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ALTERATION AT THE SAM GOOSLY
COPPER-SILVER DEPOSIT,
BRITISH COLUMBIA

by

PAUL JOHN WOJDAK
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May, 1974

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Paul J. Wojdak

Department of Geological Sciences

The University of British Columbia
Vancouver 8, Canada

Date May 29, 1974

ABSTRACT

Copper-silver mineralization at Sam Goosly occurs as a conformable lens within pyroclastic dacites of probable late early Cretaceous age. Most mineralization is contemporaneous with development of aluminous alteration minerals. Distribution zones of scorzalite, andalusite, and an innermost corundum zone, are concentric and broadly outline the mineralized zone. Southwards, along strike, the andalusite zone becomes an andalusite-pyrophyllite zone in which mineralization post-dates aluminous alteration. Regional metamorphism has overprinted a propylitic, or greenschist, assemblage on aluminous alteration. Country rocks and mineralization are intruded by two stocks: a 59 ± 3 m.y. quartz monzonite to the west of the ore zone, and a 51 ± 3 m.y. gabbro-monzonite stock to the east. Contact metamorphism associated with the gabbro-monzonite has produced a narrow, discontinuous zone of biotite hornfels and recrystallized metallic minerals in the ore zone.

Alteration mineral assemblages and sulphide exsolution textures imply temperatures between 350°C and 625°C in the main ore zone. The assemblage andalusite-pyrophyllite-quartz indicates alteration temperatures of about 350°C in the andalusite-pyrophyllite zone. Chemical analysis of the altered volcanic host rocks suggests significant loss of soda and lime, and residual concentration of silica and alumina. These chemical changes probably result from exchange of Na^+ and Ca^{++} for H^+ from a hydrothermal fluid, resulting in formation of aluminous minerals and quartz. The value of $\log m_{\text{K}^+}/m_{\text{H}^+}$ of the fluid phase is deduced to be between 1 and 2. By analogy with other occurrences, this process probably takes place in a high-temperature solfataric, or geothermal environment.

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INTRODUCTION

PURPOSE

Sam Goosly is a recent copper-silver discovery in central British Columbia. The local geology and history of discovery have been described by Ney, Anderson and Panteleyev (1972), and the local and regional geology, by Church (1969, 1970, 1973). Although a mineralogical study of the deposit was made by Nielsen (1969) at an early stage in the drilling history, a comprehensive study had not been undertaken. Nielsen's work gave a good insight into the complex nature of the alteration, but posed rather than solved problems. This study was undertaken because of the significance of the unusual alteration assemblages and because of an uncertainty as to the genesis of the deposit. Recent diamond drilling allows a detailed investigation of the host rocks and alteration mineralogy. This investigation contributes to a better understanding of the deposit.

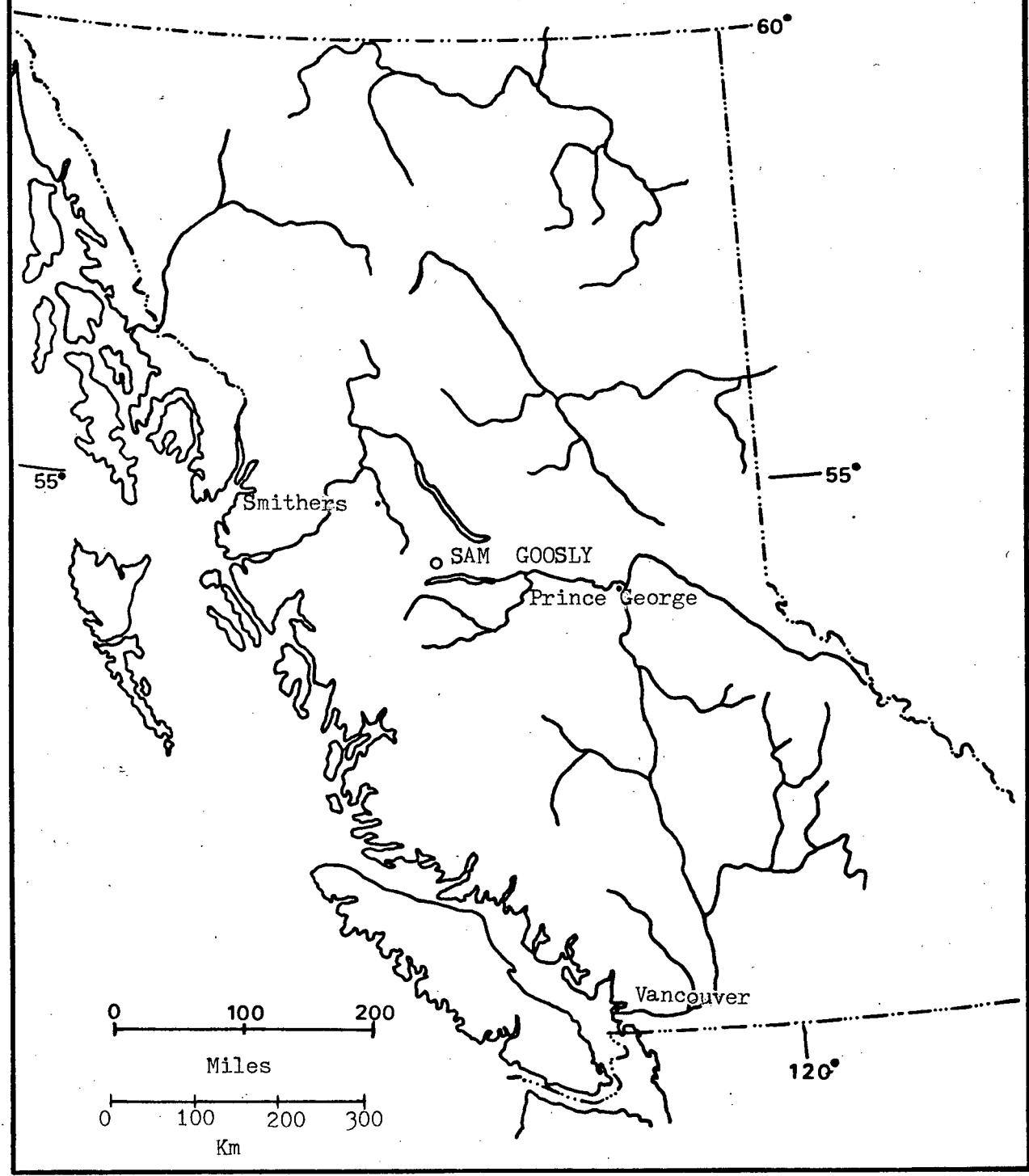
LOCATION AND ACCESSIBILITY

The Sam Goosly prospect is located 35 km. (22 miles) south of Houston, British Columbia at latitude 54°11' north and longitude 126°16' west (Figure 1). It is 6.5 km. (4 miles) ENE of Goosly Lake¹ from which the property takes its name. The property is 56 km. (35 miles) along the Buck Creek Road from Highway 16 near Houston. Buck Creek Road is a dry-weather gravel and logging road.

1 On most recent maps the name "Sam-Goosly Lake" has been shortened to "Goosly Lake".

FIGURE 1

LOCATION MAP



PHYSIOGRAPHY AND PLEISTOCENE GEOLOGY

Sam Goosly is located in gently rolling country in the west-central region of the Nechako Plateau (Holland, 1964). Regionally, the relief ranges from 600 m. (2,000 feet) to 1,500 m. (5,000 feet) and the deposit is at an elevation of 1,300 m. (4,300 feet). A resistant plutonic stock immediately east of the mineralized zone forms a prominent hill reaching an elevation of 1,600 m. (5,300 feet). Tributary streams radiate from this high area, draining on the southwest toward Goosly Lake and into Buck Creek, and on the northeast into Foxy Creek. Except for areas of recent lumber harvesting and an old forest fire 'burn', the region is well forested.

Glacial drift is widespread and a high percentage of the bedrock is obscured. Outcrop areas are restricted to ridges and some creek beds. The mineralized zone outcropped in only one small exposure in a creek bed. Except for the hill of plutonic rocks to the east, rocks are poorly exposed on the property.

Contradictory evidence for the direction of Pleistocene ice movement has been reported by Ney et al (1972) and by Church (1969). Regionally, Holland (1964) indicated that ice movement was eastwards and northeastwards from a centre in the vicinity of Ootsa Lake. This direction is supported locally by Church who found glacial striae indicating ice movement towards 075 degrees. However, Church also found that granite erratic boulders were transported several hundred feet southwest of a source area. This direction is in closer agreement with Ney et al who determined the direction of ice movement to be 245° , based upon glacial smoothing of some resistant dykes. Their evidence is supported by a southwesterly direction of transport of

glacial till necessary to explain the position of the silver anomaly in the soil geochemistry. Their silver anomaly map shows a pronounced southwesterly displacement of anomalies relative to the mineralized zone.

A model involving two periods of glacial advance, in essentially opposite directions, appears necessary to reconcile all evidence. Tipper (1971a) has discussed the evidence for multiple glaciation in central British Columbia. He suggested that a limited re-advance of ice took place after the main (Fraser) glaciation. Thus, the best explanation of the data is that a regional northeasterly moving ice sheet was followed locally by a southwesterly moving one. The later one caused the westerly displacement of silver anomalies in till, the dispersion of granite boulders and planed the surface of some dykes, but did not scour deeply enough to remove all evidence (the glacial striae) of the earlier, regional, ice sheet.

HISTORY

The history of discovery of the Sam Goosly deposit as presented here is taken in large part from Ney et al (1972).

In 1961, as part of regional geochemical surveys in British Columbia, the sediments of a stream east of Goosly Lake were found to be slightly anomalous in zinc and copper. This anomaly was not followed up until subsequent analyses of the samples disclosed anomalous fluorine values. With this amount of geochemical information, plus the knowledge that inliers of Mesozoic volcanic rocks in the Tertiary volcanic sequence existed in the area, an

exploration program was initiated in 1967. This deposit was probably unknown prior to its discovery by Kennco Explorations in 1967.

Prospecting in the area uncovered two types of mineralization: chalcopyrite in quartz monzonite and pyritized volcanic rock with one occurrence of tetrahedrite. At this stage claims were staked. Due to poor bedrock exposure, a soil sampling program was undertaken and yielded broad copper and molybdenum anomalies and a large silver anomaly. The copper-molybdenum anomaly led to weak porphyry-type mineralization in a quartz monzonite stock. The silver anomaly, interpreted with a westerly direction of transport of glacial till led to drilling targets which outlined the mineralized zone.

Between 1969 and 1971, diamond drilling of 62 holes was completed and a 27 ton bulk sample was taken for metallurgical studies. Faced with the dual problem of a comparatively small tonnage and a metallurgically difficult ore, Kennecott Copper optioned the property to Equity Mining Capital (of Vancouver) and Congdon and Carey Mineral Exploration (of Denver) in 1972. Subsequently, additional drilling and work on the metallurgical problems have been undertaken.

METHODS OF STUDY

The mineralized zone, as outlined by drilling to 1971, has the form of a steeply dipping slab or lens, elongate parallel to strike. A number of cross sections along the length of the mineralized zone were selected for detailed observation and

sampling. These were holes 39, 56, 60 and 61 in the south, holes 12 and 48 farther north, holes 9 and 45 in the central zone, and holes 29 and 33 in the north (Fig. 3). These were supplemented by a less detailed observation and sampling of other diamond drill holes. These were holes 19, 20, 21, 22 and 30 which provided a complete cross section of the stratigraphy, hole 41 which passed through the facies change that distinguishes the southern cross section from those farther north, and hole 24 which had the longest ore-grade intersection. For comparative purposes, holes 1 to 8 which were studied by Nielsen (1969) were looked over, but not sampled in detail. Checks and some limited sampling were made on other diamond drill holes.

The silicate mineralogy of rock samples was investigated by means of thin section and X-ray diffraction work. For X-ray diffraction, the rock was powdered and a whole rock sample was produced by administering the powder to a glass slide as an acetone slurry. The clay mineral fraction was investigated by allowing the rock powder to settle in a beaker of water for 15 seconds. A concentration of the lighter clay fraction resulted by using an eye-dropper to extract the supernatant liquid. This was then administered to a glass slide and allowed to dry for 6 hours or longer to produce an oriented clay fraction. The clay mineralogy of many specimens was investigated further by placing the sample in a sealed jar with an atmosphere of ethylene glycol for a period of several days (achieving glycolation of expandable clays), and/or by heating the sample in a muffle furnace at 600-650°C for at least

two hours. The cut surface of many rock samples were stained for potassic minerals using a hydrofluoric acid etch and a sodium cobaltinitrite stain. In addition, a limited investigation of the opaque mineralogy was carried out by examining a small suite of polished sections.

GEOLOGICAL SETTING

INTRODUCTION

The Houston map-area was first mapped by Lang (1942), and later re-examined by Tipper (1971b). Church (1973) has recently published a preliminary geological map of the Houston - Burns Lake area and Figure 2 is a simplification of a portion of that map.

Most of the Houston map-area is underlain by a diverse suite of Mesozoic volcanic and sedimentary rocks. In the southeast quarter of the map-area, these rocks are exposed as inliers or as windows through an extensive cover of Tertiary volcanic rocks. The Sam Goosly prospect occurs within one of these inliers.

MESOZOIC STRATA

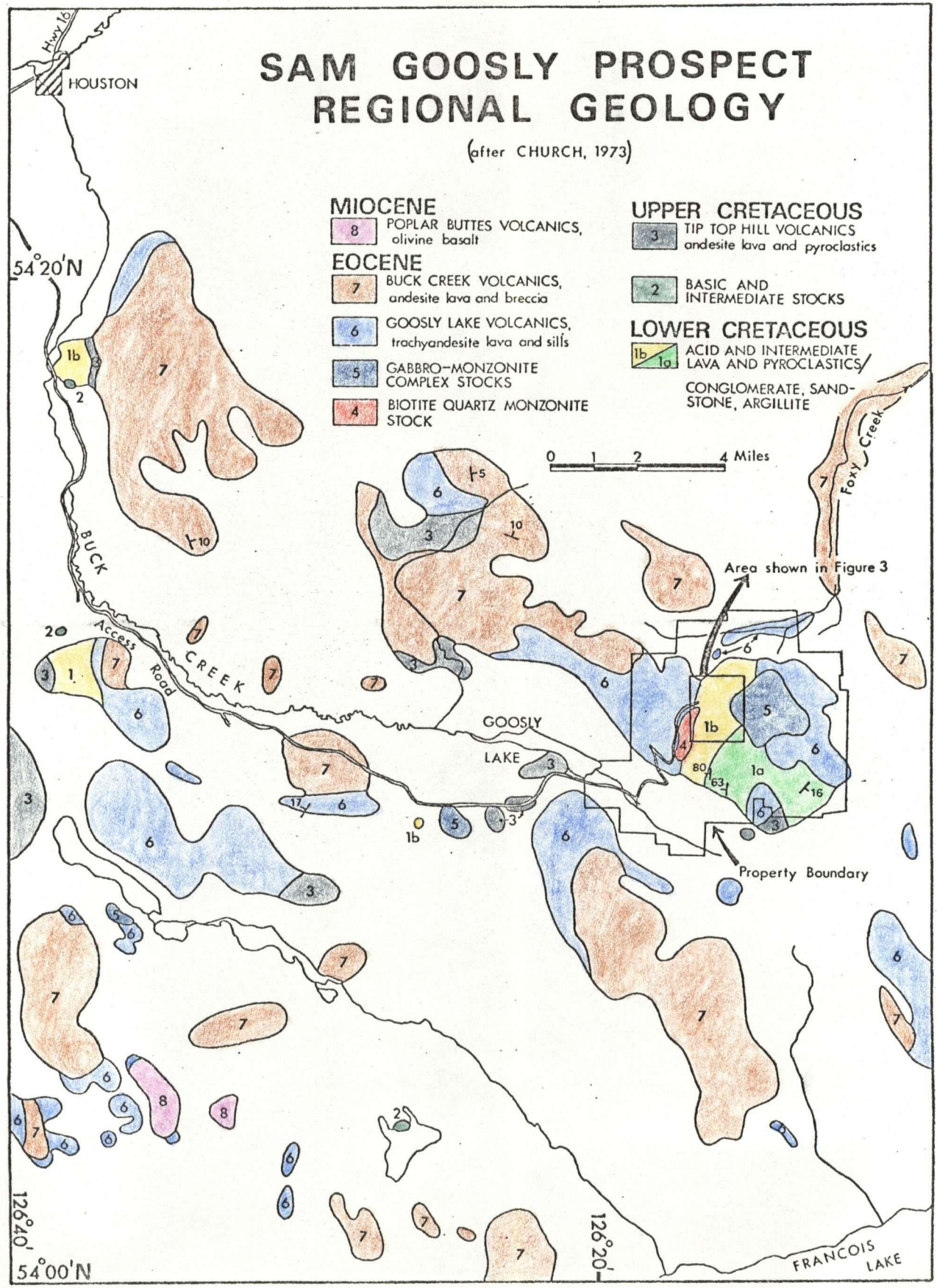
The Hazelton Group consists of a diverse suite of volcanic and sedimentary rocks. Due to the paucity of fossils and the lithologic variability of these rocks, Lang (1942) had little success in subdividing the unit. However, two basic subdivisions have been achieved by Tipper (1970).

The older unit consists of bedded green, gray and purple fragmental volcanic rocks of mainly andesitic composition. Sedimentary interlayers may be up to several hundred feet thick and consist of impure limestone, shales, graywackes and rarely cobble and pebble conglomerate. Their age was determined to be Sinemurian to Pliensbachian (Early Jurassic).

The younger unit contains a higher proportion of sedimentary rocks of varied lithology. Tuff, breccia, shale and graywacke are

SAM GOOSLY PROSPECT REGIONAL GEOLOGY

(after CHURCH, 1973)



overlain by fragmental andesitic to basaltic volcanic rocks. These volcanic rocks are in turn overlain by and interlayered with (?) black shale, minor graywacke and rare conglomerate lenses. The age of these rocks ranges from Bajocian to Callovian (Middle Jurassic).

Windows of pre- Upper Cretaceous strata are scattered over Church's map-area. These consist mainly of acid and intermediate lavas and pyroclastics, with lesser amounts of argillite, sandstone and conglomerate. Until recently, these inliers were thought to belong to the Hazelton Group. Tipper now has evidence that some of these rocks are of Cretaceous age (pers. comm., 1973).

Chert pebble conglomerates and shales outcrop near Francois Lake and north of Houston. The Francois Lake locality contains the pelyceps Aucellina (Aptian to Turonian) and Trigonia (Middle Triassic to Upper Cretaceous) while an ammonite Cleoniceras (Albian) was found at the Houston locality (Tipper, pers. comm., 1973). The Goosly Lake inlier, exposed between these two localities, contains similar chert pebble conglomerate and shale. Based on similar lithology, Tipper is confident that the rocks of this inlier are also of Albian (late early Cretaceous) age.

With the exception of the Brian Boru Formation in the Rocher Deboile Range (Sutherland Brown, 1960), Cretaceous strata were previously unknown in this part of north-central British Columbia. Tipper suggests that such rocks may be quite extensive but not recognized because they are generally unfossiliferous. In addition to the uncertainty regarding extent and correlation of these Cretaceous strata, the status of unfossiliferous rocks assumed to belong to the Jurassic Hazelton Group is not clear.

TERTIARY VOLCANIC SEQUENCE

Church (1970) has subdivided the late Mesozoic to Tertiary sequence into four volcanic units, with a total maximum thickness of about 1,300 m. (4,300 feet).

(1) Tip Top Volcanics

These are Upper Cretaceous (75.8 ± 2.7 m.y.) in age and are 460 m. (1,500 feet) thick at their type locality. The rocks are volcanic breccias of andesitic to dacitic composition. They consist of about 35% plagioclase phenocrysts, together with accessory biotite, pyroxene and hornblende suspended in a fine-grained matrix.

(2) Goosly Lake Volcanics

This unit consists of 460 m. (1,500 feet) of mainly trachyandesite lavas, of Eocene age (48.0 ± 1.8 m.y.). They are thought to be equivalent to the Ootsa Lake Group. Large lath-shaped plagioclase phenocrysts are distinctive of this unit, although they only account for about 15% of the rock. The plagioclase phenocrysts, together with accessory diopsidic augite, magnetite, biotite and hornblende are set in a fine-grained feldspathic matrix.

(3) Buck Creek Volcanics

These are basaltic andesite lavas of Eocene age (47.3 ± 1.6 m.y.). The thickest section observed, along Kloo Creek, measures 300 m. (1,000 feet). This unit is a typical 'plateau basalt' with gently dipping flows capping many of the hills and ridges of the area.

The flows consist of 80% plagioclase microlites and 10% of pyroxene with the remainder being biotite, magnetite and chlorite. This unit is probably equivalent to the Endako Formation.

(4) Poplar Buttes Volcanics

This 70 - 100 m. (200 - 300 feet) thick unit of columnar olivine basalt forms the capping of some buttes in the area. The flows are of Miocene age (21.0 ± 1.1 m.y.) and represent the youngest rocks of the area. These are undersaturated lavas, containing normative nepheline. In thin section they contain 3% olivine phenocrysts set in a fine-grained matrix of plagioclase microlites and ferromagnesian minerals.

INTRUSIVE ROCKS

The oldest intrusive rocks are the Topley Intrusions which are restricted to the northeast part of the Houston map-sheet. They are part of a batholith complex consisting mainly of quartz monzonite and granite, and are 138 ± 3 m.y. in age (White, Sinclair, Harakal and Dawson, 1970).

A medium-grained diorite sill (74.0 ± 1.0 m.y.) is exposed at the Nadina Mine, east of Owen Lake. Locally, this is known as the Mine Hill microdiorite and is thought by Church (1970) to be a feeder to the Tip Top Hill Volcanics.

Granitic intrusions younger than the Topley Intrusions are also exposed in the area. Church (1970) reported that these stocks are texturally porphyritic or microporphyritic with 20-50% plagioclase phenocrysts in a quartz-feldspar matrix.

The femic minerals are biotite and hornblende. One such stock outcrops on the Sam Goosly property.

Probably the most interesting intrusions in the area are a series of gabbro-monzonite stocks. Petrographically, they consist of 65-80% plagioclase (as large bladed phenocrysts), 5-20% augite, and accessory biotite, magnetite and apatite. Interstitial potassium feldspar and minor quartz complete the monzonite phase, whereas pyroxene and relict olivine crystals complete the gabbroic phase. Three stocks of this compositional range lie at approximately 13 km. (8 miles) intervals along an east northeasterly striking line. The mineralized zone at Sam Goosly lies immediately west of the most easterly of these intrusions. Distinctive, bladed feldspar porphyry dykes, similar to these stocks, are exposed at the Nadina Mine, 40 km. (25 miles) west southwest of Sam Goosly. Their presence may indicate a similar gabbro-monzonite stock hidden at depth and would extend the number of these aligned stocks to four. Church has shown these intrusions to be the source of the petrographically and chemically similar Goosly Lake Volcanics.

MINERALIZATION

Good coverage of the mining properties and description of mineral showings in the area are provided by Church (1969, 1970). The two most important properties in the area are Sam Goosly and the recently closed Nadina Mine operated by the Bradina Joint Venture.

Sam Goosly consists of disseminations of fine-grained

sulphides with local lenses of more massive, coarse-grained sulphides. The principal sulphide and oxide minerals are pyrite, chalcopyrite and tetrahedrite with lesser amounts of sphalerite, magnetite, hematite and pyrrhotite.

Mineralization at Nadina Mine is in veins which consist of sphalerite, pyrite, chalcopyrite, galena and tennantite (Church, 1969). Veins are generally one metre (3 to 4 feet) wide, and exhibit a symmetric encrustation of ore and gangue minerals.

Church (1969, 1970) has suggested that these two deposits are complementary and taken together represent the complete range of a single ore-forming process. This is supported by the close spatial association of both deposits with a stock, or related dykes, of nearly identical monzonite.

GEOLOGY OF SAM GOOSLY

INTRODUCTION

At Sam Goosly Cu-Ag mineralization occurs as a generally conformable layer within Mesozoic volcanic and volcanoclastic rocks. Two stocks and a number of dykes intrude the Mesozoic strata. A quartz monzonite stock outcrops west of the mineralized zone and a gabbro-monzonite complex stock lies to the east.

Three sections, equally spaced at thousand foot intervals along the main part of the mineralized zone, were selected for detailed study of the alteration associated with mineralization. These are Section 13,400 N (Fig. 4, drill holes 29 and 33) at the northern end, Section 12,400 N (Fig. 5, drill holes 9 and 45) near the centre and Section 11,500 N (Fig. 6, drill holes 12 and 48) at the southern end. Mineralization extends southwestward as a narrow zone and Section 9,100 N (Fig. 7, drill holes 39, 56, 60 and 61) was selected to examine the associated alteration. In addition, a section between the two stocks, through drill holes 19, 20, 21, 22, 5 and 30 (Fig. 8, approximately 11,800 N) was also studied. This section, with the addition of holes 11 and 23 was studied by Church (1970) and by Ney et al (1972). Drill holes 12 and 48 have been projected less than 300 feet into this section. The geological map (Fig. 3) is a combination of surface geology mapped by Kennco geologists and drill hole data projected to surface by the author. The outline of the mineralized zone was obtained from Equity Mining and is based on more detailed drilling, not shown in Fig. 3.

LEGEND (for Figures 4 to 8)

EOCENE OR YOUNGER

I Quartz latite dykes

EOCENE

Trachyandesite dykes (Bladed feldspar porphyry)

Andesite dykes (aphanitic)

E Biotite pyroxene monzonite (Gabbro-monzonite complex)

PALEOCENE

D Biotite quartz monzonite

LOWER CRETACEOUS

C Sedimentary-volcanic division

B₆ Welded ash tuff

B₅ Dust tuff

B₄ Epiclastics

B₃ Volcanic breccias

B₂ Brecciated dacite

B₁ Basal pyroclastics

A Coarse clastic division

————— Geologic contact, observed

- - - - - Geologic contact, projected

- . ? - - - - ? - Geologic contact, inferred

— — — — — Scorzalite zone

— — — — — Andalusite zone

— — — — — Corundum zone

Mineralization (equivalent to 3 ounces silver per ton)

Minerals

a- andalusite

b- biotite

c- corundum

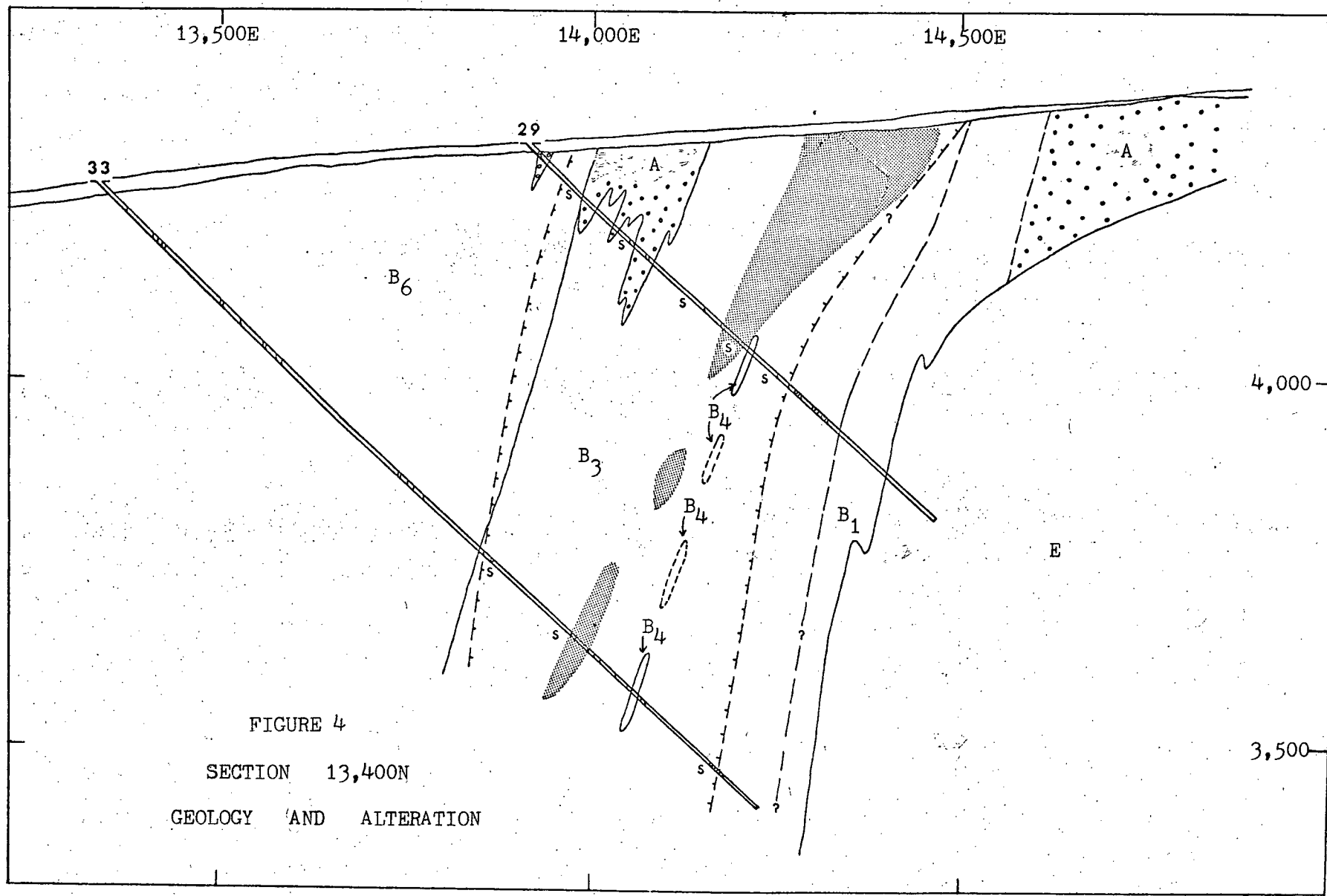
d- dumortierite

p- pyrophyllite

s- scorzalite

sp- spinel

T- tourmalinization



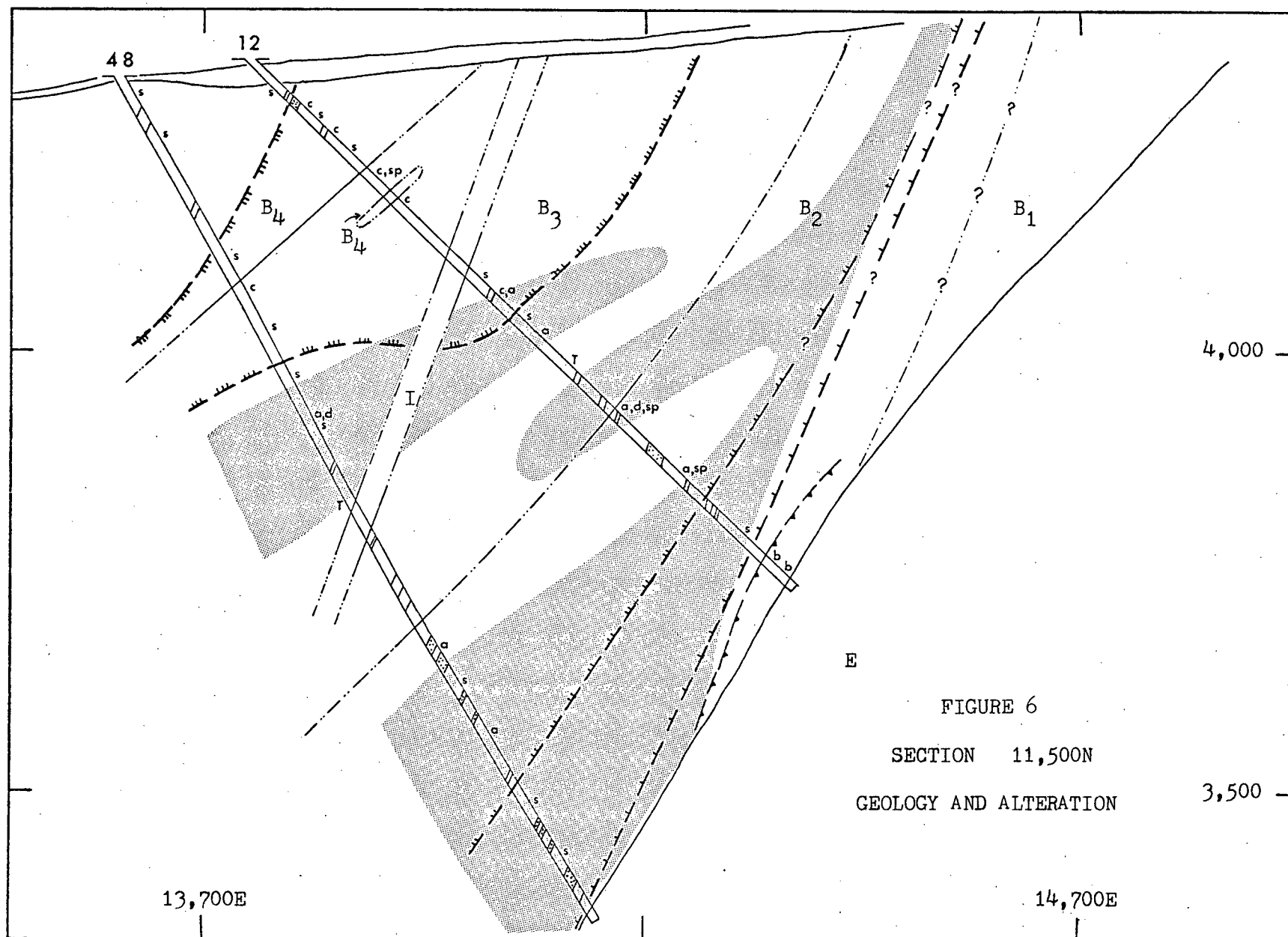
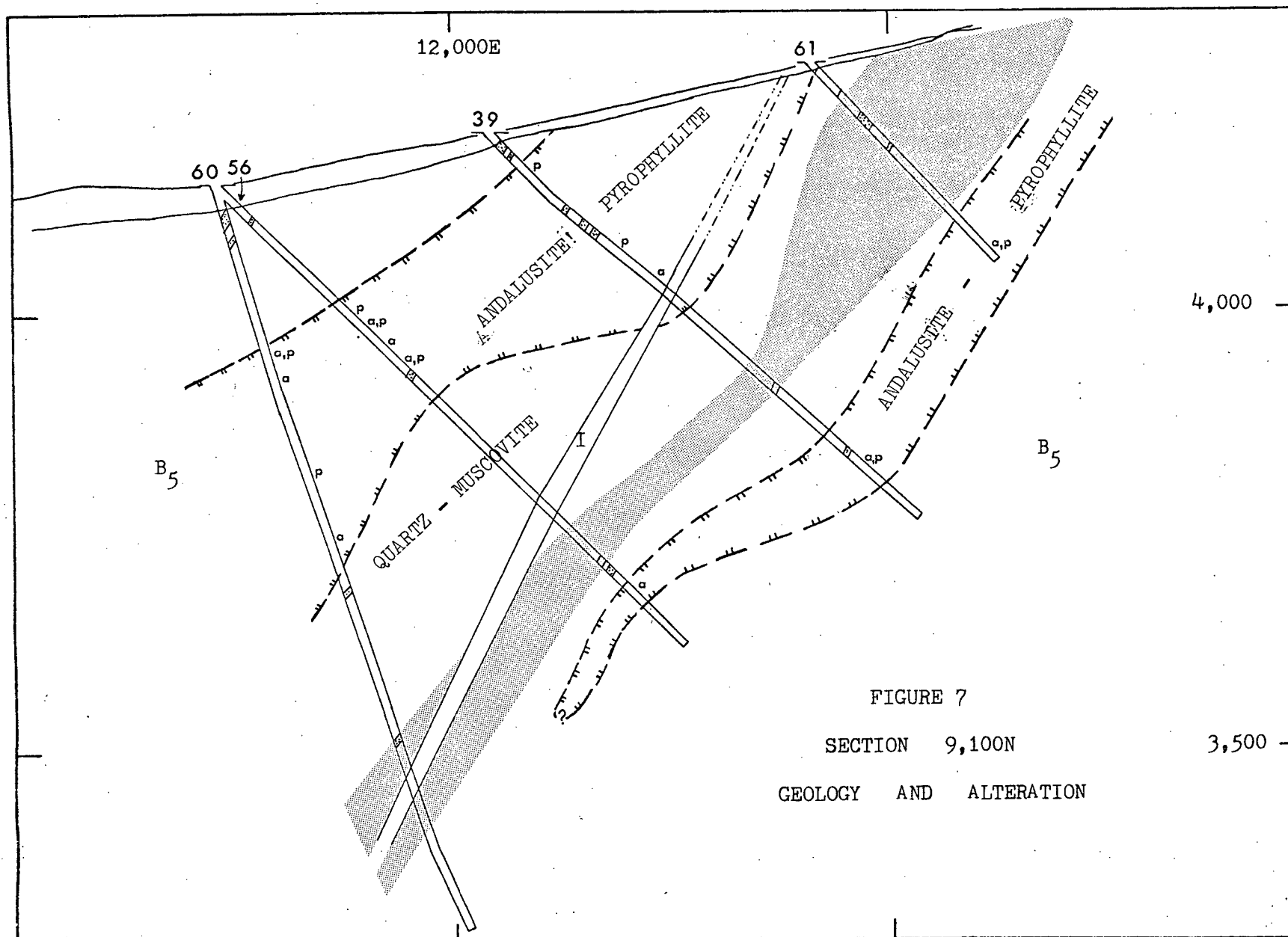


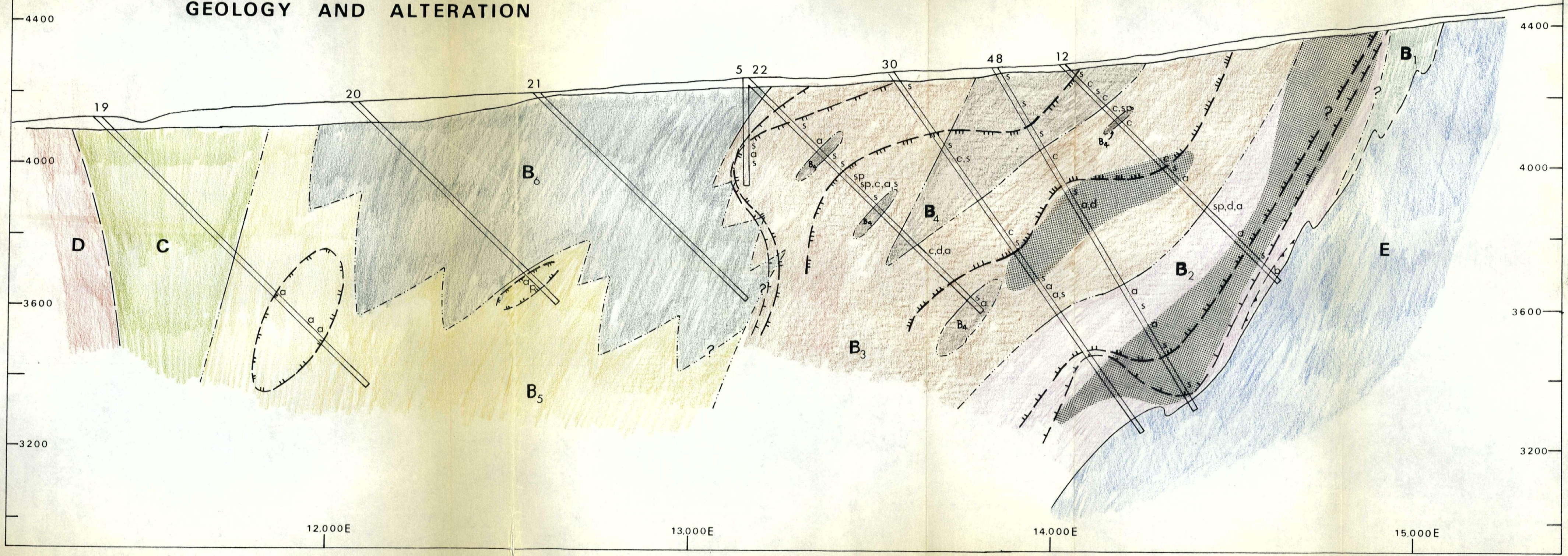
FIGURE 6
SECTION 11,500N
GEOLOGY AND ALTERATION



SECTION 11,800N (APPROX.)

FIGURE 8

GEOLOGY AND ALTERATION



MESOZOIC ROCKS

The Lower Cretaceous inlier has been subdivided into a lower coarse clastic division (unit A), a middle pyroclastic division (unit B) and an upper sedimentary-volcanic division (unit C) by Ney et al (1972). These are retained in this study but the middle pyroclastic division has been further subdivided.

Clastic Division (Unit A)

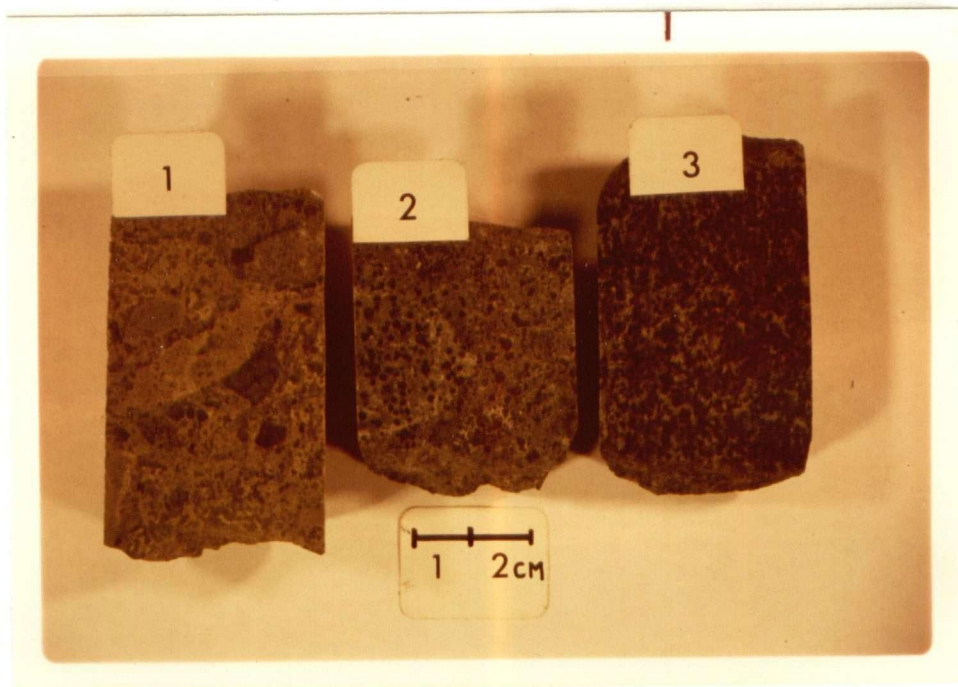
The lower division consists mainly of conglomerate with lesser amounts of argillite and sandstone. Ney et al (1972) have further subdivided the unit into a lower polymictic conglomerate and an upper chert pebble conglomerate. The gradational change in the conglomerate unit can be seen in drill hole 52 (6,000 N, 12,620 E) but the lower subdivision does not occur within the area shown in Fig. 3. Ney et al estimate a maximum thickness of 8,000 feet for the clastic division. Local intercalations of well indurated chert pebble conglomerate persist into the pyroclastic division. These horizons are in marked contrast to the immature, poorly sorted volcanic conglomerates, dust tuffs and volcanic breccias of the pyroclastic division, and suggests an interplay of two sources. Very well-washed chert pebble conglomerates may represent a shoreline facies (Tipper, pers. comm., 1973).

Pyroclastic Division (Unit B)

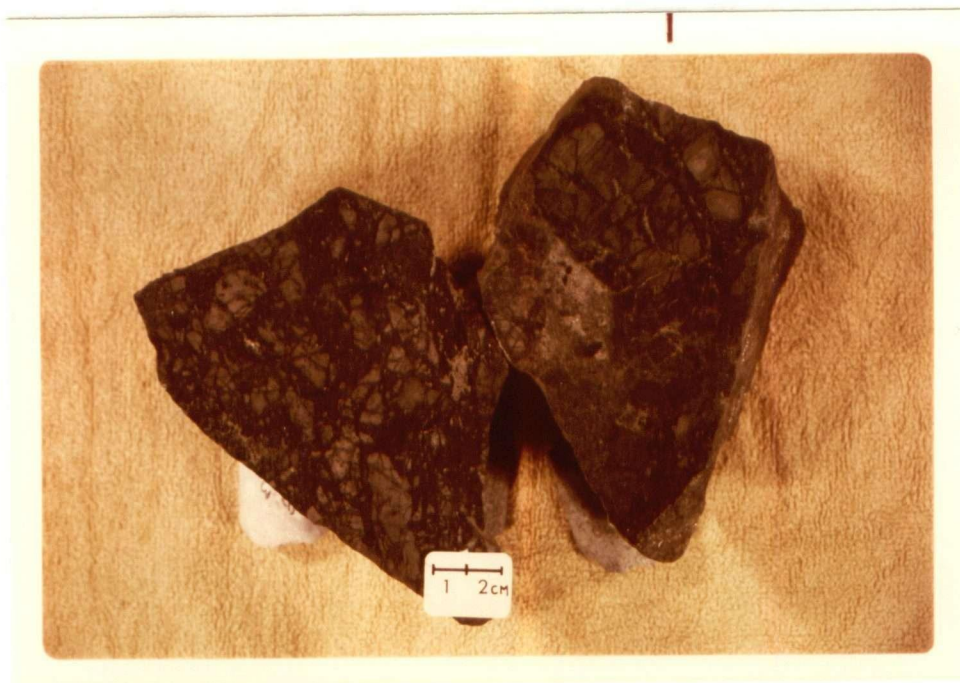
The pyroclastic division is host for Cu-Ag mineralization and is the most economically important of the three divisions. Within limits of drill hole information, it is about 2,500 feet thick, but lateral facies changes could produce significant thickness variations. In logging core, Kennco geologists distinguished among dust, ash and lapilli tuff, and volcanic breccia based on maximum particle diameters of 0.5 mm., 5 mm. and 50 mm. respectively. A subdivision based on fragment size is unsuccessful because not all of these rocks were of pyroclastic origin and units defined by fragment size cannot be correlated between drill holes (see Ney et al, fig. 5, p. 57). For these reasons a subdivision based on rock types has been used here, and these units are described below.

Basal Pyroclastics (Unit B₁)

These are mainly tuffs and flow breccias. They commonly contain numerous blocky pseudomorphs of pyroxene phenocrysts and, less commonly, altered plagioclase phenocrysts (photograph 1). Only altered primary minerals are present, but pyroxene and plagioclase with little quartz suggest the original volcanic was of intermediate composition. Accidental chert fragments are numerous and undoubtedly were derived from the underlying chert pebble conglomerate. Of six units of the pyroclastic division this one is the least clearly defined. It is not extensive as it occurs only in drill holes 7, 9, 29 and 45. In these holes it has been intruded by the gabbro-monzonite stock, so that the base of the unit has not been observed.



Photograph 1 Basal pyroclastic unit; note chert fragments in specimen 1.



Photograph 2 Brecciated dacite unit, with Cu-Ag mineralization.

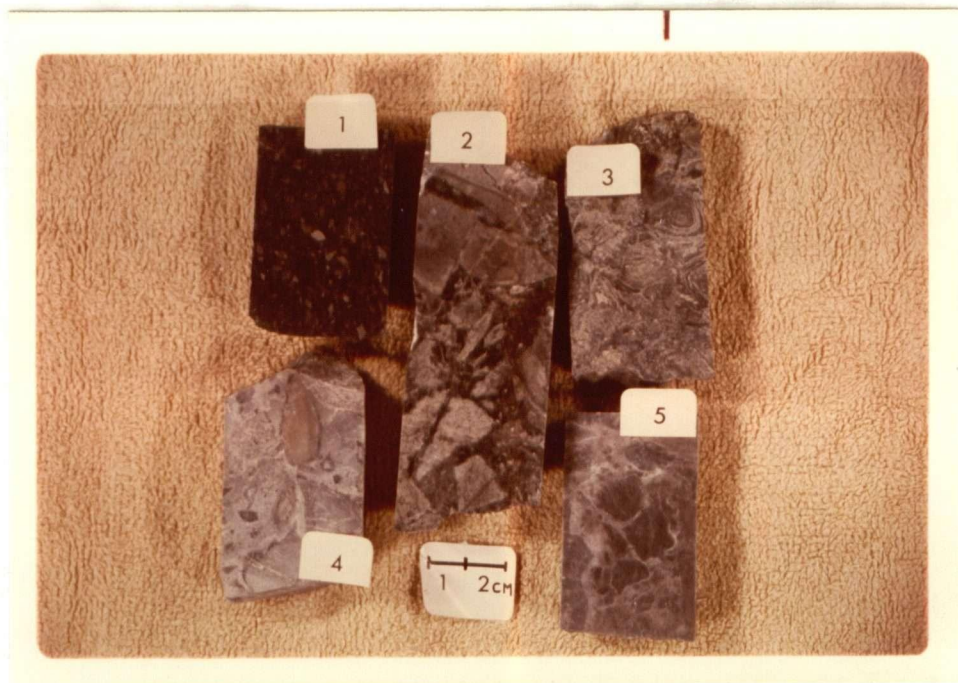
A minimum thickness of the basal pyroclastic unit is 100 feet. The transition with the overlying brecciated dacite is sharp but that with the volcanic breccias is gradational.

Brecciated Dacite (Unit B₂)

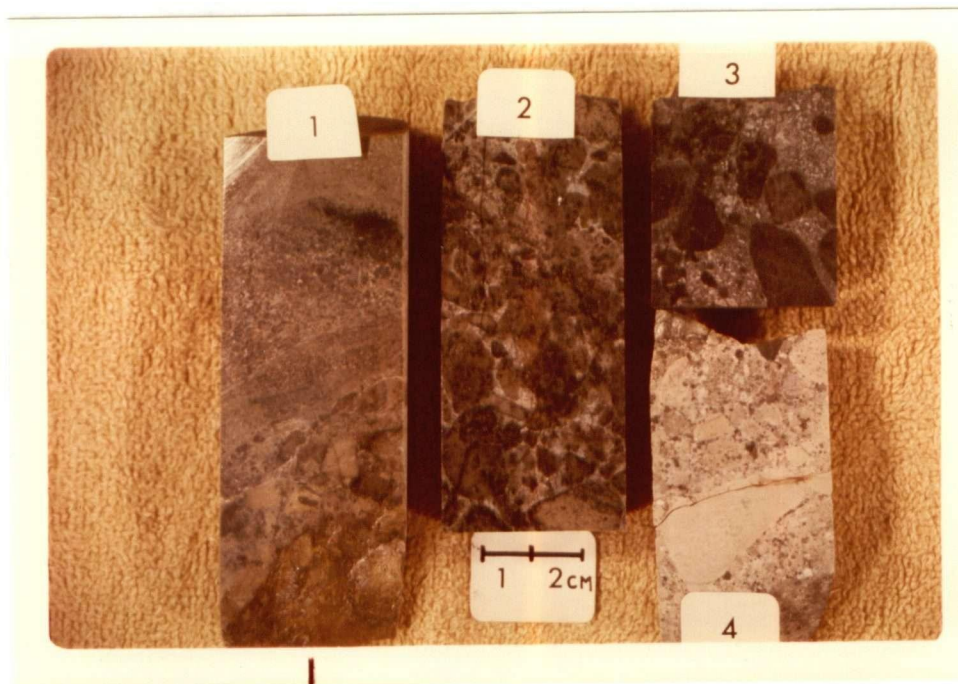
This is a brecciated rock composed of light-coloured aphanitic fragments in a dark, commonly sulphide-rich matrix (photograph 2). The original nature (before brecciation) of this rock is uncertain. It has been referred to as a "brecciated dust tuff" by Ney et al and as a "shattered dacite (possibly an autobrecciated lava dome)" by Church (1970). Considerable similarity between these brecciated rocks and rocks considered by Horikoshi (1969) to be part of autobrecciated dacite lava domes supports Church's (1970) suggestion. Because of intense alteration the writer did not find sufficient evidence to decide if these rocks are a dust tuff or a fine-grained lava. The lower contact of this unit is sharp but upwards the unit grades into volcanic breccias. This unit is exposed in drill core and in the adit and decline that was constructed in 1973. The brecciated dacite is approximately 300 feet thick, and of limited areal extent.

Volcanic Breccias (Unit B₃)

These are coarse volcanoclastic rocks (photograph 3). The aphanitic fragments range in size from 0.5 to 5 centimetres. They are predominantly acidic volcanics, although locally several texturally different types may be present. Within a hand specimen, fragments vary from rounded



Photograph 3 Volcanic breccia unit; specimens 1 and 2 may be lahars; light pink colour in specimen 5 is dumortierite.



Photograph 4 Epiclastic unit.

to very angular. Some specimens consist predominantly of fragments but others are a chaotic mixture of fragments supported in a very fine-grained "muddy" matrix. Some of these latter rocks are very similar to rocks described by Fiske (1963) as "subaqueous pyroclastic flows". However, unlike the stratigraphic sequence Fiske was studying, there are no turbidite beds at Sam Goosly. Mud-supported fragmental rocks at Sam Goosly may be mud flows or lahars. In other rocks the fragments exhibit a pronounced selva or onion-skin texture, as though the fragment was hot at the time of deposition. Such rocks may represent a true pyroclastic accumulation.

This unit is quite diverse and tends to include all rocks that cannot be recognized as belonging to one of the other units. The volcanic breccia unit is broadly equivalent to the undivided pyroclastic division in the southern part of the map-area. The thickness is clearly variable, but in the central part of the property is approximately 1,000 feet.

Epiclastics (Unit B₄)

A number of lenses of volcanic conglomerate and sandstone occur within the volcanic breccia unit (photograph 4).

If the volcanic breccias are partly lahars, intercalated epiclastic layers would be expected. These epiclastic rocks are usually poorly sorted and clasts up to several centimetres in diameter range from subangular to subrounded. Locally they show size sorting and, possibly, graded bedding. The clasts

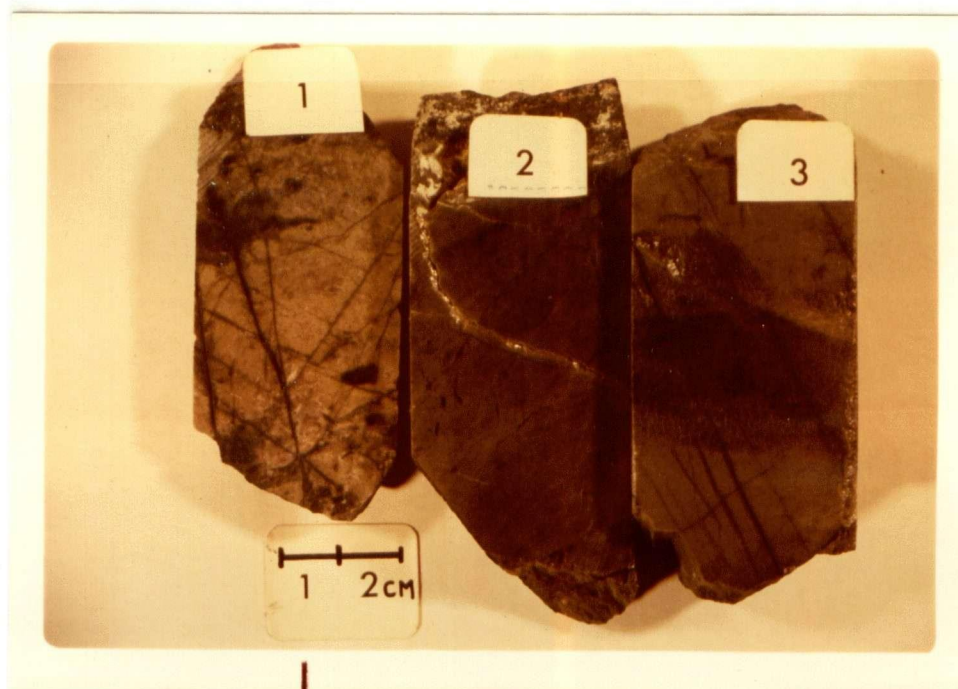
are usually aphanitic but here and there, plagioclase or rare ferromagnesian phenocrysts develop. Unaltered primary minerals are absent. In drill hole 48, the first 200 feet are volcanic sandstone and conglomerate of a thick epiclastic lens.

Dust Tuffs (Unit B₅)

These are very fine-grained pyroclastic rocks (photograph 5) that interfinger with the coarser volcanic debris. Ney et al aptly described these rocks as being "peculiarly massive for many tens of feet without change of grain size or recognizable bedding." Although primary internal structures are lacking, chlorite has formed parallel to the bedding in some rocks. In thin section, dust tuffs that were not strongly altered, contain angular quartz and feldspar crystal fragments, and sparse lithic fragments up to 0.1 mm. in size, but no glass shards. Brecciation is present, but is not as intense as that in the brecciated dacite unit. Much of the rock exhibits a reticulate fracture pattern.

Welded Ash Tuff (Unit B₆)

These rocks are predominantly ash and lapilli tuffs with welded fragments and glass shards (photograph 6). The fragments are angular and aphanitic. Locally porcellaneous dust tuffs are present. These are very similar to some porcellaneous varieties of the dust tuff unit (B₅), except that the dust tuffs of B₆ are welded. The lapilli tuffs of this unit may be contrasted with the underlying volcanic breccia unit (B₃). In unit B₃ alteration and recrystallization



Photograph 5 Dust tuff unit, with chlorite fractures.



Photograph 6 Welded ash tuff unit; specimens 2 and 3 are welded.

have strongly affected the breccia matrix, and fragments may be corroded, with hazy and indistinct boundaries. In comparison, rocks of Unit B₆ are unaltered. The transition between the volcanic breccia and welded ash tuff units is sharp in drill hole 33, but gradational in drill hole 22. The welded ash tuff unit is approximately 1,200 feet thick.

Sedimentary - Volcanic Division (Unit C)

This is the third major division of the Mesozoic strata made by Ney et al. Rocks of this division were seen only in drill hole 19 and consist of well-bedded tuff, tuffaceous argillite, quartzite and pebble conglomerate. Contact with the dust tuff (B₆) is gradational and the boundary is placed at the point at which good bedding develops.

Comparison of Geologic Sections

Geologic sections corresponding to Fig. 8 have also been drawn by Ney et al. and by Church (1970). The most useful comparison is with Church's section. The chert pebble conglomerate at the base of Church's section probably corresponds to the basal pyroclastic unit (B₁) with abundant accidental chert fragments. In drill hole 7, 250 feet north of Church's section, chert pebble conglomerate is interbedded with pyroclastic rocks. Boundaries of the brecciated dacite (B₂) correspond to Church's shattered dacite. The association of economic sulphide mineralization with this rock type is also indicated by Church.

Church noted "a progressive increase stratigraphically downward in the volume of tuff breccia and coarse volcanic debris". This change occurs as shown schematically between drill holes 21 and 22 and corresponds to the gradational change between the volcanic breccias (B_4) and welded ash tuff (B_6). Many epiclastic lenses (B_3) occur stratigraphically higher than indicated by Church and consist predominantly of volcanic detritus rather than chert. Minor chert pebble conglomerate lenses are intercalated with the volcanic breccias elsewhere (see Fig. 4). The "laminar bedded tuffaceous argillite" in drill hole 19 corresponds to the base of the sedimentary - volcanic division (C). Thus, when considered carefully, the correspondence between Church's section and Fig. 8 is good.

Composition of Mesozoic Volcanic Rocks

The original composition, both mineralogically and chemically, of the Mesozoic volcanic rocks is problematical. Alteration is widespread, so that primary mineralogy is not preserved. Most rocks have a low colour index and contain abundant quartz so that an acidic composition may be deduced.

The chemical composition of a suite of 15 lava and pyroclastic rocks from Sam Goosly was estimated by Church (1969) using the method of Mathews (1951). This method involves arc fusion of the sample and measurement of the refractive index of the glass. By this method, the volcanic rocks are dacitic, with a narrow compositional range from rhyodacite to dacitic andesite, large scale chemical changes have taken place during alteration

TABLE 1

Chemical Composition of Lower Cretaceous

Volcanic Rocks at Sam Goosly

(Church, 1973, pers, comm.)

SiO_2	65.72%
TiO_2	0.98
Al_2O_3	18.95
Fe_2O_3	1.42
FeO	3.77
MnO	0.09
MgO	1.39
CaO	1.03
Na_2O	0.72
K_2O	2.42
P_2O_5	0.09
SO_3	0.48
CO_2	0.01
H_2O^+	2.80
H_2O^-	0.22
	<hr/>
	100.09 %

TABLE 2

Comparison of Sam Goosly and
Nockold's (1954) Average Volcanic Rocks on a Water-Free Basis

	Sam Goosly	Andesite	Dacite	Rhyodacite	Rhyolite
SiO ₂	67.72	54.68	63.95	66.72	74.24
TiO ₂	1.01	1.32	0.64	0.66	0.22
Al ₂ O ₃	19.53	17.32	16.76	15.50	13.56
Fe ₂ O ₃	1.46	3.51	2.25	2.15	1.26
FeO	3.89	5.54	3.02	2.25	0.76
MnO	0.09	0.15	0.11	0.07	0.03
MgO	1.43	4.39	2.13	1.58	0.32
CaO	1.06	7.99	5.56	3.71	1.14
Na ₂ O	0.74	3.70	4.00	4.16	3.01
K ₂ O	2.49	1.12	1.41	3.03	5.39
P ₂ O ₅	0.09	0.28	0.17	0.17	0.07
SO ₃	<u>0.49</u> 100.00	<u>-</u> 100.00	<u>-</u> 100.00	<u>-</u> 100.00	<u>-</u> 100.00

Molecular Normative Minerals

Qtz	46.2	5.8	19.7	20.9	33.5
Or	15.1	6.8	8.3	17.9	31.9
Ab	6.8	31.3	34.4	35.4	25.3
An	5.0	27.4	23.4	14.6	5.0
Cor	15.6	-	-	-	0.9
Wo	-	4.2	1.3	1.3	-
En	4.1	11.0	5.3	3.9	0.8
Fs	3.5	5.3	2.8	1.3	-
Mt	1.6	5.1	3.3	3.0	1.9
Ilm	1.4	2.4	1.2	1.4	0.5
Py	0.5	-	-	-	-
Ap	0.2	0.7	0.3	0.3	0.2

of some rocks and its effect of the refractive index is not certain. A whole rock analysis of a composite of the 15 samples was done and is presented in Table 1 (from Church, 1969). For comparison, the analysis is recalculated to 100 per cent and tabulated with Nockold's (1954) average andesite, dacite, rhyodacite and calc-alkali rhyolite (Table 2). The respective igneous molecular norms are included. The purpose of this comparative table will be discussed in a later chapter. The anomalous composition of the volcanic rocks is readily apparent in the norm and this is most probably due to alteration. The closest match is with a rock of dacite to rhyodacite composition.

TERTIARY STRATA

At Sam Goosly, gently dipping Tertiary volcanic rocks consist mainly of distinctive bladed feldspar porphyry lavas of trachyandesite composition, named Goosly Lake Volcanics by Church (1969). These flows surround Mesozoic strata except to the west and northwest where trachytes outcrop. The trachyte is a local compositional variant of the trachyandesite. In the far northwest corner of the property, Goosly Lake Volcanics are overlain by plateau basalts of the Buck Creek Volcanics.

INTRUSIVE ROCKS

Quartz Monzonite

A compositionally homogeneous quartz monzonite stock is exposed near the western edge of the Mesozoic inlier. It is approximately 2.2 km. (1.3 miles) long by 0.9 km. (0.5 miles) wide and elongated northerly. Texturally, it is microporphyritic with subhedral microphenocrysts of plagioclase set in a fine-grained matrix of quartz potash feldspar and biotite. Church (1969) determined the mineralogy and chemical composition of a typical specimen, and these appear in Table 3. Two biotite potassium-argon age determinations have been made on independently prepared concentrates taken from the same sample. Geochron Laboratories determined the age to be 61.1 m.y. (no error limits given by Ney et al), and N.C. Carter at U.B.C. obtained a value of 56.2 ± 3.0 m.y. (Church, 1969). The stock intrudes Mesozoic rocks. Only weak sulphide mineralization occurs within the stock. Ney et al reported that "extensive fracturing, sericitization, and copper - molybdenum mineralization" are present at the north end of the stock. Veinlets containing tetrahedrite outcrop at another locality toward the south end.

Gabbro - Monzonite Complex

Because this stock is close to the mineralized zone and is compositionally complex, it has received much attention. It is located east of the quartz monzonite at the eastern margin of the Mesozoic inlier. The stock is roughly circular in plan

TABLE 3
Chemical Analyses of Intrusions and
Tertiary Lavas at Sam Goosly
(from Church, 1969)

	Quartz monzonite	Monzonite	Goosly Lake Trachyandesite
SiO ₂	65.02	52.80	55.86
TiO ₂	0.65	1.82	1.26
Al ₂ O ₃	15.76	16.95	17.52
Fe ₂ O ₃	2.12	3.97	4.95
FeO	1.54	3.63	1.41
MnO	0.04	0.14	0.08
MgO	1.27	3.85	3.16
CaO	3.21	6.03	6.18
Na ₂ O	4.21	4.10	4.13
K ₂ O	3.59	3.30	2.05
H ₂ O ⁺	1.69	1.90	1.17
H ₂ O ⁻	0.21	0.18	1.44
CO ₂	0.08	0.02	0.02
P ₂ O ₅	0.28	0.91	0.44
SO ₃	0.01	0.01	0.02
BaO	0.18	0.27	0.18
	<u>99.68</u>	<u>99.68</u>	<u>99.87</u>

Modal Analyses

Plagioclase	50	58 (An ₄₅)
K-feldspar	19	25
Quartz	25	2
Augite	-	8
Biotite	4	2
Magnetite	2	5
Apatite	-	1

and measures about 2.5 km. (1.7 miles) across. Ney et al distinguished six plutonic and hypabyssal phases. Large feldspar laths in a trachytoid alignment is a distinctive textural feature common to all phases. The most basic phase is a gabbro containing 60 per cent labradorite and 30 per cent augite, with accessory biotite, magnetite and apatite. Quartz and potash feldspar occur locally as micrographic intergrowths along margins of plagioclase phenocrysts. With a slight decrease in anorthite content of plagioclase, and an increase in the amount of interstitial potassium feldspar, the gabbro grades through diorite to monzonite. An increase in biotite and a decrease in augite accompanies this transition. The monzonite phase is considerably larger than the basic phases and intrudes the mineralized volcanic rocks. Modal and chemical analyses of this main phase (Table 3) show the monzonite is enriched in P_2O_5 . This is corroborated by Ney et al who stated that the apatite content may amount to as much as 5 per cent.

The gabbro - monzonite stock does not contain Cu-Ag mineralization and is only weakly altered. Pyroxenes are variably unalitized to a mixture of amphibole, chlorite and calcite, and potassium feldspars may be clouded, but plagioclase is unaltered.

Of the remaining three phases of the complex distinguished by Ney et al, one is a series of bladed feldspar porphyry dykes, another is a "dyke-like" body of biotite monzonite, and the third is a large body of unknown form that merges to the north with lavas of the Goosly Lake Volcanics. There appears to be a genetic

relationship between the plutonic rocks, hypabyssal rocks, and lava flows. Based on a comparison of the chemical analyses of the monzonite and Goosly Lake trachyandesite (Table 3) and mineralogical and textural similarities, Church (1969, 1970) suggested the stock is the core of a volcano, surrounded by its own eruptives. Biotite potassium-argon ages of 48.3 ± 3.0 m.y. for the monzonite, and 48.0 ± 1.8 m.y. for the trachyandesite flows, are reported by Church (1973). Ney et al reported a biotite potassium-argon age of 52.5 m.y. (no error limits given) for the monzonite.

Dykes and Sills

A large number and variety of dykes and sills cut the Mesozoic strata. They are particularly abundant between the quartz monzonite stock and the gabbro - monzonite complex, and account for 15 per cent (Ney et al) to 20 per cent (Church, 1970) of the rocks. A comparison of northern and southern sections (Fig. 4 and Fig. 7) indicates the number of dykes diminishes southwards. Neilson (1969) identified three types of dykes and sills; gray andesite porphyry (bladed feldspar porphyry), light greenish-gray altered andesite, and chalky white altered quartz latite porphyry. Neilson observed, and the writer concurs, that fresh bladed feldspar porphyry dykes grade into altered, aphanitic andesite dykes.

Andesite porphyry and aphanitic andesite dykes are very abundant and individual bodies cannot be correlated between drill holes. Those exposed in the adit strike at 060° to 100°

and dip steeply southward to vertical. Most are 1 to 2 metres thick, although dykes up to 10 metres in apparent thickness have been seen in drill core. The presence of bladed plagioclase phenocrysts strongly suggests that the dykes are consanguineous with the gabbro - monzonite complex. Fresh porphyritic varieties are texturally and mineralogically similar to the monzonite phase of the intrusive complex. Altered aphanitic dykes consist of chlorite, albite and carbonate.

Pale gray to chalky white quartz latite dykes form a much less abundant, but distinctive, type. These contain 2 - 4 mm. plagioclase phenocrysts, 2 - 3 mm. quartz phenocrysts and flecks of biotite in a fine-grained micrographic matrix of quartz and potash feldspar. Plagioclase and biotite phenocrysts are altered to mixtures of chlorite, sericite, albite and calcite, and potash feldspar of the matrix is clouded by incipient clay alteration. Scattered cubes of pyrite are common. Quartz latite dykes are far fewer, but thicker, than andesite dykes. In outcrop and in the adit, these dykes strike about 125° and dip steeply to the southwest. Because of their thickness and rarity they can be correlated between drill holes with some confidence. Rare, small aphanitic felsite dykes are similar in colour and may be related to the quartz latite dykes.

All dykes cut Cu-Ag mineralization in the volcanic rocks. Even though the host rocks may consist of massive sulphides, the dykes are sparingly pyritized or are unmineralized, and therefore post-date Cu-Ag mineralization. Andesite porphyry dykes are intrusive into the quartz monzonite stock. A thick

quartz latite dyke cuts the gabbro-monzonite complex. In drill core, quartz latite dykes cut andesite dykes.

The intrusive history is summarized below.

- (1) Intrusion of the quartz monzonite stock at 59 ± 3 m.y. (average K-Ar date).
- (2) Differentiation and intrusion of the gabbro-monzonite complex at 51 ± 3 m.y. (average K-Ar date), accompanied by a variety of andesite, commonly bladed feldspar porphyry dykes, and by extrusion of the Goosly Lake Volcanics.
- (3) Intrusion of quartz latite dykes.

STRUCTURE

The structure of the Mesozoic volcanic strata is a simple homocline with tops facing west as suggested by Church (1970), Ney et al (1972) and accepted in this study. Bedding attitudes near the mineralized zone consistently strike about 025° and dip steeply ($60^\circ - 80^\circ$) westerly. Therefore sections defined by drill holes are not necessarily normal to strike (Fig. 4 to 8). In the central part of the property, the strike apparently changes to 000° and sections are nearly perpendicular to strike. Corrections of apparent dips measured from sections 11,500N, 12,400N and 13,400N indicate true dips to be 55° , 50° and 75° respectively. Top determinations from graded sandstone beds, both in outcrop and in drill core, indicate that the section is the right way up.

The contact of the gabbro-monzonite stock dips at about 50° westerly (Fig. 6 and 8), and is subparallel to the dip of

volcanic strata near the main ore zone. In detail, irregularities in the intrusive contact cut unit B_1 so that unit B_1 is penetrated by some drill holes, but in others it has been truncated by the intrusive stock (Fig. 8). Possibly the volcanic strata dip more steeply than the intrusive contact, as unit B_1 is present in shallow drill holes, (such as 7 and 9), but rarely in deeper holes (such as 12, 30 and 48). Such a relationship is inferred in Fig. 6.

ORE MINERALOGY

INTRODUCTION

Considerable effort has been expended by Kennco and is being continued by Equity on studies of the ore mineralogy. These include work by Neilsen (1969), Mariano (1971), Gasparrini (1971) and Ney et al (1972). A number of samples from various types of ore grade and sub-ore grade material were examined in order to correlate differences in metallic mineralogy with silicate alteration mineralogy.

METALLIC MINERALOGY

Pyrite is the most important metallic mineral throughout the Mesozoic volcanic rocks regionally and within the zone of Cu-Ag mineralization in particular. Chalcopyrite, pyrrhotite, magnetite, hematite, tetrahedrite and sphalerite are other important metallic minerals that occur within the deposit. In addition, very minor amounts of unidentified sulphosalt (?) minerals, associated with chalcopyrite and tetrahedrite occur in some specimens. One specimen contains arsenopyrite. Traces of marcasite, argentite, pyrargyrite, boulangerite, pearceite, berthierite and bournonite have been reported by Mariano, or by Ney et al, but were not identified during this study. Gasparrini identified freibergite (tetrahedrite with more than 3% silver in solid solution).

Should development of the property proceed, silver, copper and gold would be recovered using an open-pit mining operation. The amount of sphalerite is not sufficient to economically

recover zinc.

DISTRIBUTION AND CHARACTER OF MINERALIZATION

The character of mineralization exhibits a close relationship with specific host rocks of the local stratigraphic succession. The zone of Cu-Ag mineralization is broadly conformable with the volcanic strata. Metallic mineralogy associated with each unit is described below.

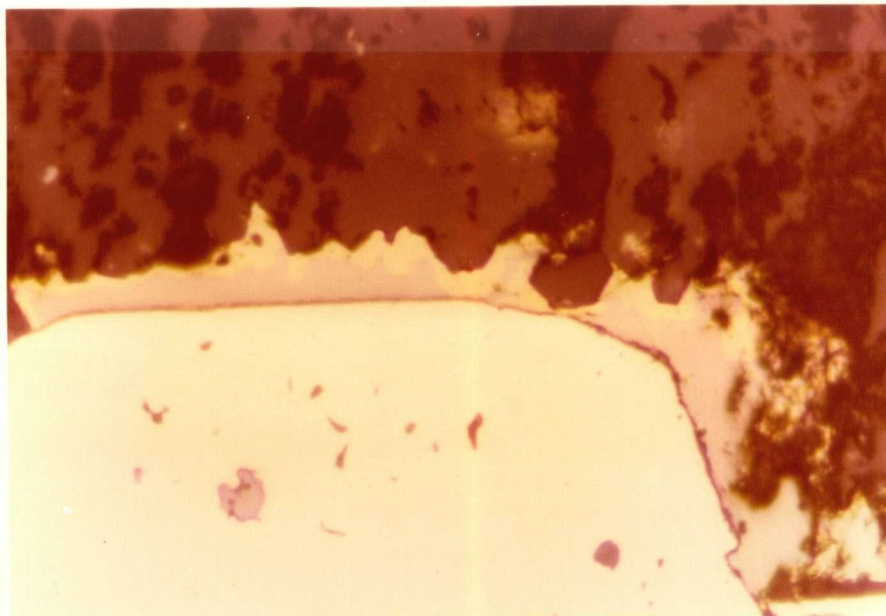
Chert pebble conglomerates of the coarse clastic division (A) intercalated with pyroclastic division rocks (B) contain pyrite cubes (1 mm.) disseminated throughout the matrix. The basal pyroclastic unit (B_1) contains up to 3 per cent finely disseminated pyrite and magnetite.

Brecciated dacite (B_2) is the most specific host rock for Cu-Ag mineralization and is invariably associated with economic grades. Overall sulphide content is also highest in this unit, ranging from less than 5 per cent to over 50 per cent locally. Sulphides occur as disseminations, veinlets or irregular masses within the breccia matrix. Typical specimens of disseminated sulphide ore contain an average of 10 per cent sulphide minerals, consisting of about 9 per cent pyrite, 1 per cent chalcopyrite and less than 1 per cent sphalerite, pyrrhotite and tetrahedrite. Pyrite grains range from 0.02 mm. to 1 mm., chalcopyrite from 0.01 to 0.1 mm.; sphalerite is about 0.03 mm. and tetrahedrite is about 0.01 mm. Grain size becomes more variable in zones of massive sulphide but generally increases to several millimetres. The proportion of minerals is extremely variable; pyrite 30-80

per cent, magnetite 10-60 per cent, chalcopryrite 5-20 per cent, sphalerite 0-20 per cent and pyrrhotite 0-60 per cent. Brecciated dacite does not extend to the northern part of the ore zone (D.D.H. 24 and 29). Here, sulphides are in the matrix of volcanic breccia (B_3).

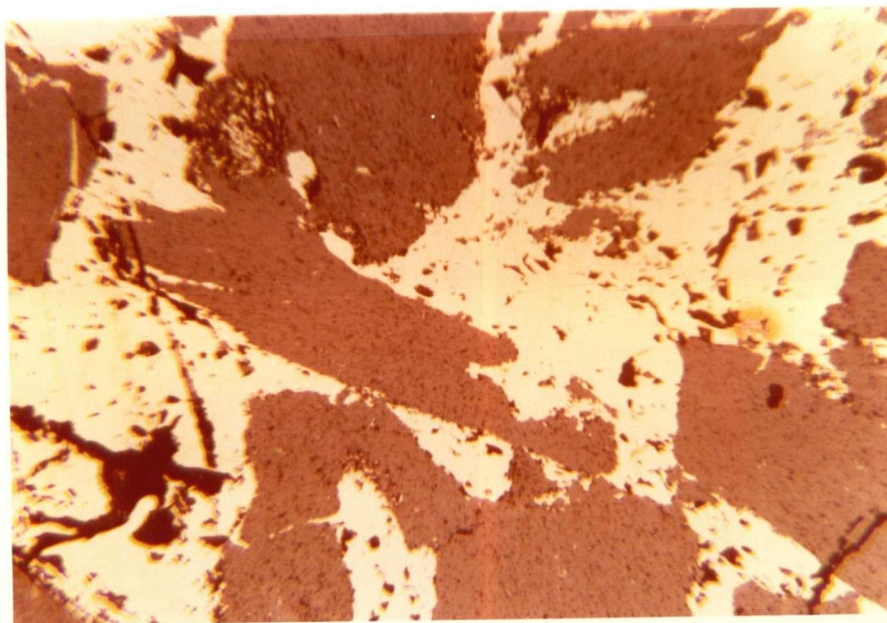
Volcanic breccias (B_3) and epiclastics (B_4) overlying Cu-Ag mineralization contain disseminated pyrite and local zones of massive sulphide, consisting of about 70 per cent pyrite, 0-30 per cent magnetite and 0-30 per cent specular hematite. The average grain size is 1 to 2 mm. Massive zones may contain millimetre-size vugs lined with specular hematite, or more rarely pyrite. Stratigraphically upwards, disseminated and massive forms diminish and in the welded ash tuff rare 2 mm. pyrite veins account for much less than one per cent of the rock.

The character of mineralization changes as the ore zone is followed southward along strike into dust tuff (B_5). In the north economic grades are maintained over more than 200 feet (true thickness), but southward the ore zone narrows to less than 50 feet in B_5 . The main ore control is intensity of fracturing and brecciation. Total sulphide content of the ore rarely exceeds 20 per cent. The decrease in total sulphide content from the main ore zone to the north, is principally due to a large decrease in pyrite. Outside the ore-zone chlorite-filled fractures range from hairline width to 1 cm. These fractures usually have pyrite, or rarely chalcopryrite, at their core. Locally, a network of fractures may progress into a chlorite-cemented breccia. Brecciation becomes very important in the ore zone where breccia fragments are



0 0.005 0.01 mm.

Photograph 7 Vein ore in dust tuff unit. Surface coating of tetrahedrite (gray) and chalcopyrite (gold) on pyrite (pale yellow).



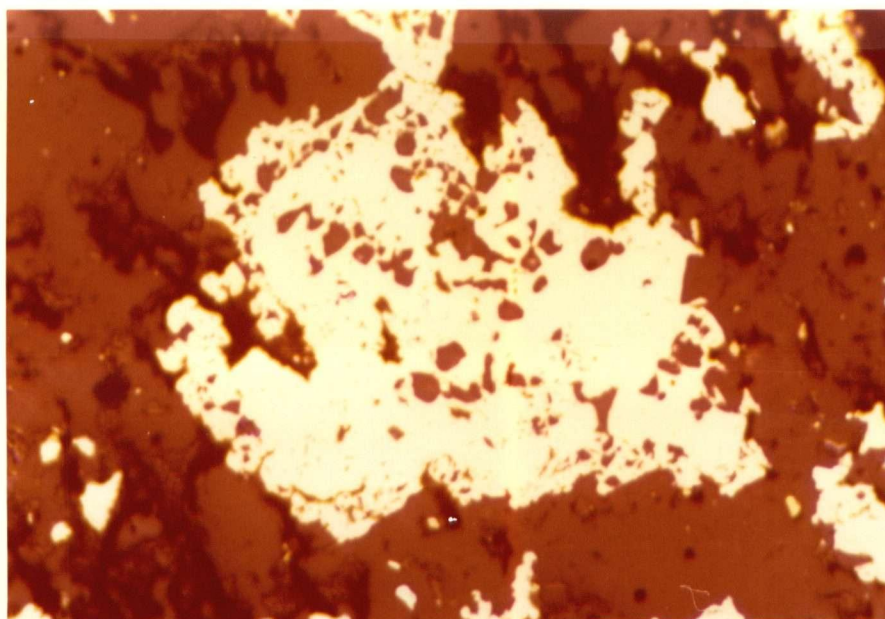
0 0.5 1 mm.

Photograph 8 Breccia zone in dust tuff unit, cemented by chalcopyrite.

cemented by sulphides and vein quartz. Sulphides do not occur as very fine-grained disseminations in the matrix, as in brecciated dacite, but form vein structures and fill open spaces between breccia fragments. Symmetric banding and textures such as those shown in photograph 7 indicate the paragenetic sequence is pyrite, tetrahedrite, chalcopyrite. Commonly the dust tuff has been very weakly brecciated, or "crackled" and the cement of such a breccia may consist solely of chalcopyrite (photograph 8), or in other areas, of sphalerite. In rocks that are more strongly brecciated, the cement consists of vein quartz, pyrite, chalcopyrite, sphalerite, tetrahedrite and tourmaline. Sulphide grain size varies from 0.5 to 5 mm.

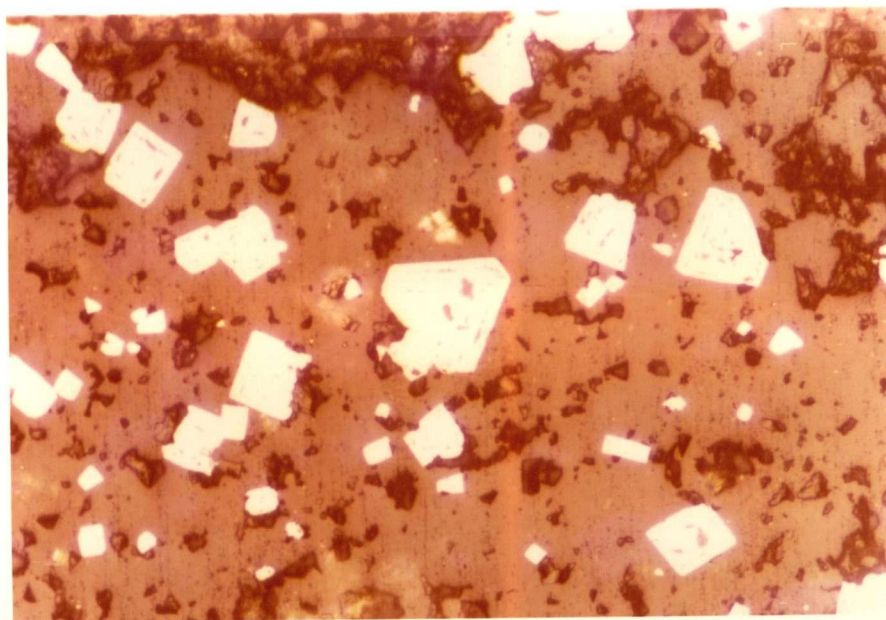
MINERAL ZONING

Church (1969) sampled the brecciated dacite at the creek exposure of the ore zone (12,200N, 14,600E) and it assayed: gold, 0.05 ounces per ton; silver, 4.7 ounces per ton; copper, 1.04 per cent; zinc, 0.23 per cent; lead, 0.015 per cent; antimony, 0.10 per cent. This is approximately twice the average grade of the main ore zone. The silver to copper ratio for this sample is 0.016 which is similar to ratios from drill core inter-sections of the brecciated dacite in D.D.H. 7, 9, and 45. Silver to copper ratios were also calculated from drill core assays of the other drill holes studied. These show an erratic distribution in the main ore zone but range from 0.016 up to 0.05. The narrow, southern extension of the ore zone has a lower silver content, and silver to copper ratios are typically 0.01. On the basis of the 25 polished sections studied, tetrahedrite, the main silver-bearing



0 0.05 0.1 mm.

Photograph 9 Pyrite aggregate with randomly distributed silicate inclusions.



0 0.25 0.5 mm.

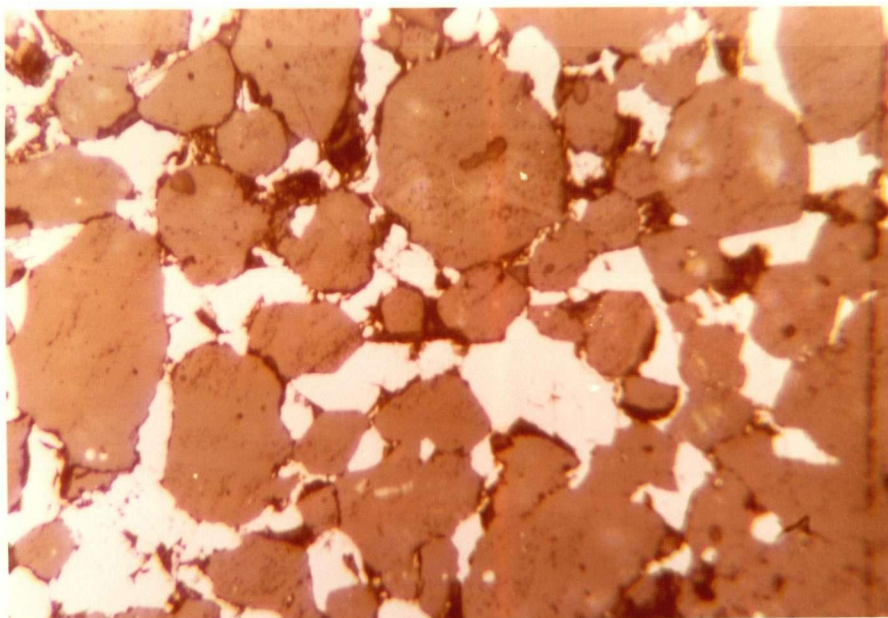
Photograph 10 Euhedral pyrite with zones of silicate inclusions.

mineral, tends to occur in zones of disseminated sulphides, not with massive sulphide.

MINERAL TEXTURES

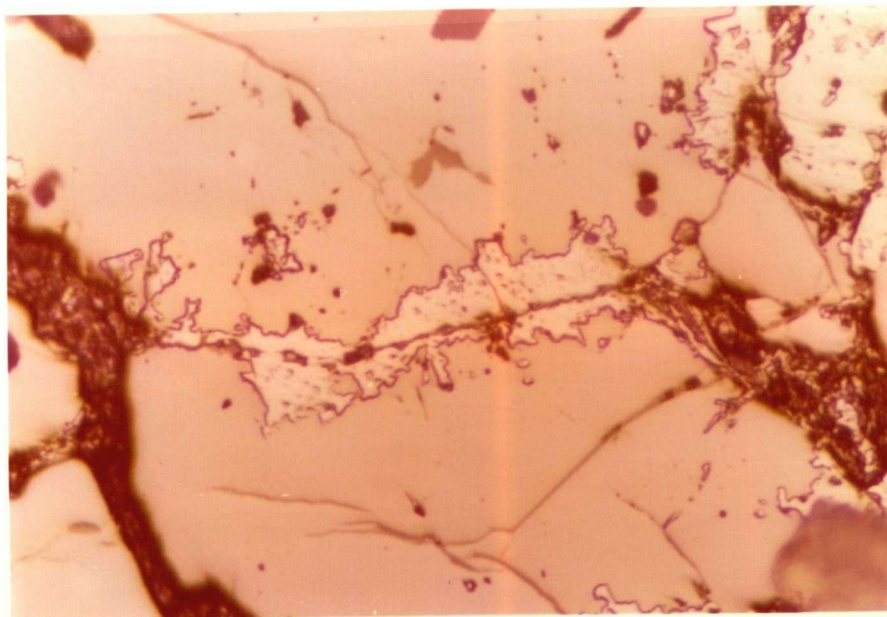
In the main ore zone, pyrite commonly occurs as highly irregular crystal aggregates, with randomly distributed gangue material (photograph 9). In other samples, pyrite crystals may be euhedral and contain zones of inclusions parallel to crystal boundaries (photograph 10). Similar, euhedral single crystals of pyrite become visible macroscopically adjacent to the thick quartz latite dyke and the gabbro-monzonite complex. In D.D.H. 48 these pyrite crystals increase in size from 2 mm. at 175 feet from the contact to 10 mm. adjacent to the contact. Because these are single, euhedral crystals with inclusions, and not anhedral crystal aggregates, they are probably pyrite porphyroblasts rather than clastic fragments. Pyrite porphyroblasts in sulphide mineral deposits probably result from metamorphism (Vokes, 1969). Stanton (1972) proposed a sulphide - oxide - silicate idiomorphic sequence based on studies of metamorphosed sulphide deposits. Pyrite is high in the sequence, comparable with garnet and, like garnet, tends to form porphyroblasts. Chalcopyrite, tetrahedrite and pyrrhotite are low in the sequence and are comparable with chlorite. These minerals tend not to recrystallize as idiomorphic porphyroblasts. Photograph 11 shows pyrrhotite interstitial to granoblastic quartz.

In the hanging wall of the main ore zone, specular hematite extensively replaces magnetite (photograph 12). Hematite is later than magnetite and becomes more prevalent than magnetite strati-



0 0.1 0.2 mm.

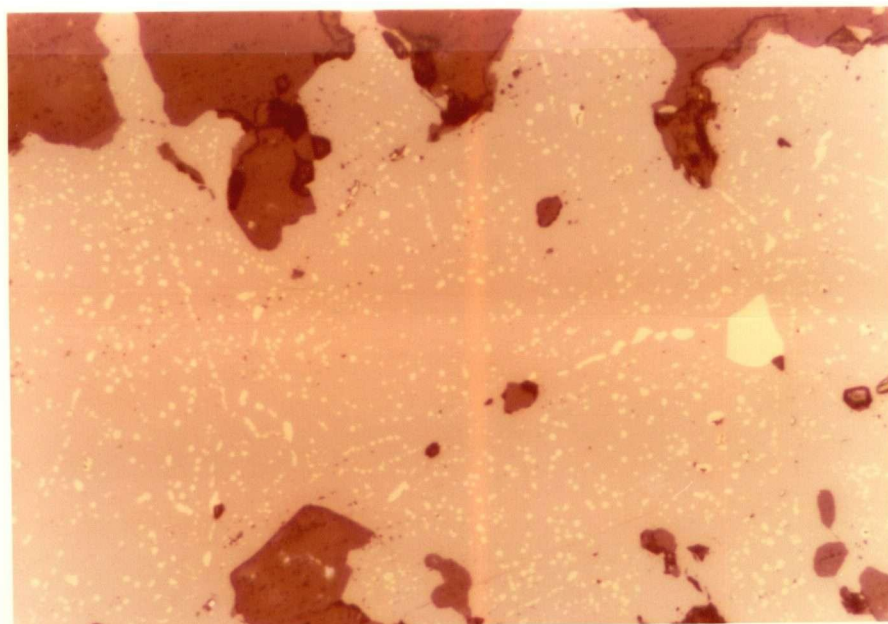
Photograph 11 Pyrrhotite interstitial to granoblastic quartz
(adjacent to quartz latite dyke).



0 0.01 0.02 mm.

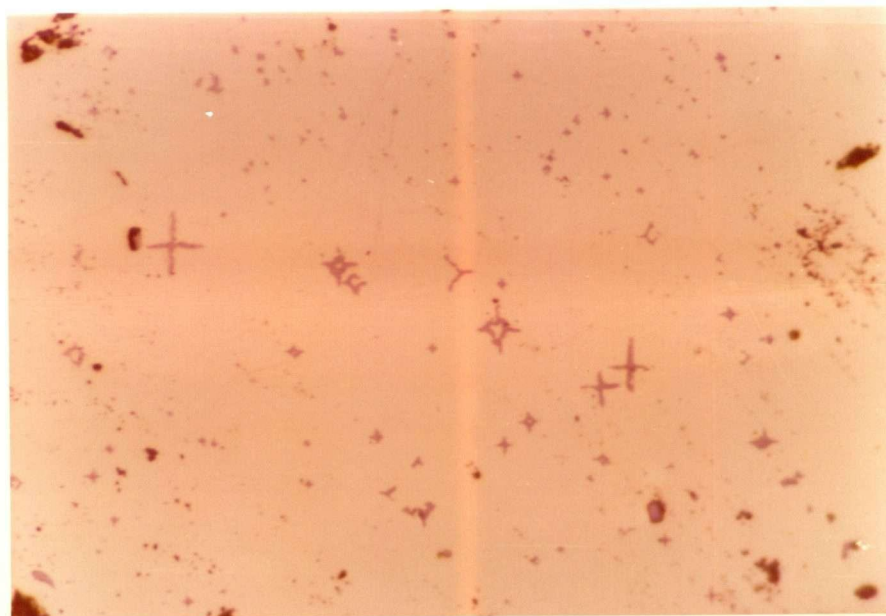
Photograph 12 Hematite replacing magnetite along fractures.

graphically upwards. Appearance of hematite corresponds approximately with the lower boundary of the corundum alteration zone (p. 61) Sphalerite in the main ore zone contains blebs of chalcopyrite (photograph 13). These are due to unmixing of chalcopyrite originally contained within host sphalerite (Stanton, 1972). Stanton noted that unmixing of sphalerite from a chalcopyrite host is much less common. In two specimens, chalcopyrite contains 'stars' of exsolved sphalerite (photograph 14).



0 0.1 0.2 mm.

Photograph 13 Chalcopyrite exsolved from a sphalerite host.



0 0.1 0.2 mm.

Photograph 14 'Stars' of sphalerite exsolved from chalcopyrite.

ALTERATION AND METAMORPHISM

INTRODUCTION

Four types of alteration and metamorphism are recognized in the Lower Cretaceous rocks at Sam Goosly.

(1) Aluminous alteration is characterized by a suite of aluminous minerals including scorzalite, andalusite, pyrophyllite and corundum. Alteration zones are conformable with some stratigraphic boundaries but crosscut others. These alteration zones also show a systematic spatial relationship to the mineralized zone.

(2) Quartz-muscovite alteration is associated with brecciation and mineralization in the dust tuff (B₅).

(3) Regional metamorphism has affected all volcanic rocks, producing a propylitic, or greenschist, assemblage of muscovite, chlorite, albite, kaolinite, quartz and carbonate. Proportions of these minerals are determined by the nature of the host rock.

(4) Contact metamorphism by the gabbro-monzonite resulted in a narrow, discontinuous zone of biotite hornfels and a more extensive zone of recrystallized pyrite porphyroblasts. Potash feldspar has developed adjacent to the quartz monzonite stock.

ALUMINOUS ALTERATION

The alumina-rich minerals andalusite, corundum, pyrophyllite, dumortierite, spinel, scorzalite and augellite are developed in units B₂, B₃, B₄, and B₅. They form three alteration zones: scorzalite,

TABLE 4

Mineralogy of Aluminous Alteration

Mineral and Chemical Composition	Identifying Features
Andalusite, Al_2SiO_5	<ul style="list-style-type: none"> -occurs as euhedral crystals or aggregates, showing good cleavage. -usually colourless, more rarely pleochroic from colourless to pink. -chiastolite occurs very rarely.
Augellite, $\text{Al}_2(\text{PO}_4)(\text{OH})_3$	<ul style="list-style-type: none"> - occurs as anhedral aggregates with poor cleavage. -low first order interference tints. - colourless, which distinguishes it from scorzalite. - distinguished from quartz by moderate positive relief and axial angle of $+45^\circ$.
Corundum, Al_2O_3	<ul style="list-style-type: none"> - very high relief, low first order interference and prominent parting are distinctive; uniaxial negative. - usually colourless, but may be zoned with a blue pleochroic core.
Dumortierite, $\text{Al}_8\text{Si}_3\text{BO}_{19}(\text{OH})$	<ul style="list-style-type: none"> - prismatic to tabular crystals are pleochroic from colourless to lavender. - minute crystals are acicular, non-pleochroic, and similar to sillimanite except dumortierite is length-fast.
Pyrophyllite, $\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$	<ul style="list-style-type: none"> - occurs in fine micaceous aggregates, very similar to muscovite can be positively identified only by X-ray diffraction.
Scorzalite, $(\text{Fe,Mg})\text{Al}_2(\text{PO}_4)_2(\text{OH})_2$	<ul style="list-style-type: none"> - blue in hand specimen and pleochroic bright to dark blue in thin section. - grains are anhedral with no cleavage. - mid-second order interference tints that are commonly masked by the body colour. - spectrographic analysis by Church (1970) gives 12 per cent FeO and 2.5 per cent MgO.
Spinel, $(\text{Fe,Mg})\text{Al}_2\text{O}_4$	<ul style="list-style-type: none"> -occurs as isotropic octahedra with extreme positive relief; isotropic. - colour ranges from dark green to light green.

andalusite and corundum. In the dust tuff unit (B_5), the andalusite zone becomes an andalusite-pyrophyllite zone. Chemical compositions and identifying features of aluminous minerals are summarized in Table 4.

Throughout the aluminous alteration zones, quartz and muscovite predominate and only locally are andalusite or pyrophyllite a significant volume of the rock. Muscovite polytypes were investigated following the method of Carroll (1970). Application of Carroll's criteria suggests that 1Md, 1M and 2M polytypes are present.¹ Nielsen (1969) identified predominantly 1Md muscovite and some 2M muscovite within the zone of aluminous alteration. Where muscovite polytypes could be distinguished, it is indicated throughout the following descriptions.

Scorzalite Zone

The scorzalite zone is 3,000 feet long by 1,200 feet wide and broadly outlines Cu-Ag mineralization. The zone is not centered on the ore zone but is offset towards the west, or hanging wall, side. Due to its blue colour, scorzalite was noted in drill core logging, if not correctly identified. Drill logs of all 62 Kennco holes were used to define the scorzalite zone. Because drill logs could be used, the scorzalite zone extends from the area studied in detail into the area marked "insufficient data" (Fig. 3).

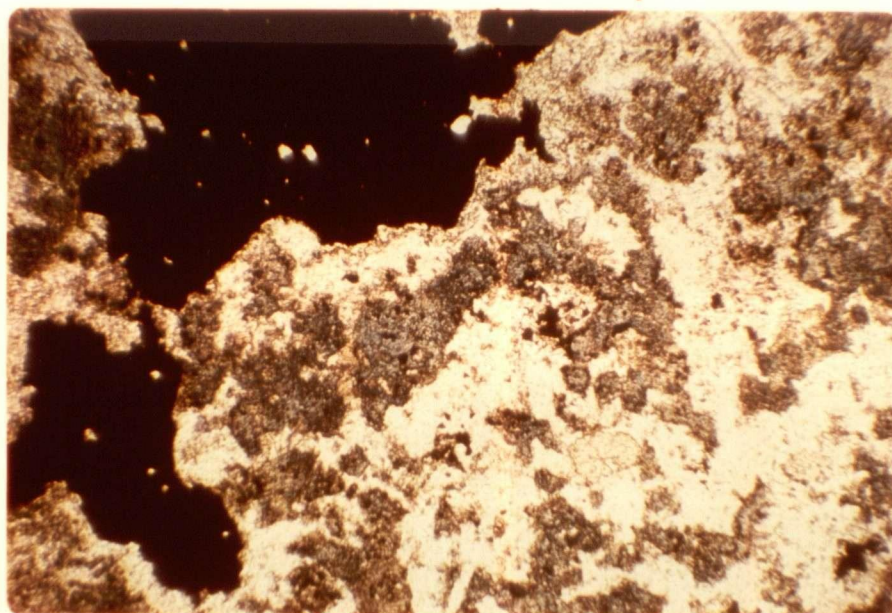
1 Of six possible muscovite polytypes, the naturally occurring ones are 1Md, 1M, 2M and 3T where 1, 2 and 3 refer to the number of octahedral layers in the unit cell, M and T designate monoclinic or trigonal symmetry, and 'd' denotes a disordered crystal structure.

Pyrite, muscovite and quartz usually contact scorzalite (photograph 15) and locally andalusite or chlorite may be present. Commonly, scorzalite is intimately associated with pyrite and other sulphides. This close association suggests a genetic relationship between scorzalite and sulphide minerals. However, scorzalite and pyrite are not closely associated on the western, stratigraphically highest, side of the scorzalite zone as in drill hole 22 where scorzalite occurs with 1M muscovite, corundum, spinel, andalusite, rutile and very minor pyrite. Augellite was found with scorzalite in two samples, D.D.H. 6-300 feet and D.D.H. 22-450 feet. Augellite, in comparison to scorzalite, lacks iron and magnesium. This difference is consistent with the decrease in pyrite associated with scorzalite.

Apatite occurs sporadically in the scorzalite zone but it is not directly associated with scorzalite. The underlying basal pyroclastic unit (B_1), and dykes cutting the volcanic rocks, contain accessory apatite, but no scorzalite.

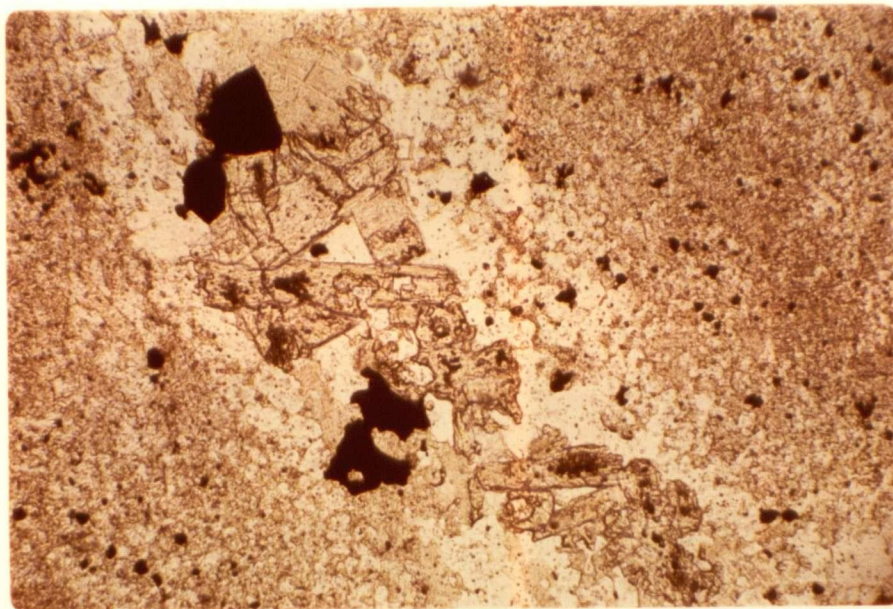
Andalusite and Andalusite-Pyrophyllite Zones

Andalusite was first identified at Sam Goosly by Nielsen (1969). It develops sporadically and is identifiable only in thin section. Thus the boundary of the zone cannot be located as precisely as that of scorzalite. The andalusite zone is over 4,500 feet long by a maximum surface width of 1,200 feet, and is elongate parallel to the strike of the pyroclastic strata. The zone encloses most of the Cu-Ag mineralization but is offset to the west so that it is not concentric with mineralization. Across the facies boundary



0 1 mm.

Photograph 15 Scorzalite (blue) associated with pyrite and muscovite (clear).



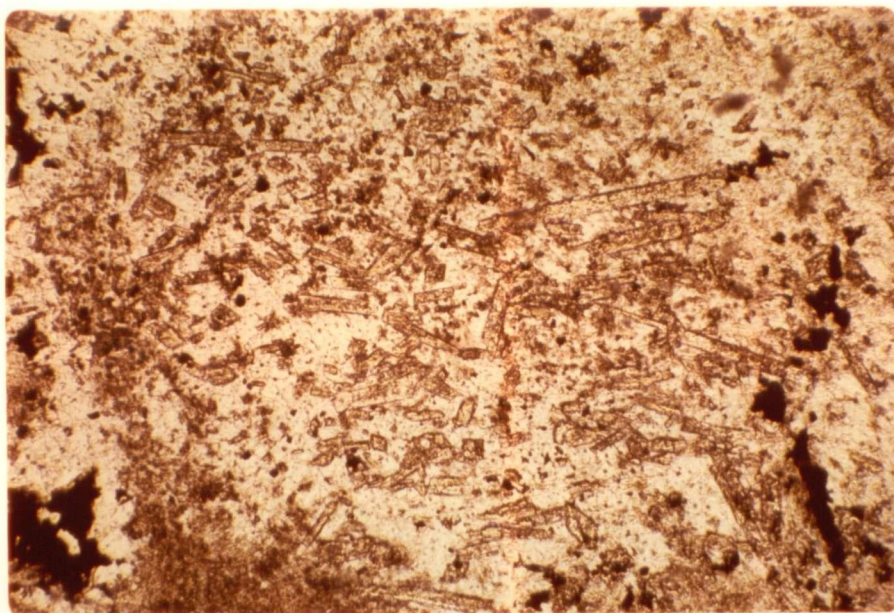
0 1 mm.

Photograph 16 Band of andalusite, pyrite and quartz (clear), in a quartz-muscovite rock.

into the dust tuff unit (B_5), pyrophyllite develops and the zone becomes an andalusite-pyrophyllite zone.

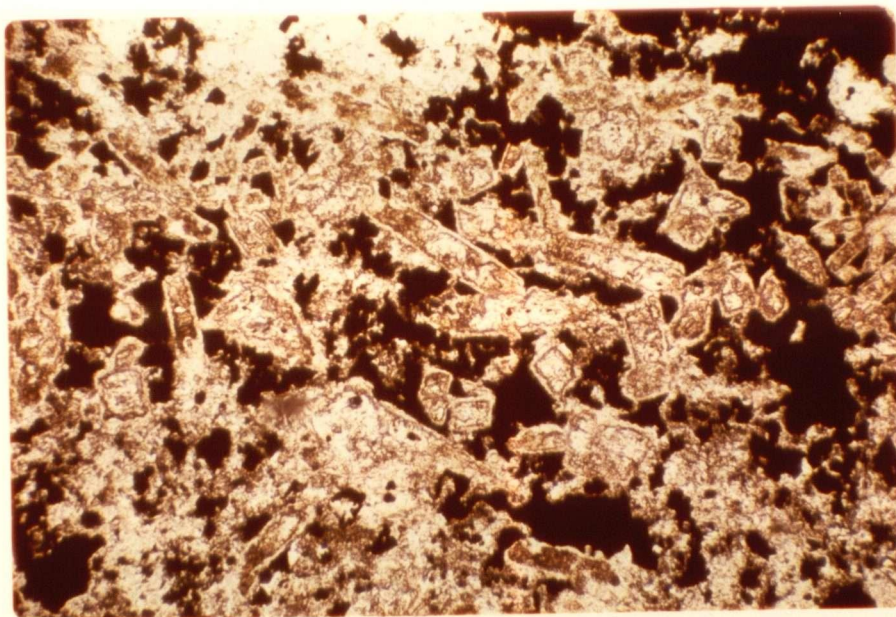
The andalusite zone develops most prominently in brecciated dacite (B_2) and immediately overlying volcanic breccias (B_3). In Section 12,400N (Fig. 5), every thin section of brecciated dacite contains andalusite but none of the underlying basal pyroclastics (B_1) contains it. The boundary of the andalusite zone corresponds very closely to the stratigraphic boundary between B_1 and B_2 . Alteration of the brecciated dacite, consisting of a submicroscopic mixture of quartz and 1Md muscovite, begins along fractures and progresses into fragments. In very weakly brecciated rocks, some fractures only 0.5 mm. wide are cored by andalusite. With increasing intensity of alteration, fractures increase in width to several millimetres and form a dense network. In this network, andalusite is disseminated in the breccia matrix, and it has coarsened to 0.3 mm., quartz to an average of 0.2 mm. and 2M muscovite to 0.02 mm. Rocks consist either of dominant muscovite with minor quartz and rare andalusite, or dominant quartz plus andalusite with minor muscovite (photographs 16 and 17). The most andalusite-rich domains consist of about 75 per cent quartz, 15 per cent andalusite, 5 per cent 2M muscovite, and 5 per cent sulphides. These modal relationships suggest muscovite has been converted to andalusite plus quartz, with a loss of potassium.

Andalusite and sulphides are spatially related in the matrix of the dacite breccia. A polished section (D.D.H. 9-120 feet) contains clusters of pyrite, chalcopyrite and tetrahedrite with



0 1 mm.

Photograph 17 Prismatic andalusite with quartz (clear).

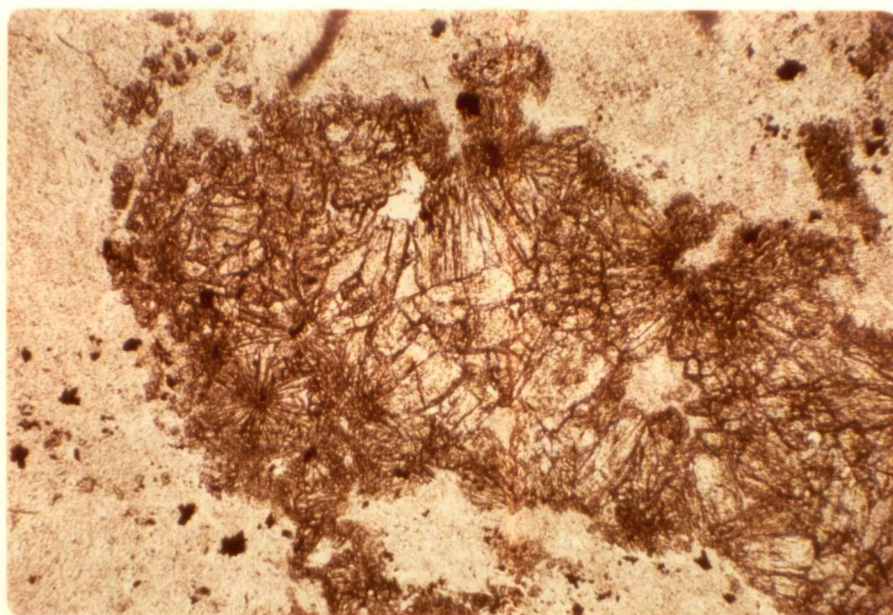


0 1 mm.

Photograph 18 Andalusite (partly altered) intimately intergrown with pyrite and chalcopyrite.

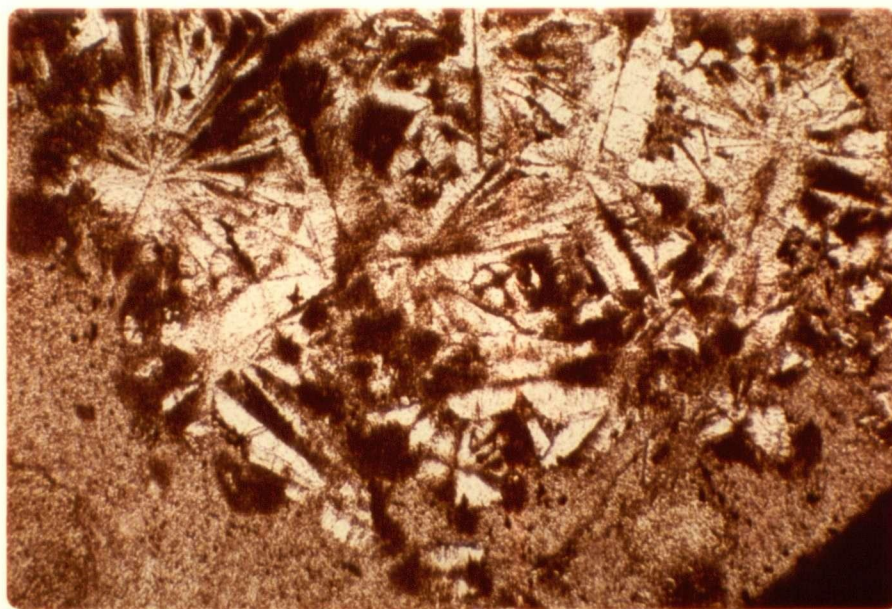
andalusite and quartz around the margin. In other rocks, sulphides are interstitial to, or included within, andalusite (photograph 18). These textures suggest that pyrite, chalcopyrite, tetrahedrite, quartz and andalusite formed contemporaneously. This conclusion accords with the observations of Ney et al (1972) who noted silicification was closely related to mineralization.

Andalusite becomes sporadic in volcanic breccias (B_3) and epiclastics (B_4). It occurs in the matrix of volcanic breccias but in epiclastic rocks. Where the matrix may be very siliceous, andalusite forms within muscovite-bearing clasts. A conglomerate from an epiclastic lens in drill hole 22 contains 2 cm. dacitic clasts in a very fine-grained siliceous matrix. A 1-2 mm. thick outer rim of the clasts has concentrations of andalusite (now pseudomorphed by chlorite) and pyrite. Stratigraphically higher, andalusite is not closely associated with sulphides and corundum becomes more abundant than andalusite. Andalusite occurs as clusters of rosettes (up to 0.5 mm. in diameter) producing a solid mass or pod of andalusite several millimetres in size (photograph 19). The rosettes are centred by a few grains (0.02 mm.) of rutile, with andalusite radiating outward. This texture suggests that rutile has acted as a point for nucleation of andalusite. Highly aluminous zones occur locally that consist of 80 per cent fine-grained 2M muscovite, 10 per cent andalusite, 2 per cent disseminated rutile, a variable amount of tourmaline, but no quartz. One such rock from D.D.H. 22-276 feet is banded, with alternating 1 cm. wide tourmaline-rich and andalusite-rich bands, which may have formed at the same time.



0 1 mm.

Photograph 19 Andalusite rosettes, centred by rutile.



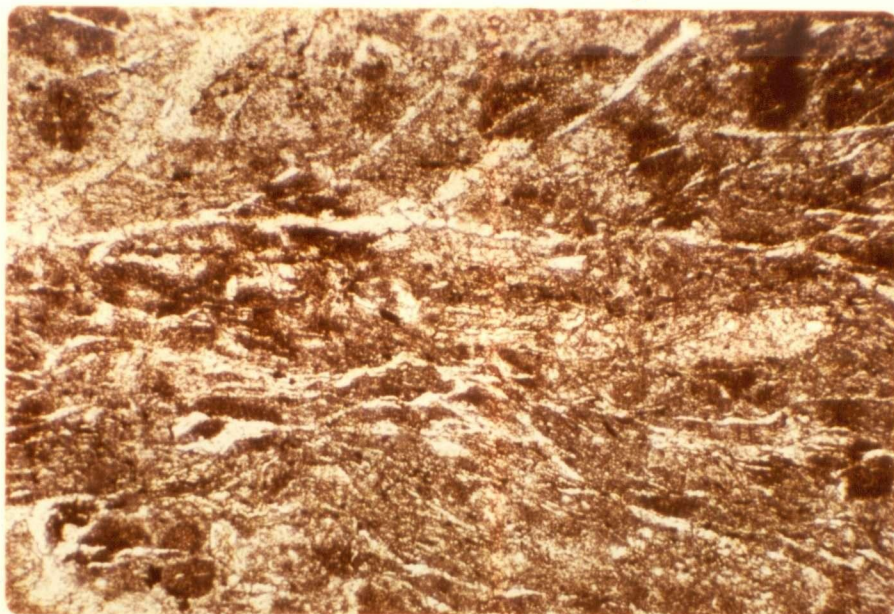
0 1 mm.

Photograph 20 Chiastolite in dust tuff unit.

In dust tuff unit (B₅) andalusite, pyrophyllite and chlorite form the typical assemblage of the andalusite - pyrophyllite zone. Andalusite is not spatially associated with sulphides or brecciation, but develops in two zones flanking Cu-Ag mineralization (Fig. 7). Andalusite usually occurs as 0.1 to 0.4 mm. disseminated grains, or as aggregates up to 5 mm. in size. The chiastolite variety occurs locally (photograph 20). Andalusite lies in a very fine-grained matrix, identified by X-ray diffraction as muscovite (either 1M or 2M polytypes), pyrophyllite, chlorite and quartz. Pyrophyllite is not present in all rocks and in others, pyrophyllite occurs without andalusite. Although secondary quartz is associated with andalusite, quartz never becomes a major constituent of the rock as it does in the brecciated dacite. In the lower andalusite - pyrophyllite zone, narrow (0.02 mm.) veinlets of andalusite are common. These are parallel to and intimately associated with thin, wispy chlorite veinlets (photograph 21).

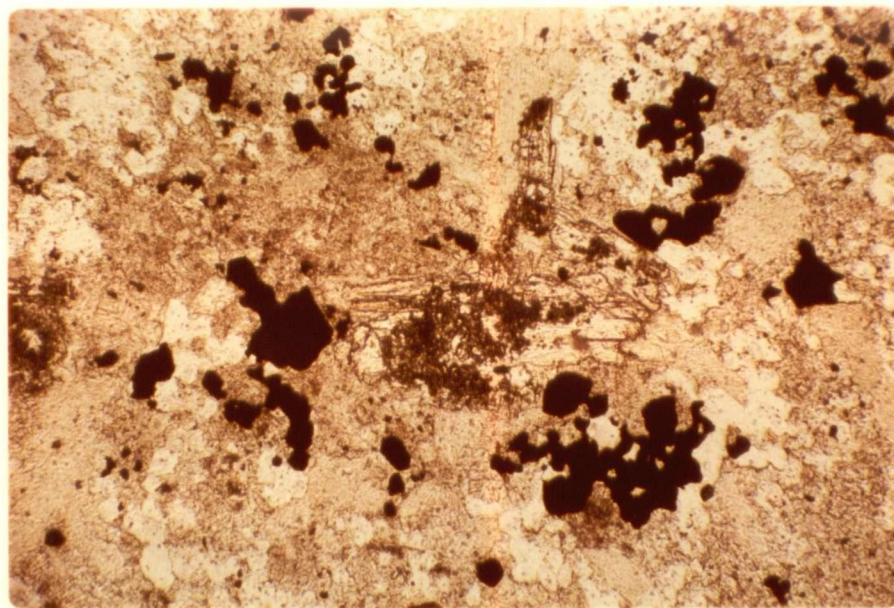
Corundum Zone

Scattered occurrences of corundum lie within a zone that is 1,300 feet long by 500 feet wide. The zone is completely enclosed by the andalusite and scorzalite zones. It lies stratigraphically above Cu-Ag mineralization and shows the same westerly displacement as described for the preceding alteration zones. The corundum zone may have extended as far north as 13,400N, as possible corundum pseudomorphs occur in drill hole 29. Although corundum is sparse, several different associations have been recognized.



0 1 mm.

Photograph 21 Parallel veinlets of andalusite; thin section from hand specimen 1, photograph 25.



0 1 mm.

Photograph 22 Andalusite with inclusions of high relief corundum.

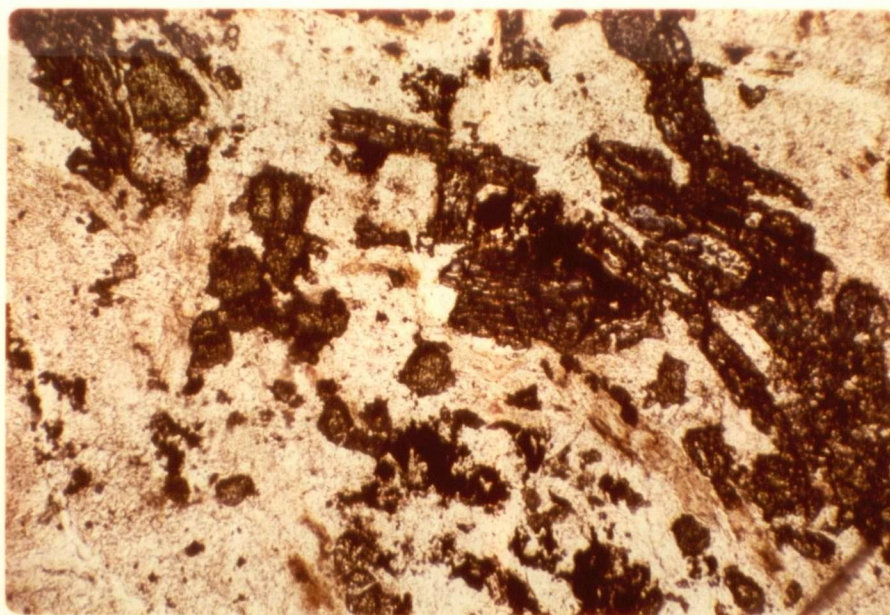
(1) In a sample from D.D.H. 12-683 feet, corundum forms inclusions in andalusite (photograph 22). Margins of large (0.3 mm.) prismatic andalusite grains are altered to muscovite but centres are crowded with minute corundum grains.

(2) Corundum and muscovite may occur as 0.5 to 3 mm. nodules. Corundum is separated from the surrounding quartz-bearing matrix by a sheath of fine-grained muscovite. Spinel may be associated with corundum (photograph 23).

(3) At D.D.H. 22-452 feet, a highly aluminous rock consists of 65 per cent 1M muscovite, 15 per cent scorzalite, 10 per cent augellite, 3 per cent spinel, 2 per cent rutile and 5 per cent randomly distributed corundum, but no quartz. Rare andalusite grains are ragged and embayed by surrounding corundum and muscovite. These three types of corundum occurrences indicate a close spatial, and possibly genetic relationship, between andalusite and corundum (see p. 91).

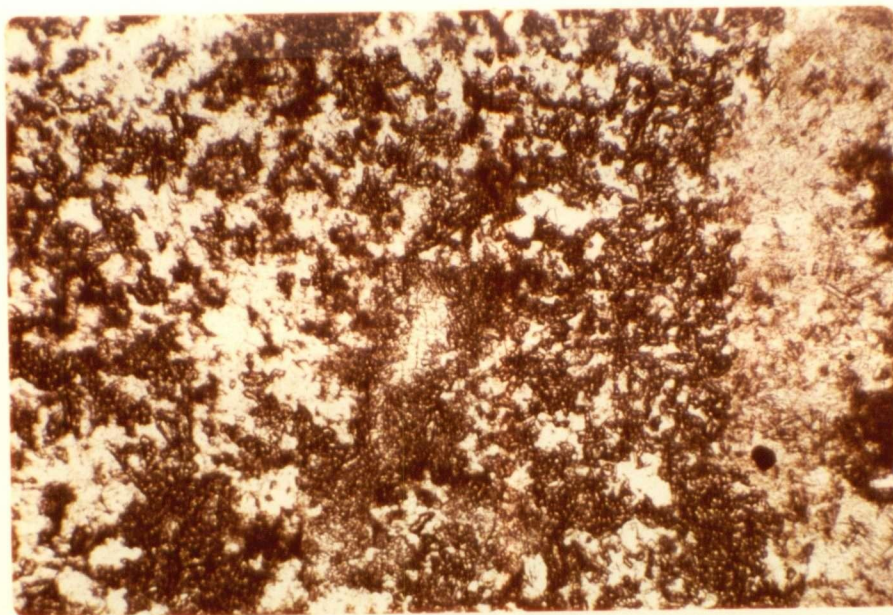
(4) Corundum, with pyrite and tourmaline, fills fractures less than 1 mm. wide. At D.D.H. 30-314 feet, for example, a 0.4mm. wide quartz-pyrite veinlet abruptly becomes a corundum-pyrite veinlet. Although quartz and corundum are not in contact, they are part of the same vein system.

(5) At D.D.H. 22-706 feet, quartz and corundum form a 5 mm. thick layer cutting a rock of quartz, muscovite and dumortierite. Muscovite pseudomorphs of andalusite are also present. The layer has a narrow muscovite-rich border and contains minor dumortierite and rare andalusite in addition to quartz and corundum (photograph 24). Andalusite grains are ragged and replaced by corundum.



0 1 mm.

Photograph 23 Zoned blue corundum and green spinel in matrix of muscovite.



0 1 mm.

Photograph 24 Corundum (high relief) and quartz (clear).
Andalusite replaced by corundum at centre of photo.

Other Minerals

Spinel is associated with corundum and, less commonly, with scorzalite or andalusite. In one specimen scorzalite mantles spinel indicating that, at least locally, spinel was present before the formation of scorzalite.

Dumortierite in the brecciated dacite (B_2) occurs as rare disseminated grains, or as a cluster of grains bordering pyrite. Dumortierite is closely associated with andalusite and in some rocks replaces andalusite. In D.D.H. 22, about 200 feet above Cu-Ag mineralization, fibrous dumortierite is developed throughout the matrix of a volcanic breccia, giving the matrix a pale lavender colour over a distance of 30 feet.

Tourmaline, another boron mineral, has a very widespread distribution as an accessory mineral, occurring in Lower Cretaceous and Tertiary volcanic rocks at Sam Goosly. However, textural evidence, such as the banded andalusite - tourmaline rock (p. 59) suggests at least some tourmaline is related to the formation of aluminous minerals. Locally within the andalusite zone, volcanic breccias consist almost entirely of schorlite tourmaline. One such zone is shown on Section 11,500 N (Fig. 6), where intense tourmalinization extends over 10 to 15 feet in both drill holes 12 and 48. The trend of this tourmalinized zone is similar to that of other alteration zones, suggesting a genetic relationship. Schorlite, the iron-rich tourmaline dominates in the mineralized zone, and dravite, the magnesium-rich variety, occurs only locally. In D.D.H. 12-600 to 800 feet, large (0.5 mm.) scattered dravite poikilolitically encloses quartz grains, is rimmed by schorlite, and

is in contact with andalusite.

ALTERATION ASSOCIATED WITH MINERALIZATION IN UNIT B₅

In the dust tuff unit (B₅), Cu-Ag mineralization occurs as open-space filling in a breccia zone. Strongly fractured dust tuffs are altered to a pale tan or buff rock consisting of 1M and 2M muscovite and quartz for at least 1,4000 feet between D.D.H. 41 and D.D.H. 39, 56, 60 and 61. These rocks are 250 feet thick and are flanked, above and below, by gray andalusite - pyrophyllite rocks. Brecciation decreases in intensity away from the quartz - sulphide breccia of the ore zone into pyrite - chlorite fractures. These fractures crosscut chlorite - andalusite veinlets (p. 61) and indicate at least two generations of chlorite (photograph 25). Where andalusite - pyrophyllite rocks are cut by chlorite - pyrite fractures, pale tan or buff alteration envelopes, from a few millimetres to 20 cm. wide, consist mainly of muscovite and quartz. Commonly, kaolinite also develops in the envelope but pyrophyllite is rare and andalusite is absent. This distribution of minerals implies that kaolinite replaces andalusite and pyrophyllite in the alteration envelope. The small scale alteration envelopes about single fractures are analagous to the quartz - sulphide breccia zone and its large scale alteration envelope of muscovite and quartz. Therefore, the two andalusite - pyrophyllite zones in the south (Fig. 7) may have been one large andalusite - pyrophyllite zone which has been dissected by quartz - muscovite alteration associated with mineralization. Thus, sulphide deposition in the dust tuff unit is later than andalusite alteration, and

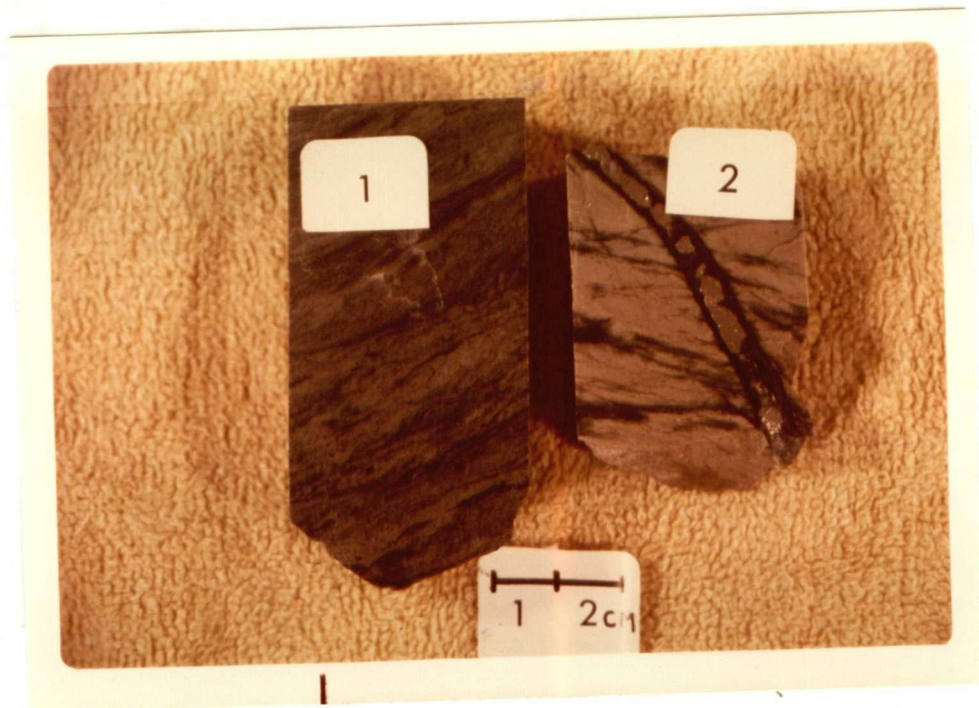
contrasts with the ore zone farther north where a single andalusite zone is contemporaneous with sulphide deposition.

REGIONAL METAMORPHISM

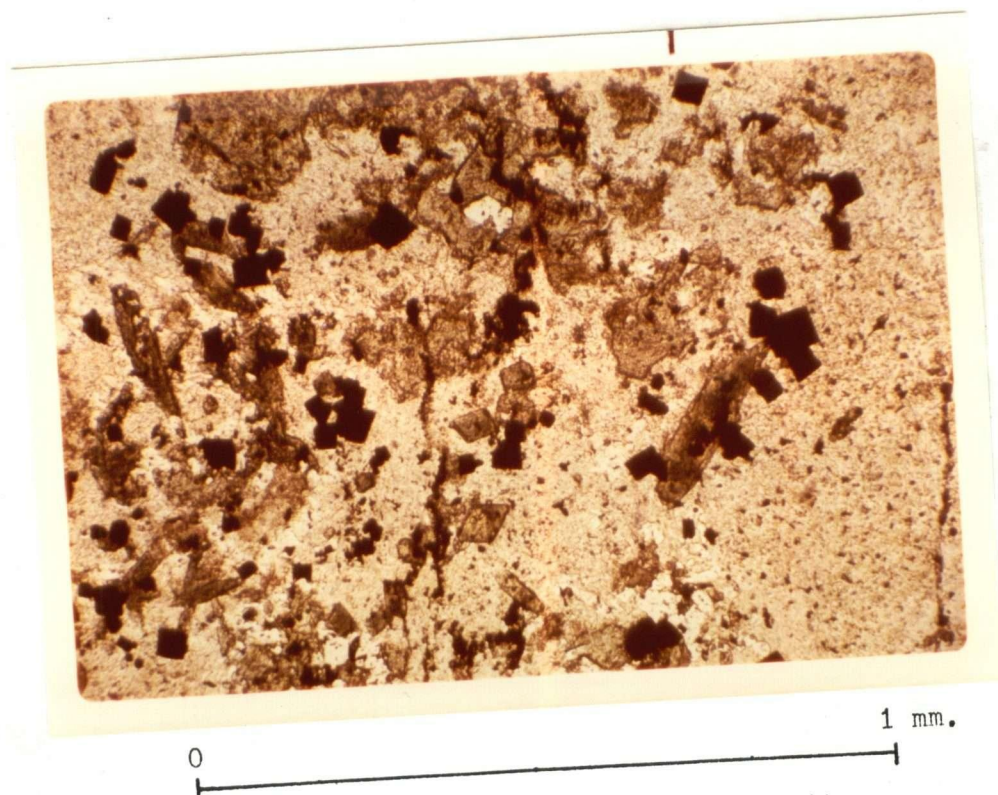
Outside the aluminous alteration zones, rocks of the pyroclastic division consist of muscovite, quartz, chlorite, albite and calcite with mineral proportions depending on host rock composition. A corresponding assemblage is developed sporadically within the zone of aluminous alteration. The following is a systematic description of the units.

In the basal pyroclastic unit (B_1) chlorite, pyrite, and quartz commonly replace pyroxene phenocrysts. Less abundant feldspar phenocrysts are dusty brown and pseudomorphed by An_{0-5} plagioclase. A fine-grained groundmass consists of quartz, muscovite, albite and calcite. An estimated average mode is 20 per cent chlorite, 25 per cent albite, 20 per cent quartz, 27 per cent muscovite, 5 per cent calcite and 3 per cent pyrite.

In the brecciated dacite (B_2) andalusite is replaced by kaolinite, muscovite and chlorite. Most commonly, andalusite grains are replaced by kaolinite with an outer rim of muscovite. Andalusite closely associated with sulphides is replaced by chlorite, such that a completely replaced grain may have a chlorite core with a kaolinite or muscovite margin. Scorzalite intergrown with andalusite is not as susceptible to alteration and only rarely alters to chlorite. A more prominent feature is chlorite halos, or alteration rims about sulphide grains. Chlorite and carbonate (siderite?) microveinlets occur locally.



Photograph 25 Parallel, wispy chlorite-andalusite veinlets (specimen 1) cut by chlorite-pyrite vein (specimen 2).



Photograph 26 Chlorite (green) pseudomorphs of andalusite.

Chlorite-albite-carbonate alteration is well developed in volcanic breccias (B_3) and epiclastics (B_4). Muscovite and quartz with variable amounts of chlorite comprise the matrix of volcanic breccias. Locally, chlorite may account for 60 per cent of the matrix as in the 'muddy' matrix of possible lahar units. Chlorite mantles on sulphides are more prominent than in unit B_2 . Here and there radiating bursts of tourmaline (schorlite) are intergrown with chlorite. Andalusite is variably replaced by kaolinite, muscovite and chlorite (photograph 26), and corundum alters readily to a brown micaceous aggregate. In addition to the ubiquitous muscovite-quartz assemblage, breccia fragments may also contain albite and calcite. Albite pseudomorphs rare plagioclase microlites, or more commonly, forms a patchwork of cloudy, untwinned 0.05 mm. grains.

Chlorite alteration is not as prominent in epiclastic horizons where carbonate alteration develops more strongly. Composition of the carbonate depends on its local environment of formation. Ankerite, or rarely siderite, is closely associated with pyrite whereas calcite develops within clasts, away from pyrite. In some rocks, pyrite mantled by ankerite is ragged but adjacent pyrite, without a carbonate mantle, is euhedral. The inference is that pyrite has supplied iron for ankerite. Muscovite in epiclastic horizons is predominantly 2M polytype.

A typical dust tuff from unit B_5 , outside the andalusite pyrophyllite zone consists of 25 per cent crystal and lithic fragments in a fine-grained mesh of chlorite, muscovite and quartz. Crystal fragments are mainly quartz and clear, untwinned albite. Lithic

fragments are extremely fine-grained and consist predominantly of muscovite and quartz. Patches and stringers of calcite occur sporadically. Microveinlets and a few patches of epidote were found in one sample. In many rocks within the andalusite-pyrophyllite zone, andalusite is replaced by oval 'spots' (0.1 to 0.3 mm.) of kaolinite. In some rocks evidence is contradictory as andalusite veinlets cut through kaolinite 'spots'.

Rocks of the welded ash tuff unit (B_6) have been altered to a quartz-muscovite-albite-calcite assemblage. Ash-size fragments are converted to a very fine-grained mixture of 2M muscovite and quartz, and lie in a siliceous matrix. Feldspar crystal fragments, 0.5 to 2 mm. in size, are replaced by twinned low-temperature albite (An_{0-8}). Calcite occurs as patches, generally within lithic or crystal fragments rather than the matrix. An average specimen contains 50 per cent quartz, 35 per cent 2M muscovite, 10 per cent albite and 5 per cent calcite. Tourmaline is extremely rare and occurs as radial aggregates.

CONTACT METAMORPHISM

D.D.H. 19 shows contact effects of the quartz monzonite stock. The contact was not cut in this hole, but projection of surface geology indicates the drill collar should be within 100 feet of the intrusion. Potash feldspar alteration is very strong within the first 10 feet of core, and is associated with chlorite and muscovite. Over the next 150 feet sporadic pyrite veins, 2 or 3 mm. wide, have strongly bleached envelopes (2 cm. wide) consisting

of relatively coarse-grained (up to 1 mm. in size) flakes of muscovite and quartz. Outside vein envelopes the rock contains chlorite, muscovite, albite and quartz, a typical assemblage of the regional metamorphism. Vein envelopes and the small zone of potash feldspar may be related to the quartz monzonite. This type of alteration is typical of 'porphyry' environments and may be related to the weak copper-molybdenum mineralization within the quartz monzonite.

D.D.H. 9, 12, 24, 45 and 48 show contact effects of the gabbro-monzonite complex. In marginal phases of the intrusion, plagioclase phenocrysts (An_{45}) up to one cm. long are broken and ragged. Rare 2 mm. pyroxene phenocrysts are altered to chlorite and biotite. Plagioclase and pyroxene phenocrysts lie in a fine-grained (0.1 mm.) matrix of plagioclase, secondary biotite, chlorite, quartz, magnetite and apatite. Scapolite and calcite occur locally. In drill holes 9 and 45, an assimilation zone up to 10 feet thick consists of unit B₁ pyroclastic rocks with disseminated ragged plagioclase laths similar to the intrusion. Within this zone, micrographic intergrowths of quartz plagioclase and potash feldspar indicate partial fusion. The main effect of the intrusion on the silicate mineralogy is formation of a narrow discontinuous zone of biotite hornfels. The biotite zone is about 20 feet wide in drill hole 9 and about 30 feet in drill hole 12. Biotite is disseminated in a matrix of granular quartz, muscovite, potash feldspar, chlorite and magnetite. Where biotite is absent, the principal effect on silicate mineralogy has been recrystallization to a granoblastic texture. Pyrite porphyroblasts become prominent in drill holes 12 and

48 within 175 feet of the contact, and in drill hole 33 within 80 feet. In drill hole 48, pyrrhotite becomes a major sulphide constituent within 200 feet of the contact (see p. 48).

DISCUSSION

SEQUENCE OF ALTERATION EVENTS

Alteration, regional metamorphism and contact metamorphism developed in a complex sequence summarized in Fig. 9. Aluminous alteration is probably the earliest alteration event. Textures such as the replacement of andalusite by fine-grained kaolinite, muscovite and chlorite (p. 67) indicate aluminous alteration predates regional metamorphism. Aluminous alteration also predates quartz - muscovite alteration associated with mineralization in unit B₅ (p. 66). Trachyandesite dykes crosscut quartz - muscovite alteration and hence, this alteration pre-dates contact metamorphism. The age relationship between quartz - muscovite alteration and regional metamorphism is uncertain and this is indicated in Fig. 9. If Cu-Ag mineralization was a single event, then quartz - muscovite alteration associated with mineralization in unit B₅ pre-dates regional metamorphism.

Adjacent to the gabbro - monzonite intrusion, a biotite hornfels, caused by contact metamorphism post-dates aluminous alteration. Contact metamorphism is probably later than regional metamorphism. Biotite in the hornfels zone is not chloritized, and plagioclase and augite in the intrusive are unaltered.

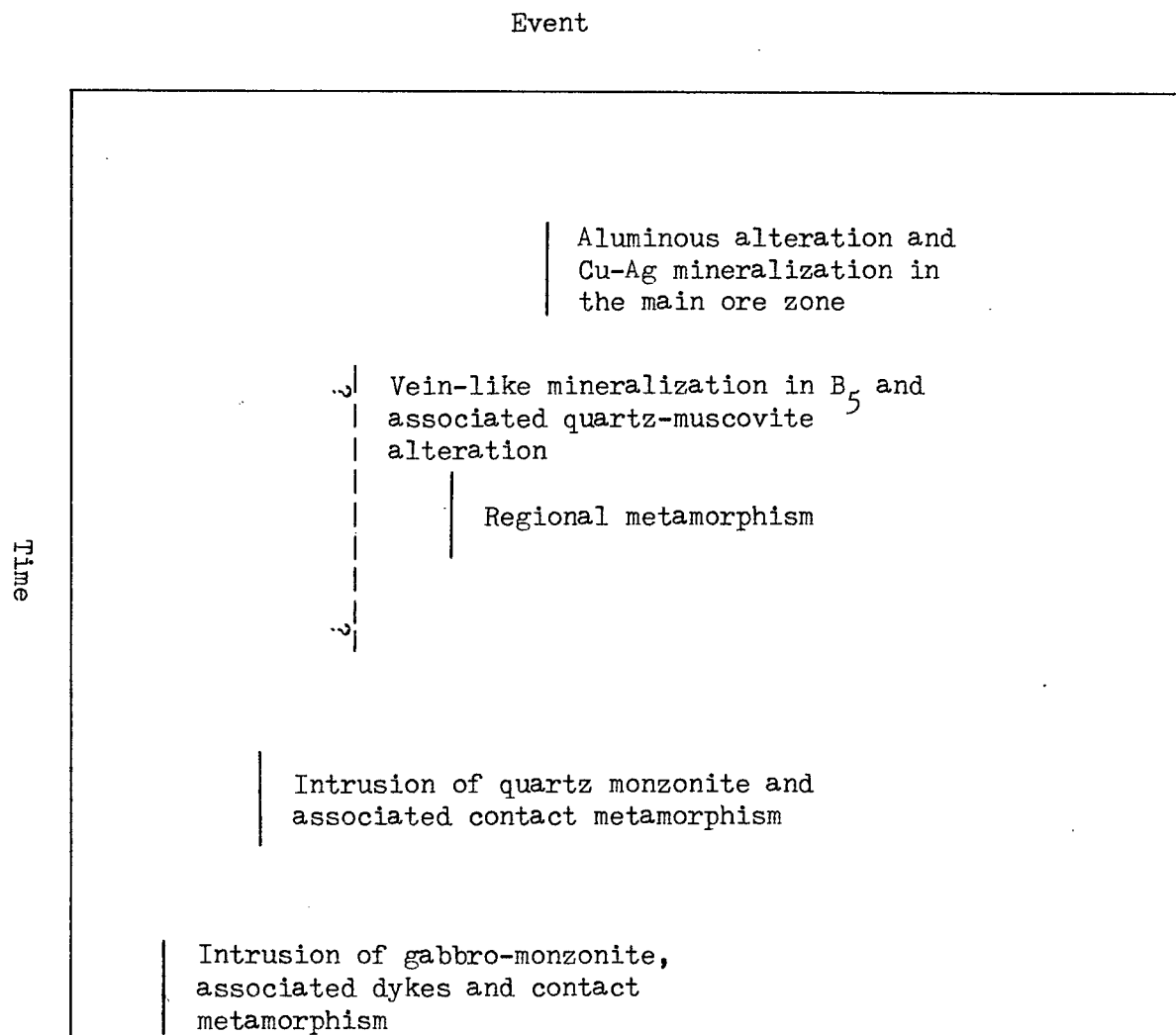
GRAPHICAL REPRESENTATION OF ALTERATION ASSEMBLAGES

Aluminous Alteration

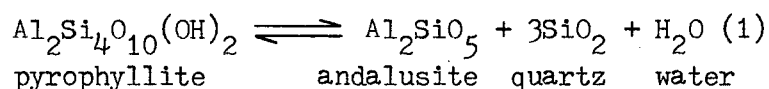
The three-component system $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ portrays equilibria

FIGURE 9

Sequence of Alteration Events (Schematic)



among the aluminous alteration minerals andalusite, corundum and pyrophyllite and quartz. Additional phases can be accounted for by the presence of additional components, such as K_2O for muscovite, B_2O_3 for dumortierite, P_2O_5 for scorzalite, S for pyrite, TiO_2 for rutile, MgO and FeO for spinel and tourmaline. At Sam Goosly, assemblages of three solid phases in the system Al_2O_3 - SiO_2 - H_2O are uncommon. The most strongly altered rock, the brecciated dacite, is characterized by the assemblage andalusite - quartz (Fig. 10-a). Kaolinite replaces andalusite and is clearly in disequilibrium. Corundum generally occurs sporadically in a quartz-free microenvironment, as the assemblage corundum - andalusite or as corundum alone (Fig. 10-b). The only rock observed to contain a three-phase assemblage, corundum - andalusite - quartz is considered an unstable assemblage. In the andalusite - pyrophyllite zone the assemblage andalusite - pyrophyllite-quartz is common and may result from the system being closed, so that H_2O is not a mobile component, or because the rock is buffered on the breakdown curve of pyrophyllite,



In a hydrothermal system, water is a mobile component, and the latter alternative is favored. Rocks in the andalusite - pyrophyllite zone are interpreted as transitional between a pyrophyllite - quartz assemblage and an andalusite - quartz assemblage (Fig. 10-c).

Regional Metamorphism

Regional metamorphism results in muscovite - quartz - chlorite \pm albite \pm calcite \pm kaolinite \pm epidote. Within the aluminous alteration

Figure 10 Graphical Representation of Aluminous Alteration

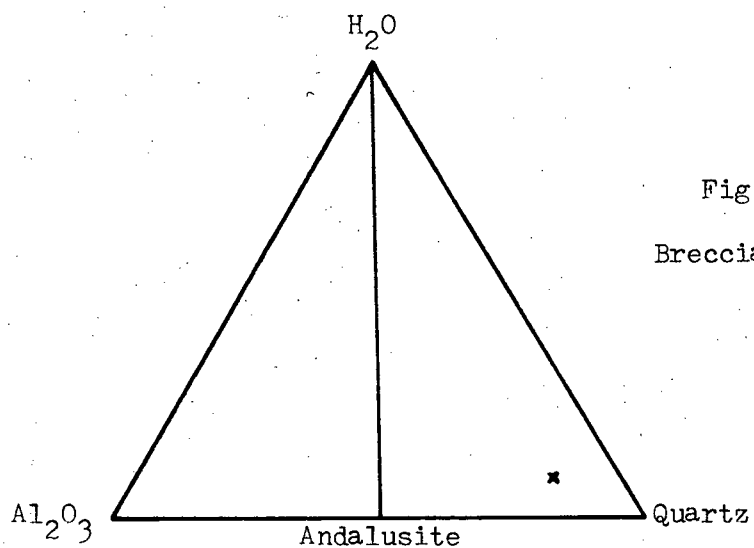


Fig. 10a

Brecciated Dacite

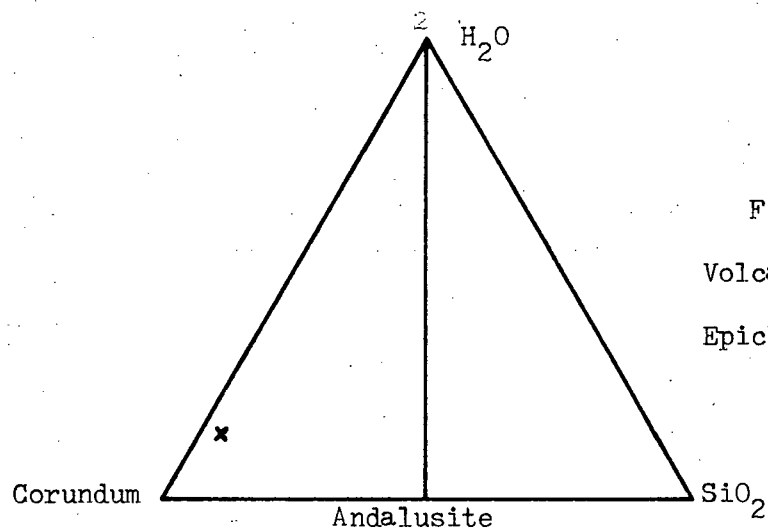


Fig. 10b

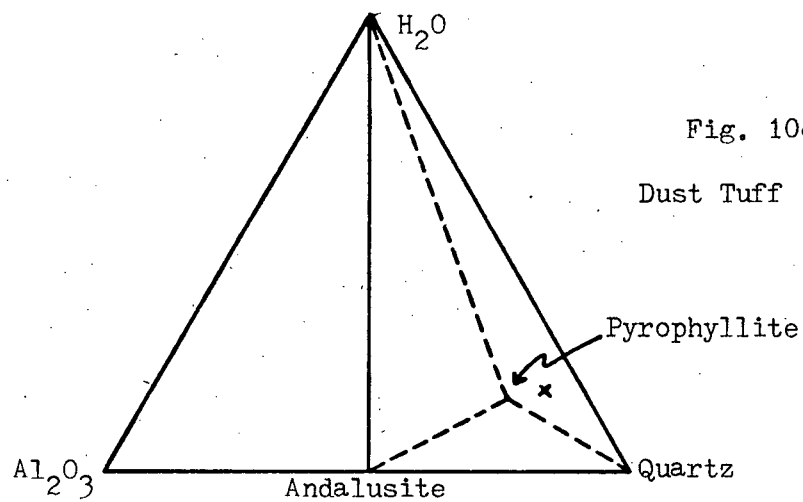
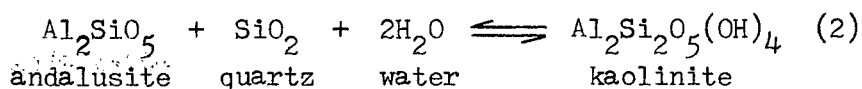
Volcanic Breccias and
Epiclastics with corundum

Fig. 10c

Dust Tuff

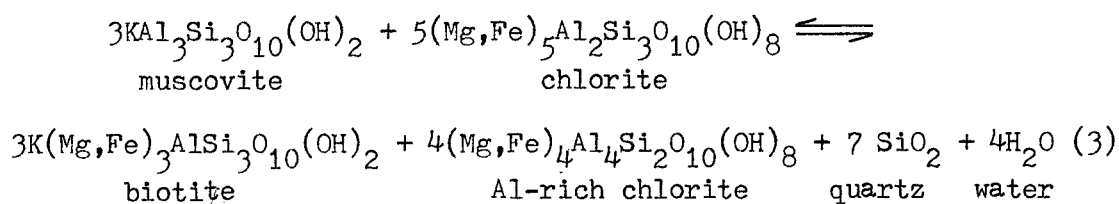
zone, the typical assemblage is quartz - muscovite - chlorite - kaolinite - which is shown on an $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ diagram and on an A^1KF projection in Fig. 11-a. The formation of kaolinite is expressed by,



which indicates conditions of regional metamorphism were below the stability of pyrophyllite. Rocks outside the aluminous alteration zone do not contain kaolinite. The typical assemblage is muscovite - quartz - chlorite - albite - calcite but no projection represents this assemblage suitably. The very rare occurrence of epidote in this assemblage can be shown in an ACF projection (Fig. 11-b).

Contact Metamorphism

Biotite within the contact hornfels zone adjacent to the monzonite intrusion forms with chlorite and muscovite. A possible reaction is,



Winkler (1967, p.99) suggested this reaction accounts for the first appearance of biotite in regional metamorphism. However, in the absence of andalusite and cordierite within the contact hornfels zone, a similar reaction may account for the formation of biotite at Sam Goosly. The muscovite - K-feldspar - quartz and biotite -

FIGURE 11

Graphical Representation of Regional Metamorphism

Fig. 11a Assemblages Within the Aluminous Alteration Zone

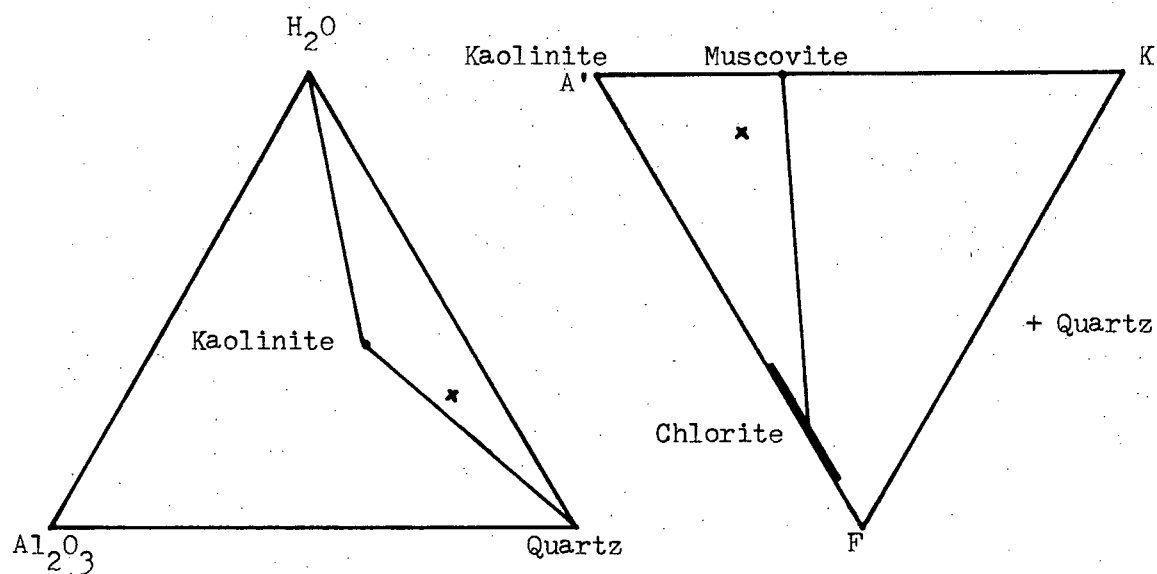


Fig. 11b Assemblage Outside the Aluminous Alteration Zone

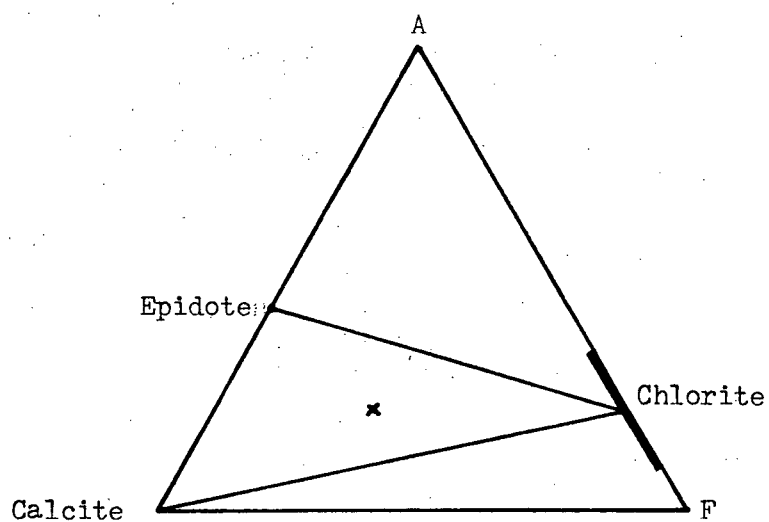
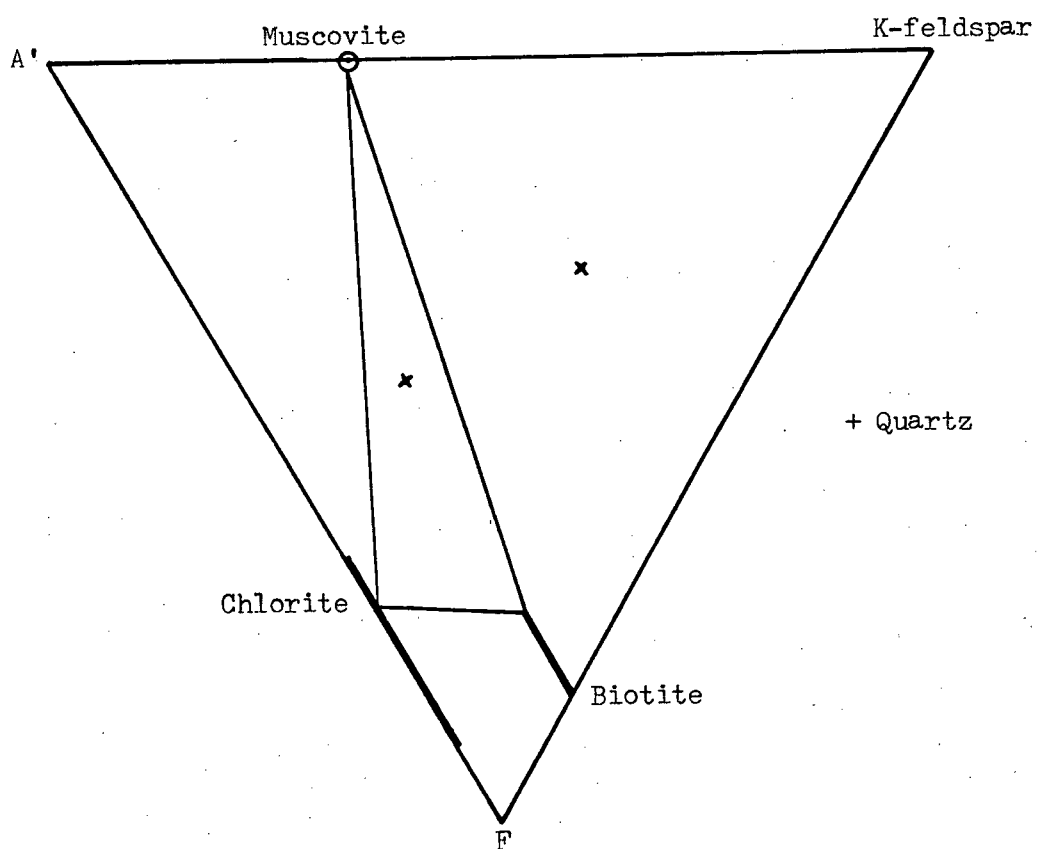


FIGURE 12

Graphical Representation of
Assemblages in the
Hornfels Zone

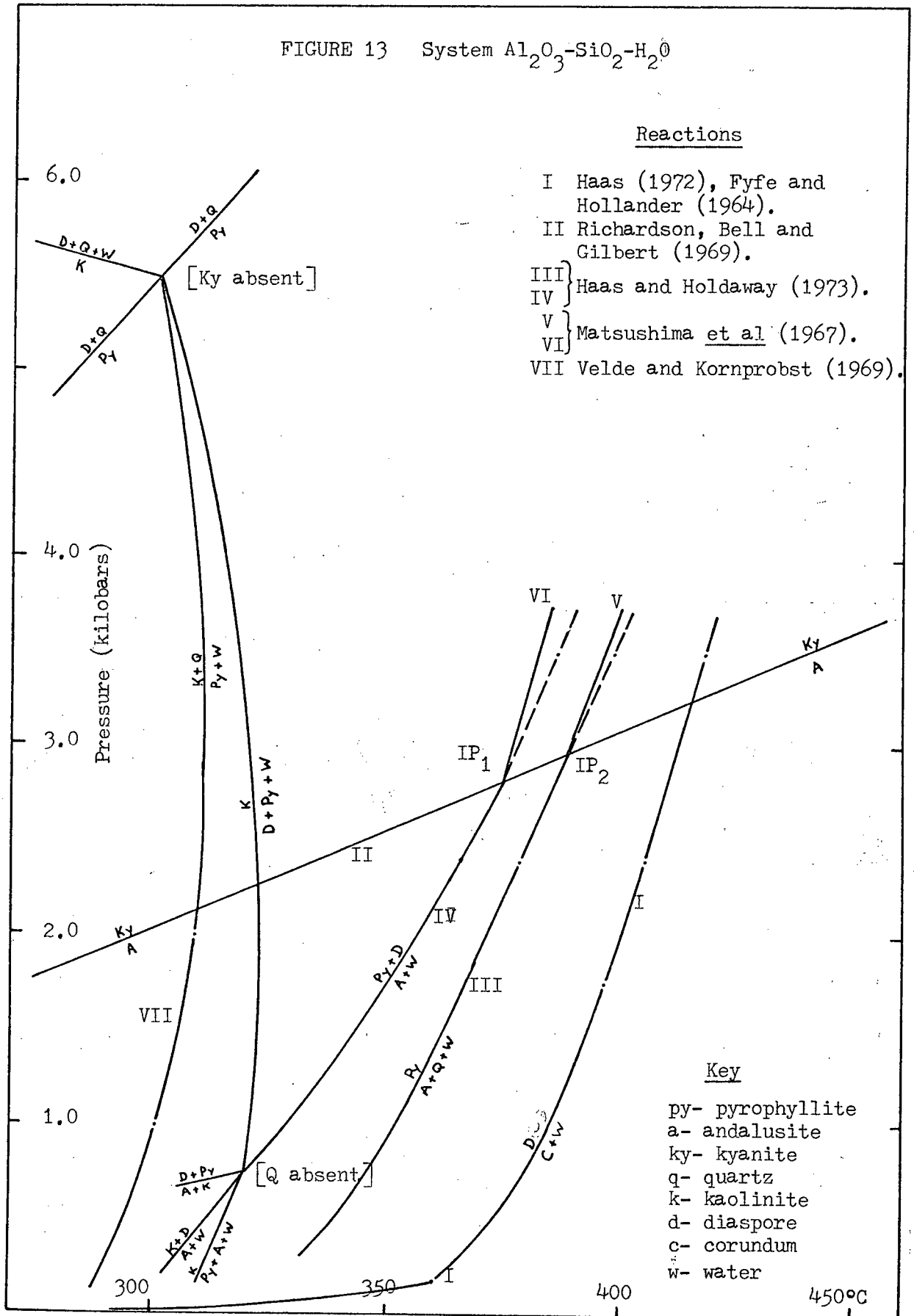


muscovite-chlorite-quartz may be represented graphically by the A^1_{KF} projection (Fig. 12). According to Winkler (1969) both these assemblages occur in the albite-epidote hornfels facies. However the assemblage muscovite-biotite-K-feldspar-quartz is stable until the K-feldspar-cordierite hornfels facies.

INTERPRETATION OF ALUMINOUS ALTERATION

Pressure-Temperature Estimates from the System $Al_2O_3-SiO_2-H_2O$

Considerable experimental work has been performed in the system $Al_2O_3-SiO_2-H_2O$. Some of the critical reactions have been examined up to nine times with a range of P-T estimates. A portion of the $Al_2O_3-SiO_2-H_2O$ system is shown in Figure 13 with a number of reaction curves. The discontinuity in the diaspore-corundum curve arises from its intersection with the water-steam curve. The intersection of the breakdown curves for pyrophyllite and pyrophyllite plus diaspore, with the kyanite-andalusite boundary produces two degenerate invariant points, IP_1 and IP_2 . The only experimental determination of the breakdown of kaolinite to diaspore plus pyrophyllite (Aramaki and Roy, 1963) appears to be at too high temperature (390°C at 4 kb) and has not been used. The location of this curve is based only on the calculated position of the " Al_2SiO_5 absent" invariant point of Wall and Essene (1972). The position of the "quartz absent" invariant point is also arbitrary. Other reactions are added to complete the consideration of the two non-degenerate invariant points. The position of other invariant points in the system is unknown.

FIGURE 13 System $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ 

Mineral assemblages in the system $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ at Sam Goosly give little information on pressure conditions during alteration. The only constraint is the presence of andalusite rather than kyanite. Within the pyrophyllite stability field this limits pressures to less than 3 kilobars. Within the brecciated dacite and volcanic breccias, the presence of andalusite, quartz plus assumed water and the absence of pyrophyllite gives a minimum temperature of about 350°C depending on pressure. The occurrence of corundum plus assumed water rather than diaspore, provides an independent minimum temperature estimate of $360^\circ\text{-}400^\circ\text{C}$. The only constraint on maximum alteration temperatures is the andalusite-sillimanite boundary, which at pressures of 1-2 kilobars is at $750^\circ\text{-}800^\circ\text{C}$ (not shown in Fig. 13).

Lower temperature conditions can be deduced for the pyrophyllite-bearing dust tuffs. At pressures within the andalusite stability field, a quartz-pyrophyllite assemblage indicates temperatures between about 300°C and 380°C . Rocks that contain andalusite, pyrophyllite and quartz probably are buffered on the pyrophyllite breakdown curve (p.75). Since the diaspore-corundum equilibrium lies at a higher temperature than the pyrophyllite breakdown curve, it can be predicted that corundum will be associated with andalusite but not with pyrophyllite. This agrees with alteration assemblages at Sam Goosly; pyrophyllite and corundum are not associated. Diaspore should occur within the andalusite-pyrophyllite zone, but none has been identified.

Hydrolysis Equilibria

Evidence from thin sections (p.57) indicates that andalusite

and quartz form at the expense of muscovite by the hydrolysis reaction,

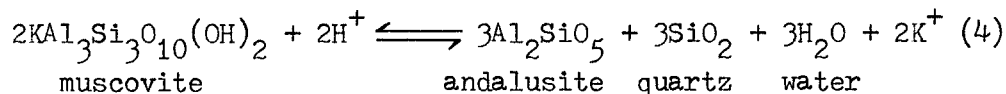
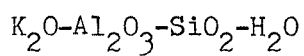


FIGURE 14

Some Equilibria in the System



(from Hemley and Jones, 1964)

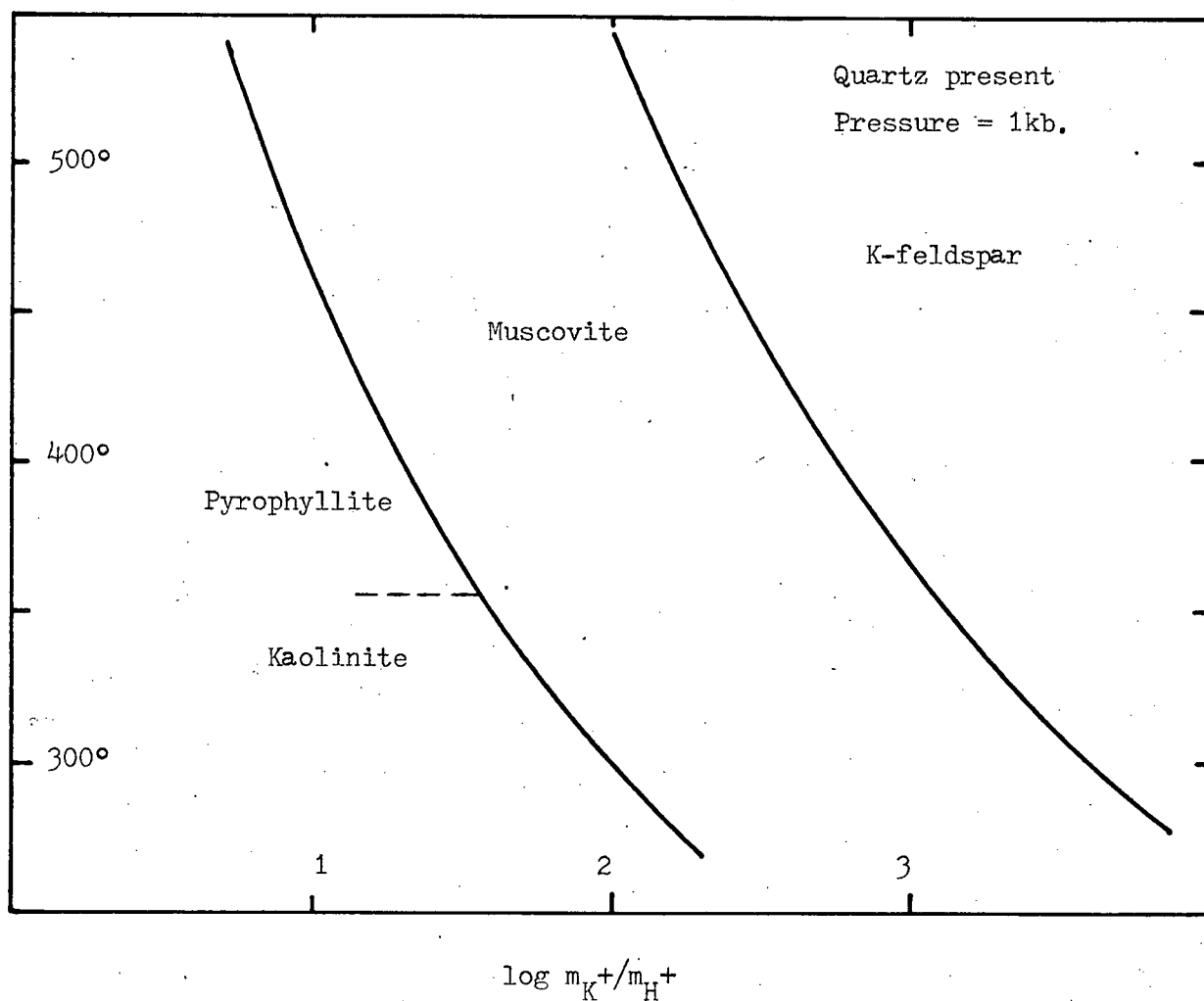
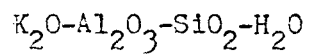
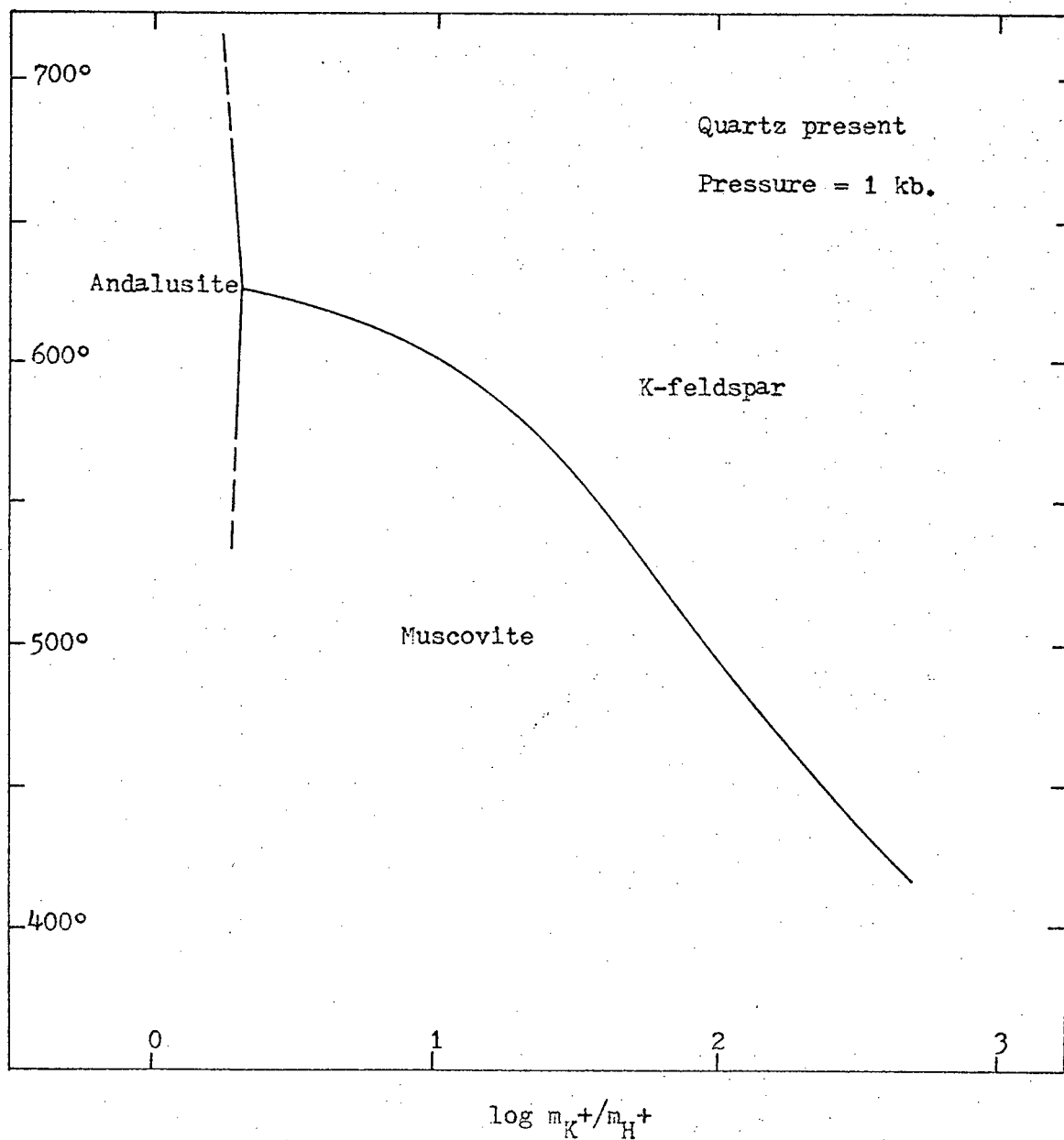


FIGURE 15

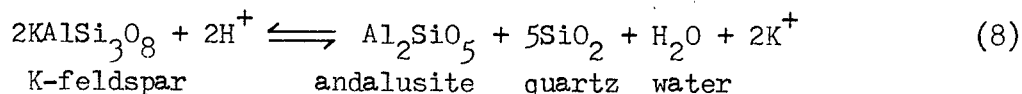
Some Equilibria in the System



(from Shade, 1968)



Shade (1968) has expanded their investigations to higher temperatures, examining hydrolysis equilibria between K-feldspar, muscovite and Al_2SiO_5 (Fig. 14). The reactions involved are (4), (6) and,



These two sets of experimental data show good internal consistency and together give a more complete representation of hydrolysis equilibria in the system $\text{K}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ (Fig. 16). The aluminosilicate field has been divided into kaolinite, pyrophyllite and andalusite consistent with Figure 13.

In the andalusite-pyrophyllite zone the assemblage muscovite, andalusite and pyrophyllite implies that the system is buffered at a particular solution composition and temperature, if equilibrium is maintained between the fluid and mineral phases (Fig. 16).

The potassium molality of the fluid for a moderately acidic pH of 4 (neutral pH at 350°C is 5.4) is 0.005. However, in an open, hydrothermal system it may be dangerous to assume equilibrium is attained.

Eugster (1970) has calculated the hydrolysis equilibria among muscovite, K-feldspar and aluminosilicate assemblages from experimental and thermochemical data. Following the suggestion of Helgeson (1967, p. 375-378), Eugster rejected Hemley's experimental data (Fig. 13) for reaction (6) in favour of "best estimates" based on thermochemical data. At high temperatures this "best estimate" deviated from Hemley's data by several orders of magnitude. Eugster combined the thermochemical data with Evans' (1965) experimental data on the thermal stability limit of muscovite plus quartz, to derive expressions for the equilibrium constant in terms of H^+

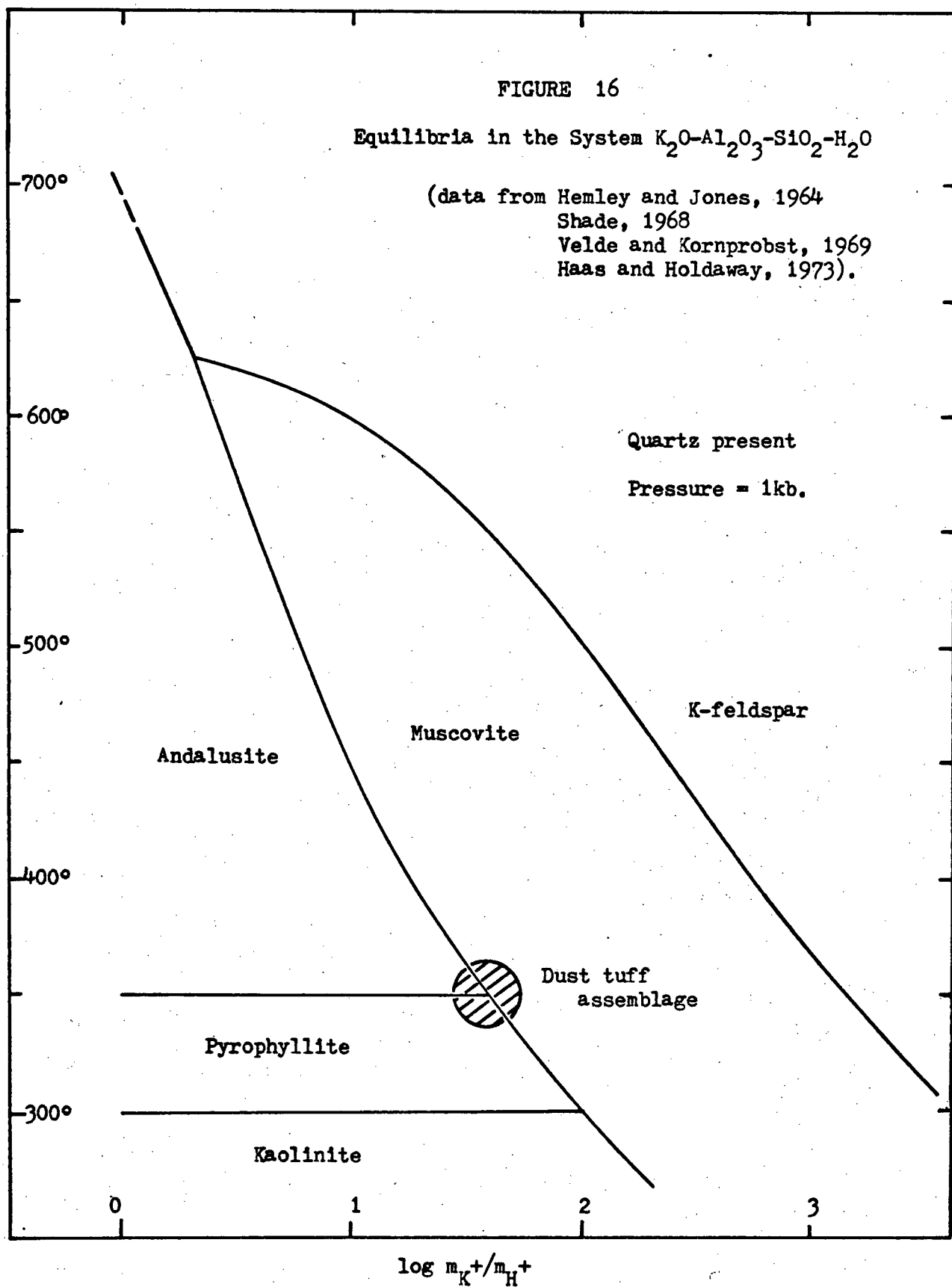
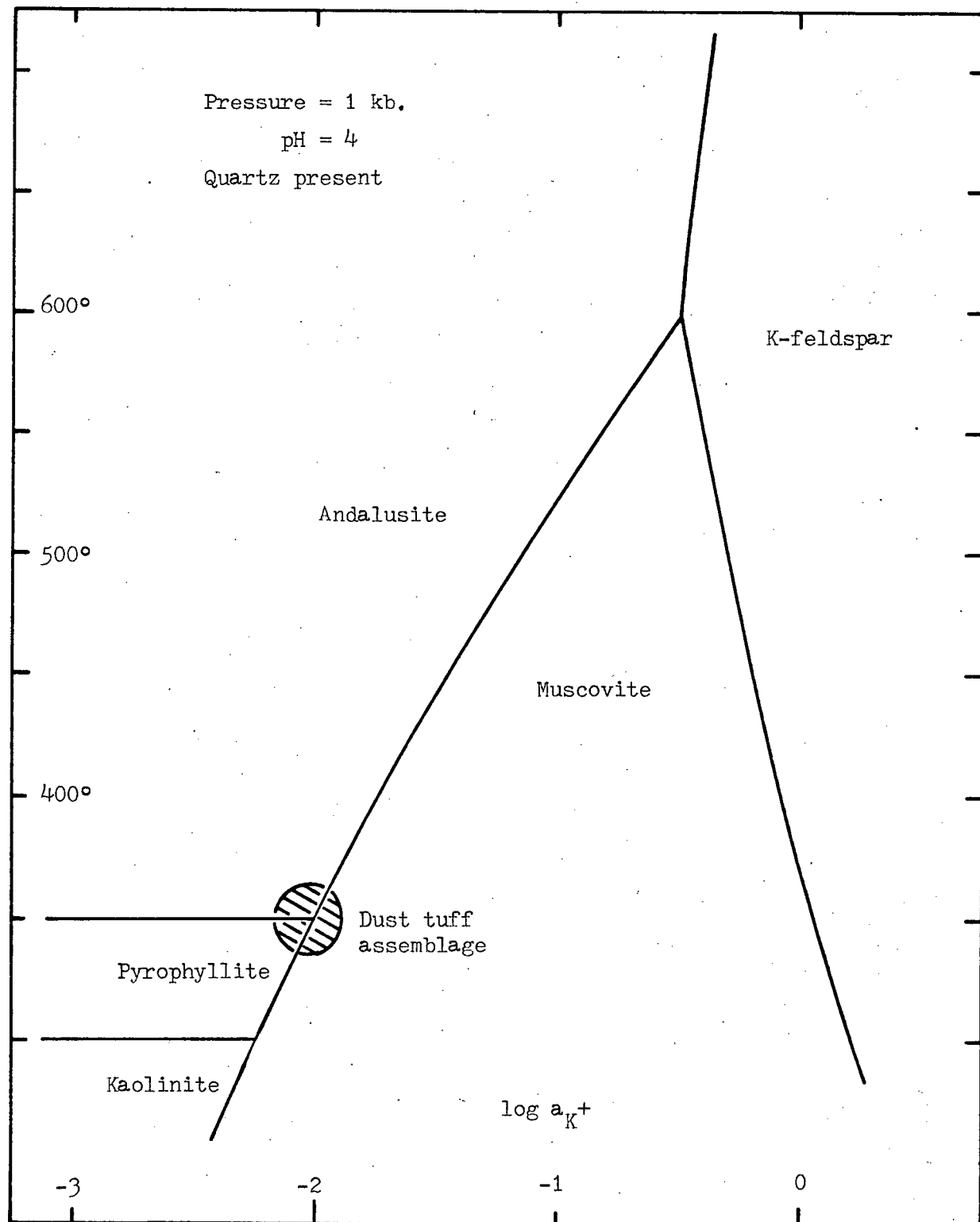


FIGURE 17

a_{K^+} - T Relationships for Muscovite, K-feldspar and Al_2SiO_5

(after Eugster, 1970)



and K^+ activities, for reactions (4) and (8). The results are presented, together with stability fields of kaolinite, pyrophyllite and andalusite (Fig. 17). The discrepancy between Eugster and Hemley and Jones may be determined by finding the K^+ molality at the muscovite-andalusite-pyrophyllite equilibria, as before. The activity coefficient of K^+ may be estimated from Helgeson (1969) and the resulting K^+ molality is 0.06. This compares with a value of 0.005 deduced from Hemley and Jones' (1964) data (Fig. 16).

Consideration of hydrolysis equilibria in the system $K_2O-Al_2O_3-SiO_2-H_2O$ provides a maximum temperature estimate of alteration. Because andalusite forms from muscovite and not from K-feldspar, the maximum temperature is that of the isobaric invariant point at which K-feldspar, muscovite and andalusite coexist. This maximum, at 1 kb, is 600°C from Eugster's data (1970) or 625°C from Shade's data (1968).

Correlation of Sulphide Temperatures and Silicate Alteration Assemblages

Exsolution of chalcopyrite and sphalerite has been investigated experimentally. Buerger (1934) found that chalcopyrite exsolved from sphalerite at 350°-400°C. The temperature of unmixing of sphalerite from chalcopyrite was determined by Borchert (1934) to be 550°C. This high temperature agrees with the empirical observations of Ramdohr (1969) who noted that "sphalerite stars [exsolved from chalcopyrite] are very much restricted to high temperature deposits". The occurrence of both of these exsolution textures in the main ore zone at Sam Goosly indicates very high temperatures and agrees with the temperature range inferred from silicate alteration mineralogy (between 360°C

and 625°C). Based on Buerger's experimental result, the absence of sphalerite-chalcopyrite exsolution textures in the southern ore zone suggests temperatures less than 350°-400°C. The maximum temperature of andalusite-pyrophyllite alteration in nearby dust tuffs is deduced to be about 380°C. Sulphide deposition is later than aluminous alteration in the southern ore zone (p.66). Since temperatures estimated from sulphides and from silicate assemblages are consistent, the time lapse between events may be short.

Effect of H^+ on Aluminosilicate Stability

Althaus (1966) has suggested that the temperature of the pyrophyllite-andalusite equilibrium is depressed as much as 80°C in acidic solutions. His experiments were performed with HF, HCl, H_2SO_4 and H_3BO_3 . Aluminosilicates containing fluorine (topaz) and chlorine (zunyite) developed as intermediates between the breakdown of pyrophyllite and the formation of andalusite. This may be relevant since zunyite and topaz occur as part of the aluminous mineral assemblage in some other deposits (see Appendix). Althaus' experiments with boric acid failed to produce the boron analogue, dumortierite.

Althaus attributed the depression of the pyrophyllite breakdown to a lowering of the activity of water. Kerrick (1968) has calculated that the temperature depression for this reason to be very slight. For example the activity of water in a 4N H_2SO_4 solution is 0.918 at 60°C. Since the ionization of acids decreases with increasing temperature, the activity of water in a 4N H_2SO_4 solution will be closer to unity at higher temperatures. Using 0.918 the effect on ΔG can be found from,

$$\Delta G = RT \ln a$$

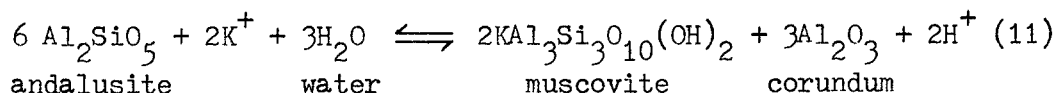
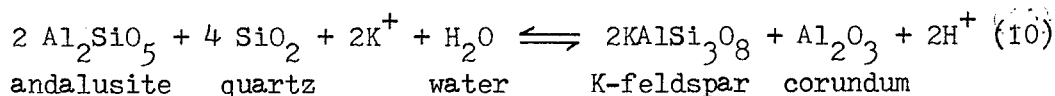
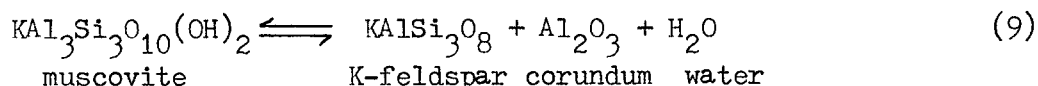
to be -130 calories. The temperature depression can then be found from,

$$\delta \Delta G = - \Delta S \delta T$$

to be only 7°C. Kerrick suggested that the main effect of H^+ in Althaus' experiments was that it acted as a catalyst in the breakdown of pyrophyllite. This explanation appears plausible, as Althaus' temperatures for the pyrophyllite-andalusite equilibrium without acid are too high, but with acid they agree closely with Kerrick (1968), Hemley (1967) and Haas and Holdaway (1973).

Formation of Corundum

Three reactions may be considered in the formation of corundum,

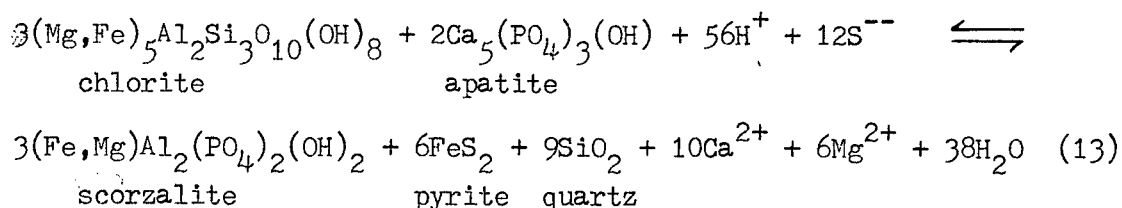


Reactions (9) and (10) require the association of corundum with K-feldspar, which is not observed. The last reaction is consistent with the observed mineralogy and has been proposed by Rose (1957) to account for the formation of corundum and muscovite at the core of an andalusite grain. This texture described by Rose is comparable, but not identical, to the inclusions of corundum within andalusite described earlier (p.63). If andalusite at Sam Goosly has formed by hydrolysis of muscovite, as in reaction (4) and that, at a later stage, the composition of the fluid phase changes toward a higher m_{K^+}/m_{H^+} (perhaps by a decrease in acidity), then muscovite will form at the expense of andalusite. If quartz is available, the

stability, such as those of Aramaki and Roy (1963), commonly resulted in metastable quartz and corundum instead of Al_2SiO_5 for these reasons. Hydrothermal alteration processes may also produce non-equilibrium assemblages.

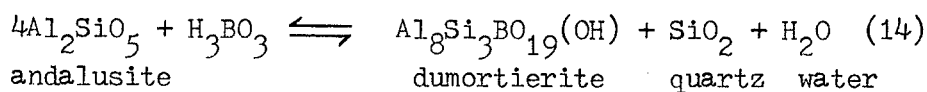
Formation of Other Aluminous Minerals

Unusual phosphate minerals, such as scorzalite, lazulite and augellite, are typical of aluminous alteration assemblages (Geijer, 1963, Espenshade and Potter, 1960). Although chemical analyses of P_2O_5 content of altered rocks are rare, available ones (Espenshade and Potter, 1960) range from 0.06 per cent to 0.33 per cent. These values are very similar to the average P_2O_5 content of unaltered volcanic rocks, such as 0.17 per cent in dacite (Table 2). Thus phosphorus does not occur in abnormal amounts, but what is unusual is its occurrence as aluminum-bearing phosphates rather than the calcium phosphate, apatite. Geijer (1963) suggested that the absence of apatite is due to the marked depletion in calcium, typical of aluminous alteration. The chemical analysis of altered rocks from Sam Goosly (Table 1) shows an average P_2O_5 content (0.09 per cent) but an unusually low CaO content of 1.03 per cent. At Sam Goosly apatite occurs outside the scorzalite zone, but not within it (p. 55). The irregular distribution of scorzalite, and its occurrence in veinlets implies at least local transfer of phosphorus. Possibly calcium and phosphate are taken into solution from apatite, but the phosphate is subsequently precipitated where iron and aluminum are available. Reaction (13) would account for the association of scorzalite with pyrite and quartz, though there



is not specific evidence that they have formed from chlorite.

A reaction supported by good textural evidence is the formation of dumortierite from andalusite. These two minerals are chemically similar and dumortierite forms by the addition of boron,



Lacking thermodynamic data for dumortierite, little can be done with this reaction.

Magnesium-bearing aluminosilicates, such as cordierite, chloritoid or spinel are not reported in other occurrences (see Appendix). The association of spinel with corundum, andalusite and scorzalite at Sam Goosly is anomalous. Unfortunately, there is no clear textural evidence to indicate the spinel-forming reaction. Chlorite is rarely present in spinel-bearing rocks, and textures suggest chlorite is a late mineral and probably has formed from spinel. Thus, spinel has formed from some pre-existing mafic aluminosilicate, such as a primary mafic mineral (biotite?), or an aluminous alteration mineral, such as cordierite, $(\text{Mg,Fe})_2\text{Al}_4\text{Si}_5\text{O}_{18}$, or chloritoid, $(\text{Fe,Mg})\text{Al}_2\text{SiO}_5(\text{OH})_2$.

CONCLUSIONS

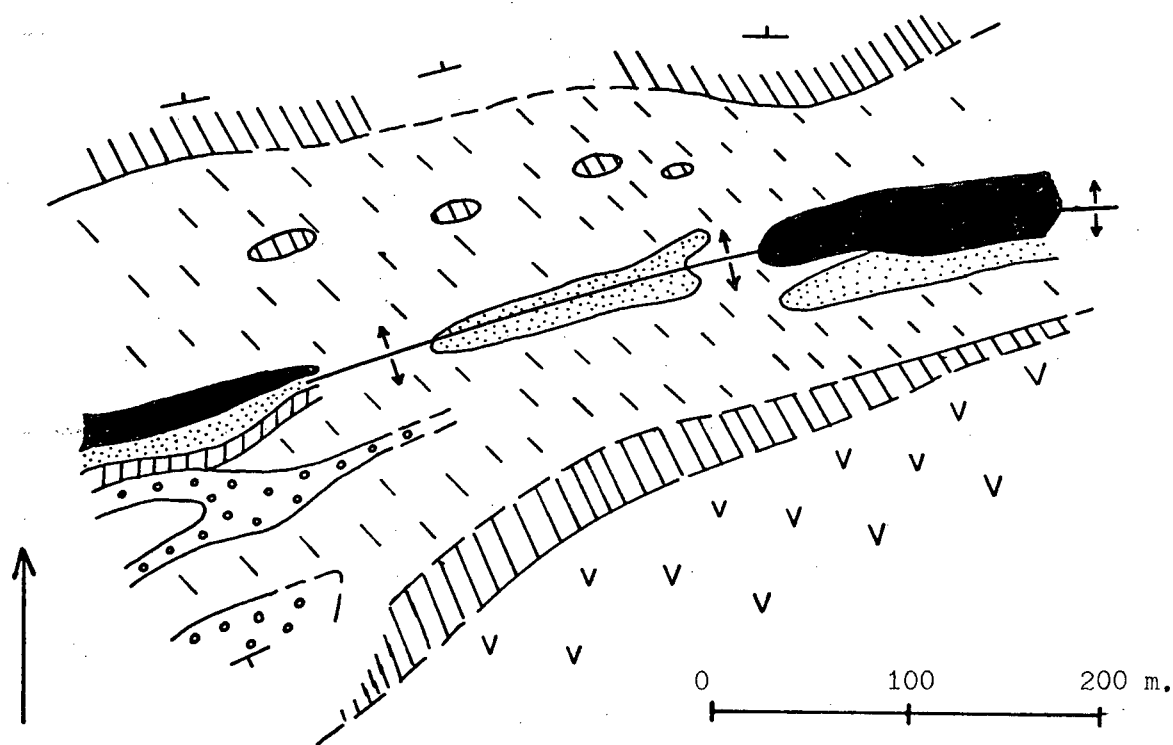
OTHER OCCURRENCES OF ALUMINOUS ALTERATION










Some of the aluminous minerals can occur in a variety of geologic environments. According to a literature survey (see Appendix) all of the aluminous mineral assemblages occur in a restricted environment. This environment is typical of some Japanese deposits in volcanic rocks (Fig. 18). Typically the aluminous alteration zone occurs within siliceous volcanic rocks (rhyolite to dacite) as an irregular to lenticular body, conformable with the volcanic strata. Commonly the rocks are tuffs, which may be brecciated. The most altered rocks are very rich in quartz and aluminosilicates. They are enveloped by quartz-muscovite rocks which grade outward into unaltered rock. In some deposits there is a peripheral chlorite-rich zone. Characteristic minerals of the aluminous assemblage include andalusite, corundum, diaspore, pyrophyllite, muscovite, dumortierite, kaolinite, quartz, lazulite-scorzalite, rutile and pyrite. Many unusual minerals such as svanbergite, topaz and zunyite are common. In some deposits, alteration is closely associated with high-level intrusions, contemporaneous with the volcanics. The grade of metamorphism of associated rocks ranges from zeolite facies to amphibolite facies. The host rock in high-grade metamorphic terrains is a quartz-muscovite schist, usually deduced to have been a siliceous volcanic unit. Kyanite, rather than andalusite, commonly occurs in such deposits. Deposits that are mined for their aluminosilicate content do not necessarily have any economic sulphide mineralization. Boliden, Sweden, is the only deposit known to have

FIGURE 18

Typical Japanese Aluminous Deposit

(from Iwao, 1970)



- | | |
|---|---|
|  Corundum-andalusite-pyrophyllite rock |  Silicified rock containing andalusite |
|  Andalusite-diaspore-pyrophyllite clay |  Altered tuff containing sericite and pyrophyllite |
|  Sericite-kaolin-pyrophyllite clay |  Chloritized tuff |
|  As above, with less of the clay fractions |  Anticline |
| |  Dip and strike |

been mined for metals (Au, Ag, Cu, As) and for aluminosilicates. If sulphide mineralization is present, pyrite is the dominant mineral. Chalcopyrite, silver-bearing sulpharsenides and gold are the most common economic minerals, while sphalerite and especially galena are less important.

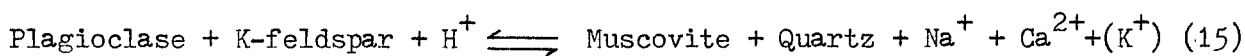
The genetic model proposed normally involves a high temperature, low pressure environment. Hot, acid solutions leach most cations except Si, Al, Ti and K. These remain to produce assemblages of quartz, plus aluminosilicates, rutile, and muscovite except in the most strongly altered rocks. Iron may remain fixed as pyrite, or may be leached as are magnesium, calcium and sodium. Magnesium (and iron?) may be concentrated in a peripheral zone as chlorite. The hot fluids responsible for these effects are attributed to nearby intrusions or to high-level volcanic processes (solfataric). Aluminous alteration at Sam Goosly is similar to that described in other areas. Associated sulphide mineralization is comparable, though not identical. A major difference is that antimony, in tetrahedrite, is prominent at Sam Goosly rather than arsenic.

ALTERATION MODEL

The altered volcanic rocks at Sam Goosly are very impoverished in Na_2O and CaO and enriched in alumina and silica (Table 1 and 2, p. 32-33), compared to Nockold's (1954) average dacite or rhyodacite. K_2O content is not significantly different from that of a typical dacite. The relationships among elements is best displayed by the norm, which contains 15 per cent corundum, shows a marked depletion in albite and anorthite and a large increase in quartz relative

to average dacite or rhyodacite. In the rock, alumina is partly incorporated in muscovite. Recalculating the norm with muscovite in place of K-feldspar still indicates 10 per cent excess alumina. This excess forms the suite of aluminous alteration minerals in the mode.

The first step in the alteration sequence is the conversion of an acidic volcanic rock to a quartz-muscovite rock, by a leaching of sodium and calcium. The general reaction is,



This reaction remains qualitative unless the ratio of orthoclase:

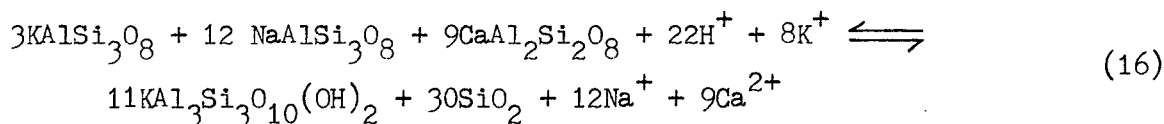
albite: anorthite is known. Because fresh rocks, with primary

feldspars, are absent at Sam Goosly, this ratio can not be determined.

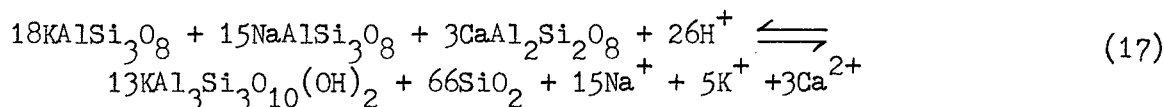
The ratio may be determined for Nockold's average volcanic rocks

and two examples are given below:

Dacite: Or:Ab:An 1:4:3



Rhyolite: Or:Ab:An 6:5:1



The important feature to note from these reactions is that K^+ must be added in the alteration of a dacite, or more basic rock, but is removed in the alteration of a rhyolite. For a range of compositions between dacite and rhyolite, all the feldspars may be converted to muscovite without appreciable change in the K_2O content of the rock. In all rocks Na_2O and CaO must be removed. If alteration has proceeded in this manner, then there must be a charge balance,

with respect to cations lost and gained, in order to preserve electroneutrality. Compared with Nockold's average dacite, the volcanic rocks at Sam Goosly show a loss of 4.44 per cent CaO, 3.22 per cent Na₂O and a gain of 1.16 per cent K₂O, 2.24 per cent H₂O. Recalculating to ionic percentages, and multiplying by the valences of the ions, results in 99.2 units of positive charge removed as Ca²⁺ and Na⁺, for every 100 units added as K⁺ and H⁺ (Table 5).

TABLE 5

Cation Charge Balance

	Sam Goosly	Average Dacite	Change	Charge Balance
CaO	1.09%	5.53%	-4.44%	99.2 units removed
Na ₂ O	0.76%	3.98%	-3.22%	
K ₂ O	2.56%	1.40%	+1.16%	100 units added
H ₂ O	2.80%	0.56%	+2.24%	

	Sam Goosly	Average Rhyodacite	Change	Charge Balance
CaO	1.09%	3.68%	-2.59%	89.7 units removed
Na ₂ O	0.76%	4.13%	-3.37%	
K ₂ O	2.56%	3.01%	-0.45%	
H ₂ O	2.80%	0.68%	+2.12%	100 units added

Similar calculations for rhyodacite indicate 89.7 units of positive charge removed as Ca²⁺, Na⁺ and K⁺ for every 100 units added as H⁺. The calculations are highly dependent upon the H₂O content of fresh and unaltered rock and such close agreement is fortuitous.

The calculations demonstrate that application of a hydrolysis reaction of the general form of reaction (15) to altered volcanics at Sam Goosly

is consistent with charge balance requirements.

The second step in the alteration sequence is the appearance of pyrophyllite and andalusite by hydrolysis of muscovite, as indicated by reactions (4) and (5). Calculation on the Goosly analysis show that a complete leaching of cations would yield a residual rock with 32 volume per cent andalusite and 68 volume per cent quartz, compared to the estimated mode of 75 per cent quartz, 15 per cent andalusite, 5 per cent muscovite and 5 per cent sulphides of the most strongly andalusite-altered rocks. Gresens (1971) has proposed a similar sequence of reactions to explain the formation of quartz-kyanite schists, bordered by muscovite schist within a metarhyolite.

The close association of pyrite with andalusite suggests that iron was not leached with other cations, but was fixed as a sulphide. The total iron content of the altered rocks is close to that of an average dacite or rhyodacite and only differs by an increase in the ferrous:ferric ratio. The analysis shows that sulphur has been added during alteration and iron is generally combined with sulphur as pyrite. Assuming that iron was present in the original volcanic rocks as a silicate then hydrolysis by sulphuric acid could produce pyrite and aluminosilicates, perhaps accounting for the close spatial association of andalusite and pyrite in the brecciated dacite. Significantly, andalusite and pyrophyllite in the dust tuff are commonly associated with chlorite, and not with iron sulphides. The aluminosilicates in the dust tuff must be the result of hydrolysis of muscovite. In the brecciated dacite, andalusite would be produced from both muscovite and chlorite (?) with subsequent release of iron to form sulphides.

In summary, alteration involved acidic solutions which profoundly affected the original rock composition. Some elements, such as Na and Ca have been extensively leached and the residual rock is enriched in quartz and aluminous minerals. Mineral assemblages indicate temperatures between a minimum of 300°C in the dust tuff to a maximum possible temperature of 625°C in the brecciated dacite. This alteration could occur in the following environments:

- (1) Geothermal, caused by meteoric and possibly juvenile water circulating through the hot pyroclastic strata.
- (2) Chemical weathering, followed by metamorphism. Soon after deposition of the volcanic strata, surficial chemical weathering could leach soluble cations, leaving a residual of clay minerals (kaolinite and muscovite) and quartz. Subsequent metamorphism would be isochemical, but produced a higher temperature assemblage.
- (3) Hydrothermal fluids from the gabbro-monzonite complex or the quartz monzonite may have been responsible for alteration and mineralization.

The pronounced stratigraphic control of both alteration and mineralization favours either of the first two alternatives. Because of this and for the following reasons the third alternative is considered very unlikely:

- (1) The shape of the alteration zones is not spatially related to either intrusion. For example they do not rim one or other of the intrusions. The north end of the alteration and mineralization lies more than 1 km. from the granite, whereas the southern end is more than 1 km. from the gabbro-monzonite.
- (2) Contact metamorphism related to the stocks differs from the

aluminous alteration in the ore zone. Biotite hornfels is associated with the gabbro-monzonite and K-feldspar is associated with the quartz monzonite.

(3) Dykes related to the gabbro-monzonite cut mineralization and aluminous alteration. Only deuteric alteration occurs within the dykes.

(4) Comparison with other occurrences of aluminous alteration shows no correlation between alteration and intrusions but a good correlation between alteration and acidic volcanic rocks.

A model of chemical weathering followed by metamorphism is considered unlikely for the following reasons:

(1) The geometry of the alteration zones is not similar to a weathered horizon. Alteration zones are concentric, cross stratigraphic boundaries and are not evidently related to a disconformity. Horizons produced by weathering would be asymmetric.

(2) Textural evidence indicates that regional metamorphism is later than aluminous alteration (p.69).

(3) If concentration of silica and alumina results from chemical weathering, then such deposits should be associated with a variety of rock types, and not only with acidic volcanic rocks.

Aluminous alteration may develop in a geothermal environment, that is, a hydrothermal process genetically related to the volcanic rocks. Acidic tuffs or high-level lava domes, brecciated by steam explosion would be hot, permeable, possess a high surface area, and be open to meteoric water. Circulation of large volumes of fluid through the rock would result in compositional changes in the rock as it attempted to equilibrate with the fluid. This model would

account for the gross parallelism of the alteration zones with the volcanic strata. It is tempting to interpret the brecciated dacite as an autobrecciated lava dome, consistent with this model.

Present-day geothermal systems are associated with areas of recent volcanism. The solutions involved are acidic potassium and sodium chloride brines, with large amounts of other dissolved species. Sulphide mineralization (chalcopyrite, sphalerite, galena) may be present in minor amounts, as at Broadlands, New Zealand (Browne and Ellis, 1970), to large amounts, as in the Red Sea geothermal area (Degens and Ross, 1969). The K^+ molality in a number of geothermal areas is compared to that deduced for Sam Goosly in Table 6. Both estimates of the solution K^+ molality during alteration at Sam Goosly are within the range found in geothermal brines, but the agreement is closer using the estimate based on Hemley and Jones (1964). In the Matsukawa geothermal area, Japan, Sumi (1969) described a pyrophyllite zone, with pyrophyllite, quartz, andalusite, diaspore and zunyite. The pyrophyllite zone is irregular and is currently overlapped by three other zones- montmorillonite, kaolinite and alunite. Maximum temperature currently recorded in the field is 254°C. The brines are acidic (with pH as low as 2.5) and are characterized by a high content of sulphate and low content of chloride ions. This is consistent with the formation of acidic minerals such as alunite, pyrite and kaolinite. Composition of the solution from drill hole MR-1 of the Matsukawa field is given in Table 7.

The formation of aluminous minerals and Cu mineralization at Sam Goosly likely occurred in a near-surface geothermal environment. The geothermal solutions were characterized by a low pH, a high

TABLE 6 (information from Ellis, 1969¹
and Sumi, 1969²)

Potassium Molality in Various Geothermal Waters

LOCATION	K ⁺ MOLALITY
Hole 44, Wairakei, N.Z. ¹	0.006
Hole 2, Broadlands, N.Z. ¹	0.005
Hole 7, Otake, Japan ¹	0.003
Hole 63, Hveragerdi, Iceland ¹	0.0007
Hole I.I.D., No.1, Salton Sea, California ¹	0.6
Hole G.S.2, Steamboat Springs, Nevada ¹	0.002
Hole MR-1 Matsukawa, Japan ²	0.004
Sam Goosly (based on Eugster, 1970)	0.06
(based on Hemley and Jones, 1964)	0.005

TABLE 7 (from Sumi, 1969)

Chemical Composition of Brine in Hole MR-1, Matsukawa

Temperature = 254°C

pH	4.9	
HCO ₃ ⁻	36.6	p.p.m.
SO ₄ ⁻	1779.9	"
H ₂ S	tr.	
Cl ⁻	12.4	"
Fe ²⁺	507.7	"
Al ³⁺	28.6	"
Mg ²⁺	8.7	"
Ca ²⁺	22.9	"
Na ⁺	263.5	"
K ⁺	143.5	"
SiO ₂	599.5	"
HBO ₂	248.2	"

sulphate ion content, and temperatures greater than 300°C but less than 600° to 625°C.

GEOLOGIC HISTORY

Volcanic activity in late early Cretaceous resulted in the accumulation of some 2500 feet of mainly dacitic pyroclastic debris. This may have taken place at or near a strand-line, represented by the chert pebble conglomerates. A limited amount of reworking of the volcanic rocks produced interbeds of volcanic sandstone, conglomerate, and possibly, lahar. Meteoric water circulating through the hot volcanic pile, mixed with metalliferous primary water, and was heated above the boiling point. The resulting steam explosion fractured unit B₂, providing solution channelways through it. Since unit B₂ is the most pervasively altered and mineralized, it may have been the major heat source, possibly a lava dome. Units B₂, B₃, B₄ and B₅ were highly permeable, whereas the underlying unit, B₁, and overlying unit, B₆, were relatively impermeable. Very hot acidic solutions circulated through the permeable horizons and reacted with the surrounding rock. These reactions resulted in the exchange of H⁺ ions from the solution with cations, mainly Na⁺, Ca²⁺ and some K⁺ and Mg²⁺, from the rock. Iron from the rock combined with sulphur and metals in the solution to form pyrite and other metallic minerals. As the rock was depleted in cations, quartz, aluminosilicates, scorzalite and other aluminous minerals formed. Lower temperatures, and possibly a change in composition of the solution, could account for the lack of ore closely associated with aluminous alteration in unit B₅. Ore solutions deposited

sulphide minerals in open spaces with limited chemical interaction with the host rocks. Later regional alteration and contact metamorphism associated with the intrusion of quartz monzonite and the gabbro-monzonite have been superimposed on aluminous alteration and on copper-silver mineralization.

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APPENDIX

Summary of Occurrences of Aluminous Alteration

Location (Reference)	Host Rock	Age	Associated Intrusion	Metamor- phism	Shape	Zoning & Mineralogy	Economic Minerals	Genesis
Japan (1), (2), (3), (4)	dacite, andesite, pyro- clastics	late Cre- taceous to Eocene	high level granite domes (2)	no specific data, but low grade	lenticular bedded, mushroom- shaped	1. corundum-diaspore 2. pyrophyllite- kaolinite 3. sericite Other minerals: andalusite, quartz, alunite, dumortierite, zunyte, hematite, rutile (3).	Al- silicates	Leaching of cations leaves the rocks enriched in Al_2O_3 and SiO_2 . Takes place in near- surface, acid hot springs environ- ment, related to volcanism (1), (3).
	Green Tuff Formation (variety of sub- marine volcanics)	Miocene	none		as above and pipe- shaped	Pyrophyllite with diaspore, kaolinite, sericite.	copper, pyrite	
	dacite, andesite tuffs and lavas	Pliocene to Recent	none		geothermal areas	Pyrophyllite, quartz with andalusite, diaspore, zunyte, montmorillonite, kaolinite, alunite (4)	none	

Location (Reference)	Host Rock	Age	Associated Intrusion	Metamor- phism	Shape	Zoning & Mineralogy	Economic Minerals	Genesis
Puerto Rico (5)	andesite, basalt	Late Cre- taceous to early Tertiary	granodiorite	none	elongate patches within a belt 50km x 5km.	1. Alunite-quartz 2. Pyrophyllite 3. Clay-sericite Other minerals: kaolinite, halloysite andalusite, topaz, zunyte, svanbergite, pyrite, barite.	none	Magmatic emanations from granodiorite removed CaO, MgO, FeO and added SiO ₂ , S and possibly K ₂ O.
Boliden, Sweden (6)	quartz porphyry, keratophyre dacite	Pre- cambrian	none	low grade	lenticular but cross- cut strati- graphy	1. Sericite-andalusite -quartz, with corundum, diaspore 2. sericite-quartz 3. chlorite-sericite quartz. Other minerals: rutile, apatite, tourmaline	massive pyrite- arsenopyrite with Au-Ag- Cu-As Al-silicates	Ore and alteration produced by hydrothermal process. No change in volume. Al ₂ O ₃ , K ₂ O, TiO ₂ , SiO ₂ , H ₂ O added to zone 1. FeO, MgO removed from zone 1, added to zone 3. Overall loss of Na ₂ O and CaO.

Location (Reference)	Host Rock	Age	Associated Intrusion	Metamor- phism	Shape	Zoning & Mineralogy	Economic Minerals	Genesis
Cordillera (7), (8), (9), (10)	tuff, rhyolite, trachyte	Triassic	granite	Green- schist	conform- able lenses	1. Andalusite- dumortierite with muscovite, quartz 2. Muscovite-quartz	Al- silicates	Formed by pneumatolytic and hydrothermal processes, related to granite intrusion.
			quartz- monzonite	very low grade	irregular (8)(9).	Quartz, muscovite, pyrophyllite, diaspore, corundum, lazulite, rutile, alunite etc.		
	latite, quartz latite	Tertiary	quartz monzonite	very low grade	lenticular conformable (10)	1. Quartz-sericite- andalusite with kaolinite, diaspore, rutile, carbonate. 2. Sericite-quartz	Breccia zone with Pb, Ag	High T, low P leaching of Na_2O , CaO , MgO . Residual concentration of K_2O , SiO_2 , Al_2O_3 . FeO removed unless fixed as pyrite.
Russia (11), (12)	dacite, ignim- brite(11) spilite, kerato- phyre(12)	Mesozoic and Cenozoic	none	range from unmeta- morphosed to epidote actinolite facies	lenticular, conformable with volcanic stra- tigraphy	1. Secondary 'quartz ites' with corundum, andalusite, diaspore, dumortierite, zunyite, pyrophyllite, topaz, rutile, apatite, tourmaline. 2. Sericite-quartz, with pyrophyllite, kaolinite. 3. Sericite-Chlorite with quartz. 4. Chlorite, with quartz, carbonate, epidote, sericite.	Zone 1 has sulphur- arsenic- pyrite(11) Zone 2 has pyrite. Zone 3 has Cu-Pb-Zn(12) and Au-Cu- Sn (11).	Volcanic environ- ment. Leaching by volcanic gases produces residual concentration of alumina and silica in zone 1, and fixation of halogens. K_2O , leached from zone 1, is concentrated in zone 2. MgO and FeO are redeposited in zones 3 and 4. CaO is concentrated in zone 4. Na_2O is completely removed.

Location (Reference)	Host Rock	Age	Associated Intrusion	Metamor- phism	Shape	Zoning & Mineralogy	Economic Minerals	Genesis
Bulgaria (13)	dacite	Upper Cre- taceous	no information	no infor- mation	within a belt 10km x 1.5km.	1. "monoquartzites" 2. pyrite-sericite, with diaspore 3. quartz-sericite 4. chlorite-epidote albite Dumortierite is also present, zone not given.	no information	Hydrothermal alteration
Sweden (14)	rhyolite, dacite	Pre- cambrian	none	very low grade	no information	Mainly quartz- sericite. Also Chlorite, andalusite, kyanite.	Pyritic Cu-Zn ore occurs with chlorite and kyanite	Chemical changes produced by volatile magmatic emanations operating at low pressures but high temperatures. Al_2O_3 and SiO_2 represent material present in the original rock.
	quartzite	Pre- cambrian	none	high grade (host rock is gneiss)	lenses or irregular	Quartz, kyanite, muscovite, lazulite, hematite, rutile, pyrite, augellite. Pyrophyllite and svanbergite as late veins.		
India (15)	quartz- muscovite schists (derived from acid tuffs)	Archean	none	moderate to high grade	bedded	Kyanite, topaz, andalusite, dumortierite, tourmaline, muscovite, damourite (after corundum).	Al- silicates	Thermal activity during volcanism produced fluids which leached the tuffs and added boron and halogens.

Location (Reference)	Host Rock	Age	Associated Intrusion	Metamor- phism	Shape	Zoning & Mineralogy	Economic Minerals	Genesis
Appalaichan (16),(17)	rhyolite, dacite	Pre- cambrian or Paleo- zoic(?)	none	amphib- olite facies	bedded, strati- graphic units	Pyrophyllite- andalusite-quartz. Other minerals: muscovite, diaspore, lazulite, rutile, topaz, kyanite.	Al- silicate	Chemical weather- ing of volcanic flows and tuffs followed by metamorphism (16),(17).
					irregular lenticular	Kyanite-quartz. Also muscovite, pyrophyllite, lazulite, topaz, pyrite, rutile.		Solfataric activity removed nearly all constituents except SiO_2 , TiO_2 , Al_2O_3 . (16)

- (1) Iwao (1968)
- (2) Shimada and Nagayama (1969)
- (3) Iwao (1970)
- (4) Sumi (1969)
- (5) Hildebrand (1961)
- (6) Nilsson (1968)
- (7) Kerr and Jenny (1935)
- (8) Kerr (1932)
- (9) Gross and Parwell (1968)
- (10) Butler (1913)
- (11) Romanova and Petrachenko (1970)
- (12) Smirnov (1970)
- (13) Radonova (1967)
- (14) Geijer (1963)
- (15) Dunn (1937)
- (16) Espenshade and Potter (1960)
- (17) Zen (1961)