The Geology and Geochemistry of the Summit Creek Molybdenum Prospect, Custer County, Idaho

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THE GEOLOGY AND GEOCHEMISTRY OF THE SUMMIT CREEK
MOLYBDENUM PROSPECT, CUSTER COUNTY, IDAHO

by

Thomas Murray Hanna

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
Kalamazoo, Michigan
April 1983
The Summit Creek stock, a molybdenum prospect located in the Pioneer Mountains of central Idaho, is a 46.7 m.y. old medium grained, slightly porphyritic quartz monzonite, which has intruded the late Ordovician Phi Kappa formation. Trend surface analysis shows that the stock is the product of one intrusive event. Pervasive mineral alteration usually associated with such porphyry (stockwork) molybdenum deposits is not present in this pluton, and the alteration that is present is confined to local faults and fractures.

Geochemical and petrographic evidence suggest that the pluton is a felsic differentiate from a melt which originated at a depth of 220-260 kilometers along an east-dipping subduction zone. Whole rock major element geochemical analysis indicates that the stock is a high potassium calc-alkaline intrusion. Trace element analysis shows similarities to other stocks associated with economic molybdenum deposits. In addition, chemical analysis of argillic assemblages are similar to those of porphyry molybdenum deposits.
ACKNOWLEDGMENTS

My thanks to Utah International for their financial and logistical support during the field work on this project. In particular, I would like to thank Richard J. Thompson who started me in economic geology and for his guidance and stimulating discussion of the area. Also thanks to Miles G. Shaw for his support and help in the field.

Additional thanks go to Chris Schmidt, Cynthia Wood for their review of the manuscript, and Ron Chase for his discussions in the field. I would like to thank John Grace for his critical review of this paper and his help with the laboratory procedures.

Thomas Murray Hanna
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CHAPTER I

INTRODUCTION

Purpose of Study

The purpose of this study was to produce a geologic map of the Summit Creek stock, the overlying Phi Kappa formation, the associated structures, the post intrusive quartz veining, the mineralization, and alteration in order to determine the interrelationships of these geologic units and events.

An additional purpose was to perform detailed petrographic and geochemical analysis on the stock in order to compare it with other stocks in the Rocky Mountain area and to evaluate its potential as an economic molybdenum deposit.

Location

The Summit Creek stock is located in Custer County, Idaho, in the Pioneer Mountains on the edge of the Sawtooth Recreation Area, 55 kilometers east of the Idaho batholith. The area of study covers portions of sections 16, 17, 20, 21, 25, 25 of unsurveyed T6N, R19E (Figure 1). This area is 24 kilometers northeast of Ketchum, Idaho and is accessible in the summer by the Mackay-Ketchum road.

Description of the Study Area

The Summit Creek stock is a slightly porphyritic quartz monzonite intrusion and has a K-Ar date of 46.7 m.y. (Armstrong, 1974).
Figure 1. Location map of the Pioneer Mountains and study area. Modified from Dover (1969).
The intrusion crops out along the lower elevations of the steep slopes of the glacially formed Summit Creek Valley. The stock is exposed on the south side of Summit Creek. The southern exposure is approximately 4.6 kilometers long and 1.6 kilometers wide and has a vertical relief of 460 meters.

Geology of the Pioneer Mountains

The Pioneer Mountains, located in central Idaho, are flanked to the west by the Idaho batholith and to the south and east by the Snake River Volcanics (Figure 2). To the north and including an area within the Pioneer Mountains is an extensive region predominated by Paleozoic sedimentary rocks.

Dover (1969) has documented the complex stratigraphy and structure of the Pioneer Mountains. Many of the formations have now been mapped and studied in detail, and new structural interpretations have given a more comprehensive geologic history than earlier studies. Figure 3 is a generalized stratigraphic column for the Pioneer Mountains, modified from Dover (1969).

Stratigraphy

The lowest structural unit containing the oldest rocks in the Pioneer Mountains is the Precambrian Wildhorse Canyon Migmatic Gneiss Complex which occupies 50 square kilometers of the Wildhorse and Cave Creek areas 8 kilometers southeast of the Summit Creek stock. This sequence consists of a basal quartzite unit, a marble marker horizon, a middle quartzitic to granitic gneiss unit, a mafic gneiss unit, an
Figure 2. General geologic map of Idaho and location of the Pioneer Mountains. Modified from Dover (1969).
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Figure 3. General stratigraphic column of the Pioneer Mountains. Modified from Dover (1969).
upper quartzitic unit, and a granitic gneiss unit. These units were subjected to high grade regional metamorphism, forming upper almandine-amphibolite assemblages. Dover (1969) suggests a sedimentary origin for the entire gneiss complex.

Overlying the Wildhorse Canyon Migmatic Gneiss Complex are medium to high grade metasedimentary rocks that were divided into the Hyndman and East Fork formations. The formations have subsequently been subdivided into eight units (Umpleby, Westage, & Ross, 1930) (Figure 3).

The Hyndman formation outcrops in the northeastern two-thirds of the Hyndman-East Fork formation trend and is divided into four units. Unit A is a pelitic schist, unit B a gneissic quartzite, unit C is a green banded calc-silicate rock, and unit D is a gneiss-ose quartzite. The Hyndman formation has a total thickness of approximately 3,700 meters.

The overlying East Fork formation consists of the upper portion of the metasediments and outcrops in the western third of the Hyndman-East Fork formation trend. This formation is also divided into four units. Unit E is a dolomitic marble, unit F is a vitreous quartzite, unit G is a marble, and unit H is a quartzite. The East Fork formation has a total thickness of 410 meters.

Mineralogical and textural studies indicate that the metasedimentary rocks of the Hyndman and East Fork formations have undergone synkinematic isochemical metamorphism in the upper almandine-amphibolite facies during post-Ordovician regional, orogenic meta-
morphism (Dover, 1969). The metasediments are considered to be allochthonous uppermost Precambrian and/or lower Paleozoic.

The remainder of the Paleozoic sections (Figure 3) in the Pioneer Mountains are represented by the Phi Kappa, Trail Creek, Milligen, and Wood River formations. These weakly metamorphosed Paleozoic argillites and quartzites overlay the crystalline core of the Pioneer Mountains. The rocks are allochthonous and tectonic emplacement postdates post-Ordovician metamorphism. Argillaceous parts of these Paleozoic rocks have been converted to slates and phyllites.

The Phi Kappa formation is exposed in a northwesterly trend 8 kilometers wide along the crest of the Pioneer Mountains. It consists of black flinty argillite units interbedded with fine-grained quartzites that have a matrix of recrystallized quartz. This sequence is 915 meters thick. The formation has abundant graptolites which have been paleontologically dated at lower to upper Ordovician (Charkin, 1963).

The Trail Creek formation outcrops on the west side of the upper portion of Trail Creek, and is Silurian in age. It consists of a siliceous argillite, quartz sandstone, and contains many graptolites.

The Milligen formation is composed mainly of grey, weathered, phyllitic, argillaceous rocks. Due to the poor exposures, extensive deformation, and absence of fossils, the age of the Milligen formation has not been positively determined. Thomasson (1959) considers the Milligen formation to be lower Mississippian in age.
by stratigraphic correlation. The formation lies in three irregular belts that trend northwesterly.

The Wood River formation outcrops in the upper plate of an extensive northwestern trending thrust belt on the west side of the Pioneer Range. The Wood River formation has been dated Pennsylvanian through Permian age by stratigraphic correlation (Dover, 1969). The formation is approximately 2350 meters thick and is widely exposed in the Pioneer Mountains. The formation contains a basal member of brownish quartz conglomerate, a unit of grey limestones interbedded with conglomerates, and a sandy blue limestone unit containing corals and brachiopods.

An unnamed formation of coarse clastic and calcareous Upper Paleozoic rock outcrops northeast of the Pioneer Mountains ridge crest. The age has been designated late Paleozoic by stratigraphic correlation (Ross, 1934). It consists of four units: 1) a chert-quartzite pebble conglomerate and breccia, 2) gritty quartzose to greywacke sandstone, 3) dark shale, and 4) limestone.

Igneous Units

Synorogenic Jurassic intrusive rocks form the core of the Pioneer Mountains. They outcrop in a fan shaped belt that is approximately 1.6 kilometers wide in the south, and broadens to 9.6 kilometers wide to the north of the Broad Canyon area. The plutonic rocks have a range in composition ranging from clinopyroxene-hornblende biotite quartz diorite to leucocratic hornblende biotite quartz monzonite. The rocks are coarse-grained and range texturally
from nonfoliated to strongly gneissose and porphyritic. The intrusion has a Pb-Alpha age of 144 m.y. (Dover, 1969).

During Cretaceous time, the Laramide fold and thrust belt formed in eastern Idaho. Also at this time the Cretaceous Idaho batholith and Thompson Creek stock were emplaced northwest of the Pioneer Mountains, and eugeosynclinal strata in western Idaho were deformed and thrust against the plutonic rocks of the Cordilleran orogen (Burchfield & Davis, 1972).

Porphyritic quartz monzonite, granodiorite, and quartz diorite rocks make up the eastern part of the Atlanta lobe of the Idaho batholith. These rocks form a composite pluton composed of compositionally different phases, having K-Ar dates of 75-100 m.y. (Armstrong, 1974).

Post-orogenic quartz monzonites outcrop near the crest of the Pioneer Mountains. The largest of these intrusions is located along Summit Creek. This may be related to the 44 m.y. old (Armstrong, 1974) Sawtooth batholith located on the eastern edge of the Idaho batholith. The Summit Creek stock consists of a medium grained biotite quartz monzonite. The quartz monzonite has been K-Ar dated at 46.7 m.y. (Armstrong, 1974).

Porphyritic dikes with a composition ranging from granite to quartz diorite cut through all units of the Pioneer Mountains. The dikes are less than 3.5 meters thick. The dikes are designated Tertiary in age, due to their spatial relationship with Tertiary intrusions and the Challis Volcanics (Umpleby et al., 1930).
Small areas of Tertiary volcanics are described in the Pioneer Mountains by Dover (1969). These rocks are considered to be members of the Challis Volcanics (Umpleby, 1917; Ross, 1934). The Johnstone Creek member consists of andesitic and latitic, red-purple to grey porphyritic flow rocks with plagioclase and quartz phenocrysts. The White Mountain member consists of a succession of greenish tuffaceous beds with dark porphyritic flows. The volcanic rocks lie on top of all other stratigraphic units and are thought to be Tertiary because they truncate post-mid-Cretaceous thrust faults (Dover, 1969). To the west of the Pioneer Mountains the Challis Volcanics have a K-Ar date of $49.2 \pm 1.3$ m.y. to $43.8 \pm 1$ m.y. (Armstrong, 1974).

Finally starting in Miocene time a second episode of Cenozoic volcanism began with the eruption of Columbia Plateau and Snake River basalts to the south of the Pioneer Mountains (Figure 2). This has continued until the present.

Structure

The thrust belt in the Pioneer Mountains covers an area that is several thousand square kilometers. There are three major thrust faults in the Pioneer Mountains. These are the Fall Creek thrust, Wildhorse thrust, and Summit Creek thrust. Eastward movement of several miles or more is assumed by Dover (1969). The thrust sheets have been warped by post thrusting uplift of the crystalline core of the Pioneer Mountains in early Tertiary (Dover, 1969).

Post-Challis high angle faults cut the thrust sheets and Tertiary volcanics (Dover, 1969). These major late Tertiary faults
are the Kane Creek normal fault, Pioneer reverse fault, and White Mountain normal fault. The present relief is largely a product of Tertiary and later uplift along these faults.

Regional Ore Deposits

Mineral deposits in the Pioneer Mountains and nearby mountains in central Idaho include: 1) high temperature molybdenum and tungsten deposits that occur in plutons in quartz veinlet systems and associated metamorphic halos, or sometimes disseminated in metamorphic halos; 2) low and medium temperature lead, zinc, silver, and other metal bearing veins in Paleozoic sedimentary rocks near igneous plutons, and within the plutons; 3) zinc, lead, and silver bearing hydrothermal replacement deposits in sedimentary rocks; and 4) placer deposits of gold and heavy black sand metals (Cavanaugh, 1979).

Plate Subduction and Porphyry Molybdenum Deposits

Spatial and temporal relationships between plate subduction, arc magmatism, and the formation of post Paleozoic porphyry molybdenum deposits in the western United States suggest that in the western Cordillera, magmatism and porphyry (stockwork) molybdenum deposits are related (Westra & Keith, 1981). Geographic position of arc magmatism as well as the potassium geochemistry of magmas are produced by partial melting as a function of depth along an inclined subducting slab (Figure 4). The shifting magma chemistry patterns (Figure 5) of the western United States are believed due to the changes in subduction angle with time (Keith, 1978).
Figure 4. Depth to subducting slab for differentiated granitic stocks (Westra & Keith, 1981).
Figure 5. Spatial distribution of magmatism and areas of differentiated granitic intrusions associated with stockwork molybdenum deposits between 52 and 45 m.y. (Westra & Keith, 1981).

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Potassium content can be used to determine depth at which a melt has originated (Dickinson, 1975) by partial melting of subducted oceanic lithosphere at successively greater depths (Figure 4). As melts are generated deeper along the subducting slab the potassium content increases (Figure 4). Stocks such as the Summit Creek stock and stocks associated with porphyry molybdenum deposits have undergone some modification on their way to the surface (Wyllie, 1979), but molybdenum is most likely derived from the subducted slab (Westra & Keith, 1981).

Sillitoe (1972) explains that molybdenum in post Paleozoic deposits in the western United States was originally derived by hydrothermal concentration of molybdenum through ocean water-basalt interaction at the East Pacific Rise. From the East Pacific Rise metals were carried toward the margins of the Pacific Ocean basins as components of basaltic crust, and thrust underneath the western United States. Molybdenum was released from the underthrust oceanic crust and sediments during partial melting and incorporated in ascending diapirs of calc-alkaline magma (Sillitoe, 1972).

**Porphyry Molybdenum Systems in North America**

Porphyry molybdenum deposits are the most economically important type of molybdenum deposits. Ages of porphyry molybdenum deposits in North America range from 17-140 m.y. There are three distinct provinces in North America: 1) Southern Rocky Mountain belt in Colorado and New Mexico, 2) White Cloud-Cannivan porphyry belt in Idaho and Montana, 3) Interior belt of British Columbia.
Host stocks of porphyry molybdenum deposits are related to siliceous oversaturated rocks found in the three provinces. Petrologic composition of intrusions range from granodiorite through quartz monzonite to granite. Granodiorite type deposits are related in space and time to emplacement of the younger phases of major calc-alkaline Mesozoic batholiths, including the Boulder, Idaho, and Sierra Nevada batholiths (Mutschler, Wright, Ludington, & Abbott, 1981). Quartz monzonite type deposits are associated with small composite stocks or late phases of batholiths. A few deposits are related to simple single phase stocks (White, Bookstorm, Kamilli, Ganster, Smith, Ranta, & Steininger, 1981).

Alteration

Hydrothermal alteration is very frequently found in the host intrusion and is occasionally found in the country rock. In classic alteration assemblages there are halos or zones of alteration surrounding the ore body (Figure 6). Four zones of alteration commonly found in porphyry molybdenum deposits in order of decreasing intensity are:

1) Potassium feldspar zone--total replacement of plagioclase by potassium feldspar.
2) Quartz-sericite-pyrite zone--sericitization of potassium feldspar and plagioclase and abundant pyrite.
3) Argillic zone--argillization of feldspars, replaced by montmorillonite, kaolinite, and sericite. Biotite is
Figure 6. Schematic cross section of a porphyry molybdenum deposit. Modified from Mutschler et al. (1981).
replaced by muscovite, sericite, and small quantities of rutile, leucoxene, pyrite, carbonate, and fluorite.

4) Propylitic zone--characterized by calcite, clay, and minor sericite derived from plagioclase, minor chlorite, and epidote occurring with biotite (White et al., 1981).

**Mineralization**

In porphyry molybdenum deposits, molybdenum is the only mineral of economic importance with the exception of Climax which recovers the byproduct cassiterite, heubnerite, and pyrite. Next to molybdenite, pyrite is the most abundant sulfide mineral present. Other sulfides that occur in only minor amounts are chalcopyrite, sphalerite, galena, and pyrrhotite. Small amounts of tungstates may be present, such as heubnerite, scheelite, and wolframite.

In porphyry molybdenum deposits the molybdenum introduced into the hydrothermal system is derived from a crystallizing magma (Westra & Keith, 1981). Moderately high temperatures of 300-400° C are usually associated with the fluids in porphyry molybdenum systems (Lowell & Guilbert, 1970). Molybdenum occurs early in the mineralizing epoch associated with a plutonic event (Clark, 1972). It may be accompanied by magnetite and the alteration mineral assemblages that usually precede the mineralizing event. Pyrite and other sulfides may be deposited contemporaneously, but usually appear after the molybdenum. Quartz is the earliest gangue mineral, being associated with early ore minerals and alteration assemblages. Topaz, fluorite, and carbonates are usually deposited later.
Ground preparation in porphyry molybdenum systems is important as it is the primary means by which the fluids are moved and the location where the ore is deposited. These six examples are the major ore occurrences in porphyry molybdenum deposits (Clark, 1972).

1) Quartz veinlets containing molybdenite that are regular spaced and fracture controlled. Replacement occurs along irregular wall rock contacts and there is no offset where veinlets cross.

2) Fissure-vein deposits, contain primary quartz, and molybdenite.

3) Fine fractures, where molybdenum occurs as "paint" on fracture or joint surfaces.

4) Molybdenum filling in openings in shear zones or in mineralized fragments of breccias, some of which have been cemented by molybdenum bearing quartz.

5) Disseminated molybdenum that occurs as small flakes and grains by replacement in host rocks.

6) Oxide molybdenum minerals that occur in weathered deposits.

Table 1 compares geologic and economic characteristics of the Summit Creek stock to other molybdenum deposits of central Idaho. All these deposits are located in the White Cloud-Cannivan porphyry molybdenum belt of Idaho and Montana (Armstrong, Hollister, & Haukel, 1978). In all of the deposits molybdenite occurs in quartz veins, and
there is a later set of barren quartz veins; also, the deposits do not appear to be deep.
Table 1
Comparison of Molybdenum Deposits in Central Idaho
(Modified from Cavanaugh, 1979)

<table>
<thead>
<tr>
<th></th>
<th>Little Boulder Creek</th>
<th>Thompson Creek Deposit</th>
<th>Little Falls Prospect</th>
<th>Summit Creek Stock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximity to Stock</td>
<td>35 km NW</td>
<td>27 km North</td>
<td>96 km West</td>
<td></td>
</tr>
<tr>
<td>Elevation</td>
<td>2592-2867 m</td>
<td>2318-2379 m</td>
<td>1022-1281 m</td>
<td>2562-2623 m</td>
</tr>
<tr>
<td>Host Rocks</td>
<td>tectite adj. to porphyritic quartz monz.</td>
<td>porphyritic quartz monz.</td>
<td>rhyolite dikes and quartz monz.</td>
<td>quartz monz. and aplite pegmatite</td>
</tr>
<tr>
<td>Age in m.y.</td>
<td>83.6</td>
<td>85.9</td>
<td>post-Eocene</td>
<td>Eocene 46.7</td>
</tr>
<tr>
<td>Structural Controls</td>
<td>in down-dropped block adj. to N 15°E fault</td>
<td>in fault zone with N 60°W trend</td>
<td>in N 35°E dike swarm</td>
<td>in fault zone with N 20-30°W trend</td>
</tr>
<tr>
<td>Alteration</td>
<td>silicified, potassic zones, sericite near fault and late breccia veins</td>
<td>completely altered to at least propylitic grade. Envelopes throughout include all grades (prop-silic.)</td>
<td>silicified, sericite throughout, potassic dikes</td>
<td>silicified, sericite, minor silification along faults and fractures</td>
</tr>
<tr>
<td>Average Deposit</td>
<td>0'-300'</td>
<td>0'-500'</td>
<td>0'</td>
<td>0'</td>
</tr>
<tr>
<td>Burial Depth (to top)</td>
<td>0-91.5 m</td>
<td>0-152.5 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size in Meters (approx.)</td>
<td>180 x 900 x 300; 150 x 180 x 180; 120 x 60 x 120</td>
<td>600 x 180 x 240</td>
<td>900 x 300 x ? a 1 x 12 x ?; 3 x 90 x ?</td>
<td></td>
</tr>
<tr>
<td>Tonnage (est.)</td>
<td>167 million</td>
<td>100 million+</td>
<td>&quot;significant&quot;</td>
<td>information not available</td>
</tr>
<tr>
<td>Grade (est.)</td>
<td>0.15% Mo</td>
<td>0.15% Mo</td>
<td>&quot;subeconomic&quot;</td>
<td>information not available</td>
</tr>
</tbody>
</table>

*Zone of visible Mo
Table 1 (continued)

<table>
<thead>
<tr>
<th></th>
<th>Little Boulder Creek</th>
<th>Thompson Creek Deposit</th>
<th>Little Falls Prospect</th>
<th>Summit Creek Stock</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Occurrence</strong></td>
<td>in fine quartz,</td>
<td>in coarse quartz veins</td>
<td>in fine quartz veinlets</td>
<td>in fine to coarse quartz veins and veinlets</td>
</tr>
<tr>
<td></td>
<td>quartz-Kspar</td>
<td>veins</td>
<td>and veinlets</td>
<td></td>
</tr>
<tr>
<td><strong>Molybdenite</strong></td>
<td>fine flakes on veinlet margins</td>
<td>coarse flakes in veins and silicified zones</td>
<td>fine flakes in veinlets</td>
<td>fine flakes in veinlets</td>
</tr>
<tr>
<td><strong>Description</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Veinlet</strong></td>
<td>gen. concord. w/bedding--N 15°E, dip 70°W</td>
<td>.highly complex</td>
<td>information not available</td>
<td>N 20-30°W dip vert.</td>
</tr>
<tr>
<td><strong>Orientation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Late Barren</strong></td>
<td>present</td>
<td>present</td>
<td>present</td>
<td>present</td>
</tr>
<tr>
<td><strong>Quartz Veins?</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pyrite</strong></td>
<td>about .5% in veinlets and dissem. No halo.</td>
<td>in veins, and veinlets with ore zone. Coarse crystals. Subtle halo.</td>
<td>&quot;intense&quot; in zone 10,000' x 2000'. Distinct halo.</td>
<td>in veins and dissem. No halo.</td>
</tr>
<tr>
<td><strong>Association</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Scheelite</strong></td>
<td>in veinlets throughout ore zone. Distinct outer halo.</td>
<td>trace in ore zone veinlets. Ore grade in veins adj. to deposit</td>
<td>information not available</td>
<td>in tectites on stock margins</td>
</tr>
<tr>
<td><strong>Association</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Magnetic</strong></td>
<td>on side of large magnetic high</td>
<td>in magnetic high</td>
<td>information not available</td>
<td>in magnetic high</td>
</tr>
<tr>
<td><strong>Expression</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER II

ANALYTICAL PROCEDURES

Sampling

Field work was carried out during the 1979 and 1980 summer field seasons. A 1":200" scale topographic map was used for general field work. All outcrops in the study area were mapped in detail (Plate 1).

Samples collected for the trend surface analysis were collected as nearly as possible to equal intervals across the study area to insure the integrity of statistical analysis (Plate 1). Of the fifty samples collected for the trend surface and geochemical analysis, forty samples were used in the trend surface analysis. The samples used for the trend surface analysis were large enough to provide three representative thin sections and a hand specimen. The other ten samples were taken for use in the geochemical analysis.

Because of the excellent vertical exposure of the stock, a two-dimensional trend surface analysis was made to determine mineralogical variation as a function of depth. This information is useful in determining if the stock was formed by multiple intrusions and if it had undergone a change of orientation since its emplacement.
Petrographic Analysis

The petrographic thin sections were stained with sodium cobaltinitrate and rhodizonic acid dipotassium salt to aid in identification of potassium feldspar and plagioclase feldspar. The method used is outlined by Houghton (1980).

Calculation of volume percent of minerals was determined by counting 1,000 points on three thin sections from each of the forty samples cut in at least two different orientations (Table 2). Chayes (1956) notes that the best results are attained by analyzing three thin sections per sample.

Geochemical Analysis

Rock samples were powdered and fused into glass beads, then powdered again to insure homogeneity as described in Hutchison (1974) for X-Ray Fluorescence and Proton-Induced X-Ray Emission (PIXE) analysis.

The powdered rock samples were combined in the ratio of one part rock mixed with ten parts H$_3$BO$_3$ to increase cohesiveness, and pressed into discs to be loaded into XRF and PIXE.

SiO$_2$ and Al$_2$O$_3$ were analyzed using a Phillips Universal X-Ray Spectrograph. Potassium, iron, titanium, manganese, and calcium, along with trace elements molybdenum, strontium, niobium, and rubidium were analyzed in ppm by PIXE (Chapter VII). The rocks were dissolved in hydrofluoric acid as outlined in Hutchison (1974) and analyzed for sodium using the Beckman Atomic Absorption
Table 2  
Petrographic Modal Analysis  
Listed in Volume Percent of Total Volume

<table>
<thead>
<tr>
<th>Sample</th>
<th>Quartz</th>
<th>Potassium Feldspar</th>
<th>Plagioclase Feldspar</th>
<th>Color Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.7</td>
<td>38.7</td>
<td>25.7</td>
<td>3.2</td>
</tr>
<tr>
<td>2</td>
<td>36.9</td>
<td>33.2</td>
<td>28.5</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>30.9</td>
<td>29.3</td>
<td>34.7</td>
<td>1.8</td>
</tr>
<tr>
<td>4</td>
<td>35.0</td>
<td>33.1</td>
<td>30.5</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>29.3</td>
<td>32.6</td>
<td>34.3</td>
<td>3.9</td>
</tr>
<tr>
<td>6</td>
<td>29.3</td>
<td>34.6</td>
<td>32.6</td>
<td>3.1</td>
</tr>
<tr>
<td>7</td>
<td>28.6</td>
<td>34.3</td>
<td>32.9</td>
<td>4.2</td>
</tr>
<tr>
<td>8</td>
<td>28.2</td>
<td>32.3</td>
<td>30.8</td>
<td>8.7</td>
</tr>
<tr>
<td>9</td>
<td>21.6</td>
<td>42.8</td>
<td>31.1</td>
<td>2.9</td>
</tr>
<tr>
<td>10</td>
<td>23.8</td>
<td>35.5</td>
<td>36.4</td>
<td>4.3</td>
</tr>
<tr>
<td>11</td>
<td>34.2</td>
<td>21.7</td>
<td>41.8</td>
<td>2.3</td>
</tr>
<tr>
<td>12</td>
<td>28.6</td>
<td>41.3</td>
<td>28.1</td>
<td>1.7</td>
</tr>
<tr>
<td>13</td>
<td>28.8</td>
<td>33.4</td>
<td>33.7</td>
<td>4.1</td>
</tr>
<tr>
<td>14</td>
<td>27.4</td>
<td>26.6</td>
<td>26.5</td>
<td>5.1</td>
</tr>
<tr>
<td>15</td>
<td>28.8</td>
<td>41.7</td>
<td>27.6</td>
<td>2.0</td>
</tr>
<tr>
<td>16</td>
<td>23.1</td>
<td>33.4</td>
<td>32.1</td>
<td>3.4</td>
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<td>28.5</td>
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<td>34.0</td>
<td>5.3</td>
</tr>
<tr>
<td>18</td>
<td>19.4</td>
<td>48.7</td>
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<td>6.7</td>
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<tr>
<td>19</td>
<td>25.3</td>
<td>34.5</td>
<td>36.3</td>
<td>3.9</td>
</tr>
<tr>
<td>20</td>
<td>28.5</td>
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<td>3.2</td>
</tr>
<tr>
<td>21</td>
<td>31.9</td>
<td>26.9</td>
<td>37.1</td>
<td>4.1</td>
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</table>
Table 2 (continued)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Quartz</th>
<th>Potassium Feldspar</th>
<th>Plagioclase Feldspar</th>
<th>Color Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>41.3</td>
<td>35.3</td>
<td>19.8</td>
<td>3.8</td>
</tr>
<tr>
<td>23</td>
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<td>36.2</td>
<td>31.4</td>
<td>1.2</td>
</tr>
<tr>
<td>24</td>
<td>32.3</td>
<td>31.5</td>
<td>33.1</td>
<td>3.2</td>
</tr>
<tr>
<td>25</td>
<td>32.2</td>
<td>35.3</td>
<td>31.3</td>
<td>4.1</td>
</tr>
<tr>
<td>26</td>
<td>32.1</td>
<td>30.7</td>
<td>34.8</td>
<td>2.3</td>
</tr>
<tr>
<td>27</td>
<td>34.5</td>
<td>31.5</td>
<td>28.3</td>
<td>5.0</td>
</tr>
<tr>
<td>28</td>
<td>33.1</td>
<td>31.5</td>
<td>32.6</td>
<td>2.7</td>
</tr>
<tr>
<td>29</td>
<td>32.6</td>
<td>31.1</td>
<td>34.7</td>
<td>1.4</td>
</tr>
<tr>
<td>30</td>
<td>30.9</td>
<td>26.1</td>
<td>36.0</td>
<td>7.1</td>
</tr>
<tr>
<td>31</td>
<td>28.1</td>
<td>32.8</td>
<td>32.5</td>
<td>6.6</td>
</tr>
<tr>
<td>32</td>
<td>25.0</td>
<td>33.3</td>
<td>36.9</td>
<td>4.7</td>
</tr>
<tr>
<td>33</td>
<td>26.9</td>
<td>38.1</td>
<td>31.1</td>
<td>3.9</td>
</tr>
<tr>
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<td>34.8</td>
<td>36.2</td>
<td>27.8</td>
<td>11.7</td>
</tr>
<tr>
<td>35</td>
<td>48.6</td>
<td>0</td>
<td>48.7</td>
<td>1.0</td>
</tr>
<tr>
<td>36</td>
<td>26.1</td>
<td>31.3</td>
<td>38.5</td>
<td>4.1</td>
</tr>
<tr>
<td>37</td>
<td>28.6</td>
<td>40.1</td>
<td>29.9</td>
<td>1.5</td>
</tr>
<tr>
<td>38</td>
<td>24.9</td>
<td>28.0</td>
<td>42.6</td>
<td>4.4</td>
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<tr>
<td>39</td>
<td>31.0</td>
<td>37.9</td>
<td>28.2</td>
<td>1.7</td>
</tr>
<tr>
<td>40</td>
<td>32.5</td>
<td>37.0</td>
<td>29.9</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Spectrometer (AAS), Model DB-G.

USGS silicate rock standards (Flanagan, 1967; Langmyhr & Paus, 1968) were used to create a working curve to determine concentrations of unknown element concentrations (Table 3). The USGS silicate rock standards used are BCR-1, W-1, AGV-1, G-2, GSP-1.

Table 3
Values Obtained Using XRF, PIXE and AAS of USGS Standard Silicate Rocks to Determine Composition of Rocks from the Summit Creek Stock

<table>
<thead>
<tr>
<th></th>
<th>XRF Counts/10 sec.</th>
<th>PIXE ppm</th>
<th>AAS %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Si</td>
<td>Al</td>
<td>Fe</td>
</tr>
<tr>
<td>G-2</td>
<td>265</td>
<td>234</td>
<td>11883</td>
</tr>
<tr>
<td>W-1</td>
<td>112</td>
<td>168</td>
<td>57223</td>
</tr>
<tr>
<td>GSP-1</td>
<td>213</td>
<td>198</td>
<td>25838</td>
</tr>
<tr>
<td>AGV-1</td>
<td>142</td>
<td>199</td>
<td>31126</td>
</tr>
<tr>
<td>BCR-1</td>
<td>262</td>
<td>201</td>
<td>70937</td>
</tr>
</tbody>
</table>

With the known concentrations of elements in the standards, a plot of the element concentrations of the abscissa and counts on the ordinate produces a working curve. Using the equation of a line which intersects the origin \( y = mx \), and determining the number of counts of an unknown sample, the percentage of an element could be determined by dividing the total counts, minus background, by the slope of the standard line (Table 4).
### Table 4
USGS Standard Silicate Rocks Used to Create a Working Curve to Determine Composition of Unknown Rocks

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Al</th>
<th>Fe</th>
<th>Mn</th>
<th>Ca</th>
<th>K</th>
<th>Ti</th>
<th>Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-2</td>
<td>69.0</td>
<td>15.60</td>
<td>2.70</td>
<td>.034</td>
<td>1.86</td>
<td>4.51</td>
<td>0.43</td>
<td>4.0</td>
</tr>
<tr>
<td>W-1</td>
<td>52.65</td>
<td>15.27</td>
<td>11.20</td>
<td>.166</td>
<td>10.63</td>
<td>0.61</td>
<td>1.08</td>
<td>-</td>
</tr>
<tr>
<td>GSP-1</td>
<td>67.22</td>
<td>15.35</td>
<td>3.98</td>
<td>.05</td>
<td>2.07</td>
<td>5.50</td>
<td>0.66</td>
<td>2.79</td>
</tr>
<tr>
<td>AGV-1</td>
<td>59.00</td>
<td>17.10</td>
<td>6.42</td>
<td>.10</td>
<td>4.89</td>
<td>2.87</td>
<td>1.05</td>
<td>4.23</td>
</tr>
<tr>
<td>BCR-1</td>
<td>54.10</td>
<td>13.70</td>
<td>12.31</td>
<td>.19</td>
<td>6.91</td>
<td>1.69</td>
<td>2.25</td>
<td>3.26</td>
</tr>
</tbody>
</table>

**Note.** Values listed in percent of whole rock major oxides (Flanagan, 1967; Langmyhr & Paus, 1968).
CHAPTER III

GEOLOGY OF THE SUMMIT CREEK AREA

Sedimentary Rocks

Sedimentary rocks found outcropping along the ridges of the southern portion of the map area (Plate 1) belong to the lower portion of the Phi Kappa formation based on exposures near the head of Kane Creek where the complete formation is exposed (Dover, 1969). This formation contains shales, siltstones, quartzites, and greywackes. The beds dip to the west and southwest throughout the map area due to doming by the intrusion of the Summit Creek stock (Figure 7). A low angle thrust fault-splay cuts the sediments into two distinct plates.

The lower plate is a 50 m thick series of siltstones and shales. Individual beds are homogeneous. In hand specimen the siltstone is dark grey to black, very fine-grained, and has a blocky fracture (Figure 8). Silicification occurs along the contact between the siltstone and intrusion. The siltstone has undergone a low grade contact metamorphism.

The upper plate consists mainly of siltstone with interbeds of quartzite and greywacke .15 m to 2 m in thickness. The best exposure of the upper plate is found in the cirque above Little Alpine Creek. The quartzite is medium grained, brown to tan, quartz cemented, and breaks in a blocky fashion. The greywacke has a very fine-grained
Figure 7. Schematic cross section of the Summit Creek stock.
Figure 8. Siltstone of the Phi Kappa formation.
matrix, dark grey to black with chert fragments (1 mm) (Figure 9). In outcrop, the greywacke has a blocky fracture. All rock units of the Phi Kappa formation weather to a rust brown color along fractures.

Igneous Rocks

The intrusive rock in the study area is a quartz monzonite to granite composition. The intrusion is slightly porphyritic, medium to fine crystalline, and in some places grades to very fine crystalline. In hand specimen the rock is 20-30% K-spar, 30-40% plagioclase, 25-30% quartz, and 10% mafics (biotite) (Figure 10). Crystal shape is subhedral to anhedral. The rock composition varies throughout the stock, with a decrease in plagioclase and an increase in K-spar and quartz in the lower portion of the exposed pluton. This change is gradational and no contacts were found within the intrusion. Close to the contact with the country rock there is a decrease in mafic minerals. The intrusion also becomes finer crystalline in this chill zone.

Small pegmatitic stringers of K-spar and quartz were noted in the lower portion of the stock. The K-spar and quartz crystals are approximately 4.5 cm in length and the stringers are 45 cm across.

Felsic aphanitic dikes are found throughout the intrusion. The dikes are usually only 2 to 5 cm wide but may be as wide as 15 cm in some areas. Some of the dikes have fragments of the host intrusion. Many of the aphanitic dikes show a random orientation, but others appear to follow a NW-SE and SW-NE set of fracture/joint sets. All of the felsic dikes were formed during the same intrusive event. The
Figure 9. Greywacke, part of the Phi Kappa formation.
dikes may be a later phase of the main intrusive event, due to a residual wet melt that was super heated and intruded into existing planes of weakness (Hyndman, 1972).

Quartz veining is prevalent throughout the study area. There are at least two episodes of quartz veining evident from cross cutting relations. The first episode appears to be contemporaneous with the felsic dikes. A second set of quartz veins mainly fills pre-existing fractures, and may be related in time with a breccia found in the lower portion of the pluton.

One of the latest episodes of intrusive activity is the formation of the andesite dikes that trend in a SW-NE direction and are vertical. The andesite dikes are found mainly in the intrusion, and extend in places into the sediments. The andesite dikes are found predominately higher in the intrusion; the dikes appear to follow pre-existing fractures. In hand specimen the andesite is fine crystalline, green to grey, fresh, 70% mafics (hornblende and pyroxene), 20% feldspars, and 10% quartz (Figure 11).

Structure

Three main systems of faults exist in the study area. A thrust fault—which may be a splay from the Summit Creek thrust—cuts along bedding planes 70 m above the intrusion (Plate 1). The fault breccias have been cemented with silica and minor calcium carbonate. There is no field evidence to indicate direction of thrusting, however Dover
(1969) suggested a southwest thrust direction for the Trail Creek thrust system which may be genetically related to the Summit Creek thrust.

The other two major fault sets in the study area are high angle normal faults. One set of faults has a NE-SW trend, the other a NW-SE trend. The NE-SW trending faults appear to be the younger set, as they cut the NW-SE trending set (Plate 1). Fracturing parallels the fault systems. Some of the faults have slickensides that show lateral movement as well as vertical movement.

**Breccia**

A silicified breccia is located in the lower portion of the stock and appears to be the top of highly silicic pipe (Plate 1). In hand specimen the breccia is a highly silicified, massive rock with angular and clay-sericite altered clasts 12-50 mm across. The clasts are only detectable with polished rock slabs due to intense alteration. The matrix is an iron stained mixture of very fine crystalline quartz and clays (Figure 12).

**Mineralization**

Molybdenum mineralization is closely associated with quartz veining. Booklets of molybdenite are found in a small stockwork of quartz veins near the contact of the quartz monzonite and the Phi Kappa formation. Near the center of the stock a 12 cm quartz vein
with molybdenite is exposed. Also, a trace amount of molybdenite is found in the breccia.

Pyrite and magnetite are usually found in trace amounts throughout the stock, and are occasionally found in quantities of up to one percent in some areas of the stock. There does not appear to be a halo of these minerals, but a random distribution.

Alteration

The pervasive alteration associated with a typical porphyry molybdenum deposit is absent in the Summit Creek stock. In contrast, intense alteration in the Summit Creek stock is limited to narrow zones associated with fractures. The dominant type of alteration is argillic, with feldspars altering to clays and sericite, and biotite altering to chlorite (Figure 13). Altered zones along these fractures and faults range from .6 to 2 m in width. Amounts of alteration increase closer to the sediment-intrusion contact. This is because there is an increase in fracture density near the outside of the stock.

Throughout the stock there is minor propylitic alteration, plagioclase slightly altering to clay. This is not considered to be deuteritic but meteoric alteration because thin section analysis shows that the alteration is predominately confined to grain boundaries.
Figure 13. Argillic altered quartz monzonite. Compared to the fresh rock (Figure 9), the rock is totally altered to clays and friable (note fractures).
Quartz Monzonite

The quartz monzonite is slightly porphyritic to equi-granular throughout the pluton. The phenocrysts are 5 to 20 mm in size, and are predominately euhedral to subhedral plagioclase and subhedral orthoclase (Figure 14). The phenocrysts are slightly poikilitic where the rock is fresh and saussuritized and sericitized in more altered rocks. The orthoclase lacks twins and accounts for 32% of the total

Figure 14. Photomicrograph of slightly porphyritic quartz monzonite viewed under crossed nickels, magnification 35x.
rock. The plagioclase makes up 33% of the intrusion. Anorthite content of the plagioclase ranges from \( \text{An}_{34} \) to \( \text{An}_{40} \), and was determined using a universal stage and determining angle of extinction by observing the (010) axis (Kerr, 1977). Many of the grains have normal zoning. Micrographic texture is found in the lower portions of the pluton indicating a eutectic crystallization.

Twinning is extensive in the plagioclase. Most of the plagioclase grains have albite, carlsbad, and pericline twins, and a few of the grains exhibit carlsbad-albite twins. All of the feldspars have straight to slightly undulatory extinction. Fracturing of the feldspar grains is common.

The quartz is anhedral throughout the pluton and comprises 30% of the rock. The quartz is interstitial, and some grains exhibit sutured boundaries. The undulose to slightly undulose quartz is smoky grey. Many fluid inclusions and feldspars are common in the quartz. Fracturing in the quartz grains is prevalent, similar to the feldspar.

The groundmass has a subautomorphic texture throughout the stock, the crystals range in size from 1 to 17 mm. Biotite is usually found in the groundmass and accounts for 3% of the rock. It is brown-green and occurs in laths 2 to 7 mm in length and is slightly altered to chlorite. Euhedral sphene crystals 1 mm in length account for 1% of the rock in a few isolated areas of the stock, but is usually an accessory mineral. Magnetite is also found in up to 1% in the groundmass. Many of the iron bearing minerals have \( \text{Fe}_2\text{O}_3 \) staining
around them. Additional accessory minerals found in trace amounts are zircon, apatite, and sphene.

Altered Quartz Monzonite

The altered quartz monzonite consists of quartz, plagioclase and orthoclase that have been altered to clay-sericite, and biotite that is altered to chlorite (Figure 15). Most of the alteration is argillic alteration. Polygonal texture is lost due to alteration and quartz overgrowths. Hydrothermal quartz with undulose extinction and sutured boundaries is found in the altered rock. Many of the feldspars have been totally altered to clay-sericite and cannot be distinguished as either plagioclase or orthoclase. \( \text{Fe}_2\text{O}_3 \) staining is found surrounding

Figure 15. Photomicrograph of argillic altered quartz monzonite viewed under plain light, magnification 35x. Feldspars are totally altered to clays and undistinguishable as to type.
fresher grain boundaries and within the altered grains. Biotite has been completely altered to clays and cannot be identified in some of the more intensely altered rocks.

**Breccia**

The breccia is composed of angular clasts of highly altered quartz monzonite and a matrix of fine quartz and clay. They consist of xenomorphic medium grained (1 mm) feldspar and quartz crystals. The feldspars have been altered to clays and are indistinguishable as either plagioclase or orthoclase in thin section. The quartz grains have strong undulose extinction with clays and Fe₂O₃ rimming the quartz and filling microfractures.

The matrix is composed of 90% quartz, 10% clays, and Fe₂O₃, with a trace amount of pyrite and molybdenite. The quartz is fine-grained (.1 to 1 mm) and is slightly undulose and contains abundant fluid inclusions. The quartz rich matrix is subautomorphic with some interlocking of the quartz grains. The Fe₂O₃ stained matrix gives the breccia a red color in plain light.
CHAPTER V

STATISTICAL ANALYSIS

Discussion of Trend Surface Analysis Method and Presentation of Data

Trend surface analysis deals with the recognition, isolation, and measurement of trends that can be represented by lines, surfaces or four-dimensional hypersurfaces. Trend surface analysis separates large scale variations or trends from local variations. The least squares criterion is the method used in this study and has the trend surface passing above, below, or through the actual data point to form a "best fit."

The use of least squares fitting in trend surface analysis [as developed by Grant (1957)] has been demonstrated by Whitten (1959) and Krumbein (1959) as an effective tool for analyzing two-dimensional variations of granitic plutons. Krumbein (1959) extended the method to include non-orthogonally distributed data points. Whitten (1959) has shown by utilizing a least squares fitting method for trend surface analysis that many chemical and mineralogical variation trends can be detected both between and within individual granite plutons.

Trend surface analysis of non-orthogonally distributed data may be computed for any degree, depending on the number of data points. Surfaces analyzed for this study include first degree (linear), second degree (linear + quadratic), third degree (linear + quadratic + cubic), and fourth degree (linear + quadratic + cubic + quadratic) analysis.
Sample sites were selected with the x coordinate being the horizontal, and the y coordinate being the vertical. This was chosen to give a representative cross section through the intrusion. The dependent variable is the measured value at each x,y location. The surfaces of "best fit" in this analysis were all third degree surfaces. A third degree surface (Harbaugh & Merriam, 1968) has the form of:

\[ Z = A + Bx + Cx^2 + Dxy + Fy + Gx^2 + Ix^2y + Jy^2. \]

The residuals were minimized using the least squares method.

It is important to determine if the trend surfaces are statistically significant. Goodness of fit and analysis of variance (Dixon & Massey, 1969) were implemented to determine the surfaces of best fit.

Goodness of fit is calculated by summing the squares of deviations from the mean.

\[ S_{+1} = \sum_{i=1}^{n} (Z_{\text{obs}} - \overline{Z}_{\text{obs}})^2 \]

where:

- \( S_{+1} \) = total corrected sum of squares of deviations from the mean,
- \( n \) = degrees of freedom,
- \( Z_{\text{obs}} \) = observed value of variables Z at data points,
- \( \overline{Z}_{\text{obs}} \) = arithmetic mean of observed values of Z.

This is expressed as a percentage because this permits comparison of trend functions fitted to different sets of data. A perfect trend surface has a value of 100%, meaning no deviations of data point from the trend.
Analysis of variance involves freedom for variation to occur. This is determined by correlation between degrees of freedom with other statistical properties essential in analysis of variance (Harbaugh & Merriam, 1968). These statistical properties include: sums of squares apportioned among linear, quadratic, and cubic regression components; sums of squares associated with deviations from cumulative components; number of degrees of freedom associated with regression components and with deviations.

This data is used to calculate the mean square of components and the F factor as outlined in Krumbein and Graybill (1965), and Davis (1973). F factor values for first, second, third, and fourth degree surfaces are compared to determine which degree surface has the highest statistical probability of being the most accurate.

Maps of the trend surfaces of best fit for modal analysis of quartz, plagioclase, potassium feldspar, and color index of the Summit Creek stock are shown in Figures 16, 17, 18, and 19. The surfaces of best fit for this analysis are all third degree surfaces.

The percentage of quartz (Figure 16) and plagioclase (Figure 17) decrease with depth in the pluton. The potassium feldspar percentage increases with depth, as noted by the gradation from the upper east side of the pluton to the lower west section of the exposed stock. Bateman and Nokleberge (1978) explain the increased percentage of quartz and potassium feldspar in the interior of the similar Mount Givens stock by increasing rates of nucleation and crystal growth by
Figure 16. Two-dimensional trend surface analysis for quartz. Cross section of stock, vertical exaggeration 4x. The dashed line represents the contact between the Phi Kappa formation and the Summit Creek stock. The * represents the location of sample 29 (Plate 1).
Figure 17. Two-dimensional trend surface analysis for plagioclase. Cross section of stock, vertical exaggeration 4x. The dashed line represents the contact between the Phi Kappa formation and the Summit Creek stock. The * represents the location of sample 29 (Plate 1).
Figure 18. Two-dimensional trend surface analysis for potassium feldspar. Cross section of stock, vertical exaggeration 4x. The dashed line represents the contact between the Phi Kappa formation and the Summit Creek stock. The * represents the location of sample 29 (Plate 1).
Figure 19. Two-dimensional trend surface analysis for color index. Cross section of stock, vertical exaggeration 4x. The dashed line represents the contact between the Phi Kappa formation and the Summit Creek stock. The * represents the location of sample 29 (Plate 1).
moderate undercooling below the temperature of initial crystallization toward the center of the stock.

The color index appears to increase near the contact with the country rock. Also there is an increase in color index in the lower west section of the stock. Many plutons are lower in mafics and free of mafic inclusions in their interiors. Some compositional zoning may be related to contamination by wallrocks (Hyndman, 1972). Also, assimilation of some of the country rock may have produced the increase in color index in the lower west side of the exposed stock.

All of the trend surfaces show a similar pattern in the trend. There are small variations within the trends such as the double model pattern observed in Figures 17 and 18 compared to the single mode arrangement noted in Figures 16 and 19. These modes in the center are minor compared to the steep gradations near the edges of the trends and in light of the statistical nature of the analysis are probably not significant.

Of most importance, the patterns all display a smooth gradation that appears to be a function of distance from the contact. The change in gradient in the middle of the trend surfaces may possibly be related to changing temperature and pressure parameters within the cooling stock. This evidence indicates that the Summit Creek stock is the product of a single intrusion and is not a composite stock.

Also, the symmetrical homogeneity of the Summit Creek stock indicate that it is in its original orientation and has not been rotated by tectonic stress.
CHAPTER VI

PETROGENESIS

Petrogenesis of the Summit Creek Stock

As previously mentioned in the introduction, it was shown that the depth at which a melt originated can be determined from $K_{60}$ index for potassium at 60% $SiO_2$ (Dickinson, 1975). From the parameters outlined in Table 5 and Figure 4, the Summit Creek stock compares favorably with high K calc-alkaline stocks (Keith, 1978). The depth to the subducting slab and initial melt that formed the Summit Creek stock is approximately 220-260 km based on its chemical composition of a high K calc-alkaline intrusion.

Emplacement

Depth of the emplacement of the Summit Creek stock is estimated to be 6-7 km. My evidence for this is:

1) Buddington's (1959) experiments of two feldspar granites indicate that the Summit Creek stock crystallized under similar pressure and temperature conditions of mesozonal plutons (6.4-13 km depth).

2) Although baking of the Phi Kappa formation was noted throughout the study area, along the contact between the intrusion and the Phi Kappa formation there was found only minor silicification in a zone .5-1 m wide.
Table 5
Chemical and Mineralogical Parameters for Classification of High K Calc-alkaline Rocks and Depth to Subducting Slab, with Comparison to the Summit Creek Stock

<table>
<thead>
<tr>
<th></th>
<th>Depth to inclined slab</th>
<th>( K_{60.5} )</th>
<th>( \Theta ) index(^a)</th>
<th>( S ) index(^b)</th>
<th>( K_2O/Na_2O )</th>
<th>( Na_2O+K_2O )</th>
<th>( Al_2O_3 ) content</th>
<th>Selected minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>High K Calc-alkaline</td>
<td>220-260</td>
<td>2.4-3</td>
<td>38-44</td>
<td>2.3-3.2</td>
<td>.6-.9</td>
<td>4.5-7.5</td>
<td>High 15-19%</td>
<td>pyroxene; biotite</td>
</tr>
<tr>
<td>Summit Creek Stock</td>
<td></td>
<td>4.24</td>
<td>39.3</td>
<td>3.1</td>
<td>.81</td>
<td>7.3</td>
<td>15.2</td>
<td>biotite</td>
</tr>
</tbody>
</table>


\[ \Theta \text{ index} = \frac{(Na_2O + K_2O)}{Al_2O_3} \text{ SiO}_2 - 47 \]

\[ S \text{ index} = \frac{(Na_2O + K_2O)^2}{SiO_2 - 43} \]
3) No apparent reaction rims were found in the xenoliths indicating little assimilation with the intrusion, suggesting that the magma was intruded at a relatively low temperature for a mesozonal pluton.

I believe emplacement to have been forceful as evidenced by the doming of the sediments and the dike swarms intruding up into the planes of weakness of the country rock. This is especially noticeable on the north side of Summit Creek.
CHAPTER VII

CHEMICAL ANALYSIS

Whole Rock

Listed in Table 6 is the average geochemical composition of the Summit Creek stock. Also included in the table are geochemical compositions of selected producing porphyry molybdenum deposits. Henderson, Mount Emmons, and Questa are classified as "granite molybdenite" systems (Mutschler et al., 1981). White Cloud, Thompson Creek, and Cannivan deposits are termed "granodiorite molybdenite" systems (Mutschler et al., 1981). Whole rock chemical analysis of the Summit Creek stock indicates that it best fits a granodiorite molybdenite classification (Table 6).

Granodiorite molybdenite type deposits are all mesozonal and have a composition ranging between calc-alkaline granodiorite and quartz monzonite. Compared to the granite molybdenite type deposits, granodiorite molybdenite systems have lower percentages of Si and K, and higher percentages of Al and Ca (Table 6). The granodiorite molybdenite deposits in Montana and Idaho are believed to be related to emplacement of calc-alkaline Mesozoic batholiths (Westra & Keith, 1981). In comparison to source rock chemistry, ore body geometry, and trace element concentrations, the granodiorite molybdenite systems have closer similarities to the Cordilleran porphyry copper deposits than granite molybdenite systems (Lowell & Guilbert, 1970).
Table 6
Geochemical Composition of the Major Oxides of the Summit Creek Stock and Compositions from Various Molybdenum Deposits

<table>
<thead>
<tr>
<th>Sample</th>
<th>Si</th>
<th>Al</th>
<th>Fe</th>
<th>K</th>
<th>Na</th>
<th>Ca</th>
<th>Ti</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>5c</td>
<td>72.6</td>
<td>15.0</td>
<td>4.9</td>
<td>5.55</td>
<td>3.8</td>
<td>.67</td>
<td>.21</td>
<td>.02</td>
</tr>
<tr>
<td>7</td>
<td>64.0</td>
<td>15.5</td>
<td>6.3</td>
<td>5.95</td>
<td>3.88</td>
<td>1.25</td>
<td>.25</td>
<td>.03</td>
</tr>
<tr>
<td>24</td>
<td>66.8</td>
<td>15.4</td>
<td>4.6</td>
<td>3.95</td>
<td>3.5</td>
<td>1.45</td>
<td>.52</td>
<td>.05</td>
</tr>
<tr>
<td>Summit Creek</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-11</td>
<td>67.2</td>
<td>15.2</td>
<td>3.0</td>
<td>4.0</td>
<td>4.32</td>
<td>1.3</td>
<td>.26</td>
<td>.14</td>
</tr>
<tr>
<td>21</td>
<td>68.8</td>
<td>15.3</td>
<td>2.2</td>
<td>2.1</td>
<td>4.1</td>
<td>.55</td>
<td>.14</td>
<td>.03</td>
</tr>
<tr>
<td>Average</td>
<td>67.88</td>
<td>15.28</td>
<td>4.2</td>
<td>4.24</td>
<td>3.9</td>
<td>1.04</td>
<td>.28</td>
<td>.03</td>
</tr>
<tr>
<td>Little Boulder Creek^a</td>
<td>69.3</td>
<td>16.7</td>
<td>2.1</td>
<td>3.25</td>
<td>4.1</td>
<td>2.9</td>
<td>.1</td>
<td>.04</td>
</tr>
<tr>
<td>Thompson Creek^a</td>
<td>67.1</td>
<td>17.01</td>
<td>2.96</td>
<td>2.65</td>
<td>4.04</td>
<td>2.24</td>
<td>.25</td>
<td>.13</td>
</tr>
<tr>
<td>Cannivan^a</td>
<td>64.3</td>
<td>16.1</td>
<td>5.5</td>
<td>2.6</td>
<td>4.0</td>
<td>2.5</td>
<td>.05</td>
<td>.05</td>
</tr>
<tr>
<td>Henderson^a</td>
<td>76.0</td>
<td>11.9</td>
<td>1.25</td>
<td>5.0</td>
<td>2.9</td>
<td>.07</td>
<td>.01</td>
<td>.03</td>
</tr>
<tr>
<td>Mount Emmons^a</td>
<td>76.0</td>
<td>12.3</td>
<td>.8</td>
<td>6.4</td>
<td>3.1</td>
<td>.9</td>
<td>.01</td>
<td>.06</td>
</tr>
<tr>
<td>Calc-alkaline</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Granite^b</td>
<td>72.0</td>
<td>13.9</td>
<td>2.53</td>
<td>5.46</td>
<td>3.8</td>
<td>1.33</td>
<td>.37</td>
<td>.06</td>
</tr>
</tbody>
</table>

\^a Data from Mutschler et al. (1981).
\^b Data from Nockolds (1954).
Trace Element

Although differentiates of different porphyry molybdenite series may have similar major element chemistry, the minor and trace element contents of these magma series may have distinct differences. Concentrations of the trace elements niobium, rubidium, and strontium have been determined to indicate a possible affiliation with molybdenum mineralization associated with the different granite to granodiorite host intrusions (Westra & Keith, 1981).

The concentrations of rubidium and niobium in the Summit Creek stock are compared to molybdenum bearing stocks of different magma series (Figures 20 and 21). The whole rock chemistry of the Summit Creek stock closely relates to that of high K calc-alkaline series (Keith, 1978) (Table 6). Figure 20 shows that rubidium concentration falls on the edge of the field of concentrations generally associated with molybdenum deposits. Figure 21 shows that the concentrations of niobium are within the same range as those of high K calc-alkaline molybdenum deposits.

Also using Rb/Sr ratios (Westra & Keith, 1981) and plotting these values for different molybdenum deposits has shown a relation between Rb/Sr ratios of different magma series and molybdenum occurrences. The Rb/Sr ratio of the Summit Creek stock plots with the Transitional Molybdenum deposits (Figure 22). Transitional Molybdenum deposits are analogous to deposits that have a high K calc-alkaline stock (Figure 4).
Figure 20. Comparison of Rb concentrations associated with different whole rock compositions of porphyry molybdenum stocks. After Westra and Keith (1981).
Figure 21. Comparison of Nb concentrations associated with different whole rock compositions of porphyry molybdenum stocks. After Westra and Keith (1981).
Figure 22. Rb/Sr ratio for granite differentiates of porphyry molybdenite deposits. After Westra and Keith (1981).
Geochemistry of Altered Rocks

The geochemistry of the altered rock from the Summit Creek stock is presented in Table 7, along with mean compositions of other altered argillic assemblages from Henderson and other porphyry molybdenum systems.

Table 7
Composition of Argillic Altered Rocks from Summit Creek Stock, Henderson, and an Average of Porphyry Molybdenum Systems

<table>
<thead>
<tr>
<th>Sample</th>
<th>Si</th>
<th>Al</th>
<th>Fe</th>
<th>K</th>
<th>Na</th>
<th>Ca</th>
<th>Ti</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>834</td>
<td>67.8</td>
<td>15.4</td>
<td>2.4</td>
<td>12.0</td>
<td>1.95</td>
<td>1.5</td>
<td>.42</td>
<td>0</td>
</tr>
<tr>
<td>830</td>
<td>64.0</td>
<td>15.5</td>
<td>5.8</td>
<td>8.9</td>
<td>1.72</td>
<td>.65</td>
<td>.3</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>67.4</td>
<td>15.3</td>
<td>4.1</td>
<td>7.2</td>
<td>1.35</td>
<td>.72</td>
<td>.39</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>68.4</td>
<td>15.3</td>
<td>3.3</td>
<td>8.1</td>
<td>1.50</td>
<td>.78</td>
<td>.33</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>69.6</td>
<td>15.15</td>
<td>4.2</td>
<td>6.67</td>
<td>1.35</td>
<td>.65</td>
<td>.42</td>
<td>0</td>
</tr>
<tr>
<td>Average</td>
<td>67.7</td>
<td>15.3</td>
<td>3.9</td>
<td>8.574</td>
<td>1.57</td>
<td>.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Henderson\textsuperscript{a}</td>
<td>74.6</td>
<td>12.3</td>
<td>.53</td>
<td>6.13</td>
<td>.34</td>
<td>.65</td>
<td>.14</td>
<td>.3</td>
</tr>
<tr>
<td>Argillic. Average\textsuperscript{a}</td>
<td>76.84</td>
<td>14.01</td>
<td>1.39</td>
<td>3.09</td>
<td>.24</td>
<td>.29</td>
<td>.23</td>
<td>.03</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Data from Mutschler et al. (1981).

Alteration associated with porphyry molybdenum deposits is similar to that of porphyry copper (Barnes, 1979). Lowell and Guilbert (1970) state that alteration associated with porphyry systems occurs when volatiles released by the partial quenching of the stock migrate outward through fractures and brecciated zones in the...
cooler margins where alteration and mineralization occur. This is a response to gradients from near magmatic temperatures at the center of the stock to relatively cool temperature in the wall rocks. This will form a halo around the ore body consisting of a potassic inner core with an argillic zone and an outer propylitic zone as you move farther away from the source of fluids (Figure 6).

The alteration found in the Summit Creek stock is argillic and propylitic. Table 8 compares the change in major oxide composition of the unaltered rock of the Summit Creek stock (Table 6) to the average altered rock of the stock (Table 7). Aluminum and silica remained constant in the argillite assemblage (Table 8). Calcium and sodium have been depleted relative to the source pluton.

Table 8
Chemical Change in Unaltered Stock (Table 6) Compared to Argillic Altered Assemblages (Table 7) and Change of Argillic Assemblages of Various Porphyry Molybdenum Systems

<table>
<thead>
<tr>
<th></th>
<th>Argillic Alteration of Various Alteration Assemblages of Porphyry Molybdenum Systems</th>
<th>Argillic Alteration for Summit Creek Stock</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>increased 2%, S.D. 4%</td>
<td>remained constant, S.D. 2.5%</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>increased 1.5%, S.D. 1.5%</td>
<td>remained constant, S.D. .15%</td>
</tr>
<tr>
<td>Total Fe</td>
<td>remained constant, S.D. 1%</td>
<td>decreased 15%, S.D. 2%</td>
</tr>
<tr>
<td>K₂O</td>
<td>decreased 2%, S.D. 1.5%</td>
<td>increased 4%, S.D. 4%</td>
</tr>
<tr>
<td>Na₂O</td>
<td>decreased 3%, S.D. .5%</td>
<td>decreased 2.4%, S.D..4%</td>
</tr>
<tr>
<td>CaO</td>
<td>decreased 4%, S.D. 2%</td>
<td>decreased .2%, S.D. .6%</td>
</tr>
</tbody>
</table>

aData from Mutschler et al. (1981).
These results fit alteration chemistry associated with other typical porphyry molybdenum deposits (Mutschler et al., 1981; Lowell & Guilbert, 1970; Creasy, 1959).

Potassium content on the other hand shows an increase in the argillic assemblage in the Summit Creek stock (Table 8). Although this also occurs at Henderson, it is not common in most argillic alteration assemblages. This can be explained by an increase in sericite clays as compared to most argillic assemblages.

As discussed in previous chapters, pervasive alteration usually associated with porphyry molybdenum deposits is absent. Limited alteration may be explained by: 1) low $\text{H}_2\text{O}$ content of magmatic and/or hydrothermal fluids, 2) a high degree of fracture control of fluid movement, and 3) low temperature of hydrothermal fluids.
CHAPTER VIII

CONCLUSION

The Summit Creek stock that intruded into the Ordovician Phi Kappa formation has been determined to be a mesozonal stock, by comparison to similar two feldspar granites (Buddington, 1959). The magma was probably the product of melting along a subducting slab near the boundary between the top of the slab and the mantle rocks of the overriding lithosphere (Dickinson, 1975). The melt is estimated to have originated at a depth of 220 to 260 km (Figure 4). The melt differentiated upon ascent to a quartz monzonite composition.

Trend surface analysis indicates that the Summit Creek stock cooled with a border enriched in plagioclase, and became quartz and potassium feldspar rich toward the center and western side of the exposed stock. The pluton followed a normal crystallization sequence as explained by Tuttle and Bowen (1958). The stock is the product of a single intrusion and appears to be in the same orientation in which it was emplaced.

The Summit Creek stock was probably forcefully intruded into the country rock. This is evidenced by the number of fingerlike dikes of quartz monzonite along the contact. The sediments were domed up and presently dip away from the center of the stock.

Whole rock chemical analysis indicates that the Summit Creek stock is chemically equivalent to a high K calc-alkaline system.
This is synonymous with granodiorite molybdenite prospects (Mutschler et al., 1981). These intrusions are associated with steeper dipping subducting slabs as compared to the granite molybdenite composition of the Urad-Henderson (Figure 6) and Climax type deposits.

Trace elements Nb, Rb, and Sr are used to "fingerprint" stocks with similar whole rock chemistry and determine their economic molybdenum potential. In the Summit Creek stock, the Rb and Nb concentrations in ppm fell within the range expected for high K calc-alkaline composition field for stocks associated with molybdenum mineralization. Moreover the Rb/Sr ratio compared favorably with Transitional Molybdenum deposits which generally contain economic molybdenum mineralization.

The intense alteration in the Summit Creek stock is argillic. However, this alteration is localized and confined to faults and fractures, and grades into the widespread but weak propylitic alteration. The alteration geochemistry of the argillic assemblages was similar to that of argillic alteration assemblages of most other porphyry molybdenum systems.

Exposed mineralization is concentrated in quartz veining near the contact between the intrusion and the impermeable country rock. Increased fracturing near the contact between the intrusion and country rock acted as a reservoir for the fluids that moved up to the contact.

The Summit Creek stock has many similarities both geochemically and geologically to porphyry granodiorite molybdenite deposits. But
the lack of pervasive deuteritic alteration is, however, an interesting problem. This may indicate that the system did not contain large enough quantities of hydrothermal fluids, or that the system did not contain large enough quantities of mineralizing fluids. Also, it may indicate that the ore body is quite deep and the pervasive alteration is not exposed.


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- PHI KAPPA FORMAT
- QUARTZ MONZONIT
- ANDESITE
- FAULT
- BRECCIA

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