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Geology, Alteration and Mineralization
of a Copper-rich Porphyry Molybdenum Stockwork System
at Alum Creek, Summitville Caldera,
Southeastern San Juan Mountains, Colorado

A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Geology

by
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ABSTRACT

Widespread hydrothermal alteration of Tertiary volcanic rocks at Alum Creek is related to the emplacement of post-caldera calc-alkaline intrusives along the southern ring fracture of the Summitville caldera. Hot springs-style alteration transitional through sericitic overprinted potassium silicate alteration occurs about Mo±Cu bearing quartz stockwork veinlets centered on a quartz monzonite stock.

Alteration zonation, mineralogy, metal zonation and fluid inclusions associated with the stock are similar to known Cu and Mo-Cu porphyry systems and active geothermal systems. Metals are zoned with a Mo-rich core surrounded by overlapping Cu, Pb and Zn zones and an outermost Ag zone. Concentrations of gold are laterally displaced from the Mo core and partially overlap Pb concentrations.

Alteration and mineralization at Alum Creek is envisioned to have been related to magmatic vapor plume formation about the intrusive. Other similar porphyry systems exist throughout the San Juan volcanic field.
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INTRODUCTION

STATEMENT OF PROBLEM

Following Amoco Mineral Company's acquisition of the Alum Creek property in 1979, it was realized that the geology, hydrothermal alteration and style of mineralization in the area was poorly understood. The studies of Calkin (1967 and 1971) of the Alum Creek area inadequately addressed the problems of geology, alteration, and style of mineralization, especially in light of Lipman's (1975) recognition of the Platoro caldera complex and recent studies relating alteration and mineralization to large hydrothermal systems.

The study area provides a unique geological situation to study the various alteration assemblages surrounding a Mo-Cu porphyry system. Local extreme topographic relief provides good exposure of near paleo-surface alteration assemblages grading downward into alteration assemblages associated with quartz-Mo-Cu stockwork veinlets. In addition, diamond drill holes within and about the mineralized core region have provided insight and specimens from deeper within the system.

LOCATION, ACCESS AND PHYSIOGRAPHIC SETTING

The Alum Creek study area is located in southwestern Colorado within the Rio Grande National Forest (Fig. 1) in the southeastern San Juan Mountains. The study area is accessible
Figure 1. Index map showing the location of the Alum Creek area and access.
by four different dirt roads; with the Alamosa River road providing the most reliable route. The vast majority of the project area is inaccessible to motorized vehicles. The study area is very rugged. Relief is generally in excess of 760 m (2500 ft) and several peaks in the area are more than 3800 m (12,500 ft) above sea level. Much of the study area is covered by densely timbered areas of spruce, fir and aspen with sparse alpine grasses above timberline, around 3660 m (12,000 ft). Because of the high elevation the field season is generally limited to July through October. Average annual precipitation is 101.6 cm (40 in), of which approximately 60 percent occurs as snow (Calkin, 1970; Perkins and Nieman, 1982).

PRESENT STUDY

Field work was conducted during the summers of 1981 and 1982. Geology and alteration mapping by the author was done at 1 inch to 500 feet. Drill holes AAC-3 and AAC-4 were logged by the author, whereas holes AAC-1 and AAC-2 were logged in part by the author and completed by John R. Wilson. All core logs of Inspiration Development Company drill holes, IDC series, were logged by John W. Blake and re-logged by Amoco staff geologists. Seventy selected core samples, from IDC series drill holes, were examined in thin section. In addition 380 rock samples were collected, 216 of which were surface samples and 164 were drill core, ACC series, samples.
From this collection, 154 were examined in thin section and all four hundred and fifty by X-ray diffraction methods. The Earth Science, Inc. drill holes, AC series, were logged by William S. Calkin.

Seven quartz stockwork samples were selected for fluid inclusion study. However, the inclusions were too small to be useful on available fluid inclusion equipment. Inclusions were observed in thin sections and some qualitative information was drawn from this work.

Nearly 2800 rock chip and diamond core samples were analyzed for copper, molybdenum, lead, zinc, gold, silver and fluorine with spot analysis for arsenic, bismuth, antimony, tin and tungsten. All analyses of Inspiration Development Company samples were done in-house by the Safford-Talco Laboratory, Safford, Arizona. Analysis of Amoco Minerals Company samples were done by Bondar-Clegg, Inc. and Cone Geochemical, Inc., both of Lakewood, Colorado. Check analysis were performed by Barringer Resources, Inc. of Golden, Colorado and Chemex Labs, Ltd. of North Vancouver, British Columbia.

Potassium-argon and fission-track age determinations on sanidine, hornblende and zircon separates from a buried porphyritic quartz monzonite intrusive and a rhyolite dome were provided by John W. Blake of Inspiration Development Company (1981). K-Ar ages used in this paper have been adjusted for new IUGS constants through conversion by the

PREVIOUS INVESTIGATIONS, MINING AND EXPLORATION

Most of the previous investigations in the study area have dealt almost exclusively with the geology and ore deposits of the Summitville and or Platoro mining districts. The earliest geologic investigations of the region were by F. M. Endlich (1877), a geologist with the Hayden Survey and by R. C. Hills (1885). Both of these reports dealt exclusively with the Summitville district.

H. B. Patton (1917), of the Colorado Geological Survey, published the first detailed investigation of the geology and ore deposits in the Platoro-Summitville area. Larsen and Cross (1956) provided the first regional study of the volcanic rocks in the southeastern San Juan Mountains. Steven and Ratté (1960) were the first to conduct a detailed study of the geology, alteration and ore deposits at Summitville.

W.S. Calkin (1967) described the geology, alteration and mineralization of the Alum Creek area. Base-metal geochemical anomalies in the Alum Creek area were described by Sharp and Gualtieri (1968). Perhaps the most important study to date on the Platoro-Summitville area was U.S. Geological Survey Professional Paper 852 (Lipman, 1975), in which the geology and structure of the region were thoroughly described and
recognized as being related to the development and evolution of the Platoro and Summitville calderas.


The major centers of mining interest associated with the Platoro caldera complex are all located either along the ring-fracture zone, along the transecting Summitville-Platoro fault zone, at the intersection of these two major structures or within outlying mineralized areas along the northwest-trending Pass Creek-Elwood Creek-Platoro fault-graben system (Fig. 2).

Interest in the Platoro-Summitville area began in 1870 when gold was discovered in Wightman's gulch. Prospectors traced the placer gold up to its source on South Mountain. The gold-silver-copper deposits of the Summitville district are the best known and most thoroughly studied of the mineralized areas in the Platoro caldera complex. The ore at Summitville is hosted by the South Mountain quartz latite
Figure 2. Map showing the major structural features within and about the Platoro caldera complex. Stippling denotes zones of hydrothermal alteration and open triangles denote historic mining districts. Modified after Lipman (1975).
porphyry composite volcanic dome that is situated at the intersection of the northwest rim of the Platoro-Summitville caldera ring-fracture zone and the northwest-trending Summitville fault. K-Ar age determinations (Mehnert et al., 1973b; Perkins and Nieman, 1982) indicate that the alteration and mineralization of the composite dome complex formed nearly contemporaneously with the development of the dome, and about 6-7 m.y. after caldera collapse. Ore minerals are associated with pods, pipes and steeply dipping, irregularly shaped zones of "vuggy" silicification surrounded by outwardly zoned alunitized and argillized rock within much more widespread propylitized rock (Steven and Ratté, 1960). In oxidized zones, gold occurs with goethite and barite, whereas in the deeper unoxidized zones the gold is associated with pyrite, marcasite, covellite, chalcocite, digenite, enargite, luzonite, famatinite, polybasite, chalcopyrite, sphalerite and galena (Perkins and Nieman, 1982).

Following the discovery at Summitville, other nearby mining communities were established. Around 1874 the small town of Jasper and the Jasper mining district were located along the eastern margin of the Summitville caldera rim about a strongly argillized andesitic stock. Gold and silver associated with sphalerite and galena are confined to steeply dipping, northwest-trending quartz-pyrite veins.

Platoro, now a rustic resort town, was founded in 1883 when extremely rich silver-gold ore veins were located near
the base of Forest King Mountain. The Platoro mining district contains many steeply-dipping pyritic quartz veins that are located within the resurgent core of the Platoro caldera. The most frequent orientation of the veins is north-northwest along the axis of the regionally dominant Summitville-Platoro fault zone. Mineralization in the Platoro district is considered to be younger than the Summitville caldera by both Lipman (1975) and Bird (1972).

The Mammoth Revenue vein is the most persistent, with a known strike length of more than 2440 m (8000 ft), and an average width of 2.4 m (8 ft). Economic mineralization appears to diminish above the 3100 m (10,200 ft) elevation but continues below the 2835 m (9300 ft) elevation (Johnson, 1981). Vein mineralogy is principally quartz gangue with pyrite and marcasite. Bird (1972) identified the major ore minerals as pyrargyrite, proustite, silver, electrum and gold. Anomalous values of copper, zinc and molybdenum are also present. Wall rocks are sericitically and argillicly altered.

The Stunner and Gilmore mining districts are located along the intersection of the southern margin of the Summitville caldera rim and the northwest-trending Summitville-Platoro fault zone. The mines of these districts are located on quartz-pyrite veins with variable amounts of gold telluride and silver sulfosalt minerals (Patton, 1917). The veins occur in the Alamosa River stock, a variably altered monzonite, and are generally northwest-trending and steeply
dipping. Very little activity and production has been recorded from these districts.

Peripheral to the western margin of the Platoro caldera complex is the northwest-trending Pass Creek-Elwood Creek-Platoro fault-graben zone that extends towards the southern margin of the postulated Mount Hope caldera. Within this major fault-graben system there is a nearly continuous belt of altered rocks and satellitic stocks. The Crater Creek area lies within the fault-graben zone and is approximately 10 km (6 mi) west of Summitville. The area is the site of intensely altered volcanic rocks surrounding a monzonitic intrusive. Altered rock in and near Crater Creek enclose copper-lead-zinc quartz veins as well as quartz-molybdenite stockwork veining (Neuerburg, 1978). The Crater Creek area has been described by Connors (1975) and in U.S. Geological Survey Bulletin 1524 (Brock et al., 1985).

Interest in the Alum Creek area began in the 1950's with the recognition of the porphyry potential of the area. Two hundred and twenty-five lode claims were staked by Mr. J. Rigg, Mr. J. Tippit and Mr. A. Moore in the area surrounding Alum Creek. From 1963 to 1965 these claims were leased by the W. S. Moore Company. Very little information is available on the exploration program of the W. S. Moore Company, other than that the company staked an additional 20 claims. In 1966 Newmont Mining Company leased the property from the W. S. Moore Company and core drilled four shallow angle holes
totalling 948 m (3110 ft) before relinquishing the property in 1967.

Earth Sciences Incorporated leased the property in 1967 and drilled one vertical hole, near the Newmont holes, to 510 m (1675 ft). In 1968 and 1969 this hole was deepened to 912 m (2994 ft). Although no significant metal values were encountered in this hole, geological, geochemical and geophysical surveys were conducted until 1971, when the property was once again relinquished.

In 1973, Inspiration Development Company leased the property and conducted detailed geochemical and geological studies. Three core holes were drilled, near those of Newmont and Earth Sciences, totalling 3607 m (11835 ft).

Amoco Minerals Company leased the Alum Creek area from Inspiration Development Company in 1979 and conducted a drilling program based on information from the previous exploration programs. In 1981 Amoco relinquished control of the property after drilling four diamond drill holes totalling 3052 m (10015 ft).

**GEOLOGIC SETTING**

The geology, structure, and mineral deposits of the San Juan Mountains have been described by Larsen and Cross (1956), Lipman et al., (1970), Steven et al., (1974), Steven (1975), Lipman et al., (1976), Steven and Lipman (1976), Lipman et
al., (1978), and Doe et al., (1979). The San Juan Mountains of southwestern Colorado are composed largely of volcanic and hypabyssal intrusive rocks of Tertiary age. The volcanic rocks, primarily lavas of intermediate composition, volcaniclastic rocks and silicic ash-flow tuffs, constitute the largest erosional remnant of a much larger volcanic field that covered much of the southern Rocky Mountains in middle Tertiary time (Steven and Epis, 1968; Steven, 1975). Within the San Juan volcanic field, 18 large-volume ash-flow sheets have been associated with the formation of at least 15 known and three suspected calderas ranging in size from 10 to 40 km (6 to 25 mi) in diameter (Steven and Lipman, 1976; Lipman, 1984).

REGIONAL GEOLOGY

During Late Cretaceous and Early Tertiary time the San Juan region was the site of an early Laramide uplift. Portions of the Late Paleozoic Uncompahgre-San Luis Highland were re-elevated forming the Brazos uplift and the Uncompahgre Plateau (Tweto, 1975; Lipman and Mehnert, 1975; and Chapin and Cather, 1981)(Fig. 3). By the Eocene, the area was a region of general low relief as Mesozoic sediments and Precambrian crystalline rocks were rapidly eroded from the rejuvenated highlands and deposited into the nearby San Juan and Raton basins.
Figure 3. Map showing principal topographic and tectonic features adjacent to the San Juan Mountains.
Between 40 and 36 m.y. ago, major volcanic activity began dramatically with the eruption of andesite, rhyodacite, and mafic quartz latite composition lavas and breccias from numerous widely scattered stratovolcanoes (Steven and Lipman, 1976). This early-stage volcanism accounted for approximately two-thirds of the original volume of the San Juan volcanic field (Lipman et al., 1970 and Lipman, 1975).

Beginning around 36 m.y. ago, the character of volcanism changed with the explosive eruption of large volume (>100 to >3000 km³) ash-flow sheets. These ash-flow sheets were more silicic, varying from quartz latite to rhyolite, than the early intermediate-composition rocks and some sheets exhibit a zonation from early more silicic to later more mafic compositions (Ratté and Steven, 1964; Lipman, 1975; Steven and Lipman, 1976).

The earliest caldera-forming ash flows came from the eastern portion of the field and were centered on collapse structures developed above localized magma chambers that formed close about the roots of clustered early-stage stratovolcanoes. These early Oligocene age calderas, Bonanza (Varga and Smith, 1982) and the Platoro caldera complex (Lipman et al., 1970; Lipman, 1975), were filled to overflowing by intermediate-composition post-collapse lavas, compositionally similar to the lavas of the early-stage volcanoes (Fig. 4).

Ash-flow eruption and subsequent caldera collapse shifted
Figure 4. Index map showing calderas and major structural features in the San Juan Mountains in relation to the Bouguer gravity low. Calderas of the San Juan volcanic field; (B) Bachelor, (BZ) Bonanza (C) Creede, (CP) Cochetopa Peak, (LG) La Garita, (H) Mount Hope, (L) Lost Lake, (LC) Lake City, (P) Platoro, (S) Silverton, (SJ) San Juan, (SL) San Luis, (SM) Summitville, (U) Ute Creek and (UN) Uncompahgre. Modified, in part, from Lipman (1976).
to the western portion of the San Juan Volcanic field around 29 Ma and within 2 million years five calderas had formed. Compositionally zoned and compositionally different ash-flow sheets were erupted in rapid succession from precaldera centers. Postsubsidence volcanism was primarily of andesite, rhyodacite, and mafic quartz latite lavas, compositionally similar to the early-stage and eastern caldera-filling lavas.

Shortly following the onset of caldera development in the western San Juan Mountains, major pyroclastic eruptions began in the central San Juans Mountains around 28 Ma. The central caldera complex, like the western complex, is characterized by a rapid succession of lithologically different, clustered calderas and several compositionally zoned ash-flow sheets. Seven recognized calderas and eight major ash-flow sheets were formed in less than 2 million years. Unlike the other calderas, postsubsidence volcanism in the central caldera complex more closely resembles the composition of the upper portions of the ash-flows, implying that magmatic differentiation had proceeded to such a degree that the less silicic differentiates had not been tapped within the chamber (Steven and Lipman, 1976).

Unlike the eastern calderas, the western and central calderas developed above separate, rapidly rising and differentiating cupolas derived from a large composite batholith, envisioned to have begun forming under the western and central portions of the volcanic field about 30 Ma (Steven
and Lipman, 1976). A large negative gravity anomaly, ≥ -290 milligals, is believed to reflect the presence of a shallowly buried, 2 to 7 km (1 to 4 mi), batholith (Plouff and Pakiser, 1972). Only the Bonanza, Platoro and Summitville calderas lie outside of the gravity anomaly. Whereas the early eastern calderas are believed to have developed above isolated high level magma chambers, the younger calderas of the western and central complexes are envisioned to have collapsed into rising cupolas derived from the batholith (Steven and Lipman, 1976). Caldera development in the western and central San Juans is theorized to record the rise, venting and emplacement of the batholith in discrete segments.

The final developmental stage of volcanism in the San Juan volcanic field occurred around 25 Ma and continued until about 4 Ma. This latest stage of volcanism is characterized by a marked departure from the earlier style of magmatic activity described above to a petrologically distinctive bimodal assemblage of basaltic and rhyolitic association. The shift in magmatic style is closely associated in time with the onset of the basin and range style faulting of the nearby Rio Grande Rift (Lipman and Mehnert, 1975; Chapin, 1979; and Gornitz, 1982).

According to Christiansen and Lipman (1972), bimodal basalt-rhyolite volcanism is approximately concurrent with the late Tertiary crustal extension that is characteristic of much of the western North American Cordillera. Bimodal volcanism
in the San Juans, consisting predominantly of basaltic flows, formed a thin veneer over much of the volcanic field. The only large-volume rhyolitic ash-flow tuff erupted during this time was from the Lake City caldera (Mehnert et al., 1973). By the Early Miocene, the lower portions of the batholith are thought to have crystallized adequately to allow a petrographically distinctive magma body to rise, breach and develop the Lake City caldera (Steven and Lipman, 1976).

REGIONAL STRUCTURE

Within the San Juan Mountains the major structural features evident in the region are Tertiary in age and either related to the volcanic field or to the development of the Rio Grande Rift to the east. Pre-Tertiary structural features are poorly understood mainly because, most of the pre-Tertiary structures are hidden beneath younger volcanic rocks.

Structures developed in the region prior to Tertiary volcanism are suspected to be related to the late Cretaceous Laramide orogeny. This hypothesis is based on studies (Tweto, 1975 and Chapin and Cather, 1981) of Laramide structures bordering on and projecting into the San Juan Mountains.

During the Laramide orogeny, components of the late Paleozoic San Luis-Uncompahgre uplift were re-elevated forming the Brazos arch, Needle Mountains and Uncompahgre arch, a major, nearly continuous, northwest-trending highland that has been largely hidden under the middle of the volcanic field.
Adjacent late Paleozoic lowlands began subsiding and formed the San Juan and Raton basins. Uplift probably continued through Paleocene and into Eocene time, as indicated by the stratigraphic record in the bordering basins. By Eocene time these highlands had been thoroughly eroded and the area was a region of general low relief.

The major Tertiary structural features of the San Juan Volcanic field are the 17 calderas and the associated doming and faulting related to caldera development, during the late Eocene and through the Oligocene (Fig. 4). The calderas range in diameter from less than 10 km (<6.2 mi) to almost 50 km (31 mi). Most are resurgent calderas whereas a few are simple collapse depressions. The principal structural elements associated with most of the San Juan calderas are an arcuate ring fracture zone, a central resurgent dome and not uncommonly, a longitudinal graben which cuts across the caldera.

Also present in the central and eastern San Juan Mountains are several large northwest-trending fault-graben systems that exist between or are adjacent to several of the major calderas. These include the Clear Creek graben, Rio Grande graben and the Pass Creek-Elwood Creek-Platoro fault system. It is envisioned that these graben-fault systems reflect uplift and distention related to the rise and emplacement of a buried batholith below the central and eastern portions of the volcanic field (Lipman, 1975).

Concurrent with or shortly following the development of
the graben-fault systems, the eastern San Juan Mountains were tilted to the east in response to the initial development of the Rio Grande Rift, an isolated limb of the Basin and Range Province that is 15 to 60 km (9 to 37 mi) wide and greater than 800 km (500 mi) long. The Rio Grande Rift formed in response to the late Cenozoic extensional tectonics, characteristic of much of the western Cordillera of North America (Chapin, 1979). The San Luis Valley of Colorado, located directly east of the San Juan Mountains, is the widest and deepest segment of the rift and is structurally an asymmetrical horst-and-graben structure. Numerous subparallel, north-trending, west-dipping normal faults cut the volcanics along the western margin of the Rio Grande Rift.

REGIONAL MINERALIZATION

Ore deposits within the San Juan volcanic field, from which significant base and/or precious metal ores have been produced, are closely associated with the calderas. The localization of ore deposits about calderas appears to be a function of a long, complex, post-subsidence history and repeated magma intrusion along the ring fracture zones and graben structures, during the late or terminal stages of the caldera cycle. Radiometrically dated vein material or alteration minerals indicate that mineralization generally occurred long after caldera collapse and termination of major caldera-related volcanism (Mehnert, 1973, Steven et al., 1974,
and Lipman et al., 1976). However, radiometric dating of alteration minerals associated with mineralization in the Lake City caldera (22.9 ± 1.6 to 23.3 ± 1.1 m.y.) (Lipman et al., 1976 and Mehnert et al., 1979) is indistinguishable in age from that of caldera formation (22.2 ± 0.6 to 23.2 ± 0.6 m.y.) (Steven et al., 1967 and Mehnert et al., 1973).

Various types of ore deposits occur throughout the San Juan Mountains. Complex vein systems, such as the Sunnyside Mine vein complex near Silverton, Colorado, are the most common and contain significant amounts of gold, silver, copper, lead and zinc. Replacement type ore deposits associated with complex vein systems have been mined at the Creede District, the Idarado-Black Bird Mine near Telluride and at the Camp Bird Mine near Ouray, Colorado. Mineralized breccia pipes, such as those at the National Belle and Red Mountain Pipes in the Red Mountain District between Silverton and Ouray, have produced extremely rich deposits of copper, lead, zinc, gold and minor silver (Fisher and Leedy, 1973). Disseminated gold deposits associated with high level acid-sulphate systems occur at Summitville, Colorado and at Red Mountain No. 3 in the Red Mountain District. Several disseminated porphyry copper and porphyry molybdenum systems also occur in the San Juan Mountains but to date none have been proven to be economic.
AREA OF STUDY

STRATIGRAPHY

The rocks exposed within the Alum Creek study area, consist exclusively of Oligocene to Miocene extrusive volcanic and hypabyssal igneous rocks (Lipman, 1975). However, the stratigraphy of the caldera complex as well as the study area is most readily organized in terms of (1) pre-volcanic rocks, (2) pre-caldera lavas and volcaniclastics, (3) ash-flow sheets, lavas and intrusives related to the Platoro caldera complex and (4) post-caldera bimodal volcanism (Fig. 5).

PRE-VOLCANIC ROCKS

Although Pre-Cenozoic rocks do not crop out in the study area, Precambrian crystalline rocks and Mesozoic and Cenozoic sedimentary rocks most likely make up the basement rocks. Cretaceous Lewis Shale (K1) and Tertiary-Cretaceous Animas Formation (TKa) are exposed 10.5 km (6.5 mi) to the west of the western margin of the caldera complex (Lipman, 1974). Precambrian granite gneiss overlain by Oligocene Conejos Formation volcanics occurs along the lower Conejos River; Precambrian rocks are also exposed beneath the volcanics 30 km (18.6 mi) to the south, in the Tusas Mountains of New Mexico (Butler, 1971 and Lipman, 1975).

Doe et al., (1979) and Lipman et al., (1978) suggest, based on isotope ratios of lead from tuffs and ores of the
ROCKS OF THE PLATORO CALDERA COMPLEX

Figure 5. Stratigraphic column of rock units within and about the study area. Rock unit symbols are identified in text.
Platoro caldera complex, that lead was derived from 1.4 to 1.5 and 1.7 to 1.8 billion year old source materials. It seems likely that the caldera complex is underlain, in part or entirely by Precambrian crystalline rocks ranging in age from 1.4 to 1.8 billion years old, as well as sedimentary rocks most likely Tertiary or older in age.

PRE-CALDERA VOLCANIC ROCKS

In the southeastern San Juan Mountains, all of the early intermediate-composition lavas that predate the collapse of the Platoro caldera and unconformably overlie the basement rocks belong to the Oligocene Conejos Formation (Tc) of Cross and Larsen (1935) (Fig. 6). The Conejos Formation consists primarily of strikingly uniform, yet complexly interfingered sequences of alkali andesite, rhyodacite, mafic quartz latite lavas and volcaniclastic sediments (Lipman, 1975). Lavas of the Conejos Formation were erupted from numerous scattered vent areas and the volcaniclastic facies were deposited in topographically low regions about the various vents.

Vent facies and interbedded volcaniclastics of the Conejos Formation are the oldest exposed rocks in the area of study (Fig. 6 and Plate 1). Vent facies rocks consist of porphyritic andesite and minor rhyodacite lavas. Platy plagioclase and or augite are the common phenocrysts, with minor hornblende, olivine and biotite phenocrysts in a fine-grained matrix. The volcaniclastic facies in the study
Figure 6. Generalized map of the geology surrounding the Platoro caldera complex. Modified from Lipman (1976).

Explanation

Tls - late-stage volcanics, Hinsdale Formation
Ti - intrusives
Tlpc - lavas of the Platoro caldera complex
Ttm - Treasure Mountain Tuff
Tc - Conejos Formation
Tuv - undifferentiated volcanic units
area are made up of mudflow breccias, conglomerates and well sorted tuffaceous sandstones.

ASH-FLOW SHEETS OF THE PLATORO CALDERA COMPLEX

Overlying and interfingering with the upper-most lava units of the Conejos Formation is the lower unit of the Treasure Mountain Tuff (Ttl)(Fig. 5, 6 and Plate 1) as defined by Lipman and Steven (1970). The lower unit of the Treasure Mountain Tuff is an assemblage of localized, small ash-flow sheets and minor ash-fall tuff. Ash-flow units of the lower tuff are relatively phenocryst poor, commonly are only slightly welded, and are distinguished from the minor ash-flow tuffs of the underlying Conejos Formation by the presence of phenocrystic biotite (Lipman, 1975). Total phenocryst content is generally in the range of 5-10 percent, and phenocrysts consist of plagioclase, sparse biotite and rare augite and opaques. The lower unit has not been radiometrically dated, but it overlies flows of the Conejos Formation that have been dated between 31.9 ± 2.7 and 35.0 ± 1.4 m.y. (Lipman et al., 1970). Eruption of the lower unit of the Treasure Mountain Tuff is believed to have signaled the start of explosive silicic volcanism that would eventually develop into the Platoro caldera complex (Lipman, 1975).

Directly overlying the lower unit is the oldest known, widespread ash-flow sheet in the eastern and central San Juan Mountains, the La Jara Canyon member of the Treasure Mountain
Tuff (Ttj)(Fig. 5, 6 and Plate 1). The La Jara Canyon member formed both an extensive outflow sheet and an intracaldera ash-flow tuff, a relationship that indicates caldera collapse occurred during eruption of the tuff. The outflow sheet, commonly 50 to 100 m (165 to 330 ft) thick, extends, 20 to 30 km (12.5 to 18.5 mi), in every direction. Typically the outflow sheet is a multiple-flow compound cooling unit of densely welded, devitrified, phenocryst rich quartz latite. The intracaldera ash-flow tuff is also a densely welded, devitrified, phenocryst rich quartz latite, however, it is more mafic, more phenocryst rich, and regionally propylitized (Lipman, 1975). Typically, the intracaldera La Jara Canyon member exceeds 800 m (2625 ft) in thickness. K-Ar dating of the La Jara Canyon member has yielded preferred ages of 30.3 ± 1.2 and 30.9 ± 2.2 m.y. (Lipman et al., 1970).

The middle unit (Ttm), the Ojito Creek member (Tto), the Ra Jadero member (Ttr), and the upper units of the Treasure Mountain Tuff (Ttu) are not exposed in the area of study (Plate 1). It is uncertain whether these rock units were ever deposited in the study area or deposited and subsequently eroded or buried under younger rocks. Elsewhere the middle unit rests on either the La Jara Canyon member or on lava flows of the lower member of the Summitville andesite (Tsl). The middle unit, in turn, is overlain by either the Ojito Creek member or the slightly younger Ra Jadero member. Overlying the Ra Jadero member is the youngest unit of the
Treasure Mountain Tuff, the upper unit.

All of these units are quartz latite ash-flows with the exception of the middle unit, which is predominantly an ash-fall tuff. The middle unit is also the least phenocryst rich and least densely welded of all the units. All the tuffs contain plagioclase, biotite, and sparse augite, in addition, both the Ra Jadero member and the upper unit contain up to 20 percent sanidine phenocrysts.

None of the upper ash-flows of the Treasure Mountain Tuff have been radiometrically dated. However, the relative stratigraphic ages for all the units are tightly bracketed by known dates for the La Jara Canyon member and by the overlying Masonic Park Tuff (28.9 ± 1.3 m.y.) (Lipman et al., 1970; Hon and Mehnert, 1983). This stratigraphic relationship suggests that the Ojito Creek and Ra Jadero members, as well as both the middle and upper units of the Treasure Mountain Tuff, were erupted between approximately 30.6 and 28.9 million years ago. Eruption of the Ojito Creek and Ra Jadero members of the Treasure Mountain Tuff are inferred to have resulted in the collapse of the Summitville caldera, nested within the northern portion of the previously collapsed Platoro caldera (Lipman, 1975).

LAVAS OF THE PLATORO CALDERA COMPLEX

The oldest lava flows (Fig. 5 and Plate 1) in the study area related to caldera collapse belong to the Summitville
Figure 7. Photograph of selected unaltered rocks from the Alum Creek study area. Dark varieties of Tcq and Thr are vitrophyres. Rock unit symbols are the same as in Figure 5 and text.
Figure 8. Photomicrograph of fresh to weakly propylitized upper part of the Summitville Andesite. Plagioclase (P), biotite (B; moderately altered to chlorite) and augite (A; moderately altered to calcite + chlorite) in a finer grained groundmass of the same minerals plus hornblende(?) and opaques. Sample AR-16.
andesite, as described by Patton (1917) and redefined by Lipman (1975), a series of andesitic lavas, breccias, and interbedded volcaniclastics. The Summitville andesite is divided into two units. The lower member (Ts1) filled the Platoro caldera, probably to overflowing, after the eruption of the La Jara Canyon member of the Treasure Mountain Tuff. The upper member of the Summitville andesite (Tsu) filled the Summitville caldera to overflowing, following the eruption of the Ojito Creek and Ra Jadero members of the Treasure Mountain Tuff. Both members of the Summitville andesite have vertical exposures of nearly 1000 m (3280 ft) and probably were appreciably thicker (Lipman, 1975). This contention is supported by data from an Amoco Minerals Company drill hole that was collared approximately 311 m (1020 ft) below the erosional contact between the upper member of the Summitville andesite and the quartz latite of South Mountain. The drill hole penetrated 780 m (2561 ft) of upper Summitville andesite without encountering the lower Summitville andesite contact.

The two members of the Summitville andesite are remarkably similar in both general appearance and composition to each other and to the lavas of the Conejos Formation. Lavas of the Summitville andesite are weakly porphyritic to aphanitic dark andesite and minor rhyodacite with sparse plagioclase, opaque oxides, augite and rare hypersthene, biotite and hornblende phenocrysts (Fig. 7 and 8).

The upper member of the Summitville andesite has been
radiometrically dated at 27.3 ± 1.2 m.y. (Perkins and Nieman, 1982). In the authors opinion this is a suspect age date. Within the study area the rhyodacite of Park Creek overlies the upper member of the Summitville Andesite and has been radiometrically dated by Perkins and Nieman at 28.4 ± 1.1 m.y.. Furthermore, the Alamosa River stock radiometrically dated at 29.8 ± 1.2 m.y. (Lipman et al., 1970) intrudes the upper member of the Summitville andesite. It seems more reasonable to assume that the upper member of the Summitville andesite is at least older than 28.4 ± 1.1 m.y. and probably older than 29.8 ± 1.1 m.y..

The lower member lies directly atop the La Jara Canyon tuff and is overlain by the upper Summitville andesite; it is therefore probably between 30.9 ± 2.2 m.y. and 29.8 ± 1.2 m.y. old.

The rhyodacite of Park Creek (Tpd), as designated by Lipman (1975), exists along the northern and western topographic walls of the Summitville caldera (Plate 1). Within the study area, these lavas lie above the upper member of the Summitville andesite and are overlain by the quartz latite of South Mountain (Tsq) (Fig. 5 and Plate 4). The rhyodacite of Park Creek represents some of the earliest post collapse caldera-margin igneous activity in the Summitville caldera. The rhyodacite of Park Creek has been radiometrically dated at 27.7 ± 1.1 m.y. (Perkins and Nieman, 1982). This K-Ar date fits neatly in between dates (Lipman et al., 1970; Lipman,
Typically, the rhyodacite of Park Creek contains phenocrysts of plagioclase with lesser amounts of biotite, augite, Fe-Ti oxides and rare hornblende and quartz. The rhyodacite is easily distinguished from the Summitville andesite by the presence of biotite and larger, more abundant plagioclase phenocrysts.

Directly overlying the rhyodacite of Park Creek and the upper member of the Summitville andesite, within the study area is the quartz latite of South Mountain (Tsq) (Fig. 5 and Plate 1). The quartz latite of South Mountain, as designated by Lipman (1975) and described in detail by Steven and Ratté (1960) and Perkins and Nieman (1982), consists of a coarsely porphyritic composite volcanic dome and related lavas. According to Perkins and Nieman (1982), at Summitville the quartz latite composite dome consists of at least three intrusive phases and one extrusive phase of quartz latite porphyry. Size and abundance of the phenocrysts vary both among and within each phase. The various phases all contain prominent quartz, sanidine and plagioclase phenocrysts with minor biotite and hornblende (Fig. 7 and 9).

Both the U.S. Geological Survey and Anaconda Minerals Company have obtained K-Ar age determinations on the quartz latite porphyries that range from 23.5 ± 0.6 m.y. to 20.9 ± 0.9 m.y.. Radiometric dating of alunite from altered quartz latite by both the U.S. Geological Survey and Anaconda has
Figure 9. Photomicrograph of unaltered South Mountain quartz latite. Note prominent quartz (Q), sanidine (S), plagioclase (P) and hornblende (H) phenocrysts. Groundmass contains abundant biotite. Sample LOM-204.
produced ages ranging from 23.5 ± 1.0 m.y. to 22.9 ± 0.5 m.y., implying that the alteration and mineralizing events, at Summitville, occurred during formation of the dome complex. Capping the high ridges between South Mountain and Lookout Mountain, in the study area, is the rhyolite of Cropsy Mountain (Tcq) (Plates 1 and 4). The restricted occurrence of the flow on the ridge tops may support an argument for reversed topography. A local vent source, northwest of South mountain (Lipman, 1974), vented the rhyolite into a narrow south-trending valley that may have terminated or widened out in the vicinity of Lookout mountain. The rhyolite is quite striking in its appearance and easily distinguished from the quartz latite of South Mountain, even though their mineral assemblages are similar. Within the study area, the rhyolite is extremely fresh and is separated from the strongly altered quartz latite by a distinctive basal vitrophyre. The rhyolite is coarsely porphyritic with phenocrysts of sanidine, plagioclase, quartz, biotite and hornblende (Fig. 7 and 10).

Radiometric age determinations on the rhyolite of Cropsy Mountain (Steven et al., 1967; Lipman et al., 1970; Perkins and Nieman, 1982) range between 21.5 ± 0.8 m.y. and 18.9 ± 1.2 m.y.. The rhyolite of Cropsy Mountain is the youngest rock within the Platoro caldera complex related to post-collapse caldera-margin volcanism.
Figure 10. Photomicrograph of unaltered rhyolite of Cropsy Mountain. Rhyolite contains phenocrysts of sanidine (S), plagioclase (P), biotite (B) and minute quartz (Q) in a hypocrystalline groundmass. Sample LOM-102.
INTRUSIVE ROCKS

Hypabyssal andesitic to rhyolitic composition rocks are found within the area of study (Figs. 5, 6 and Plate 1). As a general rule, the various intrusives tend to be more siliceous the younger they are in age. Texturally, dikes vary from coarsely porphyritic to weakly porphyritic. The stocks, vary from equigranular to strongly porphyritic, with textural variations between different phases. Lipman (1975) noticed a possible comagmatic association between some of the intrusives and lavas related to postcollapse volcanism. Some intrusives have been radiometrically dated; however, absolute ages for all of the intrusives is difficult to establish, due to conflicting cross-cutting relationships (Plates 1, 3 and 4).

The largest, and probably oldest, intrusive in the study area is the Alamosa River stock (Tm) (Fig. 7 and Plate 1). The stock is an elongate body approximately 3 by 7 km (1.8 by 4.4 mi) in size and has a northeasterly trend (Fig. 9). Emplacement of the Alamosa River stock was most likely structurally controlled by the Cornwall fault, the southern caldera-margin ring fracture fault of the Summitville caldera.

The stock consists of two distinct initial phases that are gradational with each other and two smaller, younger, more differentiated phases. The Alamosa River stock is largely composed of a fine-grained equigranular monzonite consisting of plagioclase, biotite and augite phenocrysts in a groundmass of orthoclase, quartz, magnetite and trace amounts of hyper-
Figure 11. Photomicrograph of unaltered monzonite of the Alamosa River stock. Rock consists of plagioclase (P), orthoclase (O), quartz (Q), biotite (B) and augite (A) with minor opaques. Sample AAC-2-625'.

* Denotes sample was taken from drill hole AAC-2 at a depth of 625 feet from the collar. This format is used throughout text.
sthene and apatite (Fig. 7 and 11). In the southwestern portion of the stock (Plate 1) the medium-grained porphyritic phases of the monzonite (Tmp') exists in gradational contact with the equigranular monzonite (Tm). Mineralogically these two phases are very similar however texturally the porphyritic phase contains slightly larger plagioclase phenocrysts and more interstitial quartz.

The other porphyritic phases of the Alamosa River stock occur north of the Alamosa river and are clearly intrusive into the equigranular stock. The second phase of the porphyritic intrusives was first recognized by Calkin (1967) at Alum Creek and termed the Alum Creek porphyry. In this discussion, for purposes of clarity, this phase will be referred to as the Alum Creek phase (Tmp'). The Alum Creek phase is distinctive from the early porphyritic phase of the monzonite in that it is coarser-grained, moderately to coarsely porphyritic and is quartz monzonitic in composition (Fig 7). The Alum Creek phase is not gradational in contact, commonly contains fragments and xenoliths of the equigranular monzonite, and is the locus of intense hydrothermal alteration and stockwork quartz-pyrite-molybdenite-chalcopyrite veining. The Alum Creek phase consists of plagioclase, biotite and augite phenocrysts in a phaneritic, occasionally aphanitic, groundmass texture of orthoclase and quartz with traces of hypersthene, apatite and magnetite (Fig. 12).

In the course of drilling in the Alum Creek area, a third
Figure 12. Photomicrograph of unaltered quartz monzonite of the Alum Creek phase. The rock consists of phenocrysts of plagioclase (P), biotite (B) and augite (A) in a groundmass dominated by quartz, plagioclase and orthoclase. Sample AAC-2-121.
intrusive porphyritic phase was encountered. This third phase of quartz monzonite, to be referred to as the Lookout Mountain phase (Tmp3) in this discussion, is mineralogically similar to the Alum Creek intrusive phase with the exception that it is more coarsely porphyritic and possesses a generally coarser groundmass texture. The second phase consists of euhedral plagioclase, biotite and augite phenocrysts in a phaneritic groundmass of roughly equal amounts of orthoclase and quartz with minor hornblende, augite, zircon and traces of magnetite (Fig. 13). Contact relationships observed in drill core indicate that the second quartz monzonite phase is intrusive into both the Alamosa River stock and the Alum Creek phase. The Lookout Mountain phase possesses sharp contacts, distinct chill margin and contains fragments of both the Alum Creek phase (Tmp2) and the equigranular monzonite (Tm). Some weak hydrothermal alteration is associated with the Lookout Mountain phase although no additional mineralization is attributed to the intrusives.

The Alamosa River stock has been radiometrically dated at 29.8 ± 1.2 m.y. (Lipman et al., 1970). Emplacement of the Alamosa River stock probably occurred shortly after the newly formed Summitville caldera was filled by the upper member of the Summitville andesite. Lipman (1975) stated that the stock may have also been the magma source of the upper member of the Summitville andesite, based on the similarity of composition, age, and locality. Contact relationships in the study area
Figure 13. Photomicrograph of weakly propylitized to fresh quartz monzonite of the Lookout Mountain phase. Phenocrysts of plagioclase (P), biotite (B) and quartz (Q) lie in a groundmass of quartz, orthoclase, plagioclase and opaques. Sample AAC-2-1578'.
show that the stock intrudes the La Jara Canyon Tuff and both the upper and the lower Summitville andesite.

The Alum Creek phase has not been radiometrically dated. The Lookout Mountain phase, which intrudes both the Alum Creek phase and the monzonitic stock, has been dated by K-Ar and fission-track methods at 23.7 ± 0.6 m.y. and 23.5 ± 2.5 m.y. respectively (J.W. Blake, oral communication, 1981). The first and second quartz monzonite phases are considered to be much younger silicic differentiates of the parent magma that formed the Alamosa River stock. However, because of the close mineralogical and textural similarities of the two quartz monzonite phases as well as the style and location of the porphyries, the Alum Creek phase is believed to be closer in age to the Lookout Mountain phase than to the age of the Alamosa River stock.

Rhyodacite porphyry (Tdp) stocks and dikes that crop out within the study area consist of plagioclase, biotite and augite or hornblende phenocrysts in a phaneritic groundmass of quartz, plagioclase, hornblende, Fe-Ti oxides and sparse orthoclase (Fig. 7 and 14). Rhyodacite porphyry intrusives may be comagmatic with the porphyritic rhyodacite flows of Park Creek (Lipman, 1975).

The largest rhyodacite porphyry stock in the study area occurs in the vicinity of De Nolda and Annella Lakes (Plate 1). Other smaller stocks are exposed north of the Alamosa River stock and are spatially distributed about the southern
Figure 14. Photomicrograph of unaltered rhyodacite porphyry. This rhyodacite consists of plagioclase (P), biotite (B), sanidine (S), augite (A) and hornblende (H) phenocrysts in a fine grained groundmass of the same minerals plus opaques. Sample LOM-210.
and eastern sides of Lookout Mountain. Two of the stocks, south and southeast of Lookout Mountain, are intensely altered (Plate 2). The smallest rhyodacite porphyry intrusive, on the eastern slope of Lookout Mountain, is unaltered and exhibits excellent concentric banding and jointing with exfoliation along the concentric joints.

Although the rhyodacite porphyry has not been radiometrically dated it may be comagmatic with and possibly the source of the rhyodacite of Park Creek, dated at 27.7 ± 1.1 m.y. (Perkins and Nieman, 1982). In addition, crosscutting relationships of the rhyodacite with the quartz latite of South Mountain (23.5 ± 0.6 to 20.4 ± 1.0 m.y.) and quartz latite porphyry dikes (26.2 ± 1.0 to 21.4 ± 0.9 m.y.) (Perkins and Nieman, 1982; Mehnert et al., 1973b; and Lipman et al., 1970) suggest that the rhyodacite porphyry was possibly emplaced over a time span of seven or more million years.

Some of the most spectacular dikes and plugs in the study area are composed of quartz latite porphyry (Tqp) (Plate 1). This intrusive is easily recognized because of the abundant large sanidine phenocrysts (Fig. 7). The quartz latite porphyry consists of sanidine, quartz, plagioclase, biotite, hornblende and Fe-Ti oxide phenocrysts in an aphanitic to fine-grained groundmass of orthoclase and quartz (Fig. 15). The quartz latite porphyries generally have a fine-grained chill margin along contacts and a coarser grained core. Quartz latite porphyry dikes, in the area of study, are variably
Figure 15. Photomicrograph of unaltered quartz latite porphyry. The quartz latite consists of quartz (Q), sanidine (S), plagioclase (P), biotite (B) and hornblende (H) phenocrysts in an aphanitic to fine-grained groundmass. Sample LOM-174.
altered (Plate 2), typically crosscut different alteration types and tend to be more continuously exposed along strike, up to 1280 m (4200 ft) than any other dike rocks. The quartz latite dikes crosscut every rock type except the rhyolite of Cropsy Mountain, the rhyolite of the Hinsdale Formation, and the andesite porphyry dikes. Generally, quartz latite porphyry dikes trend in a southwestnortheast direction and where discernable tend to dip toward the Alamosa River stock.

Because of close compositional and contact relationships, the quartz latite porphyry is considered to be comagmatic with the quartz latite flows of South Mountain and the rhyolite flow of Cropsy Mountain (Lipman, 1975). K-Ar age determinations of a postmineral quartz latite porphyry dike at Summitville, occurring within the South Mountain composite volcanic dome, yielded an age of 21.4 ± 0.9 m.y. (Perkins and Nieman, 1982). Considering that the age and composition of the postmineral quartz latite porphyry dike at Summitville is in close agreement with that of the quartz latite of South Mountain (23.5 ± 0.6 to 20.4 ± 1.0 m.y.) and the rhyolite of Cropsy Mountain (20.7 ± 0.8 to 18.5 ± 1.2 m.y.) (Perkins and Nieman, 1982; Mehnert et al., 1973b; and Steven et al., 1967) would indicate that they are comagmatic. However, Lipman and others (1970) obtained an age of 26.2 ± 1.0 m.y. from a similar quartz latite porphyry dike, 6 km (3.8 mi) southeast of Summitville. Suggesting that, although the quartz latite porphyry may be comagmatic with the quartz latite and rhyolite...
flows emplacement of the quartz latite porphyry occurred over a time span of several million years.

A quartz latite volcanic vent-dome similar to the vent-dome at Summitville is believed to have formed in the area of Big and Little Red peaks, to the east of Lookout Mountain (Plate 1 and 3). The presence of a vent in this area is indirectly indicated by a number of factors. First of all, in drill hole AAC-1 137 m (450 ft) of quartz latite agglomerate and intermixed quartz latite and upper Summitville andesite agglomerate were encountered after penetrating overlying quartz latite flows. Secondly, numerous quartz latite dikes were also encountered in the drill hole. Thirdly, the peaks are the locus of isolated intense alteration similar to that at Summitville and the largest gold and lead anomalies in the study area. In addition, vuggy silica alteration, similar to that at Summitville, occurs in the saddle between the two peaks along the Summitville-Platoro fault zone. Also, the inferred vent is located near the junction of the Summitville-Platoro fault zone and the arcuate ring fracture zone of the Summitville caldera, in a geologically identical fashion to the composite volcanic dome at Summitville.

Andesite porphyry (Tap) intrusives within the study area typically consist of small, well-formed phenocrysts of plagioclase and augite or hornblende in a groundmass of plagioclase, augite or hornblende and Fe-Ti oxides (Fig. 16). The andesite porphyry is often poorly exposed and generally
Figure 16. Photomicrograph of weakly to moderately propylitized andesite porphyry. Unaltered varieties of this rock consist of plagioclase (P) phenocrysts in a groundmass of finer grained plagioclase, orthoclase, quartz and augite or occasionally hornblende. Here the andesite contains quartz, chlorite, kaolinite, illite and clinozoisite alteration minerals. Sample AAC-2-3105.'
occurs about the margins of the Alamosa river stock (Plate 1).

The andesite porphyry has not been radiometrically dated and crosscutting field relationships are insufficient to suggest a time frame. In the area of study, the andesite porphyry intrudes only the upper member of the Summitville andesite and the Alamosa River stock suggesting that the andesite porphyry is younger than the upper Summitville andesite (Lipman et al., 1970). It is possible that these dikes were emplaced about the same time as the andesite-rhyodacite volcanics of Green Ridge, 29.1 ± 1.2 to 26.8 ± 2.2 m.y. (Lipman et al., 1970), 23.6 km (14.7 mi) to the east, which they closely resemble mineralogically. The andesite dikes may also be related to the Miocene age lamprophyre dike swarm that they appear to merge with, along the eastern edge of the San Juan Basin (Bingler, 1968). This might suggest that the andesite porphyry may have been emplaced between 30 and 24 Ma.

LATE-STAGE VOLCANISM

This last stage of volcanism is characterized by a distinctive bimodal assemblage of basalt and rhyolite; a marked departure from earlier magmatic activity. The change to bimodal volcanism implies a different circumstance of magma generation, unrelated to caldera development. The shift in magmatic style is closely associated, in time, with the onset
Figure 17. Photomicrograph of the rhyolite of the Hinsdale Formation. The rock consists of phenocrysts of quartz (Q) and sanidine (S) in a groundmass of quartz, sanidine and plagioclase that exhibits some flow structure. Sample EM-4.
of basin and range style faulting of the nearby Rio Grande Rift (Lipman and Mehnert, 1975).

Bimodal volcanism in the San Juan Volcanic field consists predominantly of basaltic flows that formed a thin veneer over much of the volcanic field. Only two major accumulations of rhyolite (Thr) are recognized in the San Juan region; around the Summitville and Lake City calderas. All of the late stage basalt and rhyolite in the San Juan volcanic field have been placed in the Hinsdale Formation of Larsen and Cross (1956) (Fig. 5).

Elephant Mountain, north of Bitter Creek, is a volcanic dome of Hinsdale Formation rhyolite (Plate 1). The rhyolite dome is very fresh and is bounded by a vitrophyre on its southeastern margin and on the west side by a volcanic breccia with a partially devitrified matrix (Fig. 7). The rhyolite dome at Elephant Mountain consists of phenocrysts of quartz, sanidine and locally plagioclase, in a pilotaxitic groundmass of quartz, sanidine, plagioclase and locally sparse glass (Fig. 17).

Rhyolite of the Hinsdale Formation, immediately north of the study area, has been radiometrically dated at 22.4 ± 0.9 m.y. (Lipman et al., 1970). Radiometric dating of the rhyolite at Elephant Mountain yielded an age of approximately 19.9 m.y. according to Inspiration Development geologist J.W. Blake, (oral communication, 1981).
STRUCTURE

INTRODUCTION
Within the study area as throughout the San Juan Mountains, pre-Tertiary structures are poorly understood because they are covered by Tertiary volcanic rocks. The major structures evident in the study area are related to development of the caldera complex, emplacement of a large batholith beneath the San Juan Volcanic field and to the development of the Rio Grande rift to the east (Fig. 4).

Several structural trends are evident (Plate 1). The most conspicuous structural features are the arcuate east to northeasterly-trending Cornwall Fault and the northwest-trending Summitville-Platoro fault zone. Less obvious trends are a northeast-trending group of small faults and a group of radial faults localized in the Alum Creek area. Development of the Rio Grande depression, to the east, has imposed an eastward tilting of the region toward the San Luis Valley.

CORNWALL FAULT
The Cornwall fault, first described and named by Patton (1917), is the most conspicuous structure in the study area (Plate 1 and Fig. 6). The fault forms the southern ring-fracture zone of the Summitville caldera and truncates the resurgent block of the Platoro caldera. The Cornwall fault may have served as the vent from which the Ojito Creek and Ra
Jadero members of the Treasure Mountain Tuff were erupted (Lipman, 1975). After collapse of the Summitville caldera, the Cornwall fault scarp acted as a barrier wall to the intracaldera flows of the upper member of the Summitville andesite and allowed it to be deposited unconformably against the intracaldera La Jara Canyon Tuff of the Platoro caldera. Following deposition of the Summitville andesite, the fault appears to have localized emplacement of the large Alamosa River stock and several smaller stocks. Post-collapse and post-intrusion movement along the fault is evidenced by a nearly continuous breccia zone across nearly every rock type encountered.

In the area of study, the Cornwall fault is traceable, with difficulty, from Government Park to the ridge crest east of the Alum Creek drainage. From Alum Creek west, the fault is marked by an intensely altered zone of gouge and brecciated rock. The youngest rock disrupted by the fault is the quartz latite of South Mountain. Southwest of Lookout Mountain, the Cornwall fault is lost in talus; however, the fault may converge with the west wall of the Platoro caldera near Sheepshead on Prospect Mountain.

Between Government Park and Telluride Mountain is a subparallel portion of the Cornwall fault. This small, subparallel fault is marked by the juxtaposition of upper Summitville andesite against La Jara Canyon tuff. Most of the fault lies outside the study area, but where it has been
mapped, only an unconformable brecciated contact was recognized between the two rock units.

SUMMITVILLE-PLATORO FAULT ZONE

The Summitville-Platoro fault zone intersects the Cornwall fault at nearly a right angle (Plate 1 and Fig. 2). The Summitville-Platoro fault zone is a portion of the northwest-trending Pass Creek-Elwood Creek-Platoro fault system. The Pass Creek-Elwood Creek-Platoro fault system is a complex fault-graben system that extends from the southern margin of the Mount Hope caldera across the southwestern margin of the Platoro caldera complex. Besides the association to the fault-graben system, the Summitville-Platoro fault zone is of interest because it localized much of the postcollapse igneous activity, associated hydrothermal alteration and mineralization in the caldera complex.

Most of the Pass Creek-Elwood Creek-Platoro fault system lies outside the area of study. However, the eastern-most segment of the Elwood Creek system, the Summitville fault, and the northern segment of the Platoro fault zone pass through the center of the study area. The Summitville fault is a well-defined structure that is traceable from Park Creek, located to the north of the study area, to the Alamosa River, where it merges with and becomes part of the Platoro fault zone, a distance of approximately 22 km (13.7 mi).

At South Mountain, the Summitville fault has been mapped
as a normal fault with a southwesterly dip of approximately 60
degrees (Steven and Ratte, 1960)(Plate 1). However, in the
saddle between Big and Little Red peaks the Summitville fault
dips more steeply to the southwest, 80 degrees, and is a
reverse fault. The change in fault movement is indicated by
approximately 90 m (300 ft) of displacement between rock units
along the fault between the saddle and the Alamosa River. It
is speculated that a fulcrum point served as the center of
rotation allowing the Summitville fault to change from a
normal fault at Summitville to a reverse fault in the study
area. Such a location is visible in airphotos between South
Mountain and Elephant Mountain. A geometrically complex set
of photolinears, lying subparallel and near normal to the
Summitville fault is believed to represent a zone, the fulcrum
point, of extremely faulted and or broken rock at which the
Summitville fault was rotated. This group of photolinears is
only vaguely evident on the ground as they are located in an
area of relative low relief, well developed soil cover, and
encompass an area just under 2.6 km² (≈1 square mile)(Plate
1).

South of the Alamosa River, the Summitville fault merges
with the Platoro fault zone (Plate 1). The Platoro fault zone
is a northwest-trending series of faults that forms the
southernmost portion of the Pass Creek-Elwood Creek-Platoro
fault-graben system. Near Stunner Pass, along a jeep trail
that heads east towards Lily Pond, the graben-fault system has
displaced the contact between the La Jara Canyon tuff and the lower member of the Summitville andesite. Total displacement along this fault is uncertain. However, Lipman (1975) suggests that the displacement is at least 100 m (328 ft).

Minimum age limits on movement along the Summitville-Platoro fault zone are not well constrained by field relations (Plate 1). The latest movement along the Summitville fault displaces flows of the quartz latite of South Mountain and is younger than the Cornwall fault. This relationship is demonstrated in Blair Creek, where a quartz latite dike cuts across the trace of the Cornwall fault without displacement, yet is offset by the Summitville fault. Movement along the Platoro fault zone is younger than the Alamosa River stock and maybe contemporaneous with the Summitville fault. Bird (1972) has suggested that the Summitville-Platoro fault system and perhaps even the Pass Creek-Elwood Creek-Platoro fault zone are post-volcanic expressions of an ancient, possibly Precambrian, structure. While Lipman (1975) suggests that the Summitville fault may have formed during the eruption of the Conejos Formation and is at least older than the La Jara Canyon Tuff, which is juxtaposed to rocks of the Conejos Formation along the fault trace north of the Summitville caldera.

NORTHWEST-TRENDING FAULTS

Within the study area several other faults occur along a
northwest trend, similar to that of the Summitville fault (Plate 1). Mapping along Bitter Creek revealed a fault that extends from Government Park north to the large bend in the creek, southeast of Elephant Mountain. The fault, here informally called the Bitter Creek Fault, appears to consist of two apparently unconnected segments. No evidence of faulting between the two segments could be found. At the northwestern terminations of both fault segments, dikes cut across the trend of the fault without any apparent disruption. The Bitter Creek fault appears to have acted as the northeastern boundary in the localization of the Alamosa River stock, as well as a small cupola of andesite porphyry.

Analysis of air photos covering the study area revealed several photolinears that also have a northwest trend. The longest photolinear is located along the drainage of Iron Creek. This lineament, informally called the Iron Creek fault (Plate 1), closely follows the drainage of Iron Creek from near its junction with the Alamosa River to a point due west of Lookout Mountain, where the lineament trends northwest into Schinzel Flats. The lineament is repeatedly offset by other, generally easterly or northeasterly-trending lineaments. The Iron Creek fault merges with a fault mapped by Lipman (1974) that trends from Schinzel Flats northwestward in an arcuate fashion 8.8 km (5.5 mi) past Elwood Creek and terminates east of the headwaters of Pass Creek. Relative movement along both Lipman's fault and the Iron Creek fault are identical,
downthrown to the southeast. This structural arrangement creates a horst between the Summitville fault and the inferred structure along Iron Creek.

Another northwest-trending photolinear is located west of South Mountain (Plate 1). This linear is traceable from Schinzel Flats towards the western side of Cropsy Mountain where it may link up with a series of short discontinuous north-northwest-trending faults that have been mapped south of Cropsy Mountain, along the eastern and southeastern sides of Lookout Mountain, to just north of the Stunner / Summitville road. Proof of the existence of one continuous fault along this trend is hampered by the presence of landslide debris and talus. Relative movement is unknown.

NORTHEAST-TRENDING FAULTS

A less obvious set of faults and photolinears in the study area have a northeasterly trend (Plate 1). The most continuous fault along this trend controls the Alamosa River drainage from Stunner campground northeast towards the point where the Cornwall fault crosses the river. Along this trend the fault, informally called the Alamosa River fault, is marked by resistant outcrops of silicified and brecciated monzonite and a brecciated quartz vein. Northwest-trending faults of the Platoro fault zone repeatedly offset the Alamosa River fault. Southwest of Stunner campground the trace of the fault is expressed on the surface as linear depressions,
aligned sagponds and controlled drainages.

A series of northeast-trending faults and dikes occur between Bitter Creek and Elephant Mountain. These faults were responsible for localization of the dikes, as well as for the displacement of a dike. Northeast-trending lineaments along the Iron Creek drainage appear to be responsible for offsets of the northwest-trending Iron Creek fault.

RADIAL FAULTS WEST OF ALUM CREEK

Within the Alum Creek drainage a tightly confined system of radial faults occur (Plate 1). These faults are relatively young, as they displace flows of the quartz latite of South Mountain. Displacement of rock units along these faults is probably no greater than 30 m (100 ft). This system of radiating faults may have developed in response to the emplacement of a buried intrusive body, possibly the porphyritic quartz monzonite phase (Tmp^2) at Alum Creek. Hydrothermal solutions channeled along these faults have produced some of the more intensely altered rocks in the drainage. Besides channeling hydrothermal solutions, one of the faults appears responsible for the localization of a small plug of rhyodacite porphyry.

REGIONAL EASTWARD TILTING

Superimposed on the structure and geology of the study area is a regional eastward tilting toward the San Luis Valley.
(Fig. 6), the result of block-fault downdropping and rifting of the Rio Grande depression. North-trending, west dipping normal faults of the depression cut the east dipping volcanics along the eastern margin of the San Juan Mountains. Rifting along the San Luis Valley segment of the Rio Grande depression is believed to have begun in late Oligocene and early Miocene time (29 to 26 Ma) (Lipman and Mehnert, 1975; Chapin and Seayer, 1975; Tweto, 1979) and been recurrently active as young as 4.7 Ma (Lipman et al., 1970).

HYDROTHERMAL ALTERATION

The term hydrothermal alteration refers to those mineralogical and chemical changes that result from reactions of minerals, in rocks, with circulating and diffusing aqueous solutions. Detailed studies of alteration patterns indicate certain mineral assemblages are characteristic of specific alteration zones that reflect the reactions of rocks with aqueous solutions in which cation to H⁺ activity ratios were relatively high, intermediate or low relative to cation (Ca²⁺, Na⁺, Mg²⁺, Fe³⁺ and K⁺) activities.

The classification of alteration mineral assemblages in common use today is that of Meyer and Hemley (1967). Their basic terminology will be followed in this discussion with some modifications according to Hudson (1983) and by the
AUTHOR (Table 1).

**TERMINOLOGY**

In this paper the term "illite" refers to a 1M disordered, nonexpanding, dioctahedral, aluminous, potassic, clay-size (< 0.004 mm) mica-like mineral. By this definition illite can be specified by X-ray diffraction (XRD) techniques. It possesses a basal, d(001), reflection peak, at 10±0.05 Å (measured using the d(002)) reflection and higher order reflections), showing that it is micaceous and suggesting that potassium is the interlayer cation. It has a d(060) reflection at 1.50±0.01 Å, demonstrating that it is dioctahedral and the intensity of the d(002) reflection is greater than the intensity of the d(001) reflection/4, suggesting that it is aluminous. Finally, glycolization of samples of illitic material show no expandable interlayer. The term "sericite" refers to 2M ordered, nonexpanding, dioctahedral, fine-grained muscovite (KAl₂(Si₂Al)O₁₀(OH)₂).

The term "alsic alteration assemblage", as first used by Hudson (1983), is based on the dominance of Al-rich and aluminosilicate minerals that constitute this assemblage. Unlike Hudson (1983), the alsic assemblage has not been separated into two sub-types in this discussion.
### TABLE 1. ALTERATION ASSEMBLAGES

<table>
<thead>
<tr>
<th>Alteration Type</th>
<th>Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propylitic Alteration</td>
<td>Albite, Kaolinite, Montmorillonite, Illite, Chlorite, Epidote, Clinozoisite, Calcite, Quartz, Actinolite, Pyrite, Zeolites, Halloysite</td>
</tr>
<tr>
<td>Argillitic Alteration</td>
<td>Kaolinite, Montmorillonite, Quartz, Mixed Layer Clays, Illite, Pyrite</td>
</tr>
<tr>
<td>Illitic Alteration</td>
<td>Illite, Quartz, Kaolinite, Pyrite, Montmorillonite, Chlorite, Mixed Layer Clays, Sericite</td>
</tr>
<tr>
<td>Sericitic Alteration</td>
<td>Sericite, Quartz, Pyrite, Tourmaline</td>
</tr>
<tr>
<td>Potassium Silicate Alteration</td>
<td>Secondary Biotite, Secondary K-Spar, Quartz, Tourmaline, Pyrite, Cordierite, Anhydrite, Chlorite</td>
</tr>
<tr>
<td>Alunitic Alteration</td>
<td>Alunite, Quartz, Pyrite, Diaspore, Zunyite, Kaolinite, Topaz, Pyrophyllite</td>
</tr>
<tr>
<td>Alsic Alteration</td>
<td>Pyrophyllite, Diaspore, Quartz, Andalusite, Corundum, Pyrite, Zunyite, Lazulite, Topaz, Hematite</td>
</tr>
<tr>
<td>Silicification</td>
<td>Quartz, Pyrite</td>
</tr>
<tr>
<td>Siliceous Alteration</td>
<td>Cristobalite, Chalcedony, Amorphous Silica, Alunite, Kaolinite</td>
</tr>
</tbody>
</table>

*Minerals in all CAPITALS are characteristic of the assemblage. Capitalized are common, and uncapitalized are accessory (after Hudson, 1983).*
INTRODUCTION

Hydrothermally altered rocks within the study area occur within a much larger, roughly east-west-trending, belt of hydrothermally altered rocks (Fig. 2). This band of alteration begins around the Elwood and Crater Creeks area, west of the Summitville caldera, and extends eastward past the town of Jasper to the Cat Creek area, beyond the eastern edge of the caldera complex (Lipman, 1974). The entire belt of alteration is approximately 41 km (25.5 mi) long and as much as 6.7 km (4 mi) wide. The study area is located roughly in the center of the belt at its widest location.

Within the area of study, the most intensely altered rocks lie within a broad zone of alteration that stretches from west of Sheepshead, to east of Elephant Mountain and north from the Alamosa River towards Cropsy Mountain where it merges with the alteration about Summitville (Plate 2). Although the most intensely altered rocks are roughly centered on the Alum Creek intrusive phase, the intrusive is most probably not responsible for all the hydrothermal alteration observed throughout the study area. Other intrusives in the immediate area, both exposed and buried, developed coalescing alteration haloes that form the observed alteration pattern.

The various alteration types show a crude distribution progressing outward from a central sericitic zone into zones of illitic, argillic, alsic, alunitic, siliceous and propylitic alteration which is gradational into weakly propylitized
or fresh rock (Plate 2). In cross section (Plates 3 and 4) the zonation is more complex, due to limited exposure afforded by drill holes, yet similar zoning of the alteration assemblages has been observed.

Boundaries between alteration types were determined by field observations, thin sections and X-ray analysis of selected rock samples. Alteration overprinting occurs near the boundaries and to some degree within all the alteration zones.

PROPYLITIC ALTERATION

Propylitic alteration or propylitization is a term applied to the mineral assemblages that form under conditions where relatively few H⁺ ions are consumed and generally little or no removal or addition of Na⁺, Ca⁺⁺, Mg⁺⁺, Fe⁺⁺, or K⁺ cations occurs. The major changes that occur are cation exchanges, the addition of H₂O to form hydrous phases, such as chlorite, epidote and montmorillonite and the addition of CO₂ to form calcite and sulfur to form pyrite.

Within the study area (Plates 2, 3, and 4), the assemblage of minerals that constitute the propylitic assemblage is slightly different for every rock type (Fig. 18). The groundmass and mafic minerals in the propylitized rocks are typically the most strongly altered. However, some common mineral transitions occur. Chlorite after biotite is by far the most common transition seen in the propylitized
rocks. Biotite phenocrysts are also selectively altered, in trace amounts only, to either montmorillonite, kaolinite and or illite. Mafic minerals such as augite and hornblende are chloritized to a lesser extent than biotite. Plagioclase is typically altered along rims, microfractures and Ca-rich zones to calcite-epidote-clinozoisite-montmorillonite-traces of sericite and kaolinite. Sanidine and orthoclase are typically unaffected. Magnetite, when present, has usually been converted to pyrite (Fig. 19).

The propylitic assemblage is the second-most common alteration suite in the study area. Propylitic alteration is typically found peripheral to the more intense alteration types. Propyliticly altered rocks can often be found as discrete blocks within the more intensely altered areas of the study area and probably represent zones of rock that were not well fractured, thus were not as open to migrating hydrothermal fluids.

According to Seki (1972), Elders et al., (1978 and 1979), McDowell and Elders (1983), and McKibben and Elders (1985) the first appearance of epidote in modern geothermal systems occurs around 230-250°C. Thus, the first appearance of epidote in outcrop or drill core may suggest the location of a ≥230°C paleoisotherm boundary. The first noted appearance of epidote in drill holes at Alum Creek were so scattered as to prohibit a straight forward analysis of a possible paleoisotherm boundary. Following is a listing of drill holes that
Figure 18. Photograph of selected propylitized rocks from the Alum Creek area.
Figure 19. Photograph of typical propylitic alteration assemblage. Altered rock is the Alamosa River stock in which the plagioclase (P) has been partially altered to epidote (E), contains minor to weak illite / sericite throughout and calcite (C) adjacent to the phenocrysts; biotite has been altered to chlorite (CH). Sample AAC-4-394.5'.

0.05mm
contain epidote and its first occurrence:

<table>
<thead>
<tr>
<th>Drill hole</th>
<th>Footage</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC-1</td>
<td>1170'</td>
</tr>
<tr>
<td>AAC-2</td>
<td>2462'</td>
</tr>
<tr>
<td>IDC-1</td>
<td>1700'</td>
</tr>
<tr>
<td>IDC-2</td>
<td>1595'</td>
</tr>
<tr>
<td>AC-1</td>
<td>2695'</td>
</tr>
</tbody>
</table>

**ARGILLIC ALTERATION**

Argillic alteration is the most common alteration type in the Alum Creek area. The argillicly altered rocks throughout the area of investigation (Plates 2, 3, and 4) are readily identified in the field by the presence of abundant kaolinite-montmorillonite-mixed layer clays (illite and montmorillonite) and to a lesser extent by secondary quartz, with minor amounts of pyrite-illite and trace amounts of dickite and halloysite (Fig. 20). Argillized rocks from the study area generally have a strongly altered groundmass and moderately altered phenocrysts (Fig. 21). Alteration in the groundmass is typically quite extensive and gives the rock a general "dusty" appearance in thin section. Sanidine and orthoclase are generally unaffected, but may have weak kaolinite or illite development along rims or microfractures. Plagioclase can be weakly to strongly altered to kaolinite-montmorillonite-illite-mixed layer clays. Biotite sites are strongly altered to montmorillonite-mixed layer clays-illite. Development of
Figure 20. Photograph of selected argillized rocks from the Alum Creek area.
Figure 21. Photomicrograph of typical argillic alteration assemblage. Altered rock is the quartz monzonite of the Alum Creek phase in which the plagioclase (P) phenocryst have been pervasively altered to illite (I) and kaolinite (K) + montmorillonite (M)(dark gray patches). Biotite (B) (and augite) phenocrysts have been altered to illite. Within the groundmass quartz (Q) and orthoclase (O) are unaltered while the remainder of the groundmass consists of kaolinite, montmorillonite, illite and secondary quartz. Sample AAC-2-2222."
secondary quartz in the groundmass and phenocrysts is not uncommon.

Formation of the argillic alteration assemblage in rocks from the study area occurred under increasingly more acidic conditions. The major compositional changes in the rocks was the removal of Ca\(^{2+}\), Na\(^+\) and some Mg\(^{2+}\). Montmorillonite formation requires relatively weak acidic conditions and less cation leaching, than does kaolinite formation. Kaolinite formation requires a greater degree of leaching, more acidic conditions and relatively low SiO\(_2\) activity.

ILLITIC ALTERATION

In the illitic assemblage typical of the study area (Fig. 22);(Plates 2, 3 and 4), plagioclase is almost totally replaced by illite and secondary quartz with minor kaolinite ± traces of mixed layer clays, montmorillonite and or sericite (Fig. 23). Orthoclase and sanidine are commonly altered to illite ± trace sericite along rims and microfractures. Chlorite after biotite and mafic minerals is strongly altered to illite. Groundmass minerals are generally more severely altered than the phenocrysts and in extremely altered samples the entire texture of the rock may be obliterated.

Illitic alteration at Alum Creek is believed to represent a transitional alteration assemblage between the argillic and sericitic alteration assemblages. The assemblage consists
Figure 22. Photograph of selected illiticly altered rocks from the Alum Creek area. Note bleached nature of the feldspar phenocrysts that have been altered to illite + quartz.
Figure 23. Photomicrograph of typical illitic alteration assemblage. Altered rock is the Alamosa River stock in which plagioclase phenocrysts have been variably altered to illite (I) and secondary quartz (Q). Biotite (B) phenocrysts have been altered to a coarser illite mass. Dark gray patches are probably kaolinite (K) and opaques are pyrite (py). Sample LOM-169.
primarily of illite, quartz and pyrite but minerals common to
the argillic and sericitic assemblages are not uncommon. The
illitic alteration assemblage, as defined here and used in the
study area, generally occurs between the argillic and ser­
icitic assemblages. Unlike the widespread argillic alteration
the illiticly altered rocks are rather strongly restricted to
that region surrounding the Alum Creek porphyry (Tmp^2). This
might imply that the formation of the alteration assemblage
is, at least, somewhat temperature dependant.

This same transition, argillic through illitic to
sericitic, is noted in modern day geothermal fields. Work
done by Elders (1978) at the Cerro Prieto geothermal field has
shown that at approximately 150-180° C both montmorillonite
and kaolinite are destroyed and illite content increases
dramatically. Similar work by McDowell and Elders (1983) at
the Salton Sea geothermal field has shown that a transition
from interlayered illite/smectite clays to illite occurred
between 190° and 280° C.

Brindley (1980) has shown that higher temperature K-micas
(i.e., sericite) commonly have orderly and repeatable vertical
stacking sequences, whereas lower temperature K-micas (i.e.,
illite) have a disordered stacking of the layers. Work done
by Yoder and Eugster (1955) supports this data by showing that
a transition from 1M (illite-like) to 2M (sericite-like)
structured K-micas occurs between 200° and 350° C at 15,000
psi water pressure.
SERICITIC ALTERATION

Sericitic alteration in the study area (Fig. 24) (Plates 2, 3 and 4) consists almost exclusively of sericite, secondary quartz and pyrite (Fig. 25). Minor to trace amounts of illite and kaolinite can be present. Typically plagioclase is strongly altered to sericite + quartz. Orthoclase and sanidine are commonly altered to sericite. Chlorite, after mafic minerals, is typically converted to a more coarse grained sericite. As with the illitic assemblage, sericitic alteration is more thoroughly developed in the groundmass than in the phenocrysts and intense seritization normally destroys original rock textures.

Sericiticly altered rocks, in the Alum Creek study area, tend to be more restricted in their distribution than the argillicly altered rocks. Like the illiticly altered rocks the sericiticly altered rocks are strongly localized about the Alum Creek porphyry (Tmp2) with the exception of a large area centered on Big Red peak.

POTASSIUM SILICATE ALTERATION

Potassium silicate (Potassic) alteration in the study area occurs as locally restricted zones, as small as 2 - 3 in (5-7.5 cm) across to lengths of core several feet (< 1m) long, of disseminated secondary biotite, weak to moderate secondary K-spar formation in the groundmass and as rare secondary K-spar selvages associated with quartz stockwork veinlets.
Figure 24. Photograph of selected sericiticly altered rocks from the Alum Creek area. Note bleached phenocrysts are feldspar phenocrysts altered to sericite and quartz.
Figure 25. Photomicrograph of typical sericitic alteration assemblage. Altered rock is the quartz monzonite of the Alum Creek phase in which plagioclase phenocrysts have been pervasively altered to masses of sericite (S) with minor secondary quartz. Biotite (B) phenocrysts are altered to coarser grained sericite masses. Groundmass consists of quartz (Q), scattered sericite and disseminated pyrite (py). Sample IDC-3-1521.
(Fig. 26). The potassium silicate alteration assemblage occurs only rarely in the study area and is only easily recognized in drill core. Either the potassic alteration assemblage was never extensive in its formation or it was largely overprinted by the illitic and sericitic assemblages. For this reason, the potassium silicate alteration assemblage is not shown on any of the alteration maps or cross sections.

Work done by Elders and others (1978, 1979) indicates that the first occurrence of hydrothermal biotite in the Cerro Prieto geothermal field corresponds to the 315°C isotherm. The first appearance of hydrothermal biotite in outcrop or drill core therefore may suggest the location of a 315°C paleoisotherm boundary. Listed below are the first noted occurrences of hydrothermal biotite in drill holes:

<table>
<thead>
<tr>
<th>Drill hole</th>
<th>Footage</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC-1</td>
<td>2090'</td>
</tr>
<tr>
<td>AAC-2</td>
<td>471'</td>
</tr>
<tr>
<td>IDC-1</td>
<td>1700'?</td>
</tr>
<tr>
<td>IDC-2</td>
<td>1225-1245'</td>
</tr>
<tr>
<td>IDC-3</td>
<td>2160'</td>
</tr>
</tbody>
</table>

As in the attempt with epidote, the first noted occurrence of secondary biotite is so scattered that defining a clear cut paleoisotherm boundary is not possible, provided the limited drill hole data.
Figure 26. Photomicrograph of Alamosa River stock monzonite containing secondary biotite (B) typical of the potassium silicate alteration assemblage associated with the Mo + Cu porphyry system at Alum Creek. Sample IDC-1-1845'.

Figure 26 shows a photomicrograph of Alamosa River stock monzonite containing secondary biotite (B) typical of the potassium silicate alteration assemblage associated with the Mo + Cu porphyry system at Alum Creek. Sample IDC-1-1845'.
ALUNITIC ALTERATION

The alunitic alteration exposed in the study area (Fig. 27); (Plates 2, 3, and 4) developed under near-surface conditions, at the expense of all other alteration assemblages. Development of the alunitic alteration assemblage results from extreme cation leaching under acidic conditions resulting in a mineral assemblage of alunite, quartz, pyrite and one or more of the following minerals: kaolinite, diaspore, zunyite or pyrophyllite. Potassium is most probably derived from the rocks rather than from the addition of K⁺ in hydrothermal solutions. Sulfate ions needed for the formation of alunite are produced from the mixing of oxygen-rich, near surface, meteoric water with H₂S-rich hydrothermal fluids derived from depth. The association of quartz and alunite is a result of extreme cation leaching of silicate minerals and subsequent release of amorphous silica (Hall, 1982).

In outcrop, alunitized rock appears as strongly iron stained and resistant masses. Alunite is easily identified, with hand lens, by the sparkle of light reflected off of the numerous fine grained platlets. In thin section (Fig. 28), alunite appears as felty or herringbone-textured masses throughout the rock. Original rock textures are generally thoroughly destroyed; although feldspar sites can be identified by the crude rectangular aggregate masses of alunite which replaced them. Minor to trace amounts of topaz, zunyite, jarosite, kaolinite and pyrophyllite can also be
found associated with alunite.

Alunitic alteration is largely confined to two major rock types; the upper Summitville andesite and the quartz latite of South Mountain (Plate 2). The texture destroying nature of alunitic alteration makes identification of the two units difficult. Upon closer inspection, the presence of quartz-eye phenocrysts, which only occur in the quartz latite, help to distinguish between the severely altered rocks.

The greatest amount of aluniticly altered rocks in the study area occurs about Lookout Mountain. The distribution of the alunitic alteration, in this area, appears to indicate that the erosion surface about hill 2053 and just underneath the rhyolitic cap rock of Lookout Mountain was very near the paleo-water table if not near the paleo-surface. The distribution of aluniticly altered rocks further down the southern slope of Lookout Mountain is believed to reveal the encroachment of a more acidic alteration assemblage on to underlying argillic and propylitic assemblages. The Cornwall fault zone was most probably the zone of weakness along which descending acidic fluids travelled.

ALSIC ALTERATION

In the study area, the alsic alteration assemblage is an overprinting style of alteration (Fig. 29); (Plates 2 and 3). Evidence of sericitic, illitic, argillic or alunitic alteration often exists within the more dominant alsic alteration.
Figure 27. Photograph of selected alunitically altered rocks from the Alum Creek area. Note that the light pink to white alunite forms veins and breccia fillings and replaces feldspar phenocrysts.
Figure 28. Photomicrograph of the upper member of the Summitville andesite exhibiting typical texture destroying nature of the alunitic alteration assemblage. Rock consists dominantly of alunite (Al) and quartz (Q). Large mass of alunite in the lower left of the photograph may have been a feldspar phenocryst. Sample LOM-118t.
Alsicy altered rocks in the study area are limited to regions about fault zones, pathways for descending fluids.

As with the alunitic alteration, presence of pyrite is considered proof of hypogene origin of the assemblage and unaltered quartz-eye phenocrysts distinguish the altered quartz latite flows from the andesitic flows. The presence of alsic alteration in outcrop is not as easily determined in the field as is alunitic alteration. The presence of pyrophyllite may be inferred from the presence of a brilliant white, soapy feeling, talc-like clay in the rocks. X-ray diffraction and thin section analysis were the only methods useful in absolutely determining the presence of minerals of the alsic assemblage. In thin section (Fig. 29 and 30), abundant pyrophyllite, quartz, diasporie, pyrite with minor to trace amounts of zunyite and topaz signify the alsic alteration assemblage. Like alunitic alteration, the original texture of alsicy altered rocks is largely destroyed.

SILICIFICATION

Silicification about the area of investigation (Plates 2, 3 and 4) is closely associated with structures and zones of high permeability. Silicification results in the near total obliteration of the original rock texture (Fig. 31). Original rock minerals, with the exception of quartz itself, are replaced by quartz. Pyrite is the only major accessory mineral associated with silicification. Other minerals,
Figure 29. Photograph of selected rocks that exhibit alsic alteration from the study area. White material filling voids is pyrophyllite.
Figure 30. Photomicrograph of alsicly altered the upper member of the Summitville andesite. White masses are pyrophyllite (Pyr) in a sea of quartz + alunite (Q+Al). Highly birefringent mineral in pyrophyllite is diaspore (D) and angular voids are zunyite (Z). Sample LOM-137.
Figure 31. Photograph of selected silicified rocks from the Alum Creek area. Note "vuggy-silica" alteration of Tsq and Tsu.
noted to occur in trace quantities, are kaolinite, alunite, illite, topaz, rutile, cristobalite and diaspore. These other minerals are believed to be the remnant minerals of earlier alteration assemblages, rather than accessory minerals of silicification.

Silicification implies mineral dissolution and replacement by quartz rather than simple deposition of silica. Silicification requires both silica metasomatism and extreme cation leaching of not only alkalis but aluminum (Beane et al., 1981).

SILICEOUS ALTERATION

Formation of the siliceous alteration assemblage requires dissolution of the original rock constituents by highly acidic fluids and replacement by cristobalite and or lesser amounts of amorphous silica and quartz. Replacement by cristobalite is envisioned to occur in a style similar to that of silicification but at near-surface temperatures and pressures.

The siliceous alteration assemblage is formed by downward percolation of water and sulfuric acid created by the oxidation of \( \text{H}_2\text{S} \) above the water table, as at Steamboat Springs, Nevada (Schoen et al., 1974). Descending acidic waters leach nearly all of the original rock constituents. As with silicification, cristobalite and amorphous silica replace most of the original minerals of the rock. Cristobalite is the major alteration mineral and along with primary quartz
constitutes nearly 100 percent of the resulting rock mineralogy; minor to trace amounts of alunite and kaolinite are rare accessory minerals.

Unlike silicification, siliceous alteration in the study area is not as conspicuously associated with structural features (Plates 2 and 4). Highly permeable zones, such as flow breccias or strongly fractured rock, appear to be the most susceptible to siliceous alteration. As with silicification, siliceous alteration replaces all of the original rock constituents, except quartz (Fig. 32 and 33). Original rock textures are normally destroyed, however, in one instance, the original rock textures and color tones of breccia fragments were preserved despite total replacement by cristobalite.
Figure 32. Photograph of selected siliceously altered rocks of the Alum Creek area.
Figure 33. Photomicrograph of the quartz latite of South Mountain that exhibits typical siliceous alteration. Cristobalite (Cr) has replaced the vast majority of the groundmass and infilled voids; original quartz is unaffected. Pyrophyllite (Pyr) has replaced the feldspars and limonite stain marks the sites of destroyed pyrite grains. Sample LOM-125.
INTRODUCTION

Metal distribution throughout the study area, as with the alteration discussed earlier, is most probably related to the emplacement of the porphyritic quartz monzonite (Tmp²) in Alum Creek. Metals distributed by the quartz monzonite are evident as disseminated sulfides, quartz stockwork Cu - Mo veinlets, proximally and distally zoned anomalous metals and quartz veins with varying amounts base and precious metals. Hydrothermal fluids emanating from other intrusive bodies, both exposed and buried, are probably responsible for additional metals and remobilization of previously deposited metals.

METAL ZONATION

Anomalous Cu, Mo, Pb, Zn, Au, Ag, F, Sn and W geochemical values have been found over a large area of altered rocks in the study area. Metal zoning patterns are based on more than 1100 rock chip samples collected by Inspiration Development Company and Amoco Minerals Company geologists along an established grid pattern. Elements analyzed for were: Cu, Mo, Pb, Zn, Au, Ag and F with spot analysis for As, Bi, Mn, Sb, Sn and W. Analysis of these elements was by standard methods: Cu, Pb, Zn, Mo, Ag, Au and Bi by atomic absorption, W and As by colorimetry, Sb and Sn by X-ray fluorescence and F by specific
ion. Limits of detection, in ppm, were: Cu (1), Pb (1), Zn (1), Mo (1), Ag (0.1), Au (0.005), Bi (0.2), W (1), As (2), Sb (1) and F (100). Threshold or background and anomalous values of the various elements, selected for discussion, were determined by the graphical methods of Lepeltier (1969) and Sinclair (1974 and 1981).

PYRITIC ZONE

Anomalous metal values in the study area are largely encompassed within an extensive pyritic zone. The pyritic zone is defined as an area containing approximately two to seven volume percent pyrite, with locally high concentrations of as much as 15 volume percent, contained in rocks as disseminations or in quartz stockwork veinlets (Fig. 34).

Within the pyritic zone, erratic anomalous tin (10-40 ppm), tungsten (10-45 ppm), Manganese (800-8100 ppm), arsenic (2-350 ppm), antimony (2-28 ppm) and bismuth (1-28 ppm) values occur, however the erratic nature of their distribution and limited number of samples precludes the zoning of these elements.

MOLYBDENUM

The distribution of anomalous molybdenum values (>20 ppm) occur within a tightly confined area (Fig. 35). The most significant concentration of Mo is localized on the Alum Creek intrusive phase and along the adjacent segments of the Corn-
Figure 34. Map showing the extent of the pyritic zone, ≥ 5 volume % pyrite, in altered rocks surrounding the Alum Creek area.
Figure 35. Map showing the distribution of molybdenum in rocks about the study area, contour intervals are in ppm.
wall and Summitville faults. The major concentration of anomalous Mo is spatially associated with the sericitic, illitic and inner argillic alteration assemblages. Anomalous Mo is also most strongly associated with quartz veinlet stockwork zones.

Calkin (1970) reported selected 0.9 kg (2 lbs) samples from the Alum Creek area that assayed 0.22 and 0.33 percent MoS$_2$. Sixteen surface samples from the study area, collected by Amoco Minerals Company and Inspiration Development Company, had values that range in excess of 0.20 percent MoS$_2$ and as high as 0.91 percent MoS$_2$. Cumulative drill hole intercepts of anomalous Mo averaged 0.084 percent MoS$_2$ over 691.3 m (2,268 ft) in three drill holes. One drill hole, AAC-4, intercepted 151.8 m (498 ft) of mineralized rock that averaged 0.212 percent MoS$_2$, with an internal higher grade zone that averaged 0.452 percent MoS$_2$ over 48.7 m (160 ft).

Molybdenum occurs in quartz + Mo ± pyrite ± Cu stockwork veinlets, as moly-paint along joints and fractures and as disseminated grains (Fig. 36).

COPPER

The distribution of anomalous copper values (>20 ppm) (Fig. 37) reveals that the greatest concentration of high values are centered on the Alum Creek intrusive phase and to the east-northeast along the trace of the Cornwall fault. Anomalous Cu values also occur in a crudely developed shell
Figure 36. Photograph of typical quartz - sulfide stockwork veining from the Alum Creek area.
Figure 37. Map showing the distribution of copper in rocks within the study area. Contour intervals are in ppm.
surrounding the central area of coincident anomalous Cu and Mo. The distally distributed Cu is separated from the core region by a conspicuous zone of non-anomalous Cu values.

Anomalous Cu values occur across nearly all rock types and alteration types. The higher concentrations of Cu do tend to be spatially associated with the sericitic, illitic and to a lesser extent the argillic alteration assemblages about the Alum Creek intrusive. However, the anomalous Cu values surrounding this core area tend to be more strongly associated with argillic alteration and to a lesser extent the propylitic and alunitic assemblages. The association of anomalous Cu values with the alunitic alteration localized about the south end of Lookout Mountain may actually be an association of Cu with the Cornwall fault system that passes through the area.

Chalcopyrite, enargite, covellite and chalcocite have been observed in quartz-pyrite veinlets in surface and drill core rock samples. Ore grade Cu surface geochemical values were rarely obtained, however, one surface rock chip sample contained 0.61 % Cu. The highest concentration of Cu found in drill hole intercepts occurred in hole IDC-1 where 30.5 m (100 ft) of 0.36 % Cu was encountered. Average cumulative Cu content, from drill hole intercepts, was 0.20 % Cu.

LEAD

Anomalous lead values (>100 ppm) tend to be more randomly distributed than do Cu or Mo (Fig. 38). While a small zone of
Figure 38. Map showing the distribution of lead in rocks within the study area; shaded regions denote areas of ≥ 100 ppm lead.
anomalous Pb occurs centered on the Alum Creek intrusive the two largest concentrations of Pb, as with the majority of the Pb, occurs some distance from the intrusive. The largest concentration of anomalous Pb is strongly correlatable with the distribution of the quartz latite flows centered on Big and Little Red peaks. Other smaller lead anomalies do appear to have a spatial association with dikes or small intrusive bodies of the porphyritic quartz latite. This association is not at all unusual, as the composite quartz latite dome at South Mountain, that hosts an acid-sulfate Au-Cu ore body, also has an associated lead anomaly. Less obvious, are the series of smaller satellitic anomalies of Pb that fall along the trend of the Summitville fault. Anomalous lead values do not appear to be strongly associated with any particular alteration type.

Galena was observed only rarely in surface samples but was more abundant in drill core samples. The largest concentration of Pb occurred in drill hole AAC-1 where 50.3 m (165 ft) of 0.012 % Pb was encountered.

ZINC

Anomalous zinc values (>100 ppm) occur within discretely confined northern and southern zones (Fig. 39). A much smaller zinc anomaly does occur along the west side of the Alum Creek intrusive. The various zinc anomalies are not directly correlatable to any particular rock type or structure
Figure 39. Map showing the distribution of zinc in rocks within the study area. Shaded regions denote zone of ≥ 100 ppm zinc.
but do tend to occur within a crude circular zone about the intrusive center and largely within propylitized rocks. Anomalous zinc values do appear to be distributed outside of the central Mo-Cu zone centered on the Alum Creek intrusive.

Neither sphalerite nor any other zinc-bearing minerals have been noted in any surface samples. However, in drill core sphalerite has been observed in association with galena and chalcopyrite in quartz-pyrite stockwork veinlets. The largest concentrations of anomalous Zn in drill holes tend to occur above the zone of anomalous Mo. However, in drill hole AAC-4 the zone of anomalous Zn occurs with the zone of anomalous Mo.

GOLD

The distribution of anomalous gold values (≥10 ppb) across the study area indicates a strong relationship to structures and rock type. Both the Summitville and Cornwall fault zones are strongly correlated to zones of anomalous gold as are porphyritic quartz latite intrusives and flows (Fig. 40). Whereas the magnitude of the Au anomalies do not compare to those of Summitville, they are significant for the area because of their strong correlation to structures, rock type and their confined distribution.

In drill core and on the surface, anomalous gold values (115 - 960 ppb) were found associated with the porphyritic quartz latite dikes, plugs and flows, especially in the area
Figure 40. Map showing the distribution of gold in rocks within the study area; contour intervals are in ppb.
of the inferred volcanic vent at Big and Little Red. Two large quartz veins encountered in drilling had anomalous gold assays, 3.55 ppm (.11 o/t) and 63.9 ppm (1.98 o/t), as well as anomalous silver, copper, lead and zinc values.

SILVER

Anomalous silver values (>1 ppm) occur over a large area (Fig. 41) but do not appear to have been localized about any particular structure, rock or alteration type. However, like Zn and Cu, silver appears to concentrate outside of the Alum Creek area. The obvious separation of anomalous Ag from Au and Pb may suggest that Ag is associated with the distal metal distribution style of a porphyry system and not associated with the possible Au-Pb system centered on Big Red. Two large quartz veins encountered in drilling had anomalous silver values in assay, 55.5 ppm (1.72 oz/T) and 143 ppm (6.6 oz/T). Minor amounts of pyrargyrite (Ag$_3$SbS$_3$) have been found on several of the small mine dumps along the Alamosa River and several strands of wire silver were found in a small prospect in the head waters of Bitter Creek.

FLUORINE

Fluorine is widely distributed throughout the study area (Fig. 42) ranging in value from 600 to >10,000 ppm but does not appear to have been localized about any particular structure, rock type or alteration type. A strong negative
Figure 41. Map showing the distribution of silver in rocks within the study area; shaded regions denote zone of $\geq 1$ ppm silver.
Figure 42. Map showing the distribution of fluorine in rocks within the study area; contour intervals are in ppm.
correlation exists between fluorine and the large northwest-trending quartz latite porphyry dike where fluorine values are well below background (600 ppm). Low fluorine values about the dike may be due to actual low fluorine content of the dike or to fluorine being driven away during emplacement of the dike.

In drill core, fluorine content averaged better than 1450 ppm and in drill hole AAC-4 the fluorine content averaged 2230 ppm over 335.3 m (1100 ft). Fluorite has been observed, in thin section, as a vein filling mineral in drill core but has not been observed in surface samples. Fluorine-bearing topaz and zunyite occur as alteration minerals and could account for some of the anomalous F.

**DISCUSSION**

The elevated Cu, Mo, Pb, Zn, Ag, Au and F values that are spatially distributed throughout the study area appear to form a crude zonation about the Alum Creek intrusive. At the center of this regional zonation pattern is the Alum Creek intrusive with localized high concentrations of Cu and Mo. Anomalous concentrations of Pb and Zn are also found adjacent to this central core area. Immediately outside of the core area, anomalous concentrations of metals are almost non-existent with the exception of F and to a limited extent Pb. Fluorine is present in anomalous quantities virtually throughout the area sampled. Peripheral to the metal-poor zone
exists the outer zone of elevated concentrations of Cu, Pb, Zn and Ag. Distribution of the various elements within and about the porphyry system, present at Alum Creek, is the result of the physical and chemical conditions at the time of emplacement. Obviously, conditions were favorable for the deposition of Cu, Pb, Zn and Ag further away from the intrusive center. Whereas, Mo and some Cu, Zn and minor Pb located favorable environments within or immediately adjacent to the intrusive center. Unfavorable conditions for metal sulfide, other than pyrite, deposition obviously existed outside of the inner zone where there is a noticeable absence of Mo, Cu, Zn and Ag.

Concentrations of anomalous Au values are located largely outside the inner zone, are strongly associated with the Summitville fault and with the intrusives and flows of the South Mountain quartz latite in the region of Big and Little Red peaks. Because these features are younger than the Alum Creek intrusive phase (Tmp²) the distribution of Au and possibly the coincident Pb anomaly localized about the quartz latite is believed to have formed later than the Mo-Cu porphyry system. The gold in this area may represent redistribution of gold from the porphyry system however, anomalous gold values have not been found elsewhere in the study area. The strong association of gold and the quartz latite dikes and flows in the study area and at Summitville strongly indicate that the anomalous gold was probably derived from the porphyritic quartz latite and not from the nearby porphyry
system.

In a study conducted by the U.S. Geological Survey Sharp and Gualtieri (1968) analyzed more than 200 samples of altered rock from the Alum Creek area for Pb, Mo, Cu, Zn, Au and Ag. The methods and limits of detection for these elements were not disclosed except for Au and Ag, which were 0.5 and 0.1 ppm respectively. Anomalous Pb, Mo, Cu and Zn values were determined to exist in the area.

In comparing Sharp and Gualtieri's metal distribution plots with the plots of anomalous Pb, Mo, Cu and Zn from this study, discrepancies in the distribution of these various metals were noted. This can be attributed to a number of factors, such as sample population, sampling density, sampling bias, differing analytical methods and differing background values based on different sample populations. For example, Sharp and Gualtieri collected more than 200 samples whereas more than 1100 were utilized in this study. Sharp and Gualtieri collected primarily intensely altered samples along widely spaced traverses. Samples collected for use in this study were obtained, every 200 feet, along surveyed grid lines, spaced 500 feet apart. Neither gold nor silver were detected by Sharp and Gualtieri's analytical method, whereas both Au and Ag were detected because of the sensitive analytical methods used in this study. Differing background values for copper and molybdenum in this study resulted from analyzing a sample population greater than five times as large.
AGE OF MINERALIZATION

Disseminated and quartz stockwork Mo-Cu mineralization is spatially associated with the Alum Creek intrusive phase (Fig. 37). The temporal association with the intrusive would seem apparent given the strong association of intense alteration assemblages, stockwork veining and anomalous metal content of the intrusive. Neither the associated alteration nor the parent magma has been radiometrically dated.

The mineralized Alum Creek intrusive phase is clearly intrusive into the older Alamosa River stock (Tm), dated at 29.8 ± 1.2 m.y. The Lookout Mountain phase (Tmp3), which intrudes the Alum Creek phase, has been radiometrically dated at approximately 23.6 m.y. (23.7 ± 0.6 and 23.5 ± 2.5 m.y.) (J.W. Blake, oral communication, 1981).

Whereas this line of evidence indicates that emplacement of the Alum Creek phase and mineralization occurred between approximately 29.8 ± 1.2 m.y. and about 23.6 Ma, it does not establish a firm date. Field relationships, however, suggest that mineralization and associated alteration are probably closer to the younger age limit of 23.6 million years because:

1.) the similar compositional and textural relationships of the Alum Creek phase to the approximately 23.6 m.y. old Lookout Mountain phase.

2.) the intrusive style of emplacement of the Alum Creek phase into the Alamosa River stock, including evidence of magmatic stoping, radial fracturing and the
development of stockwork and quartz veining due to brittle fracturing radiating from the porphyry (Tmp2) into the monzonitic stock would indicate that the monzonite was quite cool at the time of intrusion.

3.) radial fractures emanating from and possible due to the emplacement of the Alum Creek porphyry (Tmp2), offset flows of the quartz latite of South Mountain (23.5 ± 0.6 to 20.4 ± 1.0 m.y.)(Perkins and Nieman, 1982 and Mehnert et al., 1973). Thus, suggesting that emplacement was post-South Mountain quartz latite in age.

ALTERATION AND MINERALIZATION MODEL

Porphyry Cu ± Mo systems, while bearing differences from one another, have some common characteristics. Some of these characteristics are:

1.) A zonal distribution of alteration shells and mineralization centered on, calc-alkaline stocks.

2.) Emplacement of stocks from ≤ 1-3 km (≤ 1.5-5 mi) below the surface.

3.) Isotopic data (Sheppard et al., 1969; Sheppard, 1971) indicating that meteoric water was the dominant water type involved in the formation of the propylitic, argillic and outer sericitic alteration envelopes.
While the potassic and inner sericitic alteration zones were dominated by magmatic water.

4.) Fluid inclusion data (Nash, 1976; Roedder, 1971) demonstrating that the outer, meteoric dominated region developed at temperatures of 350°C or less involving weakly saline solutions. The innermost alteration assemblages and associated mineralization formed involving highly saline solutions at temperatures between 350° and 700°C.

If porphyry Cu-Mo deposits are emplaced and formed at depths of 1-3 km, if most of the fluids circulating through the hydrothermal system are meteoric in origin and if submagmatic temperatures and excess heat flow are maintained close to the surface for thousands of years (Cathles, 1977), than some style of hydrothermal activity must have been expressed on the paleosurface, not unlike what has been observed about modern geothermal areas.

Lowell and Guilbert (1970), Rose (1970) and White et al.,(1971) were among the first to describe the possible connection between modern and ancient geothermal systems and the hydrothermal systems developed about porphyry systems. These authors suggested that porphyry-style mineralization and alteration resulted from circulating meteoric and connate fluids about a magmatic heat source. Sillitoe (1973) modified the above model by suggesting that mineralization was the result of late-stage magmatic evolution.
Cathles (1977) demonstrated that a self-supporting, vapor-dominated zone is commonly formed above intrusive plugs with cooler condensed water overlying a steam zone and a zone of boiling below that. Within the boiling zone, a two-phase zone where vapor and water coexist, vapor is driven up into the overlying vapor dominated zone and the remaining magmatic liquid becomes more saline due to partitioning of KCl, NaCl and other alkali chlorides.

Henley and McNabb (1978) formulated a conceptual model of mineralization and alteration development based on the formation of a magmatic vapor plume above a calc-alkaline stock. The magmatic vapor plume model appears to best explain the alteration and mineralization found in the study area.

Formation and development of a vapor plume in the Alum Creek study area is conceptualized to have occurred in the following manner. Shortly after emplacement, ground water convection systems were established and crystallization of the outer margins of the intrusive Alum Creek phase began (Fig. 43). As the outer margins crystallized, a saline aqueous phase, consisting of water, H₂S, SO₂, alkali chloride and metal chloride complexes, not incorporated in the crystallization of the minerals comprising the intrusive, were partitioned out. Due to density differences (Burnham, 1979), this saline aqueous phase accumulated at the top of the stock just below an impermeable carapace. At near magmatic temperatures, the hydrostatic pressure created by the saline aqueous phase
Figure 43. Schematic section of a hypothetical calc-alkaline stock and the initial ground water convection system established upon emplacement.
exceeded the tensile strength of the confining carapace as well as lithostatic pressure of the overlying country rock resulting in the failure and hydrofracting (Whitney, 1975). Release of the aqueous phase into the myriad of fractures created by hydrofracturing resulted in lowering of fluid pressures in the fractures and the carapace. Lowered fluid pressures caused more of the water saturated interstitial melt to crystallize ("pressure quench") and partition out even more of the saline aqueous solution. Pressure quenching of the zone below the carapace caused crystallization and carapace formation to retreat progressively into deeper levels of the stock (Burnham, 1979). Fluid pressure build-up, hydrofracturing and continued carapace retreat, due to pressure quenching, probably continued until the saline solutions were completely partitioned out or fluid pressures were too low to overcome the confining pressure and escape.

Upon release, from below the carapace, the saline aqueous fluids rapidly migrated upward along the myriad of newly forming fractures. Once under less confining pressures, and at submagmatic temperatures (700°C) the saline fluid began boiling and a vapor phase began separating from the saline fluids. Vapor partitioning of the fluid resulted in formation of a low density, chloride-poor, gas-rich vapor phase and a high density, chloride-rich liquid phase. Because of differences in surface tension, the vapor occupied the fractures while the liquid migrated into confining fractures and pore
spaces. The newly formed low density vapor phase began displacing the established ground water convection system and established a stable, self-supporting, vapor-dominated plume (Henley and McNabb, 1978).

Above the vapor-dominated plume, a water saturated zone formed (White et al., 1971) that inhibited the escape of most of the rising vapor. Formation of clay minerals and cooler condensed water, in the water saturated zone, are suspected of clogging most of the pore spaces and channels and impeding vapor escape (Fig. 44).

The high density saline liquid phase was restricted to a region below the vapor-dominated plume and about the upper-most portion of the stock, largely because of liquids lower buoyancy relative to gas. This liquid-dominated zone within the plume was a zone of boiling where liquid and vapor coexisted. During the partitioning of vapor from the saline aqueous phase, the vapor was preferentially enriched in $\text{H}_2\text{S}$, $\text{SO}_2$, $\text{CO}_2$ and other volatiles. The liquid was preferentially enriched in $\text{NaCl}$, $\text{KCl}$, $\text{CaCl}_2$, $\text{MgCl}_2$ and other metallic chloride complexes (Henley and McNabb, 1978). As more vapor escaped upward, the saline liquid became more concentrated in dissolved solids and evolved into a brine.

The liquid dominated zone was continuously enriched in dissolved solids through recharge from the hydrothermal system. Magmatic aqueous fluids, rich in alkali and metallic chloride complexes, were periodically introduced following
Figure 44. Schematic section illustrating features of the magmatic vapor plume model following hydrofracturing and establishment of the vapor plume.
rupture of the stocks carapace. In addition, circulating ground water containing dissolved solids from the country rocks were continuously being mixed along the outer margins of the liquid-dominated zone. As these fluids boiled off, dissolved solids were residually concentrated. The resulting condensate percolated downward along the cooler outer margins of the vapor-dominated plume and was mixed into the liquid-dominated plume.

Eventually, as the stock cooled and less magmatic saline fluids were introduced into the plume, greater amounts of ground water were progressively mixed in through lateral dispersion along its boundaries causing the plume to cool (Henley and McNabb, 1978). With increased ground water mixing, the magmatic component of the vapor-dominated zone eventually was overwhelmed and began collapsing. Soon after, the liquid-dominated zone cooled and released its metallic components, sulfur and halogens, etc., to the ground water dominated dispersion system (Fig. 45).

Formation of the observed alteration assemblages at Alum Creek can be attributed to the formation and collapse of a magmatic vapor plume. $\text{SO}_2$, the dominant sulfur species exsolved from magmas into the aqueous phase, was strongly partitioned into the vapor-dominated zone of the magmatic plume along with other volatiles (Burnham, 1979). As the vapor-dominated portion of the plume mixed with cooler ground water, a source of $\text{H}^+$, $\text{H}_2\text{S}$ and $\text{H}_2\text{SO}_4^-$, excess $\text{H}^+$ ions were
Figure 45. Schematic section illustrating the late stage characteristics of the vapor plume model, the resulting distribution of alteration types and mineralization and the levels of exposure in the Alum Creek study area. Note alteration levels below the sericitic zone (bold dashed lines) are exposed in drill holes only.
available resulting in increased H⁺ ion activity (acidic conditions). Thus, the highest H⁺ activities tended to occur along the outer margins of the plume and about large fractures, the zones of greatest mixing. Therefore, higher H⁺ concentrations were encountered at and inside the boundaries of the plume. Alteration assemblages stable under these acidic, higher H⁺/cation ratios, conditions (argillic, illitic and sericitic) began forming. The propylitic assemblage, formed under low H⁺/cation ratios, probably resulted from the interaction of wall rocks and heated meteoric water. The propylitic assemblage likely formed well outside the plume boundaries and within the zone of convecting ground water.

Potassium silicate alteration and the innermost portion of the sericitic alteration envelope is regarded, as indicated by isotopic data, as the remnant imprint of the magmatic plume on the ground water regime (Henley and McNabb, 1978). Within the liquid-dominated core zone of the plume, H⁺/cation concentration ratios are low because of the limited mixing with ground water and the partitioning of NaCl, KCl, MgCl₂, FeCl₂, etc. into the liquid phase. With increasing K⁺ activity, relative to H⁺ activity, sericite and eventually orthoclase could become stable. At Alum Creek K⁺ ion concentrations apparently were not sufficient to produce K-spar in abundance. Instead, hydrothermal biotite became the dominant stable potassic alteration mineral.

Because of intermixing of cooler meteoric water, de-
creased magmatic input and crystallization of the stock the magmatic plume gradually collapsed. As the plume collapsed and the convecting ground water system encroached, the concentration of H⁺ ions increased with depth and a progressive downward overprinting of the more acidic alteration assemblages occurred.

At near-surface conditions and relatively low pressure the water saturated cap, heated by the underlying vapor-dominated zone of the magmatic plume would begin boiling. During boiling H₂S would be partitioned into the vapor phase (Hedenquist, 1983) and condensation of the rising vapor in an oxidizing environment would produce an increase in the activity of H⁺.

Under near-surface conditions acid alteration assemblages (siliceous, alunitic and alsic) began forming and overprinting the initial propylitic alteration assemblages. Downward percolating acidic waters probably created leached rock at and below the surface and caused the formation of alunite at and below the water table.

The concentration, distribution and deposition of metals at Alum Creek could have also been controlled by the development and collapse of a magmatic vapor plume. According to Henley and McNabb (1978) and Eastoe (1982) concentration and transportation of ore metals within the magmatic vapor plume is conceptualized to occur as simple chloride or oxide complexes or as alkali metal chloride complexes.
At submagmatic temperatures, metals are thought to be strongly partitioned into the high density brine of the magmatic plume as simple metal chloride \((\text{Me}_x\text{Cl}_y)\) or metal oxide \((\text{MeO}_x)\) complexes. High-temperature mixing of the chloride complexes with halide salts, in the liquid dominated zone, could result in the formation of alkali metal chloride complexes \((\text{NaMe}_x\text{Cl}_y\) or \(\text{KMe}_x\text{Cl}_y)\). Alkali chloride species enhance the capability of transport by vapor of some metal oxide–water systems (Eastoe, 1982). For example, molybdenum may be transported in vapor as \(\text{Mo}_7\text{O}_{18}\text{(OH)}_6\).

With development of a long-lived magmatic plume metals can be concentrated in the high density brine for ore formation. Relatively low concentrations of metal values are partitioned in the low density vapor and carried upward.

At Alum Creek, partitioning of various metal and alkali complexes into the vapor or liquid-dominated phases could explain the metal distribution observed in the system. According to Henley and McNabb (1978), a high molybdenum content of the liquid-dominated zone would account for localization of molybdenum preferentially in the core region whereas copper and other metals migrate at high concentrations towards the core margins or beyond. This may account for the separation of Cu from Mo as well as the separation, or zonation, observed between various metals at Alum Creek.

Ore mineral deposition most likely occurred as a result of decreasing temperature and the resulting increase in \(\text{H}_2\text{S}\).
Upon mixing with meteoric water, H$_2$S becomes the dominant sulfur species and the magmatic plume cools. In the presence of H$_2$S, the alkali metal chloride, metal chloride and metal oxide complexes become unstable and sulfides precipitate.

\[
\text{Me}_x\text{Cl} + \text{H}_2\text{S} = \text{Me}_{x/2}\text{S} + \text{Y HCl}
\]

\[
\text{NaMe}_x\text{Cl} + \text{H}_2\text{S} = \text{Me}_{x/2}\text{S} + \text{HCl} + \text{NaCl}
\]

The pyritic halo found about the Alum Creek system may have formed during plume collapse as Fe chloride and alkali chloride complexes, in the condensate of the vapor-dominated phase, became unstable, dissociated and precipitated pyrite. In addition, magnetite and other Fe-rich minerals (biotite, hornblende, etc.) probably contributed to the formation of pyrite upon their breakdown.

**FLUID INCLUSIONS**

Studies by Roedder (1971), Nash (1976) and other workers have demonstrated that a zonation of fluid inclusion types exists within porphyry Cu and Cu-Mo deposits. Nash (1976) recognized three major inclusion types associated with porphyry Cu and Cu-Mo deposits:

- **Type I:** liquid-dominated, moderately saline (0-23 weight percent NaCl equivalent) with rare daughter minerals, and trace amounts of CO$_2$(g).
Type II: vapor-dominated, weakly saline (0.4-7 weight percent NaCl equivalent) and minor to trace amounts of CO$_2$(g).

Type III: liquid and vapor in variable amounts, highly saline (40-60 weight percent NaCl equivalent), commonly with daughter minerals and 3-30 mole percent CO$_2$(g).

Type III inclusions are closely associated with the zone of economic mineralization commonly enclosed within the potassium silicate and inner sericitic alteration shells. Type II inclusions are not closely associated to any particular alteration assemblages but do commonly coexist about and within the zone of type III inclusions. Type I inclusions are not closely associated with either type II or III inclusions but are associated with the largely meteoric water dominated alteration assemblages. Type I inclusions, have lower filling temperatures (200°-400°C) than type II and type III inclusions (400°-700°C) formed largely from magmatic-dominated fluids.

The zonation of the various inclusion types described by Roedder (1971) and Nash (1976) has been observed in thin sections of drill core from the study area (Fig. 46 and 47). Such a zonation of stacked inclusion types would be expected if the hydrothermal system at Alum Creek developed along the magmatic plume model. Highly saline type III inclusions would be expected to form within the deeper regions of the system where high density, saline-rich brines could be captured.
Figure 46. Photomicrograph of typical type I (top) and type II (bottom) fluid inclusions from the Alum Creek study area. Bar is common to both photographs. Samples AAC-1-2301' (top) and AAC-1-1801' (bottom).
Figure 47. Photomicrographs of typical type III fluid inclusions found in stockwork quartz veinlets from the Alum Creek study area. Both inclusions are type III inclusion with vapor (v), halite (h), sylvite (s), hematite (hm) and unknown (u) phases. Bar is common to both photographs. Samples IDC-3-1933’ (top) and IDC-1-3140’ (bottom).
Type II inclusions would be expected to form higher in the system where the exsolved vapors, driven off by the partitioning of the magmatic aqueous phase into liquid and vapor dominated phases, would be most plentiful. As the plume cooled and collapsed, type II inclusions would form at lower and lower levels gradually encroaching on and overprinting the zone of type III inclusions. With increased cooling and further collapsing of the plume type I inclusions which would be expected to form on the outer fringes of the vapor plume where the saline condensate created through the mixing of meteoric water and vapor could be trapped, would eventually overprint type II and III inclusions as more ground water was incorporated into the plume.

In thin section the stacking and overlapping of inclusion types is quite noticeable. Type III inclusions are found in greatest abundance within the zone of Cu-Mo mineralization localized in the sericitic and potassium silicate alteration assemblages. Type II inclusions occur with type III inclusions; they are however, most commonly found within later stage quartz veinlets crosscutting type III-bearing quartz veinlets. Type II inclusions tend to be concentrated within a zone lying immediately above and about the type III zone and are most strongly associated with the inner-most argillic, the illitic, and outer-most sericitic alteration zones. Type I inclusions are the most abundant inclusion type observed and tend to be the dominant inclusion type within the propylitic
and argillic phases. Type I inclusions can also be found associated with all other alteration and inclusion types. When observed with type II and III inclusions, type I inclusions tend to occur in later or the latest stage veins.

Primary fluid inclusions, in primary quartz and secondary alteration and vein quartz, observed in thin section from the study area were too small, averaging 0.007 mm in longest dimension, for use on the available freezing/heating equipment. Therefore, determinations of pressure, temperature and salinity were not possible. However, it was possible to derive some information from inclusions observed in thin sections.

Extinction angles, indices of refraction and crystal habit were employed to determine the identity of daughter minerals from type III inclusions. Halite and hematite occur as common daughter minerals. Sparse sylvite daughter minerals occur and calcite and anhydrite (?) are rare daughter minerals. Some type III inclusions contain as many as four unknown daughters in addition to those identified.

Estimations of type III inclusion salinities were made based on visual measurements of inclusion and daughter mineral dimensions and volume and density calculations. The halite cubes occupied between 4 and 35 volume percent of the inclusion and sylvite crystals, present in many of the inclusions, occupied between 0.3 and 10.5 volume percent. Salinity estimations based on calculated volume percents and
the densities of known phases (i.e., NaCl, KCl, H₂O, vapor, etc.) ranges from about 34 to 87 (averaging about 56.3) equivalent weight percent NaCl, assuming no KCl in solution. Estimations of KCl range between 21 to 39 (averaging about 25.7) weight percent.

CO₂-rich inclusions (type IV, Nash, 1976) were not observed in any thin sections from the study area. However, the presence of calcite as both an alteration mineral and as a possible daughter mineral in the fluid inclusions may indicate that CO₂ exists in the inclusions.

DISCUSSION AND RECOMMENDATIONS

DISCUSSION

In attempting to classify the porphyry system at Alum Creek, characteristics of the system were compared to other porphyry Mo and porphyry Cu-Mo deposits. The classification scheme listed in table 2 proposes two basic subdivisions for porphyry molybdenum systems, following Mutschler et al., (1981), Westra and Keith (1981) and White et al., (1981). Another source of molybdenum, and the third class in table 2, are the porphyry Cu-Mo deposits that yield molybdenite as a by-product (Clark, 1972).

Climax-type molybdenum deposits are characterized by multiple, complex intrusive phases of high silica, alkali-rich
rhyolite and/or granite porphyry stocks (Carten et al., 1988). Molybdenum ore occurs as quartz + molybdenite + fluorite stockwork veinlets that form characteristic multiple, inverted cup ore bodies. Ore grades average 0.3 to 0.45 percent MoS$_2$, with recoverable amounts of tungsten and tin also present. The alteration zonation surrounding the ore bodies is unique to Climax-type deposits. The five major zones of alteration associated with these deposits are: a core potassium silicate zone with overlying sericitic and argillic assemblages, an underlying argillic phase and a surrounding propylitic assemblage envelope. Five minor alteration zones overlap and crosscut boundaries of the major alteration zones. These zones are the vein silica, pervasive silica, magnetite-topaz, greisen and garnet zones (White et al., 1981).

Quartz monzonite-type porphyry molybdenum deposits are genetically related to small composite stocks or late phases of batholiths of quartz monzonite or granite composition, derived from calc-alkaline or high-K calc-alkaline magmas (Westra and Keith, 1981; White et al., 1981). Ore bodies consist of tabular or inverted cup shaped zones of stockwork quartz + molybdenite ± pyrite ± chalcopyrite veinlets. Molybdenite is the dominant ore mineral and ore grades average 0.1 to 0.2 percent MoS$_2$. Minor chalcopyrite and scheelite occur in some deposits, but is not a common by-products of these deposits.

Alteration about the quartz monzonite-type deposits is
similar to porphyry copper deposits. A potassium silicate core with associated mineralization is overlain and surrounded by sericitic, argillic and propylitic alteration assemblages. Westra and Keith (1981) contend that, based on Cu and Mo contents of the deposits, Rb and Sr ratios and whole-rock geochemistry of associated igneous rocks, a continuum exists between quartz monzonite Mo deposits through Cu-Mo deposits to porphyry Cu deposits. Some quartz monzonite-type Mo deposits, such as Nevada Moly and Mount Tolman, are characterized by a central molybdenite core with overlapping or peripheral copper zones (White et al., 1981).

Porphyry Cu-Mo deposits are, in fact, porphyry copper deposits with sufficiently high molybdenite content to warrant its recovery. Porphyry Cu-Mo deposits are spatially and temporally related to granodiorite or quartz monzonite bodies. Ore bodies are generally tabular or inverted cup shaped zones of pyrite, chalcopyrite and other copper sulfides in stockwork veinlets or as disseminated grains. Molybdenum content averages around 0.02 percent MoS$_2$, with some South American deposits averaging nearly 0.05 percent MoS$_2$ (Titley and Beane, 1981). Alteration zonation about porphyry Cu-Mo deposits is similar to that of porphyry Cu and quartz-monzonite-type Mo deposits.

In comparing the characteristics of the Alum Creek prospect to the three major molybdenum producing porphyry systems (Table 2), it is obvious that Alum Creek most closely
TABLE 2: Characteristics of molybdenum and Cu-Mo porphyry deposits compared to the Alum Creek prospect.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Climax-Type</th>
<th>Quartz Monzonite Type Mo-Cu</th>
<th>Porphyry Cu-Mo</th>
<th>Alum Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coenetic Rock Type</strong></td>
<td>Rhyolite - Granite porphyry</td>
<td>Quartz monzonite porphyry</td>
<td>Granodiorite - Quartz monzonite porphyry</td>
<td>Quartz monzonite porphyry</td>
</tr>
<tr>
<td><strong>Intrusive Phases</strong></td>
<td>multiple</td>
<td>composite intrusions of diorite to quartz monzonite</td>
<td>composite intrusions of diorite to quartz monzonite</td>
<td>composite intrusions of quartz monzonite</td>
</tr>
<tr>
<td><strong>Intrusive Type</strong></td>
<td>stock</td>
<td>stock or batholith</td>
<td>stock or batholith</td>
<td>stock</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td>mid - late Tertiary</td>
<td>Mesozoic and Tertiary</td>
<td>Pre-Laramide, Laramide and early</td>
<td>mid - Tertiary &gt;23.5±2.5 m.y.</td>
</tr>
<tr>
<td><strong>Orebody Type</strong></td>
<td>stockwork</td>
<td>stockwork</td>
<td>stockwork</td>
<td>stockwork</td>
</tr>
<tr>
<td><strong>Orebody Shape</strong></td>
<td>inverted cup or tabular</td>
<td>inverted cup or tabular</td>
<td>inverted cup or tabular</td>
<td>unknown</td>
</tr>
<tr>
<td><strong>Ore % MoS₂</strong></td>
<td>0.3 - 0.45</td>
<td>0.1 - 0.2</td>
<td>0.012 - 0.07</td>
<td>0.084(avg)-0.212(hi)</td>
</tr>
<tr>
<td><strong>Grade % Cu</strong></td>
<td>0.01 - 0.08</td>
<td>0.2 - 1.2</td>
<td>0.2 (avg) - 0.36 (hi)</td>
<td>0.06(avg)-0.212(hi)</td>
</tr>
<tr>
<td><strong>Orebody Tonnage (million tons)</strong></td>
<td>50 - 1000</td>
<td>50 - 1000</td>
<td>20 - 1000</td>
<td>unknown</td>
</tr>
<tr>
<td><strong>Important Elements</strong></td>
<td>Mo-F-Sn-Zn-Pb-Cu or Mo-Cu-(W)</td>
<td>Mo-Cu-(W)</td>
<td>Cu-Mo-Ag-Au-Pb-Zn</td>
<td>Mo-Cu-F-Ag-Pb-Zn</td>
</tr>
<tr>
<td><strong>Maximum F Content (%)</strong></td>
<td>0.5 - 2.0</td>
<td>0.1 - 0.25</td>
<td>0.04 - 0.4</td>
<td>0.15 - 0.22</td>
</tr>
<tr>
<td><strong>Multiple Orebodies</strong></td>
<td>common</td>
<td>no</td>
<td>uncommon</td>
<td>unknown; but doubtful</td>
</tr>
<tr>
<td><strong>Alteration</strong></td>
<td>pot-ser-arg-prop+garnet+quartz+silica+topaz+greisentoarg</td>
<td>pot-ser-arg-prop</td>
<td>pot-ser-arg-prop</td>
<td>pot(Ser)-ser-illarg-prop</td>
</tr>
<tr>
<td><strong>Examples</strong></td>
<td>Colorado: Climax, Urad-Henderson, Mt. Tom</td>
<td>British Columbia: Endako, Boss Mountain, Kitimat, Admire</td>
<td>Utah: Bingham</td>
<td>Nevada Moly</td>
</tr>
<tr>
<td></td>
<td>New Mexico: Questa</td>
<td>Alaska:</td>
<td></td>
<td>Data from: White et al., 1981</td>
</tr>
<tr>
<td></td>
<td>Montana: Mt. Tolman</td>
<td></td>
<td></td>
<td>Neave and Keith, 1981</td>
</tr>
<tr>
<td></td>
<td>Idaho: Thompson Creek</td>
<td></td>
<td></td>
<td>Brookstrom, 1981</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Giles and Thompson, 1983</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Matsueller et al., 1981</td>
</tr>
</tbody>
</table>
resembles the quartz monzonite-type molybdenum or copper-molybdenum deposits. The alteration zonation and types, cogenetic rock type, and other characteristics are nearly identical between the two deposit types and the Alum Creek system. The molybdenite content of the Alum Creek area more closely resembles that of the quartz monzonite-type Mo systems. However, the copper content of the prospect far exceeds the content typically found in such deposits. In comparison to the porphyry Cu-Mo deposits, the Cu grade at Alum Creek (0.20 percent) matches that of the lowest average grade found in these types of deposits, but it also possesses an above average MoS₂ grade. The metals of important value to the porphyry Cu-Mo deposits are similar to those metals of apparent importance at Alum Creek. Unlike the quartz monzonite-type Mo systems, the Alum Creek system has significant concentrations of Au, Ag, Pb and Zn but appreciable concentrations of tungsten do not exist. Since a minable ore deposit has not been defined at Alum Creek, the elements listed in Table 2 are those that appear to be of sufficient concentration to warrant interest as valuable metals.

The Alum Creek system is believed to be a hybrid variety of the quartz monzonite-type molybdenum deposits. It may be best defined as a Cu-rich quartz monzonite molybdenum porphyry system, since it possesses MoS₂ grade mineralization similar to the quartz monzonite Mo deposits and Cu mineralization similar in grade to porphyry Cu-Mo deposits (Fig. 48).
Figure 48. Hypogene copper and molybdenum grades in select porphyry deposits. Some deposits are shown more than once, reflecting different cutoff grade limits. Alum Creek grades, as listed in Table 2, reflect combined average grade of drill hole intercepts based upon cutoff grade limits of 0.1% Cu and 0.05% MoS₂. Modified from Westra and Keith (1981).
Other mineralized porphyry Cu and Mo systems exist throughout the San Juan Mountains (Fig. 49). Some of these systems, such as Crater Creek, Chicago Basin and Red Mountain (Lake City), closely resemble Alum Creek in style of alteration, mineralization and intrusive rock type. Other porphyry systems, such as Summitville, Wilson Peak and the Matterhorn Peak area, also resemble aspects of Alum Creek but are more Cu-rich, possibly Cu ± Mo or Cu porphyry-type systems.

The Crater Creek area is a large area of altered and mineralized rock just west of Alum Creek. Locally restricted zones of disseminated molybdenite and chalcopyrite occur within a more widespread zone of disseminated and veinlet pyrite (Brock et al., 1985; Neuerberg, 1978; Neuerberg et al., 1978; Connor, 1975). Quartz veins in the area, up to 0.3 m (1 ft) contain pyrite, galena, sphalerite and chalcopyrite. Anomalous values of Mo, Cu, Pb, Zn, Ag and Au occur in the area. Monzonitic and quartz monzonitic intrusives, similar in composition and possibly contemporaneous in age with the intrusives at Alum Creek intruded, altered and mineralized flow and vent facies rocks of the Conejos Formation. Spatially associated with the intrusives and controlled by northwest-trending structures hydrothermal alteration is zonally distributed about a sericiticly altered core progressing outward through propylitic and chloritic alteration into unaltered country rock.
Figure 49. Map showing the location of other porphyry systems discussed within or adjacent to the San Juan volcanic field. Chicago Basin (CB), Wilson Peak (WP), Red Mountain (RM), Matterhorn Peak (M), Summitville (S), Crater Creek (CC) and Alum Creek (AC).
The Chicago Basin stock, a zonally altered and mineralized composite granitic stock showing many aspects of a porphyry molybdenum system is located in the Needle Mountains, a domal uplift of Precambrian rocks, in the southwest portion of the San Juan Mountains. The oldest porphyry body, radiometrically dated at 10.1 ± 1.1 m.y. (Schmitt and Raymond, 1977) is a granite porphyry that is zonally altered and locally mineralized with molybdenite. Alteration zonation consists of a sericitic core grading outward into an illitic zone, a weak argillic zone and a propylitic zone, with an overlying and overlapping alsic assemblage consisting of dickite and pyrophyllite. Anomalous amounts (mean) of Ag (2.39 ppm), As, Au (0.066 ppm), Cu (33.2 ppm), F, Mo (111.8 ppm), Pb (90.5 ppm), Sb, Sn and Zn (83 ppm) coincide with areas of intense sericitic alteration in the stock. Quartz-pyrite veins emanating from the area of the stock contain anomalous amounts of Ag, As, Au, Ba, Bi, Cd, Mo, Sb, Sn and W, in addition to abundant Cu, Pb, and Zn (Steven et al., 1969). A younger and essentially unaltered and unmineralized rhyolite porphyry, radiometrically dated at 9.0 ± 0.9 m.y. (Schmitt and Raymond, 1977) intrudes the older granite porphyry. The Chicago Basin stock has been drilled by American Metals Climax, Inc. intercepting 0.03% MoS₂ from 0 - 152 m (0 - 500 ft); 0.01% MoS₂ from 152 - 244 m (500 - 800 ft); and insufficient MoS₂ to test for from 244 - 305 m (800 - 1000 ft) in one drill hole (Schmitt and Raymond, 1977).
Red Mountain, 5.6 km (3.5 mi) south of Lake City, is an intensely altered porphyritic quartz latite lava dome that is locally mineralized with molybdenite. This dome was emplaced along the eastern ring fracture of the Lake City caldera (Steven et al., 1977). It has not been radiometrically dated, however the dome is younger than the Sunshine Peak Tuff, and older than adjacent quartz latite lavas in the moat of the caldera, both of which have been dated at about 23.1 ± 0.6 m.y. (Mehnert et al., 1973). Disseminated alunite and vein alunite from the dome has been radiometrically dated at 22.9 ± 1.9 and 23.3 ± 1.1 m.y. (Mehnert et al., 1979). Molybdenite occurs as disseminations within quartz-pyrite stockwork veinlets associated with a sericiticly altered core region. Surrounding the core region is a zone of argillic alteration and an extensive overlying alunitic zone. Metals also show a zonation about the intrusive center with Mo and Pb strongly associated with the intrusive and the sericitic alteration whereas Cu and Zn occur in higher concentrations outside of the Mo-Pb zone.

The Wilson Peak stock, located in the northwestern San Juan Mountains, is the site of a composite stock that intruded Cretaceous age Mancos Shale and Tertiary age Telluride Conglomerate and volcanic rocks. The stock is composed of, in order of intrusion, a fine-grained granogabbro, an equigranular granodiorite and a porphyritic quartz monzonite (Bromfield, 1967). Anomalous amounts (mean) of Au (0.86 ppm),
Ag (3 ppm), Cu (7553 ppm), Mo (34 ppm), Pb (34 ppm) and Zn (98 ppm) are associated with the sericitically altered quartz monzonite (Bromfield et al., 1972). Disseminated chalcopyrite occurs in the quartz monzonite, in fractures and stockwork veinlets, as well as in quartz-pyrite veins, along with Au, Pb and Zn, that are associated with the intrusive center.

Another intrusive center similar in style to the Wilson Peak stock occurs on the north side of Matterhorn Peak, in the northern San Juan Mountains. At Matterhorn Peak a porphyritic monzonite intrusive is surrounded by altered and pyritized andesitic volcanics and is the locus of anomalous amounts (mean) of Cu (70 ppm), Pb (350 ppm) and Mo (22.5 ppm) and trace amounts of Au, Ag and Zn (Steven et al., 1977). Widespread anomalous metal values and pervasive alteration and pyritization may represent the upper portions of a disseminated porphyry Cu or Cu-Mo deposit.

At South Mountain, near Summitville, a composite dome, of porphyritic quartz latite, hosts Cu-rich gold deposits with associated anomalous amounts of Pb, Zn, Ba and Ag (Perkins and Nieman, 1982). During the late 1970's and the early 1980's Asarco, Inc. explored the porphyry Cu potential of the Summitville area. It was thought that the alteration and mineralization found near the surface was representative of the upper levels of a much deeper buried porphyry Cu system (personal communication Bob Casecelli, 1986). Even though the Alum Creek study area is only 4.33 km (2.7 mi) south of
Summitville the only anomalous Mo found in the Summitville area occurs about the entrance of the New French Mine. Even though Alum Creek and Summitville formed in similar volcanotectonic environments within the same caldera there is probably as much as 4 million years difference in their ages, (29.8 ± 1.2 - 23.7 ± 0.6 Ma versus 23.5 ± 0.6 - 20.4 ± 1.0 Ma) significantly different intrusives were evolved at each site, and formed different styles of mineralization.

Many obvious differences between these other systems and Alum Creek exist yet similarities also exist. Different levels of exposure in the Alum Creek system can be envisioned in the current levels of exposure at the various other systems discussed. For example, the upper-most, near surface portions of Alum Creek may have resembled something similar to Summitville or to Red Mountain (Lake City). The Crater Creek area appears to resemble the mid-level portions of Alum Creek (alteration and mineralization) and may be a less completely exposed Alum Creek equivalent. Of all the porphyry-type systems described within the San Juan Mountains Chicago Basin most closely resembles Alum Creek. Although rock types are different (granite porphyry versus quartz monzonite porphyry), intrusive history, alteration zonation and style of mineralization are similar.
RECOMMENDATIONS FOR FUTURE STUDY AND EXPLORATION

Many other aspects of geologic study about the Alum Creek area exist. While a number of rock units in the region have been age dated several units, several members of the Treasure Mountain tuff, the Summitville andesite, the Alum Creek porphyry, the rhyodacite porphyry and the andesite porphyry. In addition, the alteration about the Alum Creek area has never been dated. Dating of the secondary biotite may be helpful in establishing the timing of the Mo-Cu porphyry development. Dating of the alunite about with Lookout Mountain and Little Red may be helpful in determining if the high-level alteration noted there is related to the emplacement of the Alum Creek porphyry or to a different event.

Compilation of the rock chip geochemistry from about the Summitville area combined with that about the Alum Creek area may reveal a considerable amount of information concerning the regional metal distribution. This information should be available within the archives of the various mining companies that have been active in the area.

Areas for future mineral exploration exist in the Alum Creek area, too. Anomalous gold concentrations in the area, coincident with anomalous lead as at Summitville, are spatially associated with the Summitville and Cornwall faults, Big and Little Red peaks and the quartz latite porphyry plug in Alum Creek. Whereas the gold values are very low, they are
anomalous and are clearly associated with structures and intrusives similar to those at Summitville. Gold at Summitville is associated with northwest-trending dilatent structures, in the quartz latite composite dome, parallel to the Summitville fault. Gold bearing structures at Summitville were exposed by glacial erosion (Patton, 1917), possibly the single most important factor leading to the successful discovery of ore bodies in the district.

The Big and Little Red area lies within a structurally downdropped triangular block and may represent a preserved, mineralized volcanic vent, similar to South Mountain. The Summitville fault passes through the Big and Little Red peaks area and quartz-alunite and vuggy silica alteration similar to that found at Summitville is present along traces of the fault zone.

The extensive zone of alunite-bearing rock present around Lookout Mountain holds potential for utilization as a source of low-grade aluminum ore, potassium sulfate and sulfuric acid. However, alunite must compose at least 30 volume percent of the rock, with microcrystalline quartz as the principle gangue, to be considered as a potential ore. Other gangue minerals, such as cristobalite or clays and mica, in more than minor quantities would render the ore uncommercial because of high losses of \( \text{Al}_2\text{O}_3 \) and caustic soda, which are used in the leaching process (Hall, 1982).
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