xi) The subsequent deformation of the sulphides.

## 6.2 Petrogenesis of Water Bearing Magmas

The generation of a water bearing magma is a prerequisite for any hydrothermal mineral deposit which exhibits a strong genetic and spatial relationship to felsic igneous rocks. Burnham (1967) has shown that there is a far greater likelihood of such magmas being generated by partial melting within the crust than in the mantle. The water in these magmas could be derived from hydrous phases such as amphiboles and micas, or from connate pore water in the rocks being melted. Burnham believes the average water content of rocks undergoing partial melting in the crust is between 1 and 2 wt.% but it may be as high as 4 wt.%.

Burnham has further shown that a solubility gap exists between water and felsic rock melts up to 10 kb. The total solute content of the aqueous phase at this pressure is only 10% by weight. However, high concentrations of naturally occurring volatiles such as chlorine and fluorine tend to promote continuously solubility, as well as lower melting temperatures. Carbon dioxide on the other hand tends to widen the solubility gap.

Burnham has also shown that the dissolved water remains uniformly distributed throughout the magma as the diffusion rate of $H_2O$ molecules through silicate magmas is geologically insignificant. However, as the water separates from the magma it forms small bubbles which rise rapidly according to Stokes Law and accumulate towards the top of the intrusion. This dissolved water is released (boiled off) free from the magma when the equilibrium pressure of water ($P_eH_2O$) in the magma exceeds total confining pressure ($P_t$). This can be accomplished in two different ways:

(i) By a decrease in $P_t$ (e.g. by upward intrusion)
(ii) By an increase in $P_eH_2O$ (e.g. by crystallization of anhydrous minerals from the melt-$H_2O$ solution)

All the dissolved water in initially water saturated magmas tends to boil off at considerable depths. However, initially water undersaturated magmas have most of their metasomatic and hydrothermal activity concentrated over a narrow range at relatively shallow depths. This indicates that this latter type of magma can ascend to shallow depths before completely crystallizing. Furthermore, the rapid crystallization of this magma is likely to produce a rock consisting of phenocrysts set in a fine grained porphyritic groundmass.

According to Burnham, a magma containing 2% $H_2O$ initially would undergo boiling at a depth of 3 km or less (i.e. $P_t$ approx. 850 bars). Plutonic conditions in this range have already been shown to have been present in the thesis area.

### 6.3 Model

Taking into consideration the above data on the petrogenesis of water bearing magmas, the following model for the formation of the UNA Porphyry and the Two Treys ore body can be proposed. The UNA Porphyry was derived from an initially water undersaturated magma which was intruded to shallow depths. The quartz and feldspar phenocrysts set in a fine grained porphyritic groundmass, and the various criteria for a shallow plutonic environment described previously are evidence of this. The Elizabeth Creek Granite however, has a coarse grained phaneritic texture which indicates it crystallized from a magma which was not saturated with water at the time of extrusion. The lack of metasomatic activity at the granite sediment contact is further evidence of this.

The slow crystallization of the granite following its emplacement produced a steady rise in $P_eH_2O$. At some stage when the magma was approaching saturation with water but before $P_eH_2O$ exceeded $P_t$, the UNA Porphyry was intruded passively into the overlying sediments of the Hodgkinson formation in the form of a gently dipping cone sheet. Slight contact metamorphism of the intruded sediments was produced.

When the porphyry was extruded from the crystallizing Elizabeth Creek Granite the magma suffered a sudden drop in $P_t$. This caused the magma to become slightly saturated and small gas bubbles of water and other volatiles were boiled off until $P_eH_2O$ and $P_t$ reached equilibrium. Once emplaced the magma cooled quickly and began to crystallize rapidly from the margin in towards the centre. A high rate of nucleation combined with relatively low rate of crystal growth produced the fine grained granophyric groundmass of the porphyry. The bubbles of water initially boiled off during emplacement were trapped within the crystallizing magma before they could rise and accumulate. These now form drusy cavities. The minerals formed from fluids trapped in these cavities include fluorite, biotite, garnet, cassiterite, quartz, topaz and sulphides.

The rapid crystallization of the magma caused a corresponding rapid increase in $P_eH_2O$. When $P_eH_2O$ exceeded $P_t$, second boiling occurred and an aqueous phase began to separate in the centre of the porphyry. This aqueous phase was initially oxidizing with a high $fO_2$ and was rich in $H^+$, $Na^+$, $K^+$, metals and sulphur. This fluid separated throughout the porphyry and was responsible for its complete alteration.

However, as alteration progressed and $H^+$ was increasingly consumed, conditions tended to become slightly alkaline. This favoured silicification rather than sericitization. Reduced sulphur also became available and sulphides began to form. The disseminated sulphides originated in two ways, by the sulphidization of biotite, and by the deposition from metal rich volatiles trapped in drusy cavities.

Throughout the major part of the porphyry the volume of aqueous phase separated by second boiling was only sufficient to produce a thin discontinuous band of semi-massive sulphides. These sulphides are restricted to a lateral zone in the centre of the porphyry. This mineralization reflects the limited average thickness of porphyry (about 40 feet) from which an aqueous phase could separate during crystallization.

The massive sulphides however, lie within a locally thickened portion of the porphyry from which a far greater volume of aqueous phase could separate. In the Two Treys area the porphyry is 120 feet thick in places. A pool of metal rich volatiles accumulated in the centre of the porphyry here and a lense of massive sulphides was deposited. This accumulation over such a restricted region can only be satisfactorily explained by very rapid separation of volatiles from the rapidly crystallizing magma. Had crystallization and separation been more sluggish the volatiles would have tended to accumulate towards the top of the porphyry. The very rapid separation of the volatiles combined with rapid cooling at shallow depths caused the simultaneously deposition of all of the ore minerals over a temperature range of between 334$^{o}$C and 235$^{o}$C.

Two possible explanations can be offered for the zoning produced in the Two Treys ore body:

(i) The pool of volatiles separated from the crystallizing porphyry magma had an initial high $fO_2$ and low $fS_2$. Iron would have been present mostly as $Fe_3^+$ and there was no reduced sulphur. Sulphides could not form under these conditions. As alteration proceeded the outer margins of the pool of volatiles became slightly reducing and $fO_2$ began to decrease while $fS_2$ increased. However, the change in the conditions of the hydrothermal fluid proceeded so rapidly that equilibrium was not maintained between the inner and outer portions of the pool of volatiles. This produced an activity gradient of $Fe_2^+$ and $S_2^-$ within the pool. Thus $fS_2$ would have decreased inwards while $fO_2$ decreased outwards. When sulphide formation commenced the $Fe_2^+$ and $S_2^-$ rich sulphides (e.g. pyrite) formed around the outer margins while sulphides were deficient in those elements formed in the centre of the porphyry (e.g. chalcopyrite and pyrrhotite). Sulphides of an intermediate composition (e.g. arsenopyrite) formed between these two.

(ii) An alternate explanation can be offered which involves the sequential deposition of the sulphides from the margins of the pool of volatiles in towards the centre. Deposition commenced at the margins as $Fe_2^+$ and $S_2^-$ became available and continued inwards as the chemistry of the inner portions of the pool of volatiles became increasingly permissive. An increasing deficiency in the amount of sulphur, and to a lesser extent iron, is necessary to explain the progressive change in the composition of the sulphides formed.

Of these two explanations the first is considered the more plausible as there is no evidence of sequential deposition of sulphides as implied by the latter hypothesis.

A limited amount of faulting must have occurred during or immediately subsequent to separation of the aqueous phase. This provided avenues of escape for some of the separated volatiles into the overlying sediments where they formed massive sulphide bodies such as those occurring in the Ironclad, Easter Monday and Shaugraun mines.

The final stage hydrothermal fluids deposited a number of later gangue minerals under alkaline conditions. These minerals are present in veins crosscutting the massive sulphides and include fluorite, siderite, hydrated calcium silicates and amorphous silica.

Faulting, and the intrusion of porphyry dykes, subsequent to the formation of the Two Treys ore body produced the observed deformation and annealing features. The superposition of the later cassiterite, tourmaline, minor sulphide phase of mineralization over the earlier mineralization associated with the UNA Porphyry has produced the indistinct mineral zoning throughout the area.

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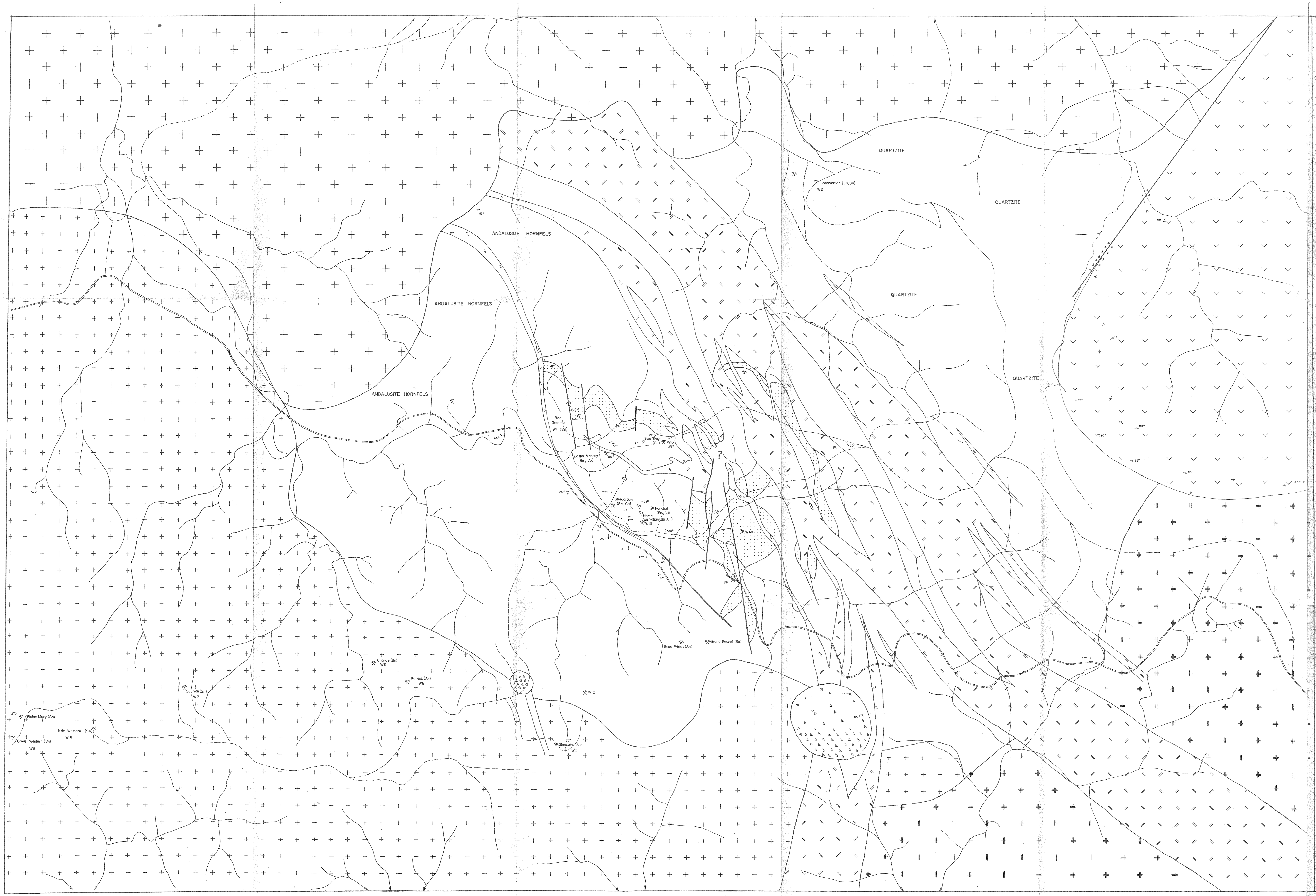
## **8.0 APPENDIX**

Map 1. Regional Geology, United North Australian Mine and Environs.

Map 2. Detailed Geology, Outcrop Map, United North Australian Mine Area

Map 3. Detailed Geology, Interpretation Map, United North Australian Mine Area

Cross Section A-B, United North Australian Mine Area



## LEGEND

| | | | |
|---|---|---|---|
| LOWER PERMIAN | WATSONVILLE GRANITE | + | |
| UPPER CARBONIFEROUS | SLAUGHTERYARD CREEK VOLCANICS | ∨ ∨ | INTRUSIVE RHYOLITE |
| | | △△△ | INTRUSIVE BRECCIA |
| | | // | PORPHYRY DYKE |
| | | ╫ | INTRUSIVE RHYODACITE |
| | UNA PORPHYRY | ⁚⁚⁚ | |
| | ELIZABETH CREEK GRANITE | + + | |
| SILURIAN—DEVONIAN | HODGKINSON FORMATION | ☐ | |

| | |
|---|---|
| — | GEOLOGICAL BOUNDARY. |
| ━ | FAULT. |
| 20° | DIP AND STRIKE OF STRATA. |
| 80° | STRIKE AND DIP OF FOLIATION. |
| ◇ | FLOW FOLIATION, VERTICAL. |
| 20° | STRIKE AND DIP OF OVERTURNED STRATA. |
| | STRIKE AND DIP OF DYKE. |
| | STRIKE AND DIP OF FAULT. |
| ⚒ | MINE. |
| W | WOLFRAMITE LOCALITY. |
| ═══ | ROAD. |
| – – – | TRACK. |
| → | CREEK. |
| ▲▲▲ | FAULT BRECCIA. |

T.N.

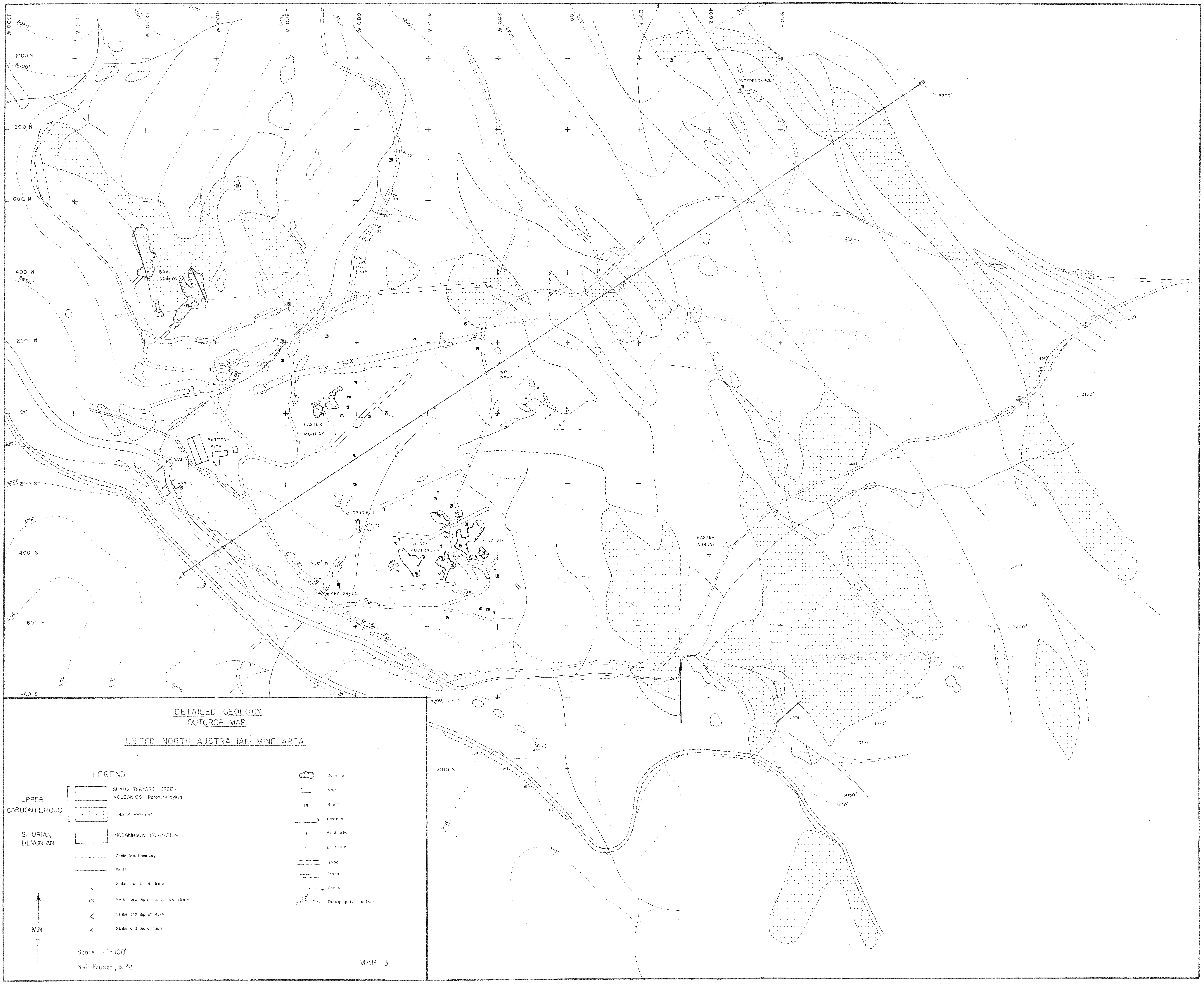
## REGIONAL GEOLOGY

## UNITED NORTH AUSTRALIAN MINE AND ENVIRONS

SCALE :- 1:4000

Neil Fraser, 1972.

MAP 1



DETAILED GEOLOGY
OUTCROP MAP

UNITED NORTH AUSTRALIAN MINE AREA

Scale 1" = 100'

Neil Fraser, 1972

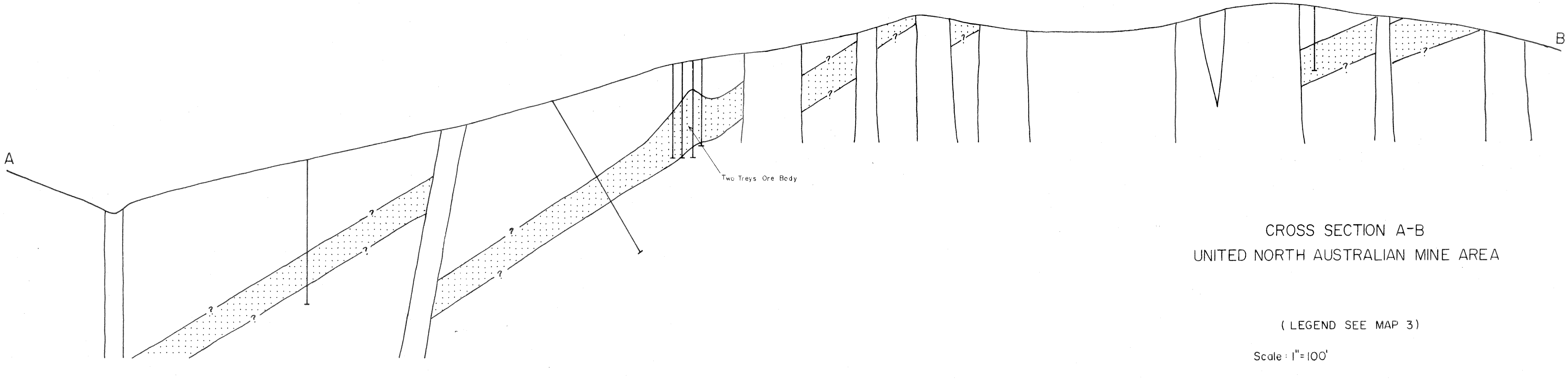
MAP 3

## DETAILED GEOLOGY
## INTERPRETATION MAP

## UNITED NORTH AUSTRALIAN MINE AREA

Neil Fraser, 1972

MAP 3



CROSS SECTION A–B
UNITED NORTH AUSTRALIAN MINE AREA

( LEGEND SEE MAP 3)

Scale : 1" = 100'

Neil Fraser , 1972