**REPORT No. 218**
GEOLOGICAL SURVEY OF JAPAN

# MOLYBDENUM MINERALIZATION AT QUESTA MINE. NEW MEXICO, U.S.A.

## —An importance of degree of magmatic fractionation for molybdenum concentration to form an ore deposit—

By

Shunso Ishihara

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Konosuke SATO, Director

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## Abstract

Molybdenum mineralization associated with hydrothermal alteration occurs at the Questa mine on the western slope of the Taos Range of the Sangre de Cristo Mountains in Taos County, northern New Mexico. Flows, tuffs, and breccias, andesitic, latitic-quartz latitic, and rhyolitic in composition, are extruded on a base of Precambrian metamorphic rocks. Dikes or plugs of monzonite-quartz monzonite, and stocks of granite and aplite accompany the effusive rocks. The igneous activities were happened in the lower Miocene.

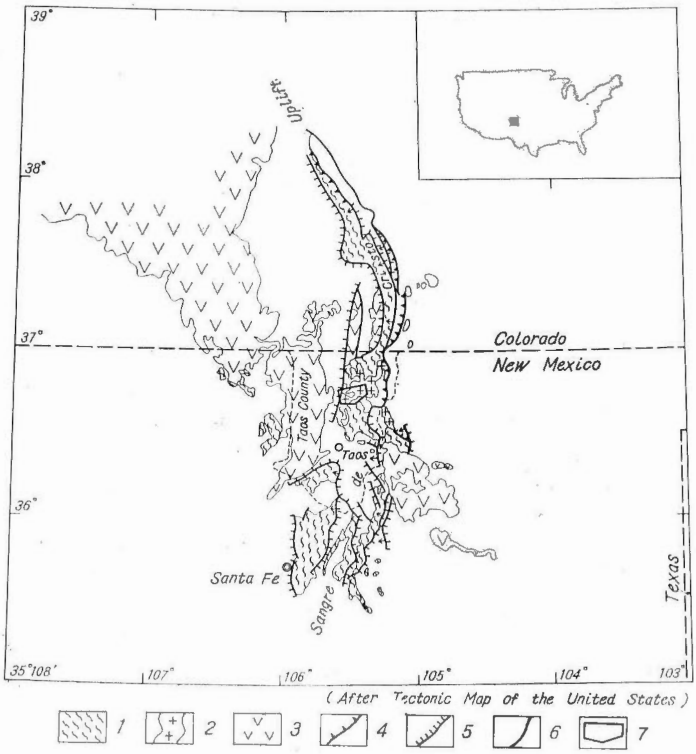
Among these intrusives, molybdenum mineralization is mostly brought by a stock-type intrusion of the most fractionated, the Questa Mine aplite. The Questa deposits are along the west flank of the aplite stock. Molybdenite mainly occurs in veins and fractures with quartz, sericite, and pyrite, and small amounts of biotite, carbonates, fluorite, sphalerite, chalcopyrite, and galena.

## I. Introduction

This is a result of the author's interest in molybdenum deposits. The study of such deposits was started in 1959, when he was working at the Geological Survey of Japan and investigated the most productive molybdenum area in Japan. In summer of 1962 and 1963 the author had an opportunity to work with a molybdenum deposit in the United States of America. The work, consisting of claim evaluation, and geological and geochemical exploration for the Molybdenum Corporation of America, was conducted under the direct supervision of Professor Robert H. Carpenter who was the adviser of the author at the Colorado School of Mines in the 1961 academic year. About seven months in total were spent in the field work.

The major parts of this present report were submitted as a thesis for the degree of M. A. at Columbia University under the sponsorship of Professor Chas. H. Behre, Jr. (ISHIHARA, 1964). After the author returned to the Geological Survey of Japan, he added some data of chemical analyses and absolute age determination. He has concentrated in descriptive and chemical petrology through his work; it is then emphasized an importance of degree of magmatic differentiation for concentration of molybdenum to form an ore deposit (ISHIHARA, 1966). It has been also in his mind local fracture systems to settle molybdenum from ore solution – "structural control"; however, this is not as important now as in the initial stage of the mine's operation around 1930. The present molybdenum price, with a large scale mining operation, is high enough to mine out whole mineralized zone instead of only high grade veins.

**Location:** The Questa molybdenum mine (locally called the "Moly Mine") is located on the western slope of the Taos Range of the Sangre de Cristo Mountains, Taos County, New Mexico (Figure 1). The mill, camp, haulage adit, and



( After Tectonic Map of the United States )

Figure 1 Index map of the Sangre de Cristo Mountains, showing the location of the Questa molybdenum mine.
1. Precambrian rocks. 2. Tertiary igneons rocks. 3. Tertiary and Quaternary volcanic rocks. 4. Thrust fault, saw teeth on up thrown side. 5. Normal fault, hachures on down thrown side. 6. Unclassified fault. 7. Area of Figure 2.

dump are distributed along State Highway 38 – Red River, a branch of the Rio Grande River. Since February 1963, a new mine office has been situated at the Cottonwood Branch of the Red River Canyon. The ore deposits are distributed from Sulphur Gulch to Goat Hill Gulch, both of which are tributaries of the Red River. The mine claims are spread over an area measuring about five miles north and south by twelve miles east and west and trending roughly N75°E.

**Topography:** The Sangre de Cristo Mountains are a part of the Southern Rocky Mountains physiographic province. The maximum relief in the Taos Range is over 6,000 feet; the local relief at the mine is over 3,500 feet. Wheeler Peak, the highest peak in New Mexico (13,155 feet), is located about ten miles southeast of the mine.

The present report area is on the north side of the Red River and is drained by many intermittent tributaries of the river. These canyons have gentle slopes at their lower parts, well covered by thick vegetation, but steep slopes, sometimes even vertical cliffs in their upper reaches. This feature may be related to the geology because rhyolitic rocks, especially when they are tuffaceous, can easily form a steep slope or a cliff.

**History and Production:** Molybdenite from this mine was first recognized in 1916 or 1917, when Jimmy Fahy had a sample analyzed for gold, silver, and copper and found molybdenum in the ore. Prior to that time, the molybdenite was mistaken for graphite; the yellow ferrimolybdite at the outcrops of the veins was though to be sulfur, giving the name Sulphur Gulch to the valley in which the outcrop occurs (Plate 3).

Fahy located some claims, and the Western Molybdenum Company was organized but little was done to develop the deposit. In November 1918, the R. and S. (Rapp and Savery) Molybdenum Company was formed. In 1920 the present owners, the Molybdenum Corporation of America, acquired the property. Mining was discontinued during the depression of 1921; however, development work was continued. Operations were on a small scale until 1923, when a mill was built on the present mill site. In 1929 this mill was rebuilt. In 1942 the present haulage adit (the Moly tunnel) was driven north of the Red River for one mile. Since then, exploration work has been continued to the lower extension of the ore body.

The maximum annual production was in 1930, when it reached 1,050,000 pounds $MoS_2$. Between 1925 and 1945, the production per year was above 500,000 pounds.

Under the strong demand on molybdenum in the past few years, the Questa mine has once again shipped concentrates to the United States domestic market. New mining equipments including a floatation plant of 10,000 tons/day were built around the mouth of the Sulphur Gulch in 1965. It is reported that an open pit of the upper ore zone at the upper Sulphur Gulch serves an estimated 20-million tons of 0.3 $MoS_2$. Underground reserves are estimated to total close to 23-million tons of 0.35 $MoS_2$ (E. & M. J., 1965).

**Previous Work:** The deposit was described initially in a brief paper by Larsen and Ross (1920). A more detailed study, consisting mostly of underground work, was made by Vanderwilt (1938). In 1956 Mackinlay mapped the geology of the Taos Range. The report of Schilling (1956) has a further, more detailed description of the deposit. Carpenter (1960) reported on the Questa deposit, relating the regional geology to his underground studies.

**Acknowledgment:** The author wishes to express his sincere gratitude to Professor R. H. Carpenter, Colorado School of Mines, for all the field arrangements, extensive help and criticism in the field, and the loan of his laboratory and thin sections for use in this study; to Professor Chas. H. Behre, Jr., Columbia University, for his suggestions and encouragement during the study, and a critical reading of the original manuscript. Furthermore, the author will never be able to forget their personal help and hospitality which made his staying in the United States fruitful and enjoyable. He is also indebted to the late Professor of Columbia University, Dr. A. Poldervaart for his suggestions on the studies of thin sections. The author was greatly impressed in his severe attitude to earth science study.

A part of this study was carried out at the U. S. Geological Survey. The author's hearty thanks are due to Drs. T. Botinelly, A. J. Gude, III, J. W. Adams, and E. J. Young of the U. S. Geological Survey, Denver, Colorado for making available his laboratory work on X-ray diffraction and microscopy and for their discussion and suggestions during this study. Dr. T. K. Remenyik, Messrs. R. Raspa, E. May, R. Strahan, J. Larsen, K. H. Rippere, E. Dickerhof, Colorado School of Mines, and Mr. H. R. Daniel, Arizona University, to whom the author wishes to express his thanks for their friendly co-operation, joined the same ex-

ploration project; a part of their contribution is included in this report. It is a pleasure to acknowledge the cooperation received from the staff of the Molybdenum Corporation of America, particularly Mr. B. Evans and Mr. A. Greslin. The surface and mine maps provided by the company were especially helpful in this study of the ore deposit.

## II. Geologic Setting

The Taos Range of the Sangre de Cristo Mountains is made up chiefly of Precambrian metamorphic rocks overlain by late Tertiary volcanic and pyroclastic rocks and intruded by late Tertiary intrusive rocks (Figure 1). Geologic units of Questa mine area are shown in Figure 2 and Table 1. No fossils were found in any of the units. Regional metamorphic rocks are assigned tentatively to the Precambrian. The volcanic and pyroclastic rocks are regarded as the late Tertiary following Schilling (1956), who says:

> The San Juan Mountains to the west are covered by a thick, widespread sequence of volcanics. Miocene andesite, quartz latite, and rhyolite flows,

Table 1 Geologic units of the Questa molybdenum mine area.

| | Extrusives and sediments | | Intrusives | |
|---|---|---|---|---|
| Age | Symb. | Lithology | Symb. | Lithology |
| Quaternary | | Valley fills<br>Fan deposits<br>Terrace gravels | | |
| Tertiary (Lower Miocene) | RIIb | Fine-grained rhyolitic welded tuff | | Goat Hill quartz porphyry (dike) |
| | RIIa | Coarse-grained rhyolitic welded tuff | $G_3p$ | Hot'ntot quartz porphyry (dike) |
| | RI | Porphyritic rhyolite | $G_7$ | Red River aplite (stock) |
| | | | $G_6$ | Questa mine aplite (stock) |
| | | | $G_5p$ | Columbine aplite porphyry (dike) |
| | | | $G_4$ | Log Cabin biotite granite (stock) and aplite porphyry (dike) |
| | | | $G_2p$ | (Hornblende)-biotite granite porphyry (plug and dike) |
| | AIV | Porphyritic (hornblende)-biotite (quartz) latite and pyroclastics | $G_1p$ | Hornblende-biotite(quartz) monzonite porphyry (dike & plug) |
| | AIII | Porphyritic hornblende-biotite (quartz) latite | | |
| | AII | Fine-grained andesite tuff | | |
| | AI | Fine-grained hornblende andesite | | |
| Pennsylvanian-Permian ( ? ) | | Sangre de Cristo ( ? ) formation (arkosic ss. and cogl., sh., ls.) | | |
| Precambrian | | | | Diabase and pegmatite (dike)<br>Foliated granite |
| | | Cabresto metaquartzite<br>Amphibolite complex with schists | | |

> breccias, and tuffs are overlain by Pliocene to Pleistocene(?) Hinsdale volcanic series. The Hinsdale series includes the basalt flows that cap the plain west of the Taos Range. In Costille quadrangle, north of the mine, these basalts overlie andesites, quartz latites, and rhyolites equivalent to the volcanic complex of this report. This relationship, plus the similarity of the Miocene volcanics of the San Juan Mountains to the volcanic complex, are the reasons for tentatively dating the volcanic complex as Miocene(?).

Recently age determination based on a K–A method has been made on biotite by Dr. K. Shibata at the Geological Survey of Japan. Two of ore veins in the Z tunnel and the old Log Cabin prospect showed values of 21 ±3 and 23 ±3 million years respectively, which correspond to the lower Miocene in the Matsumoto's Table (MATSUMOTO, 1965). The values indicate the stage of the molybdenum mineralization, i.e., the latest stage of the Tertiary igneous activity around the Questa deposits. The dating results will be reported separately.

Schilling (1956) reported Permian and Pennsylvanian sediments in the present report area. He stated (p. 11) that "the sediments (arkosic sandstone and conglomerate, shale, and limestone) occur along the eastern edge of the Taos Range; also a few poorly exposed outcrops of sedimentary rocks in other areas." Several sedimentary rock types occur in small outcrops near the Questa deposits and could be the remnants of sediments like those described by Schilling.

A hundred thin sections were studied for their petrology and modal analyses. The Spencer point counter was used for the modal analyses. The traverses were made on an area of 25 mm by 35 mm, and were spaced 0.5 mm and 0.66 mm apart. Staining with hydrofluoric acid (48%) and sodium cobaltinitrate was used to facilitate identification of potash feldspar. Percentages of each constituent in sentences are not counted by the point counter but estimated under a microscope. The symmetrical twinning method is used to determine plagioclase composition, so that the anorthite percentages give an accuracy as it has.

For nomenclature of the rocks, the classification system of A. Poldervaart was used. In the classification, alkali feldspar includes albite; plagioclase excludes albite by definition. However, mineral albite can not be actually measured accurately, though staining sodic plagioclase to a blue color may be possible. If potash feldspar (here orthoclase, perthite, sanidine, and anorthoclase) is used instead alkali feldspar as e.g. Bateman et al. (1963), which is much more adoptable not in petrogenetical but petrographical purposes, all rock names given in this report should be moved to more basic side, and the name granite disappears as proposed by Chayes (1957), except the latest phases of the Questa stocks. Controversial problems in granite nomenclature may be discussed in another opportunity. In practice, latite and andesites are distinguished at an arbitrary boundary of 10 percent potash feldspar, but alkali feldspars form less than two-thirds of the total feldspar. The terms quartz monzonite and quartz latite are used instead of

| | Alkali feldspar : | Plagioclase | (<An 50) |
|---|---|---|---|
| | >2 : 1 | 2 : 1–1 : 2 | 1 : 2< |
| Quartz>10% (vol.) | Granite<br>(Rhyolite) | Qtz. monzonite<br>(Qtz. latite) | Granodiorite<br>(Dacite) |
| Quartz or feldspath. <10% (vol.) | Syenite<br>(Trachyte) | Monzonite<br>(Latite) | Diorite<br>(Andesite) |

the more commonly used names adamellite and dellenite. Alling's nomenclature is adopted for description of perthite (ALLING, 1938).

## II. 1 Precambrian Metamorphic Rocks

No attempt was made to study the detail of the petrology of the precambrian; consequently, none of the rocks of that age was mapped as a separate unit. The rocks consist mainly of amphibolite, various kinds of schists, metaquartzite, and foliated granite.

The amphibolites cover large areas along the south side of the Red River (Figure 2). Small bodies are distributed around the ore deposit. They contain amphiboles of various grain sizes and compositions and are interlayered by quartz-biotite schist and rocks of the other green-schist facies.

The metaquartzite, called Cabresto metaquartzite by McKinley (1956, p. 8) along Cabresto Canyon, 3 miles north of the main haulage adit portal, is distributed in a limited area at the head of Sulphur and Blind Gulch on the divide between the Red River and Cabresto Creek drainages in the vicinity of the mine.

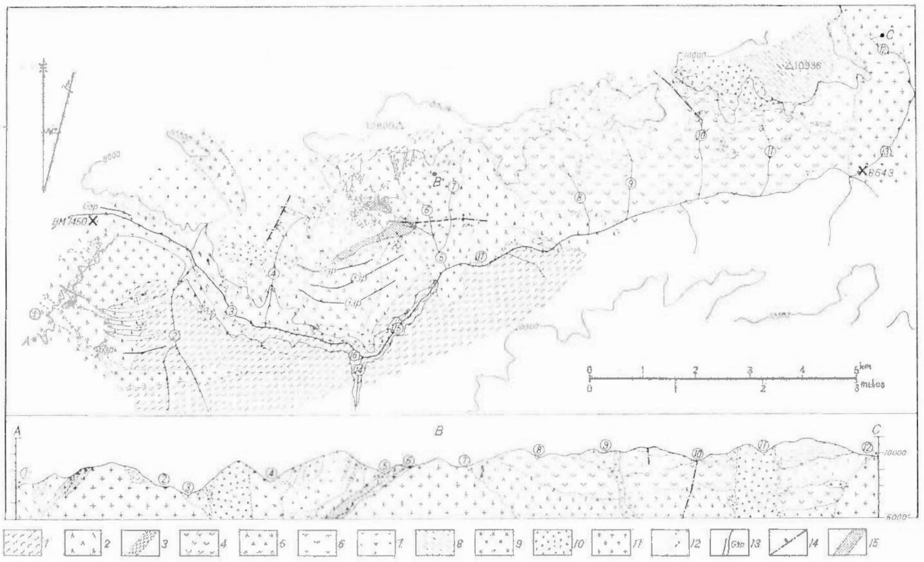


Figure 2 Geologic map and cross section of an area around the Questa molybdenum mine.
1. Precambrian metamorphic rocks. 2. Fine-grained hornblende andesite (AI). 3. Fine-grained andesite tuff (AII). 4. Porphyritic hornblende-biotite (quartz) latite (AIII). 4. Porphyritic hornblende-biotite (quartz) latite (AIII). 5. Porphyritic hornblende bearing biotite (quartz) latite and pyroclastics (AIV). 6. Porphyritic rhyolite (RI). 7. Coarse-grained rhyolitic welded tuff (RIIa). 8. Fine-grained rhyolitic welded tuff (RIIa). 8. Fine-grained rhyolitic welded tuff (RIIb). 9. Hornblende-biotite monzonite porphyry and hornblende bearing biotite granite porphyry. 10. Quartz porphyry. 11. Biotite granite and aplite. 12. Aplite porphyry and dense aplite. 13. Dikes (Quartz porphyry, and aplite porphyry). 14. Faults. 15. Mineralized zone.
① Almagre (Log Cabin) Canyon. ② Bear Canyon. ③ Red River. ④ Goat Hill Gulch. ⑤ Sulphur Gulch. ⑥ Blind Gulch. ⑦ Spring Gulch. ⑧ Bonita Canyon. ⑨ Hanson Gulch. ⑩ Straight Creek. ⑪ Hot'ntot Canyon. ⑫ Bonito Canyon. ⑬ Mallette Creek. ⑭ Columbine Creek. ⑮ Haulage adit (Questa mine tunnel). ⑯ Mine's office in 1963. ⑰ Old mine camp and new (1965) mining equipments. (The western quarter of this map is based on mapping by Mr. E. May and other colleagues.)

No quartzite has been noted in the mine.

Precambrian granite covers two areas around the mine. One of these is north of the highway, opposite the mouth of Columbine Canyon. The other area is exposed along Red River Canyon between the mouth of Sulphur Gulch and the main haulage adit. The rock varies from gneiss to weakly foliated biotite granite. Pegmatites are common in the rocks. The pegmatites generally follow the S–surface, the most prominent foliation plane, as do the basic dike rocks cutting through the granitic rocks.

### II. 2 Effusive Rock Series

The Tertiary igneous rocks are intermediate to acidic in composition. They consist of flows, tuffs, breccias, plugs, dikes, and small stocks. Volcanic and pyroclastic rocks are largely divided into two groups, one andesite, the other rhyolite. In general the former occurs topographically and geologically lower and is earlier, whereas the other is higher and later.

#### II. 2. 1 Fine-grained hornblende andesite (AI)

This is distributed around lower-lying parts of the surveyed area (Figure 2) along Red River, except for occurrences locally around small stock-type intrusions, which seem to indicate that the stocks might have lifted the andesite up when they intruded. The fine-grained hornblende andesite occurs at the lowest horizon in the volcanic series; it is the earliest product, as well as the most mafic. The thickness is not known but is several thousand feet at a maximum. It is a fine-grained, relatively homogeneous rock having a dark-green color. In places it is slightly porphyritic where phenocrysts of plagioclase and ferromagnesian minerals grow as crystals up to 1 by 3 mm. No flow structure was observed in the field. Though bedding is not visible in the andesite itself, andesite tuff (AII) interbedded perhaps conformable at the upper part of Blind Gulch shows bedding clearly.

Under the microscope, the rock is porphyritic in texture with pilotaxitic and hyalopilitic phenocrysts of plagioclase and mafic minerals, mostly hornblende, in a matrix of plagioclase microlites with interstitial cryptofelsite. Crowded microlites are disposed in a sub-parallel manner, probably the result of flow.

Phenocrysts, covering 15 to 40 per cent by volume of the rock, consist of plagioclase and mafic minerals, having a ratio of about 1: 1. The maximum size of the plagioclase is 2 by 2.6 mm. Normal zoning is not uncommon. The plagioclase is euhedral to subhedral, and has the composition $An_{27}$ (oligoclase) to $An_{46}$ (andesine), an average of $An_{36}$ (andesine). Deuteric alteration is common on the plagioclase, as indicated by fine specks of sericite[注1], kaolinite, and epidote, and of rare green biotite, opaque minerals, and hematite. It sometimes contains apatite inclusions.

The mafic minerals are mostly composed of pale grass green to bluish green hornblende in prismatic forms the maximum size of which is 0.4 by 3 mm. The maximum extinction angle was 27°. This has many inclusions of apatite and opaque minerals. Most parts of the hornblende have been altered to very fine specks of greenish brown biotite, which are now partly changed to chlorite. There is morphological evidence to prove the existence of a small amount of pyroxene

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[注1] It should be added here that fine-grained secondary muscovite is called sericite in this report; X-ray studies showed that it has a $2M_1$ muscovite structure.

(augite?) and primary biotite. Carbonates, chlorite, epidote, sphene, pyrite, and iron oxide replaced the primary mafic minerals. The mafic minerals seem to have had a continuous series of retrogressive alteration, showing pyroxene altered to hornblende, biotite, and chlorite, and elsewhere hornblende altered to biotite and chlorite or biotite altered to chlorite.

The matrix of the rock consists mainly of fresh microlites of probable andesine and cryptofelsite. Untwinned plagioclase and possibly potash feldspar replace the microlite in places. Mafic minerals in the matrix have been altered to carbonates, chlorite, and opaque minerals. These secondary minerals, including the other common minerals such as quartz, sericite, a sphene-like mineral, and hematite, tend to fill interspaces between the microlites.

Through this rock, many veinlets of calcite and gypsum, some zeolite (stilbite, as identified by X-ray methods), and/or quartz are found.

The quartz content of this rock is not more than 5 per cent in volume, even if the irregular quartz patches are included that are interpreted as a segregation product from the host rock or a foreign material formed during a deuteric stage. The ratio between plagioclase and potash feldspar is nowhere below 10: 1. This rock should be called either a fine-grained hornblende andesite or a pyroxene-biotite bearing hornblende andesite. The rock has suffered intense propylitization.

### II. 2. 2 Fine-grained andesite tuff (AII)

This rock, consisting of three thin beds, is exposed only at the upper part of Blind Gulch, close to the Questa Mine aplite (G6). This fine-grained, dark greenish brown to dark gray rock shows distinctive bedding in the uppermost unit. This generally strikes N 10–35° W and locally as much as N 80° W and it dips 35–90° SW. The middle unit has a N 5° W–40° E strike and 20° to 90° NW dip. Near Precambrian rocks these formations show a steep dip. The uppermost formation has a maximum thickness of 140 feet, the middle 80 feet, and the lowest 40 feet or less.

Microscopic study indicates that there is an extreme alteration through these formations, due perhaps to the high permeability of the rock. The rock around the aplite and within 200 to 300 feet from the contact, is now a biotite hornfels. The texture is a granoblastic-mosaic with a banding caused by the biotite. In volume, its main constituents are 30 per cent of plagioclase, 30 per cent of quartz, 25 per cent biotite with minor constituent of potash feldspar (8%), opaque minerals (5%), and the other various lesser accessory minerals (2%).

Plagioclase is a relict having been largely replaced by quartz, biotite, and opaque minerals. The plagioclase is cloudy because of many fine inclusions of biotite, apatite, and opaque minerals, which are usually parallel to laminated biotite flakes. Quartz is always anhedral, showing a mosaic texture. Biotite is euhedral to subhedral crystals, fine-grained, and prismatic and is pale to very dark brown. Potash feldspar is anhedral and always cloudy. Accessory minerals are apatite, magnetite, hematite, and jarosite.

At about 500 feet from the contact, the rock is strongly sericitized. It also shows a banded structure with a granoblastic mosaic texture in the dense, felsic parts. Here it is composed of about 70 per cent in volume of sericite with the minor constituents quartz (8%), feldspars (8%), magnetite (7%), hematite (5%), and lesser accessories (2%).

Sericite is a basis of dense crystals stained by hematite. Everywhere it contains a little magnetite. In the felsic parts the sericite fills interspaces between quartz and feldspars.

There is no clear microscopic evidence for the origin of this rock facies as would be furnished by the presence of angular phenocrysts or fragments or the like. However, in occurrence and in gradational change from the rock to fine-grained hornblende andesite, it indicates that the rock is not a Precambrian rock but is a tuff, the composition of which would be similar to that of andesite (AI).

### II. 2. 3 Porphyritic hornblende-biotite (quartz) latite (AIII)

This rock is largely distributed in the area between the mine camp and the town of Red River, and the lower north slope of the Red River Canyon (Figure 2). It conformably lies on the AI formation. The thickness, though not accurately measured, is approximately 2000 feet, maximum. This contains thin tuffaceous beds up to a few tenths of feet in thickness, as noted especially at the south slope of Sawmill Mountain, where the bedding has random directions. The rock is pale green to dark green and everywhere porphyritic. Its phenocrysts are of plagioclase, hornblende, biotite, potash feldspars, and quartz, listed in the order of decreasing abundance and varying in diameter up to 3 by 6 mm. In some places potassium feldspar goes up to 7 by 12 mm in size; here the rock has a more hypabyssal appearance. Quartz phenocrysts may be absent locally. In places the outlines of the feldspar phenocrysts become blurred by argillization.

Under the microscope this rock is porphyritic with a hyalopilitic texture or with a cryptofelsitic matrix. The phenocryst percentage is between 45 and 50; the major phenocryst constituents are plagioclase and the mafic minerals, changing the ratio from 3: 2 to 1: 1. The plagioclase is usually 2 by 4 mm in size. It is in euhedral to subhedral crystals and is commonly zoned. In composition the feldspar ranges from $An_{31}$ to $An_{40}$, though mostly about $An_{37}$ (andesine). It has slightly altered to sericite, carbonates, and chlorite, in order of decreasing abundance. The original mafic minerals, biotite and hornblende, are chiefly in a ratio of 1: 1 previous to alteration, but biotite preponderated everywhere. They are euhedral to subhedral. Biotite is in short prisms, or in booklets, or pseudohexagonal forms. The maximum crystal is 2.7 by 3.6 mm. Hornblende, which has maximum crystal sizes of 0.3 by 2 mm, is in slender prisms, usually finer than the biotite. The hornblende has been strongly altered to chlorite and to small amounts of carbonates, sericite, and iron exides; while the biotite has been replaced by chlorite and sericite, a little iron oxide, and quartz. Corroded high quartz is seen as a phenocryst, but is rare.

The matrix consists of cryptofelsitic material in which the plagioclase and potash feldspar ratio seems roughly 1: 1. In total, however, the plagioclase potash feldspar ratio of the rock is nearly 2: 1 or higher, and quartz content is less than 10 per cent by volume. Such relations fit the rock into the latite clan, although close to quartz latite in composition. Propylitization is strong.

### II. 2. 4 Porphyritic hornblende bearing biotite (quartz) latite and pyroclastics (AIV)

These rocks occur at the upper and in the middle north slopes of Red River (Figure 2). In the area east of the mining camp, where the rocks are relatively undisturbed, this rock unit occurs in small lenses or massive bodies. The largest body is exposed in the area between Goat Hill Gulch and Sulphur Gulch. Because of complexity of the structure and probably especially to the presence of many strike faults, this unit in the area appears to be a large body. It is possible instead, however, that the lower horizon of the unit may be separated and may belong to the AI or AII formations, making the main body smaller than shown in Figure 2.

In general, the rocks of the AIV type overlie the AI and AIII formations and seem to be interbedded with the RI and RII formations. Neither the bedding nor other clear field evidence show the relation of these problematic masses. Small lens shaped bodies in rhyolitic rocks (RI and RIIa) must have a similar relation to those of the RII formation, judging from their occurrences. Around the ridge between Goat Hill and Sulfur Gulches, there is discordance between the bedding of this rock unit and that of the RI and RII formations, and this seems to indicate that the unit has a very irregular form. At its contact with the RIIa formation, latite porphyry and pyroclastic unit here described is bleached for about two feet. The contact is irregularly wavy but it is sharp.

The distribution of this rock is in the vicinity of plugs or dikes of similar composition. Moreover, its detailed petrology, as determined by microscopic observation (to be described below) likewise strongly suggests that this is a material suddenly deposited near the vent after the eruption of rock now contributing to the AIII formation during successive periods of volcanism.

Finally, this rock unit has essentially the characteristic purple colors in its tuffaceous part and light to dark green in its porphyritic part, which corresponds to the parts of AIII that are similar in composition. This rock has the appearance of a volcanic breccia. In detail, rounded to subangular pebbles, averaging 2 inches but up to 1 foot in diameter, are present. Some of the pebbles have the characteristic purple color of andesite, whereas the matrix is green because of chloritization. In short, the unit is a heterogeneous body. The thickness is probably not more than 1000 feet.

Under the microscope, the purple parts of the rock show a lithic, tuffaceous texture consisting of a breccia, consisting of broken fragments of crystals of plagioclase, of potash feldspar, and of quartz together with small flakes of mafic minerals (chiefly biotite rather than hornblende) in a matrix made up of glass dust with hematite, opaque minerals, and very fine plagioclase laths.

The plagioclase crystals are up to 1.8 by 3 mm in size. Their composition ranges from $An_{29}$ through $An_{39}$, but is mostly $An_{31}$ (oligoclase-andesine). Zoning is rare. The plagioclase has been strongly carbonatized and weakly sericitized. In places, there is a subangular breccia previously mentioned consisting of plagioclase laths, potash feldspar, quartz, and opaque minerals. The breccia particles are enclosed in felty material made up in part of hydrothermal minerals such as calcite and sericite.

The mafic minerals are in prismatic crystals, in places short but rarely fragmental. They have been almost completely replaced by chlorite and opaque minerals (pyrite and iron oxides) with little sericite.

The occasional amygdules, originally vesicles, are now filled with very fine saccharoidal aggregates of quartz, which might have been opal before recrystallization. The matrix is composed of lithic, rather than glassy, material–presumably that which fell nearest the source.

In conclusion this purple, tuffaceous part of the unit here designated AIV has about equal ratios of plagioclase and potash feldspar, and nearly 10 per cent of quartz by volume, so that it is petrographically a hornblende-biotite latite tuff, close to quartz latite tuff.

The greenish part shows a porphyritic texture with a hyalopilitic matrix where glass occupies minute interspaces between microlites of feldspar in haphazard orientation. Phenocrysts cover about 45 per cent of the rock by volume. Tightly appressed microlites, generally of plagioclase, are buried by microcrystalline or cryptocrystalline potash feldspar, mafic minerals, and quartz.

On these phenocrysts, the later plagioclase is in euhedral crystals with a few subhedral ones. Their composition is $An_{29}$ to $An_{43}$, mostly $An_{35}$ to $An_{37}$ (andesine). Zoning is common in these plagioclase crystals but leaching in some places. It has been everywhere partly altered to carbonates, epidote, and some sericite. Wherever plagioclase microlites can be seen in the matrix, a sub-parallel structure is observed. The potash feldspar and quartz are usually anhedral. Quartz sometimes occurs as a corroded phenocryst. Mafic minerals are euhedral, generally in a short prismatic form, indicating that most of them are originally biotite. The biotite and the relatively small amounts of hornblende have been completely altered to carbonates and chlorite, and in some cases to quartz, sphene, sericite, and secondary biotite. The other accessory minerals are pyrite and magnetite. The hydrothermal minerals are, in order of abundance, carbonates, chlorite, sericite, kaolinite, and, in drusy parts, quartz. Some of these, especially the calcite and chlorite, also occur as veinlets.

The approximate percentages of plagioclase, potash feldspar, mafic minerals, quartz and the others of this green part of the rock are, respectively, 50, 20, 15, 7, and 8. Consequently this part of the rock should be classed as a hornblende-bearing biotite latite. This green lava part is everywhere more mafic chemically than the purple tuffaceous part.

### II. 2. 5 Porphyritic rhyolite (RI)

This is exposed at the upper north slopes of Red River Canyon (Figure 2). Its occurrence is a lens, or rarely a dike or sill. It overlies rocks of the andesite series and is interlayered with the coarse-grained welded tuff (RIIa). This rock has a light color, usually pale gray, and a porphyritic texture with phenocrysts of quartz and little feldspars. No flow structures are observed, although the impression of weak banding is conveyed by squeezed lenses of pumiceous material.

Under the microscope, phenocrysts are seen to be composed of quartz and potash feldspar, having a ratio of 3: 2. The quartz is up to 2.5 mm in diameter. About half of it is in angular fragments; the rest is euhedral. Both types have been corroded or resorbed. In many places they show a small 2V angle. The potash feldspar crystals are up to 2 by 3 mm in diameter and are euhedral to subhedral. Though not corroded, they are replaced at their margins or along cracks or cleavages by albite. Its optical properties—low index and a 2V (−) of about 43°—indicate that the potash feldspar is anorthoclase. This has been weakly altered to sericite along its cleavage or cracks. Besides the phenocrysts, there is a squeezed lens of the same material in the matrix. This lens shows two distinct zones. The outer zone consists of a wart-like, myrmekitic intergrowth of quartz and potash feldspar, while the inner zone is composed of a coarser grained graphic intergrowth of quartz, potash feldspar, and albite. This lens could be interpreted as a product of unequal concentration of volatiles in the original magma, or as a re-arrangement of salic minerals during a deuteric stage. There is also an intergrowth of radiating quartz and potash feldspar which could have been originally a spherulite subsequently divitrified.

The matrix of this rock was originally a glass and is now composed of an aggregate of mosaic quartz and potash feldspar with many specks of opaque minerals, mostly pyrite. In places, the aggregate shows a micrographic texture.

In summary, this rock consists of two major constituents – quartz and a potash feldspar (anorthoclase, soda-sanidine, and orthoclase); a minor constituent, albite; the accessory mineral, apatite and various opaque minerals; and the hydrothermal products sericite, kaolinite, and hematite. Hence, the rock is rhyolite in composition. Recrystallization throughout the rock is so strong that the origin is puzzling. The presence of spherulites may indicate that the rock was originally a lava flow, but the spherulites and granophyric aggregate of felsic minerals could be formed by recrystallization of tuffaceous materials. Most phenocrysts of this rock are not fragmental. No flattened glass shards are present. Because of these facts the rock is regarded as a porphyritic rhyolite, although there are some suggestions of a pyroclastic rock.

Myrmekite and fragmental quartz phenocrysts with a small 2V lead to an interpretation that the rock has been crystallized under special conditions of high stress with rapid change of hydrostatic pressure. An appreciable thickness of welded tuff units, rapidly deposited upon it, might have been responsible for the high stress.

In most cases the rock is highly sericitized. The feldspar phenocrysts have been completely altered to sericite except for some secondary potash feldspar around the quartz and albite surrounding the earlier potash feldspar. The matrix consists of a mat of angular quartz and fine sericite, where the sericite fills interstices between the quartz grains. Spherulites are still present in many places. The sericite also occurs in veinlets showing a network, or a subparallel manner which may be following the primary structure.

### II. 2. 6 Coarse-grained rhyolitic welded tuff (RIIa)

This is exposed on the upper north slopes of Red River Canyon (Figure 2). Around Goat Hill, however, the rock is visible even on the lower slopes. The distribution is closely related to locations of quartz porphyry. The upper formations of this rock unit is a fine-grained welded tuff; the lower parts are included in parts of the AIII, AIV, and RI formations. The thickness is probably about 1,700 feet.

This is a heterogeneous body, colored black to light gray, depending on intensity of alteration (Plate 5). The rock shows a distinctive banded structure, consisting of light gray squeezed pumiceous lapilli forming a disk or lens up to 100 mm in length or more; flattened glass shards (usually up to sizes of 3 by 15 mm) which are really black when fresh; and a matrix intermediate gray in color. Fragmental quartz and potash feldspar and lava fragments of accessory origin are in the matrix. Some of the crystals of potash feldspar grow up to 2 by 3 mm.

The bedding of the rock east of the mine camp and west of the town of Red River (Figure 2) generally strikes from north-northeast to northwest and dips 25 to 75° west; that of the western area of the mine camp has a general strike of north-northwest and steeper dips, 65 to 90° southwest or 30 to 90° northeast. In this area the rock is exposed at the topographically lower levels along Red River Canyon where this canyon crosses the strike. This indicates that the rock is faulted by many of the small north-south faults which are commonly present at the western end of the Taos Range.

The following microscopic study is necessarily based on altered rock, as no fresh smaples were obtained. The rock is banded and has a faintly vitroclastic texture. The banding is caused by (1) flattened pumice and glass shards, (2) fine dust in the aggregates of cracked quartz and fine sericite, and (3) intergrowths of sericite and dirty quartz extruding normal to the banding. Some 80 per cent of the disk of light gray flattened pumice consists solely of a mat of sericite; the remaining 20 per cent is quartz. The black flattened glass shards are composed only of quartz, as confirmed by X-ray diffraction method. The intermediate gray part consists of dirty quartz and fine sericite with phenocrysts of quartz and feldspars. Sericite develops along shear planes, which cross each other at an angle of 15°. The bedding is roughly parallel to the shear planes. It is obvious that the shearing followed the welding and antedated the sericitization.

In the intermediate gray part, the quartz, up to 1.2 by 1.5 mm in size, is in euhedral-bipyramidal to subhedral crystals and angular fragments, in about equal quantity of each. Both kinds of quartz have been corroded or partially resorbed. The feldspar, of which the maximum crystal size is 1.9 by 4 mm, is euhedral to subhedral. Originally probably resorbed. The feldspar, of which the maximum crystal size is sanidine, it has been completely replaced, partly by sericite and partly by quartz.

There are various particle sizes in the rhyolitic breccias. The smaller particles are usually highly altered. For example, one, measuring as much as 3 by 4 mm, has been completely altered to sericite and quartz. On the other hand, a large breccia pebble, 20 by 30mm in size, is still partly fresh.

The breccia consists of two types. One is porphyritic texture with a granoblastic-mosaic matrix. The phenocrysts consist of sanidine and quartz, in ratio of about 3: 2. The sanidine, up to 2 by 2.6 mm, is euhedral to subhedral. Its 2V is small (less than 10°) and optically negative. It has been partly replaced by sericite. The quartz is subhedral to anhedral and usually corroded. It has a small 2V. The matrix consists of grains of various sizes of mosaic quartz and potash feldspar, which has been slightly kaolinitized. Small amounts of sericite fill the interspaces of the quartz and the potash feldspar.

The other breccia – a very fine-grained compact one – has the same texture as that of the porphyritic type under the microscope. The phenocrysts consist of plagioclase, potash feldspar, and quartz. The plagioclase crystals range in size to a maximum of 0.4 by 0.7mm. They are euhedral. Their composition is albite ($An_1$). The potash feldspar crystals, up to 0.3 by 0.5mm in size, are subhedral to anhedral. It could not be determined whether they were anorthoclase or sanidine. They have generally been partly replaced by sericite. The quartz individuals are anhedral and have a maximum size of 0.4 by 0.6mm. The matrix is a mosaic aggregate of quartz and potash feldspar. Little sericite fills their interspaces.

In the field, there is no clear evidence that this rock is a welded tuff. A transition from welded material into some more quickly cooled, undeformed, and less compact rock of obviously pyroclastic origin is not found at the lower horizon where those evidences should be observed. Perhaps the evidence has been erased by alteration. The top and sides where the evidence should also be visible, has been eroded in the present report area. A hand specimen shows a sort of vitroclastic texture. As implied above, an intense alteration throughout the rock has erased the original texture, but flattened pumice and shards, fragmental material, and "flow" lines suggest that the rock is a welded tuff. Since the composition is rhyolitic, this rock is here designated as a coarse-grained rhyolitic welded tuff.

### II. 2. 7 Fine-grained rhyolitic welded tuff (RIIb)

This only occurs on top of the divide between Red River Canyon and Cabresto Creek (Figure 2). It concordantly overlies the RIIa formation. The thickness is probably 1,300 feet, as far as can now be determined. The rock is light to dark gray. Pumiceous lapilli are up to 2 by 20mm in size. The unit is very similar to rock of the RIIa formation, but finer-grained (Plate 6). The bedding planes are slightly different from those of the formation. The strike ranges from due north to northwest and the dip varies 40 to 65° west or southwest.

The lower part of this formation is the coarser part, yet it has less breccia than in the RIIa formation. Under the microscope, the visible banding is due to mostly dust in the matrix, but partly to black and white flattened pumice shards. The black shards have a micrographic intergrowth with quartz, potash feldspar, and spherulites in the relatively finer part, and a graphic intergrowth of quartz and potash feldspar in the coarser part. The white shards consist of lithic material of a finely mosaic intergrowth, being composed of salic minerals.

The phenocrysts of the rock are of sanidine and quartz. The sanidine, of which the maximum size is 1.5 by 2mm, consists mostly of euhedral crystals and some subhedral ones. Each crystal has a reaction rim, resulting from replacement by another alkali feldspar. In size the quartz ranges up to 1.5 by 1.6mm. All of the subhedral to anhedral crystals and angular fragments have been corroded or resorbed. There are very small amounts of biotite which have been altered to sericite. The matrix of the rock consists of cryptofelsitic material. Sericitization is intense – as strong as in the RIIa formation – attacking feldspars at first, as usually seen.

In the upper horizon of this formation the banding is faintly shown by a paper-thin white material, sericite. The rock has a porphyritic texture with an equigranular-mosaic aggregate of quartz and a little sericite. The matrix is more sorted than in the RIIa formation. The phenocrysts of this rock, increasingly euhedral upward, especially in comparison with the low part, consist of quartz and potash feldspar. The quartz, with a maximum size of 1.2 by 1.4mm is in bipyramidal or polygonal crystals with very weak corrosion. The potash feldspar, with a maximum size of 0.8 by 1.2mm, is euhedral to subhedral. It has been strongly altered to sericite. The matrix of the rock is composed of aggregates of anhedral quartz surrounded with a little sericite.

As far as the composition of this unit is concerned, it is more acidic than the RIIa formation – that is, the increase of the content of the quartz and potash feldspar. In view of the evidences of welded tuff, as described in the RIIa formation, found in this rock, this is designated a fine-grained rhyolitic welded tuff.

### II. 3 Intrusive Rock Series

The intrusive rocks in the report area can be divided into two groups for their mode of intrusion. One is in plugs, dikes, or sills of various sizes. The composition changes from hornblende-biotite (quartz) monzonite to biotite granite. The other is usually in small stocks or dikes. The composition ranges from biotite granite to aplite high in potassium. This latter type is regarded as the major ore-bringers to form the Questa molybdenum deposits.

### II. 3. 1 Hornblende-biotite (quartz) monzonite porphyry (G1p)

This occurs as a large dike, 1300 feet wide at Goat Hill Gulch, and as small dikes and as plugs scattered through the area (Figure 2). The original color is dark green but in most cases has been bleached to pale green by hydrothermal alteration. A distinctive porphyritic texture is characteristic with phenocrysts of sanidine (up to dimensions of 17 by 30mm), plagioclase (maximum 3 by 6mm), mafic minerals (maximum 2 by 4mm) and quartz (maximum diameter 7mm) in an aphanitic matrix (Plate 7). Excellent euhedral crystals of sanidine with varied twinning are found in the rock at Goat Hill Gulch; there the matrix has been altered (Plate 8). The marginal facies has a more acidic composition than the main facies, characterized by increasing quartz content.

Under the microscope the rock shows a porphyritic texture in a felty matrix. The phenocrysts consist of plagioclase, potash feldspar, mafic minerals, and quartz, in decreasing order of abundance. The plagioclase is in euhedral to subhedral crystals with composition from $An_{25}$ to $An_{34}$ in most bodies and from $An_{40}$ to $An_{43}$ in the more unusual facies. Zoning is not common. The feldspar has been partly replaced by an irregular form of potash feldspar and there are veinlets of potash feldspar as well; some replacement is by sericite with a little kaolinite. The potash feldspar, which by X-ray diffraction methods is shown to be high sanidine, is euhedral to subhedral. It contains relict plagioclase beads. The potash feldspar is more resistant to alteration than the plagioclase. The mafic minerals have been strongly altered to chlorite, and to a lesser extent to calcite and iron oxides. Their pseudomorphs indicate that there was originally more biotite than hornblende. The quartz has been corroded so that the probably euhedral high-temperature bipyramids are hardly seen. In the matrix an aggregate of anhedral fine quartz and alkali feldspar crystals fills the interspaces between the larger phenocrysts, the plagioclase laths, and the subhedral and altered mafic minerals. Sericite completely replaces the feldspar where alteration is strong.

In summary the ratio of plagioclase and alkali feldspar seems to average 1: 1. Though there are a few quartz phenocrysts in this rock, the total quartz content is less than 10 per cent in volume. The quartz content exceeds 10 per cent in the marginal facies, as well as in some small bodies. But the greater part of this rock facies clearly falls into the monzonite clan.

### II. 3. 2 Hornblende bearing biotite granite porphyry (G2p)

This is exposed on the uppermost part of Sulfur Gulch (Figure 3), as a plug and in dikes and sills. The main body, standing on the ridge between Sulfur Gulch and Iron Gulch (a branch of the Sulfur Gulch) shows a circular form having in plan a length of 1200 feet to east and west, and a width of 700 feet north and south (Plate 2). The dikes surround the main plug and form an imperfect ring-dike swarm (Figure 3). Some parts of the dikes follow the contact of AI and AIII, or AIII and RIIa formations, and can therefore be called a sill. At the tip of the dikes, the rock is often brecciated, especially along faults.

Outcrops of these rocks are pale brown to yellowish brown for alteration products such as iron-stained clays, limonite, and jarosite cover the outcrops. The main plug has a porphyritic texture with phenocrysts of potash feldspar (maximum

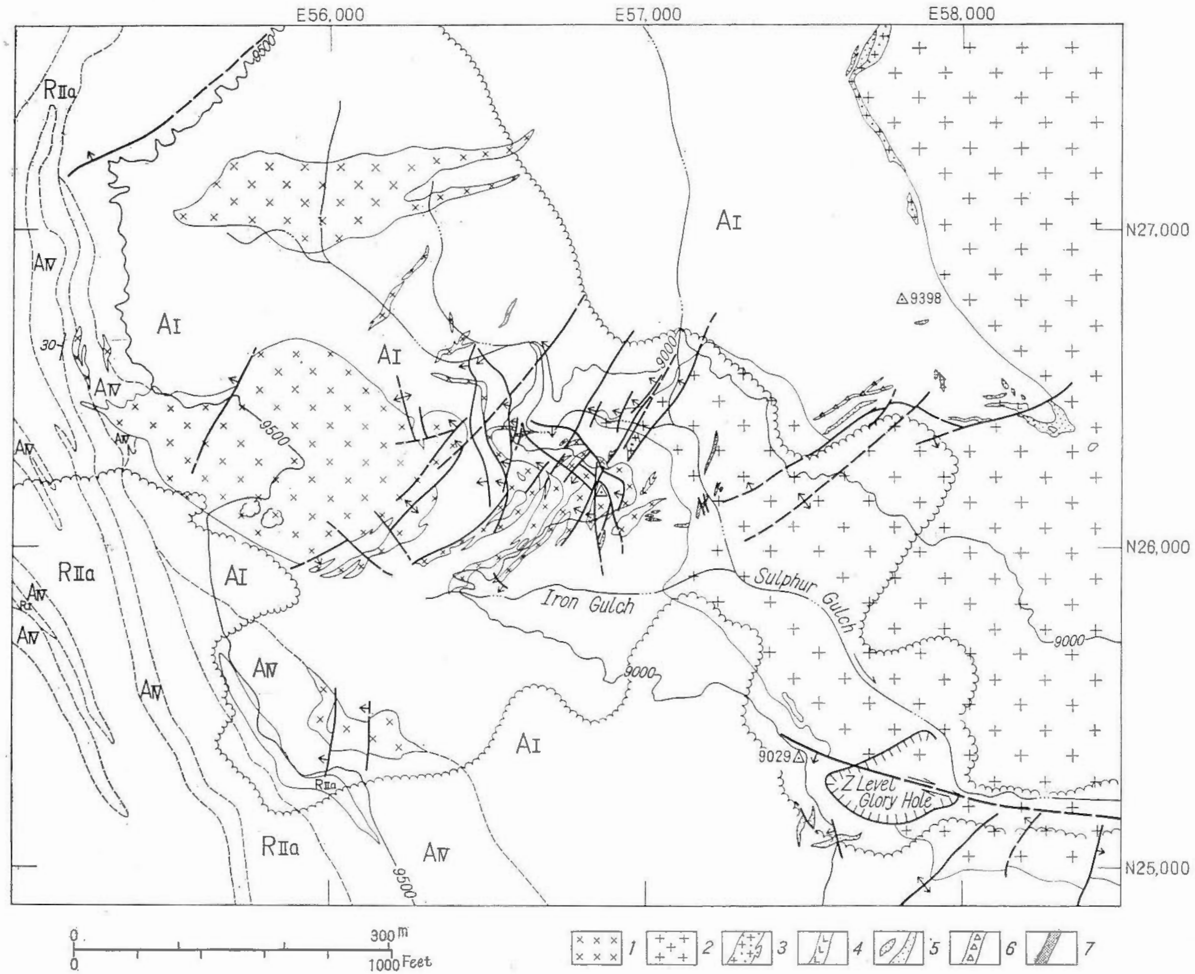

Figure 3 Geologic map of the upper Sulphur Gulch.

AI: Fine-grained hornblende andesite, AIV: Porphyritic hornblende bearing biotite (quartz) latite and pyroclastics, RI: Porphyritic rhyolite, RIIa: Coarse-grained rhyolitic welded tuff, 1. Biotite granite porphyry, 2. Medium-grained slightly porphyritic aplite, 3. Porphyritic biotite granite, 4. Aplite porphyry, 5. Fine-grained aplite, 6. Aplite-breccia dike, 7. Post-aplite dike.

size 18 by 26 mm), plagioclase (maximum 5 by 10 mm), quartz (maximum 5 mm in diameter), and mafic minerals (maximum 2 by 4 mm for biotite, 2 by 10 mm for hornblende). Pyrite is disseminated through the rock, and at the margins it tends to gather in druses.

Microscopic study shows a porphyritic texture with phenocrysts of plagioclase, potash feldspar, quartz, and mafic minerals. The plagioclase is euhedral to subhedral; the composition is $An_{10}$ to $An_{30}$, mostly $An_{12}$ (oligoclase). Sericite and a little kaolinite are common alteration products. The potash feldspar is euhedral sanidine and subhedral stringlet-perthite. The quartz is subhedral to anhedral and is corroded or resorbed. The mafic minerals are biotite (containing inclusions of apatite in places) and hornblende. Their ratio is roughly 5: 1. The biotite has been replaced by sericite, chlorite, quartz, sphene, and opaque minerals; the hornblende is replaced by chlorite, calcite, sericite, and quartz. There are a few well digested xenoliths rich in mafic minerals which range in diameter up to 10 mm. The matrix consists of small quantities of plagioclase-laths and altered mafic minerals in fine anhedral crystals of albite, potash feldspar, and quartz.

On the surface of the ground there are practically no fresh exposures of this unit. In an extreme case alteration has converted it into a quartz-sericite rock retaining the original texture. In the usual case the rock consists of phenocrysts of a mat of sericite, originally feldspars, of strongly resorbed quartz, and of a quartz and sericite aggregate, originally a xenolith, in a matrix composed of quartz and sericite with little carbonate, chlorite, and kaolinite. Quartz veinlets (having a maximum width of 10 mm) cut the rock.

As an example, modal analyses of the phenocrysts of two relatively fresh rocks are shown in Table 2.

Table 2 Modal analyses of granite porphyry.

| | Minerals | SI–9 (plug) | SI–172 (dike) |
|---|---|---|---|
| Phenocrysts | Quartz | 11.3% (vol.) | 32.5% (vol.) |
| | K–feldspar | 11.3 | 23.0 |
| | Plagioclase | 63.7 | 39.0 |
| | Mafic minerals | 5.9 | – |
| | Others | 7.8 | 5.5 |
| | Phenocrysts in total | 36.7 | 33.3 |
| | Matrix | 63.3 | 66.7 |
| | Total | 100.0 | 100.0 |

A typical sample has a porphyritic texture with phenocrysts of plagioclase, potash feldspar, quartz, and mafic minerals. The plagioclase is euhedral to subhedral and has a maximum size of 1.7 by 3.0 mm. The composition is $An_{30}$ to $An_{35}$. It has been slightly altered to kaolinite and sericite. The potash feldspar, with a maximum size of 1.7 by 2.3 mm, is in euhedral to subhedral crystals with bead-like perthite in places. It has suffered a weak kaolinization. The quartz, 3.5 by 4.6 mm or less in size, is bipyramidal or angular. Corrosion and resorption are common on it. The matrix consists mostly of anhedral crystals of potash feldspar, quartz, and plagioclase, named in order of abundance, the commonest first. These fill in between small amounts of plagioclase laths and prismatic mafic minerals.

Hydrothermal alteration is intense on the dikes and sills–stronger than on the main plug. Moreover, there is a very weak molybdenum veinlet mineralization brought by these rocks. The ore minerals are molybdenite, associated with small amounts of ferrimolybdite, pyrite, fluorite, calcite, and quartz.

The ratio of plagioclase to potash feldspar is 3: 2 to 1: 1; but that of plagioclase and alkali feldspar is around 1: 2, because of the presence of albite in the matrix. These justify classing this rock as a granite porphyry.

### II. 3. 3 Quartz porphyry (G3p)

One mass of this type of rock crosses Goat Hill Gulch, and the other crosses upper Hot'ntot Canyon (Figure 2). The former consists of several small dikes and one large body the width of which reaches a maximum of about 1,100 feet. The Hot'ntot Canyon body is about 2,000 feet wide with an associated dike at Hanson Gulch. In this paper these bodies are called, respectively, the Goat Hill porphyry, following Carpenter (1960), and the Hot'ntot porphyry.

The Goat Hill porphyry is a light-gray porphyritic rock with phenocrysts of plagioclase, potash feldspar, and quartz in an aphanitic matrix, characterized by phenocrysts of bipyramidal quartz. It is always light-gray in color because of strong alteration. The rock seems to have originally a light color, because the percentage of normative femic minerals based on a chemical analysis of the fresh rock is only about one per cent (Table 9). This rock has very weak molybdenum mineralization.

Under the microscope the rock is seen to have a porphyritic texture with a matrix that is very fine-grained allotriomorphic-granular. The phenocrysts consist of quartz, potash feldspar, plagioclase, and biotite. The phenocrysts cover an area composing between 30.6 to 35.4 per cent of the rock (Table 3). A small dike of the same general type, exposed at Almagre Canyon, has somewhat different percentages.

Table 3 Modal analyses of the Goat Hill porphyry.

| | Minerals | SI–184 | SI–185 | SI–181 |
|---|---|---|---|---|
| Phenocrysts | Quartz | 38.1% (vol.) | 31.5% (vol.) | 23.2% (vol.) |
| | Potash feldspar | 30.6 | 30.1 | 33.3 |
| | Plagioclase | 30.9 | 35.7 | 38.8 |
| | Biotite | 0.4 | 2.8 | – |
| | Others | – | – | 4.7 |
| | Phenocrysts in total | 35.4 | 30.6 | 37.2 |
| | Matrix | 64.6 | 69.4 | 62.8 |
| | Total | 100.0 | 100.0 | 100.0 |

Notes: Sample SI–181 from Almagre Canyon, Sample SI–184 & SI–185 from Goat Hill Gulch.

The plagioclase, having a maximum size of 5 by 7 mm, is euhedral to subhedral. No zoning is present but a sodic rim is present. A few crystals of it are enclosed and replaced by potash feldspar. Sericitization and weak kaolinization are commonly seen. The potash feldspar (6 by 9mm maximum dimensions) is euhedral to subhedral, in mostly the latter. It is sanidine, having a small negative 2V. Relatively fine crystals are anhedral and locally form a myrmekite with vermicular quartz. The quartz (maximum dimensions 3.3 by 6mm) is euhedral to anhedral and in many places rounded or corroded; some crystals enclose small euhedral flakes of plagioclase. The rock matrix consists mostly of quartz and potash feldspar, lesser amounts of plagioclase and sericite, with apatite and opaque minerals as accessories.

A high content of alkali feldspar in the matrix can balance the high content of plagioclase in the phenocrysts and thus make the rock compositionally a granite. With chemical data which will be described later all indicate that the Goat Hill porphyry is a highly fractionated rock. The rock is a product of the final phase of instrusive activities.

The Hot'ntot porphyry is a light-colored rock with an aphanitic matrix. Although considered a dike, it may also partly involve an effusive rhyolite tuff. This rock is somewhat in question on its mode of occurrence because of field survey not having done well. The phenocrysts are composed of rounded feldspars, 9 by 12mm in maximum size, which have been almost wholly replaced by clay minerals; other phenocrysts are of rounded quartz, with maximum diameters of 15mm; many cracks are filled with clay minerals.

Under the microscope the rock shows a porphyritic texture with an allotriomorphic-equigranular matrix. The phenocrysts consist of quartz, feldspar, and mafic minerals. The feldspars are generally subhedral, and have been corroded. They have been largely completely altered to an aggregate of amorphous clay minerals of a low crystalline-state. The quartz is subhedral to anhedral, and has been strongly resorbed and surrounded by sericite. The mafic minerals have been completely replaced by sericite, so that the original minerals can not be identified. The matrix consists of nothing but quartz and sericite. No other major minerals are found by microscopic and X-ray methods. Pyrite is a common accessory mineral. The texture of the matrix may be called a granoblastic-mosaic, indicating that the rock could be a kind of hornfels of a deuteric stage.

### II. 3. 4 Log Cabin biotite granite (G4)

This one of the second type of the intrusive series, is a small stock or dike in form, granitic to aplitic in texture. Areally, rocks of this type fall into two groups - the Log Cabin granite (G4) and the Columbine aplite porphyry (G5p).

The Log Cabin granite is found in an area between the mouths of Bear Canyon and Almagre (Log Cabin) Canyon. As fairly strong molybdenum mineralization is discovered along Log Cabin Canyon, a tentative name, Log Cabin granite is given to this rock. It forms a small stock with several divergent dikes. In plan the stock measures 9,000 feet east-west and 4,000 feet north-south. Its west and northeast rims may be fault contacts. Large blocks of Precambrian and Tertiary volcanic rocks are located on the stock. A few small well digested xenoliths are found in the body. Many roof pendants of the host rocks have been caught in the margins of the stock and dikes. Several phases are recognizable.

The main phase of this rock, which occupies more than 90 per cent of the stock, is slightly porphyritic and due to widespread phenocrysts of rounded quartz (up to 8 mm in diameter), of feldspars (up to 8 by 12 mm), and of biotite (up to 2 by 4 mm). Under the microscope this phase shows a hypidiomorphic-granular texture. The major constituents, each above 10 per cent in volume, are plagioclase, potash feldspar, and quartz. The plagioclase is euhedral to subhedral, locally zoned, and in composition ranges from $An_6$ to $An_{13}$ though largely $An_9$. Where enclosed in potash feldspar, it has a sodic rim. Fine inclusions of apatite, biotite, and opaque minerals are found in it. It has been weakly altered to kaolinite, sericite, and carbonate, in order of intensity. The alteration is especially strong in the center of plagioclase. The potash feldspar is everywhere anhedral. It consists of orthoclase, which cuts into the plagioclase and contains euhedral crystals of the latter, as well as perthite of the beads, stringlet, and rarely, interlocking types. The alteration is usually nil but there is weak kaolinitization in some places. The quartz is anhedral; rarely subhedral. Quartz phenocrysts composed of an aggregate of anhedral crystals are common. Quartz also invades the feldspars. Accessory minerals are biotite, apatite, sphene, zircon, opaque minerals, and occasionally primary muscovite. The biotite includes fine specks of apatite, zircon, and opaque minerals; it is euhedral to subhedral and is locally altered to chlorite but is generally fresh.

According to a modal analysis (Table 4), plagioclase ranges from 31.2 to 33.0, potash feldspar 30.2 to 36.2, and quartz 29.9 to 35.2 per cent in volume. These and the granitic texture give a position of the phase in granite.

Table 4 Modal analyses of the Log Cabin granite.

| | Sample number | Plagio-clase | Potash feldspar | Quartz | Biotite | Others | Mafic total | Total percentage | Total points |
|---|---|---|---|---|---|---|---|---|---|
| Main phase | SI–240 | 33.0 | 30.2 | 35.2 | 1.4 | 0.2 | 1.6 | 100.0 | 2552 |
| | SI–241 | 32.8 | 32.2 | 34.0 | 0.7 | 0.3 | 1.0 | 100.0 | 2252 |
| | SI–174 | 32.2 | 35.4 | 29.9 | 1.8 | 0.6 | 2.4 | 99.9 | 2141 |
| | SI–175 | 31.2 | 36.2 | 31.1 | 1.1 | 0.4 | 1.5 | 100.0 | 2169 |
| Marginal and later phases | SI–176 | 28.3 | 38.5 | 32.2 | 0.3 | 0.8 | 1.1 | 100.1 | 1816 |
| | (with a quartz veinlet | 27.1 | 36.8 | 35.0 | 0.3 | 0.7 | 1.0 | 99.9 | 1897 |
| | SI–177 | 19.1 | 43.7 | 36.7 | 0.1 | 0.3 | 0.4 | 99.9 | 1868 |
| | SI–180 | 11.1 | 54.4 | 34.4 | – | 0.2 | 0.2 | 100.1 | 2034 |
| | (phenocryst 49.4% | 3.4 | 67.4 | 28.8 | | 0.4 | 0.4 | 100.0 | 1002 |
| | groundmass 50.6% | 18.5 | 41.7 | 39.7 | | 0.1 | 0.1 | 100.0 | 1032 |

(Percentages by volume)

The intermediate phase is a later and marginal rock; SI–176 for example, is slightly different from the rock of the mian phase. The grain size is finer; the texture is aplitic. The major constituents of this intermediate rock phase are the same as in the main phase. Relatively larger crystals of plagioclase, up to 7 by 7mm, are subhedral to anhedral, while the smaller ones are anhedral. Some of plagioclase contains quartz patches suggesting resolution. Where plagioclase is cut by veinlets of quartz (which average 2mm in diameter), the polysynthetic twinning planes are curved No bent. Quartz veinlets also cross the boundary between two crystals of plagioclase. No zoning is seen. The plagioclase has apatite inclusions and has been weakly altered to kaolinite and sericite. The potash feldspar (measuring up to 2.5 by 3mm) is anhedral. It consists of orthoclase and perthite, in many places surrounding the plagioclase and sometimes locally replacing it, occasionally forming antiperthite, but generally with a mutual boundary with plagioclase. The albite lamellae of the perthite are thinner than those of the perthite of the main phase. The potash feldspars have been weakly altered to kaolinite and sericite. The quartz, measuring up to 4 by 6mm, is in anhedral crystals with megascopically sutured outlines. Accessory minerals are biotite (usually altered to sericite and opaque minerals), apatite, sphene, magnetite, and hematite.

The modal analysis (Table 4) indicates that the contents in potash feldspar and quartz increase and the plagioclase decreases in comparison with the contents of the same minerals in the main phase of the rock. Since the texture is aplitic and the composition is granitic with very little mafic minerals, the rock is best classified as aplite.

The marginal phase and irregular dike form-like phase of the Log Cabin granite and its associated dikes have allotriomorphic-granular textures. When the rock is porphyritic, a few phenocrysts of potash feldspar and plagioclase are euhedral to subhedral. In the usual case, this marginal phase is slightly porphyritic with large crystals of potash feldspar, and quartz and lesser amounts of plagioclase, these three minerals being the major constituents. In places, the plagioclase is a minor constituent (2 to 10 per cent in volume). The plagioclase, up to 1.5 by 0.5mm, is everywhere anhedral except for occasional phenocrysts of euhedral to subhedral forms in which a zoning is rarely found. At the margins and along cracks, the plagioclase crystals have been widely replaced by potash feldspar, so that a perthite of the replacement type is common. It has been weakly altered to sericite and kaolinite. The potash feldspar, ranges in size up to 2 by 4mm and consists of orthoclase and perthite; it contains inclusions of quartz and opaque minerals. In replacing plagioclase, the potash feldspar encloses many relicts of the former. In addition to the replacement there is a regular stringlet-like form. The potash feldspar itself has been slightly altered to sericite and kaolinite. The quartz, which measures up to 2 by 2.5mm, is usually anhedral, but some crystals have a polygonal outline, and in places phenocrysts of quartz are formed of an aggregate of anhedral crystals. Where alteration is strong, flakes of sericite may completely bury interspaces of the major minerals. The accessories and alteration products include apatite, sphene, hematite, magnetite and pyrite.

The marginal phase of this rock is texturally aplitic, and modally and chemically granite, as shown in Table 4 and 9(S1–180).

The Columbine aplite porphyry (G5p) is exposed in an eastwest band at the mouth of Columbine Creek, from which the rock is tentatively named. The rock has a maximum width of about 600 feet. It intrudes the AI formation and Precambrian granite along a trend roughly parallel to the "S"-surface of the Precambrian.

The Columbine aplite porphyry has a porphyritic texture with a fine-grained allotriomorphic-granular matrix. Its modal analysis indicates that the phenocrysts, composing about 42.5 per cent of the rock, consist of quartz (29.0 per cent), potash feldspar (36.4 per cent), plagioclase (32.3 per cent), biotite (2.1 per cent) and other minerals (0.3 per cent). The plagioclase, in size up to 3.3 by 8mm, is usually subhedral and in places euhedral. No zoning is observed. The composition is $An_{15}$ to $An_9$ with an average of $An_{12}$ (oligoclase). It has been weakly altered to kaolinite, sericite, and a carbonate. The potash feldspar (measuring up to 2.3 by 5.2mm) is euhedral to subhedral and rarely anhedral. It is composed of orthoclase and a little microperthite in small crystals. Carbonate invades the potash feldspar along the cleavages and along the lamellae of the albite in the perthite. Weak kaolinization and very weak sericitization have affected the potash feldspar. The quartz (measuring up to 3.5 by 4mm) is mostly subhedral and locally anhedral. Much of it has been corroded and many irregular cracks are developed on the larger crystals. The biotite (measuring up to 0.7 by 1.6mm) is euhedral to subhedral. It contains many inclusions of apatite and opaque minerals, and has been chloritized almost everywhere. The matrix of the rock is composed mainly of potash feldspar and quartz and of lesser amounts of plagioclase. The ratio of alkali feldspar to plagioclase is roughly 2: 1 or more.

The ratio of feldspars to the rock as a whole is over 2: 1, so that the rock belongs in granite clan. Texturally the rock is a porphyritic aplite. It appears that the Columbine aplite porphyry is a branch of the Log Cabin granite, for it resembles in composition and texture the intermediate phase of that rock. Because of its much higher content of mafic minerals and its different texture, this can not be a branch of the Goat Hill porphyry; moreover, the common presence of quartz phenocrysts, this may not be a dike that is separated from Questa Mine aplite. A similar facies of the aplite has the composition of granite and a lesser content of mafic minerals.

A brief summary of the intrusive activity of the biotite granite follows. In composition the intrusion started as a granite. The crystallization ended as a granite with high potash feldspar and low mafic minerals, while the texture was changed from granitic to aplitic. In addition, the latest facies has a more distinctive porphyritic texture than the main facies. Molybdenum seems to be concentrated in the latest rocks and has been deposited along factures in the rock itself and in the host rocks. In Figure 4, modal analyses are plotted on a ternary diagram of quartz, potash feldspar, and plagioclase. All show totals of quartz and feldspars amounting to more than 97 per cent. Evolution of these rocks is best shown by the changing

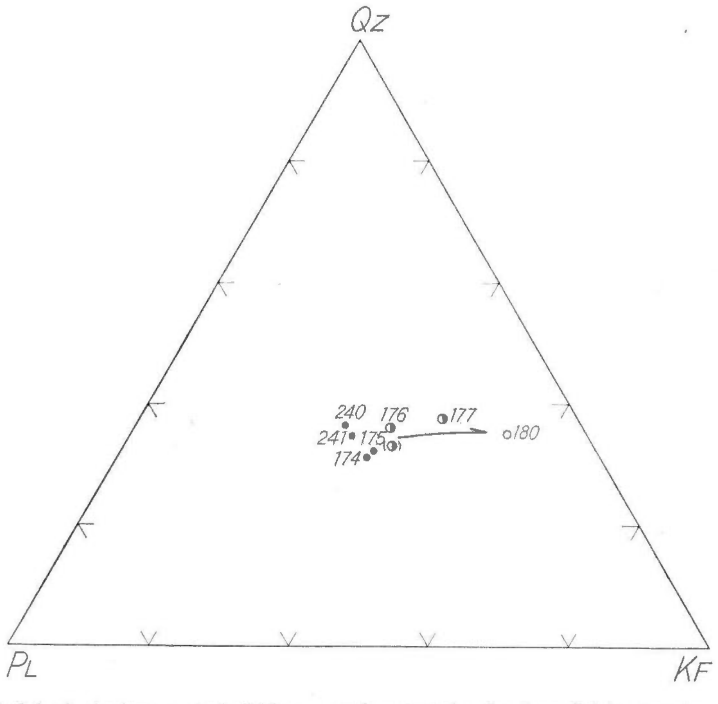

Figure 4 Modal plagioclase, potash feldspar, and quartz in the Log Cabin granite. Solid circle: main phase, half-solid circle: intermediate phase, open circle: later (marginal) phase. Percentages by volume. The arrow indicate the evolution trend.

ratio of the two feldspars. Larger amounts of potash feldspar are present in the later facies. This phenomenon agrees with the microscopic observations described already: there had been progressive replacement even to an extreme degree of plagioclase by potash feldspar in the later facies. The quartz content seems to have been stable throughout the evolution. The content of mafic minerals (Table 4) – very low compared with that of the average granite – is greatly changed from 2.4 to 0.2 per cent during crystallization.

### II. 3. 5 Questa Mine aplite (G6)

The Questa Mine aplite (after CARPENTER, 1960), the most important one of the second type in the intrusive series, is a slightly porphyritic aplite. The Questa molybdenum deposits are located along the west flank of this rock. Questa Mine aplite is exposed in an elliptical area, elongated in a north-south direction, around Sulphur and Blind Gulch (Figure 2). This stock has a length of about 10,000 feet and a width of about 4,500 feet.

This rock has discordantly intruded Precambrian rocks as well as the AI and AII formations. The contact shows a marked change in strike, but dips outward. Many large roof-pendants are present; these xenoliths have lens-like shapes, roughly parallel with the contact. Some of them have not broken free from the surrounding country rock (Plate 11). A few isolated blocks of the host rocks are located in the aplite stock. Small granodioritic masses or lenses, scattered in sparse numbers in the aplite, are regarded as xenoliths of andesitic rocks, well digested.

The Questa Mine aplite can be subdivided into the following five phases on the basis of the mode of the occurrence (Figure 3), composition, and texture:

a) Porphyritic biotite-granite (dike).
b) Slightly porphyritic aplite (stock, main phase).
c) Fine-grained aplite (chilled margin and dike).
d) Aplite porphyry (dike).
e) Aplite breccia (dike).

a) Porphyritic biotite-granite

This occurs as dikes at the northwestern rim of the stock, the greatest width observed being 40 feet. Most such dikes trend northeast, following the contact between the aplite of the main phase and the andesite; some of them cut through the andesite. As the rock has been intruded and replaced by rock of the chilled-marginal facies of the slightly porphyritic aplite, the porphyritic biotite granite is considered the earliest phase of the intrusive activity of the Questa Mine aplite. It seems likely that the dikes followed faults striking northeast, dipping steeply, and constituting one of the outstanding fault systems around the northwest margin of the stock. This rock is the most mafic among rocks in the five phases here described.

Microscopically the rock shows a porphyritic texture with phenocrysts of plagioclase and small amounts of potash feldspar and biotite. The matrix is allotriomorphic-granular, i.e., aplitic. A modal analysis is given in Table 5. Plagioclase is one of the three major constituents, the others being potash feldspar, and quartz; it is euhedral to subhedral, but mostly subhedral, and grows up to 5 by 7mm in size. Zoning is commonly present. Crystals of potash feldspar with irregular outlines are involved in the plagioclase. The plagioclase has been weakly kaolinitized and sericitized. Potash feldspar, up to 3 by 6mm, is usually anhedral though a very few crystals are subhedral. Locally the potash feldspar replaced plagioclase. Most of the potash feldspar is microperthitic. The potash feldspar has been weakly altered to kaolinite. Quartz, up to 1.5 by 2mm, is anhedral. A minor constituent is biotite, in crystals 1 by 1.5mm or less in size. It is euhedral to subhedral, pale to dark brown in color, and has been slightly altered to sericite and iron oxides. Accessory minerals are apatite, zircon, and opaque minerals.

The modal analysis indicates that this rock has the composition of granite. Although the rock shows an aplitic texture in the matrix, its content of mafic minerals, 4.9 per cent by weight, is too high to call the rock an aplite.

b) Slightly porphyritic aplite

More than 95 per cent of the stock may be composed of this rock. It is a heterogeneous and slightly porphyritic rock. The phenocrysts consist of plagioclase, potash feldspar, quartz, and biotite. Generally plagioclase is the most abundant phenocryst. The texture of the matrix is chiefly allotriomorphic, but partly hypidiomorphic (Plate 14).

Table 5 Modal analyses of the Questa Mine aplite

| Sample number | Plagio-clase | Potash feldspar | Quartz | Biotite | Others | Mafic total | Total percentage | Total points |
|---|---|---|---|---|---|---|---|---|
| SI–193 | 37. 7 | 32. 4 | 26. 1 | 3. 0 | 0. 8 | 3. 8 | 100. 0 | 1557 |
| SI–238 | 35. 9 | 30. 9 | 31. 8 | 0. 9 | 0. 5 | 1. 4 | 100. 0 | 2452 |
| SI–239 | 32. 2 | 25. 9 | 41. 1 | 0. 5 | 0. 3 | 0. 8 | 100. 0 | 2443 |
| SI–186 | 31. 2 | 32. 6 | 34. 4 | 1. 4 | 0. 5 | 1. 9 | 100. 1 | 2402 |
| SI–237 | 29. 7 | 34. 1 | 34. 9 | 0. 8 | 0. 6 | 1. 4 | 100. 1 | 2336 |
| SI–187 | 28. 7 | 35. 7 | 34. 5 | 0. 5 | 0. 6 | 1. 1 | 100. 0 | 2115 |
| SI–189 | 24. 3 | 39. 1 | 35. 1 | 1. 0 | 0. 6 | 1. 6 | 100. 1 | 2076 |
| SI–234 | 24. 3 | 41. 6 | 32. 3 | 0. 8 | 1. 0 | 1. 8 | 100. 0 | 2264 |
| SI–188 | 23. 7 | 41. 7 | 32. 7 | 1. 4 | 0. 4 | 1. 8 | 99. 9 | 1947 |
| SI–192 | 21. 4 | 38. 0 | 39. 9 | 0. 1 | 0. 6 | 0. 7 | 100. 0 | 1370 |

Notes. SI-193 : porphyritic biotite granite, SI–192: fine-grained aplite, the others: main phase aplite.
Percentages by volume.

As shown in Table 5, the rock varies in composition. Its constituents range as follows in percentages by volume plagioclase content from 23.7 to 35.9; potash feldspar from 25.9 to 41.7; quartz from 32.3 to 41.1. As seen, variations in content of quartz are rather small, while large for feldspars. This characteristic is similar to that of Log Cabin granite.

Plagioclase, measuring up to 3 by 7 mm, is euhedral to subhedral in the phenocrysts and subhedral to anhedral in the matrix. Zoning is absent or rare. The composition ranges from $An_2$ to $An_{13}$, and is generally $An_{10}$. Where plagioclase is surrounded by potash feldspar, it has a sodic rim (Plate 17). Weak kaolinization and sericitization are present in most crystals. Potash feldspar, up to 4.5 by 6.5 mm (though one grew up to 6 by 10 mm), is rarely subhedral and mostly anhedral. Large crystals of the potash feldspar contain stringlets of plagioclase and irregular patches of quartz. In addition to this stringlet perthite, many potash feldspar crystals show a micro- and crypto-perthitic texture; consequently, the content of normative albite in the rock seems to be higher than that of modal albite. The alkali feldspar has been very weakly altered to kaolinite. Quartz, up to 5 mm in diameter, is anhedral. In many cases contains inclusions of liquid and dust. Biotite, being pale greenish brown to dark brown in color, is subhedral in most cases. It includes fine specks of apatite, zircon, and opaque minerals. On some crystal the biotite has been partly altered to chlorite.

Since aplitic texture of the rock is characteristic, and the percentage of mafic minerals range up to 1.9 per cent in modal analyses, this rock is best designated a slightly porphyritic aplite.

### c) Fine-grained aplite

In a few places, the slightly porphyritic aplite has a chilled margin. This phase develops at a maximum of about 100 feet into the aplite. The rock is very similar to the aplite, but finer. It has more quartz and potash feldspar but fewer mafic minerals than the aplite.

The texture is slightly porphyritic, and the matrix is allotriomorphic (Plate 15). Phenocrysts consist of plagioclase with a maximum size of 2 by 3 mm; and lesser amounts of potash feldspar which reaches sizes up to 0.8 by 1.6 mm; and quartz with diameters of 1 mm or less. The plagioclase is euhedral to subhedral. In many places the centers and borders of crystals have been replaced by more sodic plagioclase, which is usually fresh. Replacement by potash feldspar is also present. Some small crystals in the matrix, for example, plagioclase have been almost completely replaced by potash feldspar (Plate 16). The composition is about $An_3$ (albite). Fine specks of sericite and kaolinite are present. The potash feldspar is subhedral to anhedral. In part, it forms a myrmekite and is everywhere clouded by kaolinite. Quartz is in irregularly rounded forms, each composed of an aggregate of anhedral crystals.

The matrix of the rock consists of laths or anhedral crystals of plagioclase, of anhedral potash feldspars, and of anhedral quartz. In some places the rock shows a granoblastic-mosaic texture, being composed of quartz, topaz, and sericite. The sericite fills interspaces between quartz and topaz. The topaz is rarely in short prismatic crystals; it is mostly anhedral-granular. It is colorless in thin sections, but very pale pinkish brown in few large crystals. Its birefringence is weak; its interference colors range to straw yellow of the first order. Its cleavage flakes showed very weak birefringence. It has parallel extinction in longitudinal sections. The cleavage traces of the two crystals are parallel to the slow ray, but the cleavage trace of another crystal is parallel to the faster ray. Optically the mineral is biaxial, positive, and with 2V about 60°. It has been replaced by sericite. Although there is a question as to the orientation, the other microscopic observations agree with those of topaz[注2)]. If the mineral is topaz, this part of the present rock must have been formed during a deuteric stage.

### d) Aplite porphyry

This is exposed, in the form of a dike, in the stock, around contact between the stock and the host rocks, and in the andesite and Precambrian rocks near the stocks. They cut through the previous three phases of the Questa Mine aplite. However, the largest body, exposed at the mouth of Blind Gulch (Figure 2), of

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[注2)] In recent studies on the Japan's most productive molybdenum deposits in the San'in district, the author noticed pale-colored andalusite in the latest phase of granitic rocks and in wall-rocks classically called a product of greisenization, both of which are related to the molybdenum mineralization (Ishihara, 1966 & 1967). There it seems meaningful the presence of the alumina-silicate with other "metamorphic minerals" like garnet and cordierite to the genesis of the molybdenum deposits. The mineral here described may be missidentified, leaving this question for future researchers on the Questa deposits.

Ishihara, S (1966): Study on granitic rocks and horizon of molybdenum deposits in eastern Shimane Pref., Japan. Jour. Geol. Soc. Japan, vol. 72, p. 553–572.

Ishihara, S. (1967): On so-called metamorphic minerals in the wall-rock alteration zone of several molybdenum deposits in the San'in district (abstract). Jour. Japan. Ass. Min. Petr. Econ. Geol., vol. 57 (in print).

Table 6 Modal analyses of aplite porphyry.

| Minerals | | SI–194 | SI–195 |
|---|---|---|---|
| Phenocrysts | Quartz | 26.3% (vol.) | 23.4% (vol.) |
| | Potash feldspar | 21.2 | 43.0 |
| | Plagioclase | 48.9 | 32.6 |
| | Biotite | 3.6 | 0.9 |
| Total phenocrysts | | 51.6 | 41.7 |
| Total matrix | | 48.4 | 58.3 |
| Total | | 100.0 | 100.0 |

of about 1000 feet in length and about 300 feet at the maximum width, has no trend clearly bearing on the mode of intrusion. Here the rock looks to be changed gradually to the main phase aplite.

The aplite porphyry has a porphyritic texture with a matrix of allotriomorphic-granular texture. The matrix shows a micrographic texture in places. The percentage of phenocrysts, as examples of the largest body, ranges 41.7 to 51.6 per cent by volume. The phenocrysts consist of plagioclase, potash feldspar, quartz, and small amounts of biotite. Their percentage changes from place to place. Two examples are shown in Table 6. One difference between this and the previous three rock phases is the presence of more quartz phenocrysts.

The plagioclase, which ranges in size up to 8 by 13mm, is euhedral to subhedral. Zoning is fairy common; a sodic rim is rarely seen. Some of the large phenocrysts of plagioclase contain quartz crystals shaped like rods or stringlets, which can be interpreted as replacements of plagioclase by quartz. The plagioclase has been slightly sericitized and kaolinitized, especially at its crystal margins and centers. The potash feldspar, with dimensions up to 10 by 11mm, is subhedral to anhedral. It includes many euhedral to subhedral crystals of plagioclase and occasional grains of anhedral quartz. Potash feldspar has replaced rim and center of plagioclase. Kaolinite is a common alteration product. The quartz, up to 4 by 5mm in size, has subhedral rounded to polygonal outlines. It is corroded in many places. It encloses and in part replaces the plagioclase.

The matrix of the rock consists of anhedral crystals of potash feldspar, quartz, and plagioclase, in decreasing order of abundance. Accessories of the rock are biotite, sphene, apatite, and opaque minerals. In general, the alteration of this rock type is much stronger than in the main phase of the Questa Mine aplite. The alteration products are sericite, kaolinite, chlorite, hematite, and opaque minerals.

e) Aplite breccia dikes

This rock is found around the ridge between Sulphur and Blind Gulch, along the northwestern margin of the stock. It is everywhere dike-like in form, following faults in the hornblende andesite. The dike widths are up to about 20 feet. The rock is composed of breccia fragments in a matrix of quartz and sericite. The breccia consists of fragments of fine-grained aplite and siliceous aplitic material, both up to 50 mm in diameter, and small amounts of andesite fragments, up to 15 mm in diameter. Under the microscope these aplitic breccias show an allotriomorphic-granular texture. They are composed of potash feldspar and quartz and small amounts of plagioclase and sericite. Some crystals of plagioclase are euhedral to subhedral. The plagioclase is replaced by potash feldspar. Some of potash feldspar, probably orthoclase, show small to moderate 2V, negative, which may be due to an unusual type of twinning, not further identified. The matrix is composed of mosaic crystals of quartz and very small amounts of alteration minerals.

The occurrence and the composition of the rock suggest that these dikes are equivalent to an aplite porphyry and that they were intruded along local faults when movements related to the Questa's igneous activity were still active.

Modal composition of three phases of the Questa Mine aplite is plotted in the figure 5. The main phase rocks are more widely spread out but slightly toward the right side than those of a marginal phase (SI–176) and the main phase Log Cabin granite. This may lead an interpretation, though number of the samples is not large enough, that the main phase Questa Mine aplite is more fractionated and is on the same evolution trend in comparison with the main phase Log Cabin granite. A marginal phase rock, plotted apart from the main phases to quartz apex, is from the northwestern edge of the Questa Mine aplite (c.f. Appendix). In field and underground, aplites of the main and marginal phases in which mineralized fractures are involved, are rich in potash feldspar, as an example of SI–236, which will be described in the next chapter. Two samples of aplite porphyry, which mode of emplacement is not known, are plotted below the others–low in quartz; however, large size phenocrysts of such a porphyry could make these modally analyzed figures unreliable.

### II. 3. 6 Red River aplite (G7)

An exposure of "aplitic rocks" with a horizontal diameter of about 3 miles,

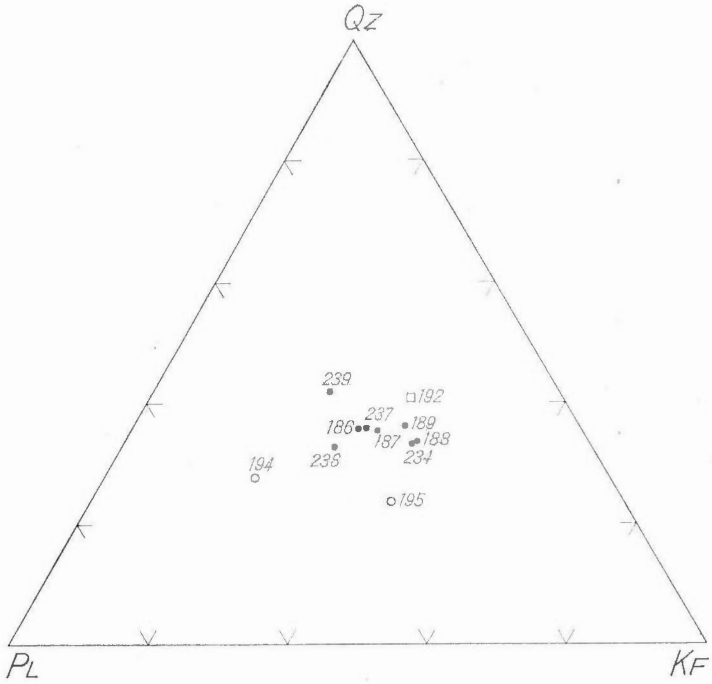

Figure 5 Modal plagioclase, potash feldspar, and quartz in the Questa Mine aplite. Solid circle: main phase, open circle: aplite porphyry, open square: marginal phase. Percentages by volume.

is located at the town of Red River, 5.5 miles east of the molybdenum mining camp (Figure 6). So far as is known in the surveyed area, which is northwest the Mallette Creek, this stock has a great variety in its composition and texture. A marginal phase at north is finer-grained than the other two phases with phenocrysts of quartz and feldspars–rhyolitic, shown by a broken line in the figure 6. The next phase occupying the major parts of the stock is a leucocratic rock which can be called a fine-grained aplite. It is characteristic of this phase that in the margin it includes many xenoliths of mafic composition some of which are as much as 2 feet in diameter. The xenoliths, remnants of roof-pendant of the (quartz) latite (AIII), are highly flooded by potassium; aplite in the matrix is rich in potash feldspar. A medium-grained porphyritic aplite and granite take place the core of the stock. Aplite porphyry and quartz porphyry, probably dikes in form, intrude the later two rock phases.

These field evidences suggest that the mode of intrusion of this stock is quite different from that of the Log Cabin granite and Questa Mine aplite. The stock could have reached up to surface during the intrusion, though most parts should have been in certain distance. A profile indicates that the Red River aplite intruded at the highest horizon among the three stocks, as is shown in Figure 28.

### II. 3. 7 Post-aplite dike

In and near the Questa Mine aplite there are several small dikes cutting through rocks even so young as molybdenite veins (Plate 9). The thickness of such dikes ranges up to 20 feet. Two such dikes were mapped on surface–one at upper Sulphur Gulch, the other just west of the mine camp. They have the general trend N10°E and dip vertically or steeply to the west, and intrude Questa Mine aplite and hornblende andesite (AI). Two of the large dikes and many small dikes can be traced in the mines. Most of these dikes are porphyritic, but a small one, with a width of 1 foot, is a dense rock. The rock is typically dark green.

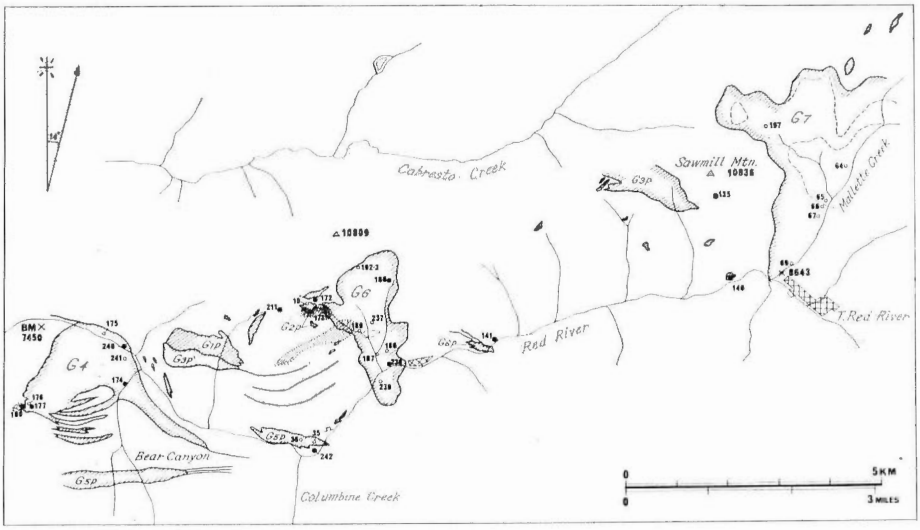

Figure 6 Distribution of intrusive bodies and sample localities treated in laboratories. Dotted area indicates strongly mineralized zone. Solid circles are for of total analysis; open circles for of lime and alkali.

Under the microscope, the rock is clearly porphyritic, with a matrix of panidiomorphic to trachytic texture. The phenocrysts generally consist of plagioclase and mafic minerals. The plagioclase, the largest of which reaches sizes of 6.2 by 10 mm, is euhedral to subhedral. The composition is $An_{23}$ to $An_{37}$ (oligoclase-andesine), small amounts of antiperthite are also present. The plagioclase has been locally replaced by potash feldspar and albite, and then by carbonate at its margin. It has also been altered to sericite, kaolinite, and chlorite. Phenocrysts or xenocrysts of quartz occur in some bodies. The mafic minerals, up to 1.7 by 2.2 mm, are euhedral to subhedral. They have been completely altered to chlorite, carbonate, and sericite, in diminishing order of abundance. Originally the mafic minerals seem to have been hornblende, biotite, and small amounts of pyroxene. The matrix of such dikes consists largely of plagioclase laths, chlorite, and opaque minerals. The laths, showing a flow structure, are filled with potash feldspar, albite, and a little quartz and zeolite, with an intersertal texture. The laths have been replaced by potash feldspar, followed by carbonate. Zeolite, together with quartz and carbonate, are also present in the drusy parts of along cracks.

The content of potash feldspar by volume is more than 10 per cent. The plagioclase has a composition of $An_{50}$ or less. Quartz is less than 10 per cent by volume in most dikes of this group. In texture the dikes are porphyritic and pilotaxitic to trachytic. Therefore, the dike rock is a latite porphyry.

## III. Chemical Petrology

### III. 1 Effusive Rock Series

Among various kinds of volcanic and their pyroclastic rocks, only three samples were examined by chemical methods. They are each example of the most

Table 7 Chemical analyses and norms of volcanic and pyroclastic rocks

| Rock Unit | AI | AVI | RII | Rock Unit | | AI | AVI | RII |
|---|---|---|---|---|---|---|---|---|
| Sample No. | SI-141 | SI-211 | SI-135 | Sample No. | | SI-141 | SI-211 | SI-135 |
| $SiO_2$ | 59.14 | 64.64 | 77.76 | Normative Constituents | il | 1.29 | 0.74 | 0.21 |
| $TiO_2$ | 0.68 | 0.39 | 0.13 | | ap | 1.03 | 0.57 | 0.02 |
| $Al_2O_3$ | 16.64 | 17.45 | 13.32 | | py | 0.21 | 0.84 | 0.09 |
| $Fe_2O_3$ | 2.67 | 1.34 | 0.62 | | mg | 3.87 | 1.94 | |
| FeO | 4.02 | 2.87 | 0.14 | | hm | | | 0.62 |
| MnO | 0.09 | 0.07 | 0.01 | | or | 16.02 | 21.51 | 20.98 |
| MgO | 4.83 | 2.56 | 0.24 | | ab | 21.07 | 20.39 | 19.63 |
| CaO | 3.97 | 0.31 | <0.01 | | an | 16.92 | | |
| $Na_2O$ | 2.49 | 2.41 | 2.32 | | C | 3.41 | 9.55 | 5.66 |
| $K_2O$ | 2.71 | 3.64 | 3.55 | | en | 12.03 | 6.38 | 0.60 |
| $P_2O_5$ | 0.47 | 0.30 | 0.01 | | fs | 4.00 | 2.74 | |
| S | 0.11 | 0.45 | 0.05 | | qz | 17.96 | 31.62 | 50.31 |
| $H_2O$ (+) | 1.60 | 2.60 | 1.04 | | | | | |
| $H_2O$ (−) | 0.38 | 0.58 | 0.49 | Total | | 97.81 | 96.28 | 98.12 |
| Total | 99.80 | 99.61 | 99.69 | Femic total | | 22.43 | 13.21 | 1.54 |
| Analyst | K. Ohta | K. Ohta | K. Ohta | SI* | | 28.9 | 20.0 | 3.5 |

Notes. SI-141: Fine-grained slightly porphyritic andesite; mafic minerals are altered to chlorite and plagioclase phenocryst partly to epidote. SI-211: This consists of two parts; one porphyritic lava; the other lithic tuff. The both are hornblende bearing biotite (quartz) latite. Mafic minerals are strongly altered to chlorite; feldspars to sericite and carbonate. SI-135: Rhyolitic welded tuff with moderate kaolinitization and weak sericitization.

*After Kuno et al. (1957).

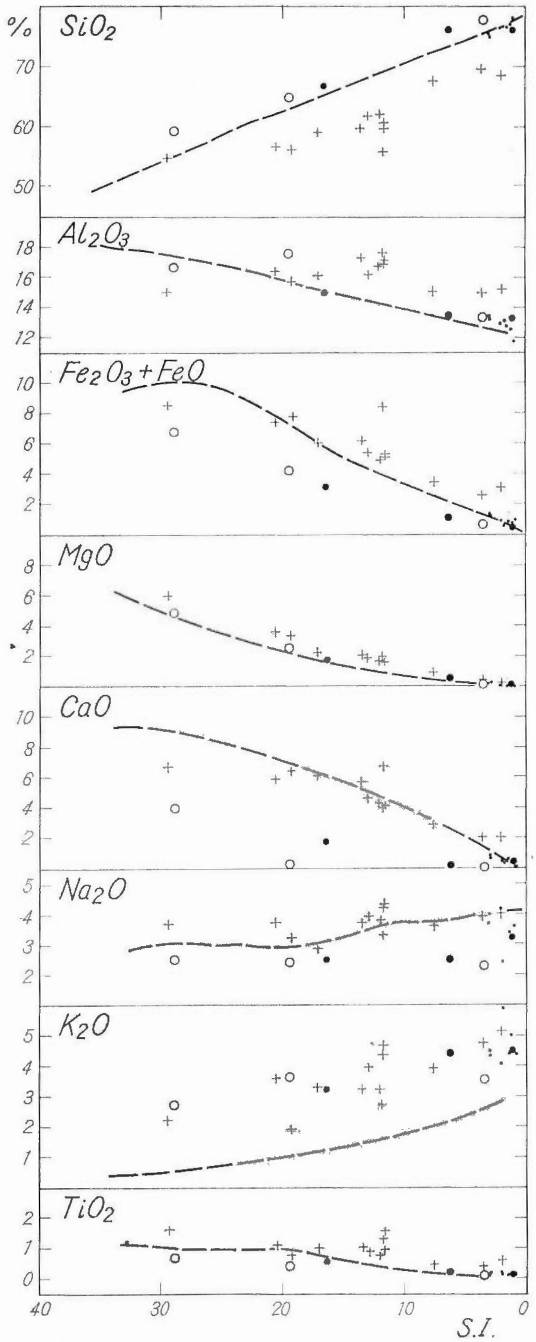

Figure 7 Variation diagram of effusive and intrusive rocks, Questa mine area, in comparison with selected rock series of San Juan region and aphyric rocks of hypersthenic rock series of Izu-Hakone region. Open circle: effusive rocks, solid circle: dike-forming intrusive rocks, solid dot: stock-forming intrusive rocks. Cross: Burns quartz latite (1 sample), pyroxene quartz latite (2) of Silverton volcanic series, quartz latite (4) of pre-Potosi volcanic rocks of San Luis Hill, and quartz latite to rhyolite (6) of Potosi volcanic series (after LARSEN and CROSS, 1956). Dashed line: generalized trend of aphyric rocks of hypersthenic rock series of Izu-Hakone region (after KUNO, 1965).

mafic, intermediate, and the most salic phase of these rocks. (Table 7) Almost all effusive rocks in the reported area have been hydrothermally altered to certain degree; however, these listed are relatively fresh.

Each component of the analyzed samples are plotted against SI value in figure 7. As is seen in this variation diagram, the effusive rocks have tendency of calc-alkali rock series, i.e., in following magmatic evolution, increasing silica and alkali, and decreasing iron from the initial stage without concentration at middle and later stages (Kuno, 1965). In comparison each oxide of the rocks with aphyric rocks of hypersthenic rock series of Izu-Hakone region, as an example of calc-alkali rock series, the Questa rocks are very rich in $K_2O$, and dominant in $SiO_2$ and $MgO$; and poor slightly in $Na_2O$ and $TiO_2$, and very poor in $Fe_2O_3+FeO$ and $CaO$. It should be noted here, however, a difference on geologic environment between these two areas. The Questa rocks are erupted in rather stable Precambrian basement; afar east from the Cordillera orogeny; while the hypersthenic rocks in the Circum-Pacific orogeny belt.

Volcanic rocks of Miocene age in San Juan region, which geologic situation is similar to that of Questa mine area and geographically near the area, are also

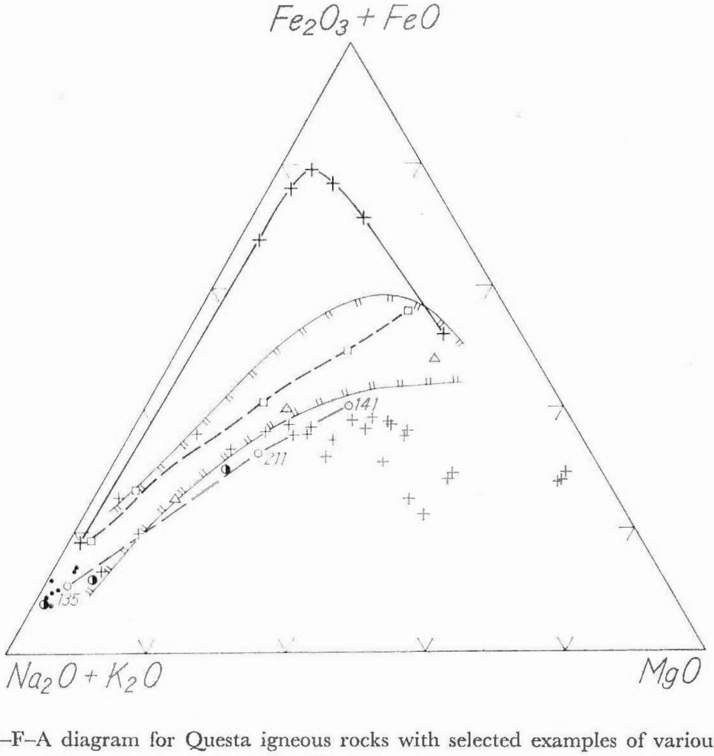

Figure 8 M–F–A diagram for Questa igneous rocks with selected examples of various rocks series. Open circles: effusive rocks, half-solid circle: dike-forming intrusive rocks, small solid circle: stock-forming intrusive rocks. Cross connected with solid line: evolution trend of Skaergaard, solid line with double hachures: field of aphyric rocks of hypersthenic rock series of Izu-Hakone region (after Kuno, 1965). Open square: averages of normal tholeiitic basalt, andesite, dacite, dellenite, and rhyolite; open triangle: averages of normal alkali basalt, latite, and trachyte (after Nockolds, 1954). Small crosses: abnormal alkali rocks of Highwood Mountains (after Larsen, Buie, and Burgess, 1941).

plotted in the figure 7. The Questa rocks are rich in $SiO_2$, a little poor in MgO, $Fe_2O_3$+FeO, $TiO_2$, and $Na_2O$, and very poor in CaO. It is characteristic that the lime content is low even at the beginning of the Questa rocks, and it seems that it is abnormally low in rocks solidified under strong disequilibrium condition like on pyroclastics and tip of dikes. This low lime content makes the alkali-lime index of the Questa rocks lower. The index assumed based on the three assays is about 54, on which a name alkali-calcic is given in the Peakock's classification注3).

It may not be possible to make a comment on which a original magma the Questa effusive rocks have deriven from. In the M–F–A diagram, selected examples of various rock series are plotted (Figure 8). The Questa rocks roughly follow the trend of the normal alkaline rocks; moreover, the field of the normal alkaline basalt, as shown by an example of Nockolds' averages, is along the trend of the Questa rocks. However, no more mafic rocks than the andesite (AI) is observed in the Questa mine area, so far as known through surface mapping and underground drilling. Since there is deposition of the effusive rocks more than 9,000 feet thick within the narrow depressed zone of about three miles wide, one can easily assume the volcanic activity accompanied with strong basemental depression. If this is true, there is a possibility of existing more mafic rocks that may give us some information about the original magma, beneath the andesite (AI).

### III. 2 Intrusive Rock Series

**Dike-forming rocks:** Lime and alkalis' content of the dike- or plug-forming intrusive rocks are given in Table 8. Although each content agrees well

Table 8 Chemical analyses and norms of Precambrian and dike-forming intrusive rocks.

| Rock Unit | PC | $G_1p$ | $G_2p$ | $G_3p$ |
|---|---|---|---|---|
| Sample No. | SI-242 | SI-140 | SI-172 | SI-232 |
| $SiO_2$ | 74.70 | 66.90 | 76.24 | 76.46 |
| $TiO_2$ | 0.12 | 0.56 | 0.12 | 0.14 |
| $Al_2O_3$ | 13.73 | 15.02 | 13.38 | 13.32 |
| $Fe_2O_3$ | 0.64 | 1.04 | 0.38 | 0.60 |
| FeO | 1.36 | 2.16 | 0.65 | 0.11 |
| MnO | 0.05 | 0.05 | 0.06 | 0.01 |
| MgO | 0.34 | 1.79 | 0.53 | 0.10 |
| CaO | 1.01 | 1.84 | 0.01 | 0.52 |
| $Na_2O$ | 3.31 | 2.51 | 2.49 | 3.25 |
| $K_2O$ | 3.29 | 3.26 | 4.39 | 4.48 |
| $P_2O_5$ | 0.07 | 0.23 | 0.06 | 0.06 |
| S | 0.02 | 0.12 | 0.07 | 0.36 |
| $CO_2$ | | 1.67 | | |
| $H_2O$ (+) | 0.60 | 2.30 | 0.97 | 0.40 |
| $H_2O$ (−) | 0.46 | 0.38 | 0.45 | 0.08 |
| Total | 99.70 | 99.83 | 99.80 | 99.89 |
| Analyst | K. Ohta | K. Ohta | K. Ohta | K. Ohta |

| Rock Unit | | PC | $G_1p$ | $G_2p$ | $G_3p$ |
|---|---|---|---|---|---|
| Sample No. | | SI–242 | SI–140 | SI–172 | SI–232 |
| Normative Constituents | il | 0.23 | 1.06 | 0.23 | 0.25 |
| | ap | 0.15 | 0.50 | – | 0.13 |
| | mg | 0.93 | 1.51 | 0.55 | |
| | hm | | | | 0.60 |
| | or | 19.44 | 19.27 | 25.94 | 26.48 |
| | ab | 28.01 | 21.24 | 21.07 | 27.50 |
| | an | 4.61 | 7.79 | 0.05 | 2.23 |
| | C | 3.04 | 4.51 | 4.51 | 2.30 |
| | en | 0.85 | 4.46 | 1.32 | 0.45 |
| | fs | 1.85 | 2.28 | 0.79 | |
| | qz | 39.52 | 32.75 | 43.79 | 39.29 |
| Total | | 98.63 | 95.37 | 98.25 | 99.03 |
| Femic total | | 4.01 | 9.81 | 2.89 | 1.23 |
| ab+or+qz | | 86.97 | 73.26 | 90.80 | 93.27 |
| D.I.* | | 88.2 | 76.8 | 92.4 | 94.2 |

Notes. SI–242: Foliated biotite granite (Precambrian).
SI–140: (Quartz) monzonite porphyry (plug).
SI–172: Biotite granite porphyry (dike).
SI–232: Goat Hill quartz porphyry (dike).
All rocks are carbonatized, chloritized, and argillized to certain degrees.
*After THORNTON and TUTTLE (1960).

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注3) Alkali-lime index: 51–56: Alkali-calcic
56–61: Calc-alkalic

to the composition taken by microscopic studies, some of the granite porphyry (G2p) show somewhat strange values. The lime content of SI-172 is unexpectably low as happened as in some pyroclastic rocks (SI–211 and SI–135). There are visible plagioclase phenocrysts in the specimens. For example, SI–172 contains 39 per cent plagioclase in phenocryst minerals that occupy 33.3 per cent of the whole rock. These make the plagioclase content of about 13 per cent in volume. For a rough estimation, if one may pick up this figure and a reasonable average An value of 12, the rock should contain CaO between 1.0 and 1.5 per cent. For this great diagreement on results between the chemical analyses and microscopic studies, the plagioclase composition should be re-examined in detail in future.

The granite porphyry of SI–173 has been strongly altered and is now almost sericite-quartz rock, though the original texture is still preserved. The lower values in $Na_2O$ and $K_2O$ are mainly due to decomposition of feldspars in the alteration process. On the contrary, the high potassium content of the granite porphyry SI–233, is due to "$K^+$ Zufuhr". The rock, taken from underground near the Questa Mine aplite body, contains large phenocrysts of potash feldspars (up to 20 by 25 mm), which are more rounded compared with sanidine crystals in the quartz monzonite porphyry (G1p). This shape and the fact that absolute quantity of the potash feldspar is much more abundant near the aplite, may indicate that some of the potash feldspars may not have been formed as primary phenocrysts. This granite porphyry also contains hornblende pseudomorph filled with very fine aggregates of secondary brownish biotite. This may be another proof for the potassium addition.

The amounts of the pseudomorph hornblende is roughly equal to that of flaky-primary biotite. This makes 1.30 per cent in CaO valid as the original content. In this case, the original content of $K_2O$ could be around 3.5 per cent, meaning potassium floading due to the Questa Mine aplite would have been so intense.

Total chemical analyses of three selected rocks are listed in Table 8. Each component plotted against the solidification index (Figure 7) shows very similar variation to those of the selected effusive rocks. In the M–F–A diagram, the three dike-forming intrusives are again just following the trend of the Questa effusive rocks.

**Stock-forming rocks:** The stock-forming intrusive rocks are compositionally all granite. In comparison with the average granite given by Nockolds (1954), the main phase rocks of the both Log Cabin granite and Questa Mine aplite (Table 9) are very poor in MgO and CaO, rather poor in $TiO_2$ and total irons; slightly richer in $Na_2O$ though roughly equal amounts in total alkalis, and higher in $SiO_2$. These characteristics are much clearer in the later phase rocks, e.g. SI–177, SI–180, and SI–236. These in short imply that the Questa granites are highly differentiated ones.

It has been proposed several parameters to indicate degree of the magmatic differentiation, such as Larsen's Index (1938), modified the Larsen's (NOCKOLDS and ALLEN, 1953), Wager's method (1956), solidification index, SI (KUNO et al., 1957), differentiation index, DI (THORNTON and TUTTLE, 1960), and crystallization index, CI (POLDERVAART and PARKER, 1964). Any of these parameters can be applicable for the petrographical purposes. However, the differentiation index is preferably used for the Questa granites, because of the following two reasons; 1) the DI is based on major three minerals of the granites; 2) unlike batholith-forming granites, it is clear that the Questa granites have at least to say passed

Table 9 Chemical analyses and norms of stock-forming intrusive rocks.

| Rock Unit | | Log Cabin biotite granite | | | | Questa Mine aplite | | |
|---|---|---|---|---|---|---|---|---|
| Sample No. | | SI–174 | SI–240 | SI–177 | SI–180 | SI–188 | SI–238 | SI–236 |
| $SiO_2$ | | 74. 98 | 76. 61 | 77. 05 | 78. 10 | 75. 10 | 76. 28 | 76. 34 |
| $TiO_2$ | | 0. 22 | 0. 15 | 0. 17 | 0. 15 | 0. 23 | 0. 15 | 0. 16 |
| $Al_2O_3$ | | 13. 50 | 12. 82 | 12. 50 | 11. 74 | 13. 29 | 12. 99 | 13. 00 |
| $Fe_2O_3$ | | 0. 96 | 0. 74 | 0. 82 | 1. 08 | 1. 03 | 0. 73 | 0. 52 |
| FeO | | 0. 42 | 0. 22 | 0. 05 | 0. 05 | 0. 40 | 0. 29 | 0. 22 |
| MnO | | 0. 05 | 0. 05 | 0. 02 | 0. 02 | 0. 04 | 0. 05 | 0. 01 |
| MgO | | 0. 30 | 0. 14 | 0. 12 | 0. 06 | 0. 31 | 0. 20 | 0. 18 |
| CaO | | 0. 76 | 0. 53 | 0. 36 | 0. 07 | 0. 66 | 0. 52 | 0. 42 |
| $Na_2O$ | | 4. 03 | 4. 05 | 3. 39 | 3. 62 | 3. 71 | 4. 18 | 2. 37 |
| $K_2O$ | | 4. 36 | 4. 40 | 5. 03 | 4. 40 | 4. 54 | 4. 08 | 5. 91 |
| $P_2O_5$ | | 0. 05 | 0. 03 | 0. 03 | 0. 03 | 0. 05 | 0. 05 | 0. 06 |
| S | | <0. 01 | <0. 01 | <0. 01 | 0. 07 | <0. 01 | 0. 01 | 0. 11 |
| $H_2O$ (+) | | 0. 26 | 0. 15 | 0. 26 | 0. 46 | 0. 41 | 0. 18 | 0. 52 |
| $H_2O$ (−) | | 0. 10 | 0. 12 | 0. 14 | 0. 14 | 0. 14 | 0. 16 | 0. 11 |
| Total | | 99. 99 | 100. 01 | 99. 94 | 99. 99 | 99. 92 | 99. 87 | 99. 94 |
| Analysts | | K. Maeda | K. Maeda | K. Maeda | K. Maeda | K. Maeda | K. Maeda | K. Ohta |
| Normative Constituents | il | 0. 42 | 0. 28 | 0. 32 | 0. 28 | 0. 44 | 0. 28 | 0. 30 |
| | ap | 0. 11 | 0. 07 | 0. 07 | 0. 07 | 0. 11 | 0. 11 | 0. 13 |
| | mg | 0. 87 | 0. 87 | 0. 23 | 0. 23 | 0. 61 | 0. 68 | 0. 29 |
| | hm | 0. 36 | 0. 14 | 0. 66 | 0. 92 | 0. 42 | 0. 26 | 0. 32 |
| | or | 25. 77 | 26. 00 | 29. 73 | 26. 00 | 26. 83 | 24. 11 | 34. 93 |
| | ab | 34. 10 | 34. 27 | 28. 69 | 30. 63 | 31. 39 | 35. 37 | 20. 05 |
| | an | 3. 47 | 2. 43 | 1. 04 | 0. 15 | 2. 98 | 2. 28 | 1. 74 |
| | C | 0. 88 | 0. 51 | 1. 10 | 0. 98 | 1. 91 | 0. 85 | 2. 06 |
| | en | 0. 75 | 0. 35 | 0. 30 | 0. 15 | 0. 77 | 0. 50 | 0. 45 |
| | qz | 32. 90 | 34. 95 | 37. 45 | 40. 05 | 34. 39 | 35. 05 | 38. 91 |
| Total | | 99. 63 | 99. 87 | 99. 59 | 99. 46 | 99. 85 | 99. 49 | 99. 18 |
| Femic total | | 2. 51 | 1. 71 | 1. 58 | 1. 65 | 2. 35 | 1. 83 | 1. 49 |
| ab+or+qz | | 92. 77 | 95. 22 | 95. 87 | 96. 68 | 92. 61 | 94. 53 | 93. 89 |
| D.I. | | 93. 1 | 95. 3 | 96. 3 | 97. 2 | 92. 8 | 95. 0 | 94. 7 |

Notes. SI–171 and SI–240: Biotite granite. SI–177: Aplite. SI–180: Porphyritic aplite. SI–188 and SI–238: Slightly porphyritic aplite. SI–236: Dense aplite containing very little molybdenite. All rocks are weakly sericitized and kaolinitized.

through a molten status, which would be a principal requirement to use the index.

The Questa granites give DI values of 93 to 95 for the main phase rocks and of 96 to 97 for the later phase rocks. The change in the later phase is rather small, because the fractionation is most proceeded between $Na_2O$ and $K_2O$. On the other hand a few examples of averaged granites show much lower values; e.g., averaged granite by Daly(1918) is the index of 80, averaged alkali granite of 93, averaged granite by Nockolds(1954) of 88, and Japanese granites more than 65 per cent in $SiO_2$ (HATTORI et al., 1960) of 81.

Lime and alkali contents of the Questa granites are also listed in Table 10. There are great similarities in each component among the Log Cabin granite, Questa Mine aplite, and Red River aplite. However, a prominent difference is sodium content. Throughout all phases of each granite body, the Questa Mine aplite is the lowest in $Na_2O$; the Log Cabin granite comes next; and the Red River aplite is the highest (Figure 9).

Table 10 Lime and alkali content of intrusive rocks.

| Rock Unit | Sample number | CaO | $Na_2O$ | $K_2O$ | $Na_2O+K_2O$ | Total | mol. num. ×1000 | | | Niggli's k |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $Ca^{\cdot\cdot}$ | $Na^{\cdot}$ | $K^{\cdot}$ | |
| $G_1p$ | SI–140 | 1. 84 | 2. 51 | 3. 26 | 5. 77 | 7. 61 | 32. 81 | 40. 49 | 34. 61 | 0. 4609 |
| $G_2p$ | SI–10′ | 0. 43 | 3. 58 | 4. 40 | 7. 98 | 8. 41 | 7. 57 | 57. 75 | 46. 71 | 0. 4472 |
| | SI–172 | 0. 01 | 2. 49 | 4. 39 | 6. 88 | 6. 89 | 0. 18 | 40. 17 | 46. 61 | 0. 5371 |
| | SI–173 | 0. 04 | 1. 09 | 2. 08 | 3. 17 | 3. 21 | 0. 71 | 17. 58 | 22. 08 | 0. 5567 |
| | SI–233 | 1. 30 | 2. 93 | 6. 43 | 9. 36 | 10. 66 | 23. 18 | 47. 27 | 68. 27 | 0. 5909 |
| $G_3p$ | SI–25 | 0. 32 | 3. 42 | 5. 35 | 8. 77 | 9. 09 | 5. 71 | 55. 17 | 56. 80 | 0. 5073 |
| | SI–232 | 0. 52 | 3. 25 | 4. 48 | 7. 73 | 8. 25 | 9. 27 | 52. 43 | 47. 56 | 0. 4757 |
| $G_4$ | SI–174 | 0. 76 | 4. 03 | 4. 36 | 8. 39 | 9. 15 | 13. 55 | 65. 01 | 46. 29 | 0. 4159 |
| | SI–240 | 0. 53 | 4. 05 | 4. 40 | 8. 45 | 8. 98 | 9. 45 | 65. 33 | 46. 71 | 0. 4169 |
| | SI–241 | 0. 52 | 3. 65 | 3. 82 | 7. 47 | 7. 99 | 9. 27 | 58. 88 | 40. 56 | 0. 4079 |
| | SI–177 | 0. 36 | 3. 39 | 5. 03 | 8. 42 | 8. 78 | 6. 42 | 54. 69 | 53. 40 | 0. 4904 |
| | SI–180 | 0. 07 | 3. 62 | 4. 40 | 8. 02 | 8. 09 | 1. 25 | 58. 40 | 46. 71 | 0. 4444 |
| $G_5p$ | SI–35 | 0. 27 | 3. 70 | 4. 07 | 7. 77 | 8. 04 | 4. 82 | 59. 69 | 43. 21 | 0. 4199 |
| | SI–36 | 0. 46 | 3. 71 | 4. 10 | 7. 81 | 8. 27 | 8. 20 | 59. 85 | 43. 53 | 0. 4211 |
| $G_6$ | SI–188 | 0. 66 | 3. 71 | 4. 54 | 8. 25 | 8. 91 | 11. 77 | 59. 85 | 48. 20 | 0. 4461 |
| | SI–234 | 0. 74 | 2. 90 | 3. 88 | 6. 78 | 7. 52 | 13. 20 | 46. 78 | 41. 19 | 0. 4682 |
| | SI–235 | 0. 98 | 3. 51 | 4. 31 | 7. 82 | 8. 80 | 17. 48 | 56. 62 | 45. 76 | 0. 4470 |
| | SI–236 | 0. 42 | 2. 37 | 5. 91 | 8. 28 | 8. 70 | 7. 49 | 38. 23 | 62. 75 | 0. 6214 |
| | SI–237 | 0. 55 | 3. 24 | 4. 31 | 7. 55 | 8. 10 | 9. 81 | 52. 27 | 45. 76 | 0. 4668 |
| | SI–238 | 0. 52 | 4. 18 | 4. 08 | 8. 26 | 8. 78 | 9. 27 | 67. 43 | 43. 32 | 0. 3912 |
| | SI–239 | 0. 38 | 3. 86 | 4. 58 | 8. 44 | 8. 82 | 6. 78 | 62. 27 | 48. 63 | 0. 4385 |
| $G_7$ | SI–64 | 0. 49 | 4. 13 | 4. 32 | 8. 45 | 8. 94 | 8. 74 | 66. 62 | 45. 87 | 0. 4078 |
| | SI–65 | 0. 95 | 4. 57 | 4. 07 | 8. 64 | 9. 59 | 16. 94 | 73. 72 | 43. 21 | 0. 3695 |
| | SI–66 | 0. 87 | 4. 07 | 4. 30 | 8. 37 | 9. 24 | 15. 51 | 65. 66 | 45. 65 | 0. 4101 |
| | SI–67 | 0. 15 | 4. 10 | 4. 26 | 8. 36 | 8. 51 | 2. 68 | 66. 14 | 45. 23 | 0. 4061 |
| | SI–69 | 0. 20 | 3. 99 | 4. 28 | 8. 27 | 8. 47 | 3. 57 | 64. 37 | 45. 44 | 0. 4138 |
| | SI–197 | 0. 57 | 3. 07 | 4. 63 | 7. 70 | 8. 27 | 10. 16 | 49. 52 | 49. 16 | 0. 4982 |
| PC | SI–242 | 1. 01 | 3. 31 | 3. 29 | 6. 60 | 7. 61 | 18. 01 | 53. 40 | 34. 93 | 0. 3955 |

Note: Analyzed by Mr. K. Ohta, Tokyo intitute of Coal and Minerals, who is a friend of the other analyst for this study, Mr. K. Maeda of Chemistry Section, Geological Survey of Japan. The alkari analyses in this paper are based on the Lawrence-Smith method.

The fact that the Questa granites have been highly differentiated is also shown in the same figure. A Neogene granite body in the Takakuma Mountainland is one of the most differentiated ones among stocks in the Outer Zone of the Southwestern Japan. The Questa granites are partly superimposed to the Japanese granite, but the most are plotted more close to the $K_2O$–$Na_2O$ side-line. Besides, after a certain stage, the differentiation seems to be headed to the $K_2O$ apex, which is shown by the arrows in the Figure 9.

In Figure 10, it is plotted modal and normative plagioclase, potash feldspar, and quartz. The later phase rock, e.g. SI–180, is the most far-off the normatives. This means that Ab molecules in the potash feldspars of the later phase rocks ought to be much higher than that of the main phase. The albite would not be separated from Or molecules, due to possibly quicker cooling rate.

Normative plagioclase, orthoclase, and quartz of the Questa igneous rocks are plotted in the system $NaAlSi_3O_8-KAlSi_3O_8-SiO_2-H_2O$ by Tuttle and Bowen (1958, p. 75). For the effusive and dike-forming rocks it is too arbitrary to calculate normative constituents because of mode of their extrusion and in-

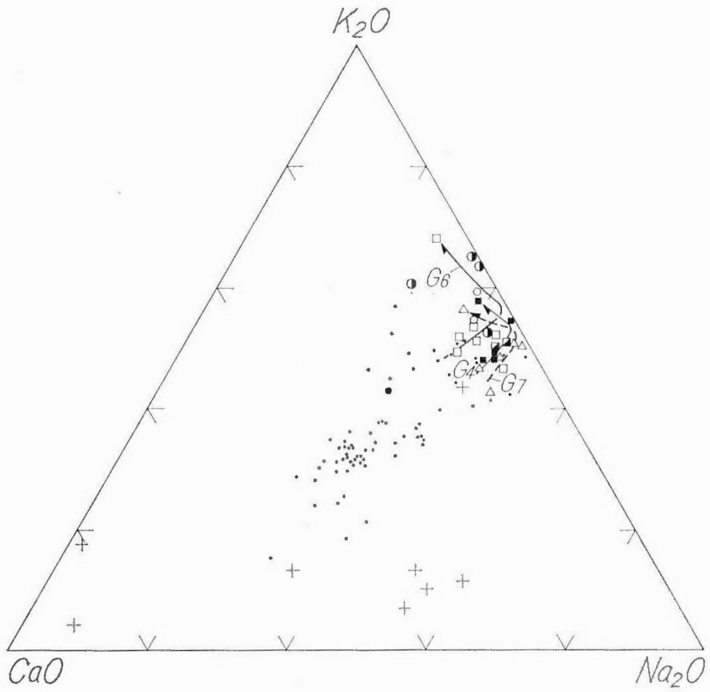

Figure 9 $K_2O$–$Na_2O$–CaO diagram of intrusive rocks, Questa mine area, in comparison with those of selected Japanese Tertiary granite.
Solid circle: (quartz) monzonite porphyry, half-solid circle: granite porphyry, open circle: Goat Hill quartz porphyry. Solid square: Log Cabin granite (G4), half-solid square: Columbine aplite porphyry, open square: Questa Mine aplite (G6), open triangle: Red River aplite (G7). Arrows indicate the evolution trend of each stock-forming intrusive rock. Dot: Miocene granite of the Southwestern Outer Zone, Japan, composed mainly of stocks intruded discordantly into upper and middle Mesozoic formations. Cross: Miocene quartz dioritic rocks of Tanzawa Mountainland associated with weak regional metamorphism.

trusion. On the other hand the Questa granitic rocks could have been solidified in an environment close to equilibrium condition.

In the figure 11 the granites are not distributed in the maximum area of plutonic rocks in Washington's Table, but along the "ternary" minimums for water-vapor pressures at 500 kg/cm$^2$ through 2000 kg/cm$^2$. Among the seven examples the later phase rocks, e.g. SI–177 and SI–180 for Log Cabin granite, and SI–236 for Questa Mine aplite, are plotted in the lower water-vapor pressure side. The main phase rocks are around 1500 kg/cm$^2$ water-vapor pressure. These may mean that the granites would have intruded into a shallow horizon, where both temperature and vapor pressures would be lost easily, and have been solidified differentiating the composition in a comparatively quick rate.

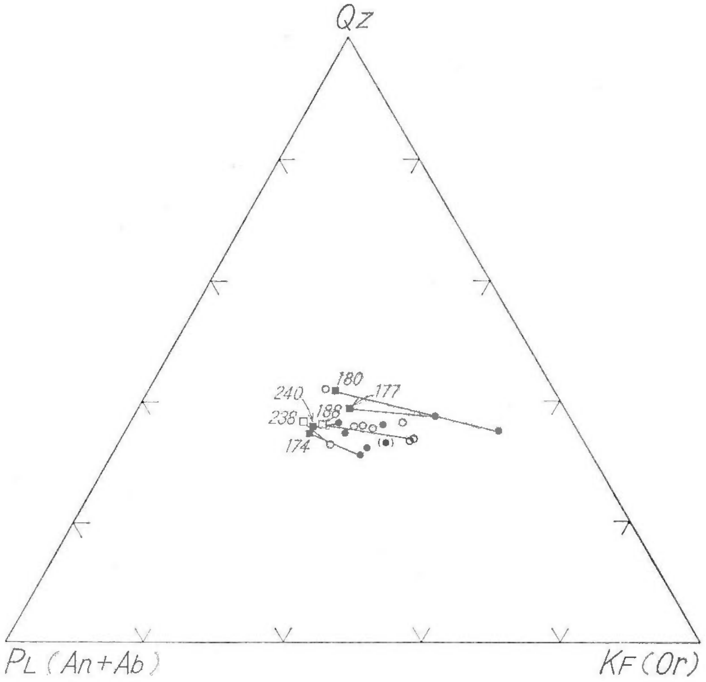

Figure 10 Normative and modal composition of the Log Cabin granite and Questa Mine aplite. Solid circle: modal, and solid square: normative Log Cabin granite. Open circle: modal, and open square: normative Questa Mine aplite. Percentages by weight. The same samples are connected with solid lines.

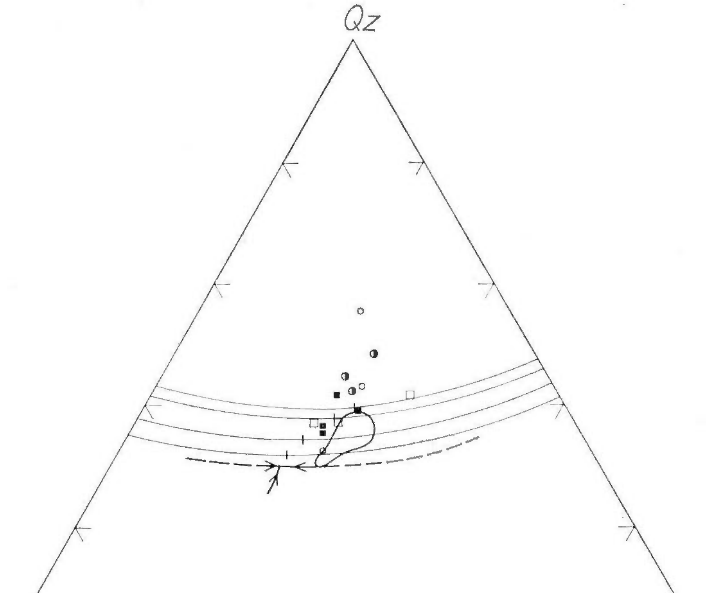

Figure 11 Normative Ab–Or–Qz of the Log Cabin granite and Questa Mine aplite plotted in the system $NaAlSi_3O_8$–$SiO_2$–$H_2O$ (after Tuttle and Bowen, 1958). Solid square: Log Cabin granite, open square: Questa Mine aplite.

## IV. Regional Structure

Only a small part of the regional structure of the Taos Range of the Sangre de Cristo Mountains lies within the surveyed area. Referring to the studies by Mckinlay (1956) and Schilling (1960), and adding observations made around the Questa mine, the history of the regional structure may be presented in the following paragraphs.

During the Precambrian era sediments and volcanic rocks were intruded by granite and subsequently all these rocks were metamorphosed and folded to form the present metaquartzite, amphibolite complex, and foliated granite. In early Paleozoic time the Taos Range was probably part of the shallow Central Colorado Basin embayment. Then it was uplifted to form the Uncompahgre-San Luis geoanticline. During late Paleozoic time this positive area was eroded, and great thicknesses of clastic sediments were deposited at the edge of the deepening basin to the east, the Rowe-Mora geosyncline. In late Cretaceous to early Tertiary times, thrust faulting occurred toward the east along the present eastern edge of the Taos Range (Figure 1). During the thrust movement the area between the Red River Canyon and Cabresto Creek was probably sheared, because the southern segment was displaced farther east, leaving the northern segment relatively farther west. The range then was block faulted and tilted along its present western edge. The faulting has continued until the present.

During the shearing and faulting, the area was highly fractured. Igneous activity followed, and thick volcanic rocks were deposited there, a graben-like depressed zone being formed at about the same time. The resulting volcanic rocks covered an extensive area even outside of the zone. During the volcanism faulting on north to northwest trends was strongly active, tilting the volcanic rocks up at the east and down at the west. The faulting was stronger in the western part of Questa Mine aplite stock than at the east, as is shown by the steeply westward dipping bedding of the volcanic rocks at the present time. In the middle of the volcanism, which was possibly in the earlier Miocene, small stocks were intruded along the depressed zone that trends N 80°E and is parallel to the S-face of the Precambrian rocks. As with the intrusions, fumarolic activity of the lates phase was controlled by the structure of the basement rocks, which left many hydrothermal pipes.

Basalt flows covered the plain west of the Taos Range from the late Tertiary through Pleistocene (Figure 1).

## V. Regional Alteration

In the surveyed area almost all rocks have been altered to a certain degree. Alteration of different stages over-lapped each other so that distribution and relations of altered rocks at the present time are extremely complex. Following the history of igneous activity, the regional alteration can be classified into the following two groups.

### V. 1 Propylitization

Practically all of the andesitic and latitic rocks have been hydrothermally altered. No matter how far the rocks are from intrusive bodies, breccia pipes, or the like, which are considered the sources of hydrothermal solutions, the rocks have been propylitized. Hence the propylitization is regarded as autometamorphism during the final stage of formation of the volcanic rocks.

Propylitization preserves the original texture of the rocks. The kind of propylitization is dependent on and varies with each rock unit. However, it is possible to generalize about the altered products as related to the original minerals. Plagioclase is usually altered to sericite, carbonate, kaolinite, and epidote. Potash feldspar is more resistant than plagioclase to propylitization and is altered to sericite and kaolinite. Among mafic minerals, pyroxene is altered to hornblende, biotite, chlorite, and opaque minerals; hornblende is changed to biotite, chlorite, pyrite, carbonate, epidote, sphene, and iron oxides; biotite is altered to chlorite, carbonate, sericite, pyrite, sphene, and iron oxides. Moreover, quartz occurs as a common secondary mineral replacing these primary minerals. Details of propylitization were described in the descriptions of the corresponding volcanic rocks.

Autometamorphism of rhyolitic rocks is characterized by strong sericitization, and by silicification and pyritization.

### V. 2 Hydrothermal Pipes

On the north slopes of Red River Canyon, there are many spots of "bad land" consisting of numerous gullies, steep slopes, and in places even cliffs (Plate 1). These treeless outcrops are yellowish gray in color, and are strongly altered. They are regarded as hydrothermal pipes formed around breccia pipes or along fault zones during the fumarolic stage, the final stage of late Tertiary volcanism. With intrusive bodies there are also hydrothermal halos distributed either around or within such bodies.

Most of the pipes are located along two lines–probably tectonic belts–trending to roughly N80°E. One can be seen at the lower and middle part, the other at the uppermost part of the slope. The former forms larger areas of "bad land" topography and more cliffs than the latter. This seems to be due mostly to differences in the composition of the original rock, a rhyolitic welded tuff, and to differences in the intensity of the alteration. The "bad lands" formed in latitic rocks make up smaller areas; yet they, likewise, have had an intense alteration, which means that in parts the original texture has been completely destroyed. The alteration is found not only in the "bad land" but also in rocks covered by thick vegetation.

In the hydrothermal pipes, the original texture of the rocks is recognizable except where alteration is most strong. Large masses of unbrecciated rock remain relatively unaltered. Alteration has also taken place along single isolated fractures and faults, even at some distance from the pipes.

Common alteration minerals are sericite, quartz, and pyrite, and small amounts of kaolinite, carbonate, and chalcopyrite. Sericite takes the place of feldspar at first, and then mafic minerals and the matrix of the volcanic rock, depending on the intensity of alteration. Quartz occurs in veinlets or druses. At the upper parts of Straight Creek, beautiful euhedral crystals of quartz, including many liquid blebs, are found in drusy veinlets. Quartz partly replaces both phenocryst and matrix of the volcanic rocks. Pyrite is mostly disseminated, together with small amounts of chalcopyrite, throughout a pipe, but it occurs as a veinlet with quartz. Kaolinite takes the place of feldspar. Generally, carbonates do not occur in rhyolitic rocks, but they are common in rocks of the andesite and latite families. Being due to later weathering, large amounts of limonite, jarosite, manganese oxides, and gypsum (selenite) cover the surface of the "bad land" and are responsible for the yellow color of the pipes.

A breccia pipe just west of upper Sulphur Gulch may be an example of the most extreme case of this type of alteration. The rock was originally hornblende andesite (AI). The hyalopilitic texture of the original rock is completely destroyed, and is replaced by a unequigranular-granoblastic-mosaic one. It consists of quartz, sericite, and feldspars; potash feldspar is more common than albite, and small amounts of pyrite, hematite, apatite, and carbonaceous material. Quartz tends to form veinlets or irregular patches. The rock was brecciated even later than the recrystallization, and the fractures were then filled with jarosite.

No molybdenum mineralization is associated with propylitization and hydrothermal alteration related to the pipes or faults.

## VI. Ore Deposits

### VI. 1 Introduction

Regionally the Questa molybdenum deposits are situated somewhat similarly to those at Climax, Colorado. The mineralization is related to a rock of the latest magmatic stage of Miocene intrusive activities–an aplite here and the Climax porphyry at the Climax mine. In detail, the Questa deposits are fissure fillings, though stock-works not unlike those at Climax, occur at Questa also. The Questa molybdenum deposits are the only minable ones among small deposits in the surrounding area which have been prospected for molybdenum, gold, silver, copper, zinc, or lead, but always with unfavorable results.

Weak molybdenum mineralization occurs in and around the Log Cabin granite, Goat Hill porphyry, and granite porphyry. The best ore occurs along the west flank of the Questa Mine aplite trending N75°E and plunging about 35°SW – the general dip of the contact between the aplite and the adjacent volcanic rocks. On the surface the aplite has north-south trend, but the structure contour map indicates that the aplite has a nose or ridge toward S80°W parallel to the trend of the bonanza (Figure 12). This is probably the most basic factor of structural control for molybdenum mineralization. On the outcrop of the upper Sulphur Gulch, at elevations of 8,600 through 9,100 feet, the deposit has a width of 2,500 feet. It was investigated down to 7,300 feet above sea level by adits and drilling. The tip of the known body is located beneath Goat Hill Gulch.

In the bonanza area Schilling (1956 p. 44–52) described that major veins develop along the boundary of the aplite and andesite (AI) or in the aplite within 50 feet from their contact. Where the boundary is so irregularly curved, the veins do not follow it but tend to run straight. In case the host rock is the andesite (AI), the veins get thinner. In general they extend more in strike-side (up to 600 feet) than in dip-side (up to 300 feet). The maximum width is about 7 feet, but it changes in a short distance.

At Questa molybdenite is the only economic mineral; no minable tin, tungsten, or other minerals are found in the Questa deposits. The molybdenite occurs with quartz, biotite, clays, chlorite, calcite, fluorite, rhodonite, pyrite, chalcopyrite, sphalerite, and galena. A few secondary molybdenum minerals, such as ferrimolybdite, ilsemanite, and possibly jordisite, occur around the outcrop and adits above ground water level.

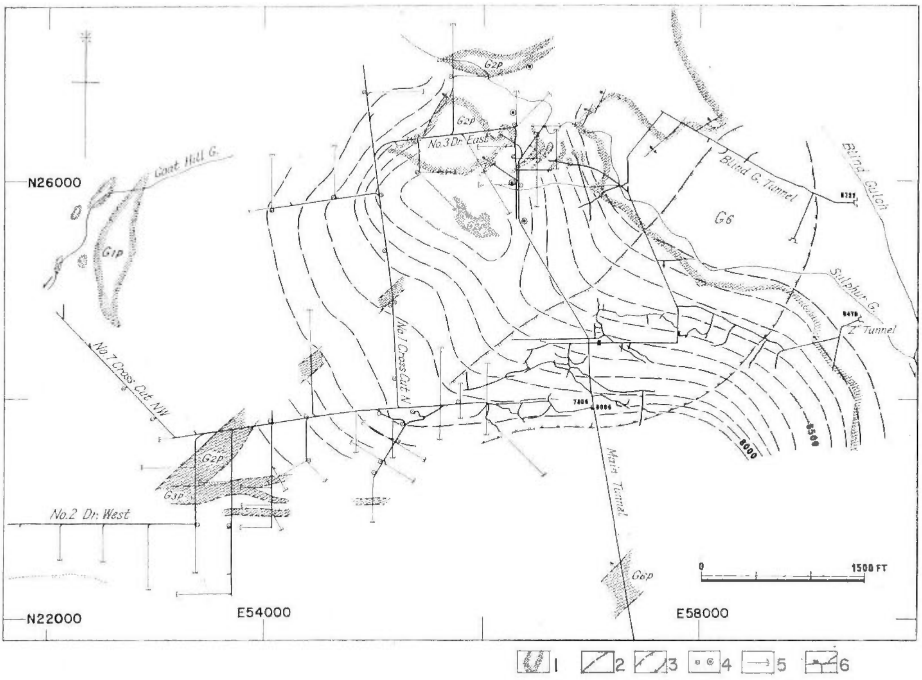

Figure 12 Index map of the Questa ore deposit
1. Intrusive rock. 2. Underground contour of the Questa Mine aplite. 3. Area of strongly mineralized zone. 4. Underground and surface vertical drilling. 5. Horizontal or inclined underground drilling. 6. Adit, drift, and shaft. Elevation in foot. (Underground geology is drawn by Prof. R. H. Carpenter)

## VI. 2 Structural Control

The area from middle through upper Sulphur Gulch, where the first discovery was made, is mineralized to a certain degree. Molybdenite veins occur in aplite and andesite around the contact between these two rocks. The mineralized zone in the aplite is usually wider than in the andesite, in contrast to the mineralization related to the Log Cabin granite, where the andesite is more mineralized than the granite. The contact at the west margin of the aplite has a general north trend. However, it locally strikes east and in other directions as well. These irregularities in dip and strike reflect the effect of topography on outcrop.

Based on mapping of a part of main tunnel, Z tunnel, Blind Gulch tunnel, and the surface, fractures in the mineralized zone can be classified into the following three groups:

Veins controlled by the contact
Veins controlled by joints
Veins controlled by local faults

### VI. 2. 1 Veins controlled by the contact

The best example of this type is shown on Figures 13 and 14. Here the best ore occurs along east-west fractures. The main vein dips to the south at moderate

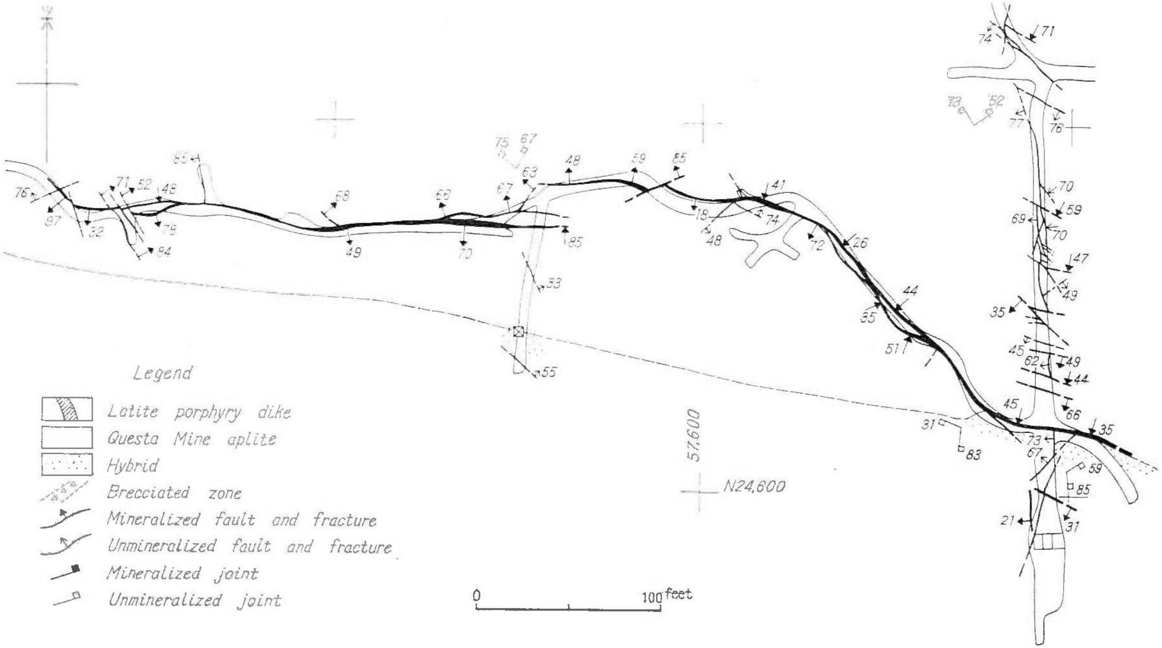

Figure 13 Sketch map of veins at Z tunnel, west of E 57,800.

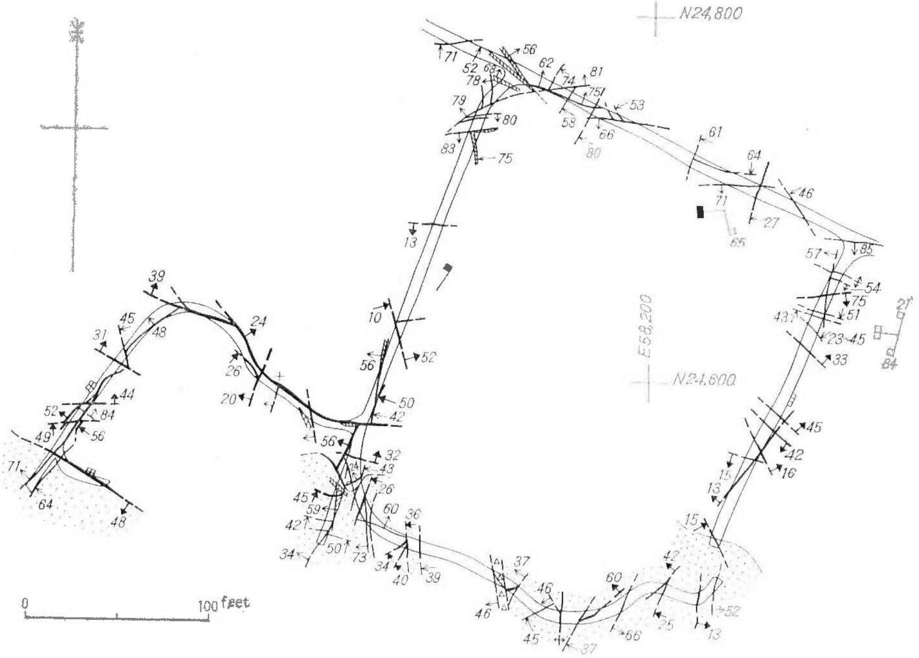

Figure 14 Sketch map of veins at Z tunnel, east of E 57,800. The same legend as of Figure 13.

angles; the branches dip to the north, having "horses" or major barren inclusions between the veins. The east-west veins are located either along the contact between the Questa Mine aplite and the fine-grained hybrid rock, which could have been originally partly a hornblende andesite and partly late Paleozoic sediments, or they lie inside the aplite side of the contact. The maximum width of these veins is two feet. Major constituents in them are molybdenite, quartz, fluorite, rhodochrosite, clay minerals, and pyrite. In many places, small fractures, consisting of molybdenite and clay minerals, cut obliquely the main veins, and in places dislocate the veins by as much as ten feet. In Figure 13, the contact is wavy; blebs, noses, and fingers of the aplite are commonly present. Fractures here have a north-south trend, and cross the general trend of the contact. Mineralization along these fractures is weak. In general, molybdenum mineralization in these cross-cut adits increase going toward the contact.

The projection of fractures plotted on equal area nets is shown in Figures 15 through 20. Jointing is not included. Every effort was made to obtain representative statistical average in compiling these data.

Figure 15 shows fractures from east of E 58,800 on the Z tunnel. Mineralization here is weak along certain fractures. There are two centers in the figure. One has a strike of east and dips steeply to north or south; the other strikes north and dips 43° west. As far as their size is concerned, the first of these two groups are larger than the second. The first seems to be at the southern margin of a group of faults passing about 400 feet north from this part of the Z tunnel to the surface, which is 70 feet above the adit (Figures 3 and 12). The second set of fractures may have been originally cooling joints of the aplite subsequently slightly fractured. About half of the 135 fractures plotted are mineralized. There is no clear

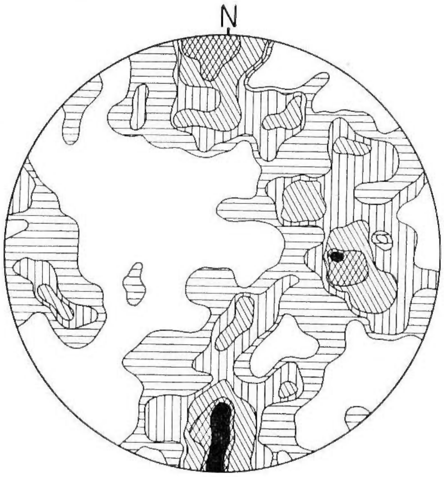

Figure 15 Projection (lower hemispheric) of fractures, Z tunnel (east of E 58,800), Questa mine. 135 points. Contours more than 0, 1, 2, 4, and 6 per cent; 1 per cent counter.

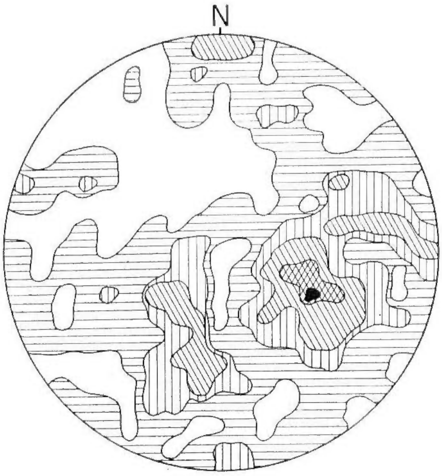

Figure 16 Projection (lower hemispheric) of fractures, Z tunnel (west of E 58,800), Questa mine. 205 points. Contours more than 0, 1, 2, 4, and 6 per cent; 1 per cent counter.

difference in patterns between mineralized and unmineralized fractures. At Z tunnel, west of E 58,800, the first center of Figure 15 has almost disappeared (Figure 16). The second center swings to northeast slightly, and has an average strike of N22°E, and dips 38°NW. Although the main veins are shown as having only a moderate concentration in the figure, it still contains the best ore in the Z tunnel. Another spot of moderate concentration is around the north pole and in the first quadrant; this is due to unmineralized fractures.

### VI. 2. 2 Veins controlled by joints

At Blind Gulch tunnel, located about 1,500 feet north and 247.5 feet above the Z tunnel (Figure 12), various kinds of fractures are present, most of which were

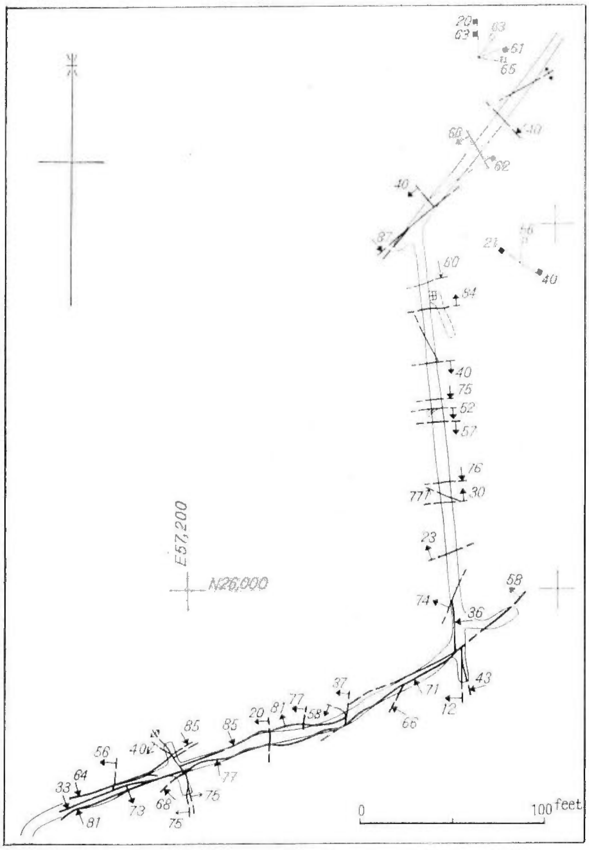

Figure 17 Sketch map of veins at Blind Gulch tunnel, Questa mine. The same legend as of Figure 13.

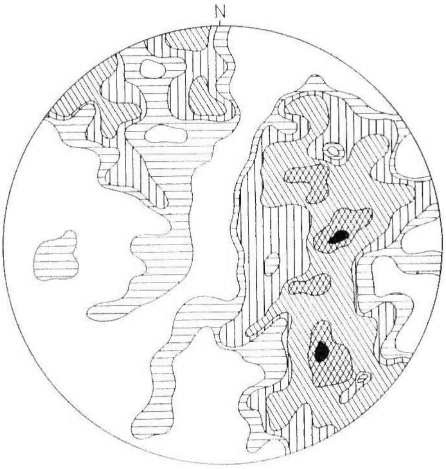

Figure 18 Projection (lower hemispheric) of fractures, Blind Gulch tunnel, Questa mine. 142 points. Contours more than 0, 1, 2, 4, and 6 per cent; 1 per cent counter.

originally joints. The best ore occurs along faults trending N75°E and dipping steeply north or south (Figure 17). The faults are cut by north-south fractures, and on them there has been slight movement. Molybdenite here is thin coating along faults, fractures, or joints, associated mostly with clay minerals, calcite, fluorite, and pyrite. Molybdenite locally occurs as stock-work ore, especially in the "horses."

The mineralized and unmineralized fractures at 142 points are plotted in Figure 18. Two eyes, representing over 7 per cent of the area, are present. They are both on a great circle connecting the two poles, north and south, much like another two spots, representing over 5 per cent of the area. One eye strikes N51°E and dips 50°NW. Vein striking similarly and dipping south are also widely distributed. Since these features are also found on joints at the surface, the fractures are probably joints or partly tension fractures. The other eye strikes north and dips west 42°. These too were originally joints, but they have also moved slightly, and along them the rock is altered and mineralized; they now represent molybdenum-clay veinlets like those in Figure 15 and 16. Most of the fractures in Figure 18 are accompanied by molybdenite to a certain degree. However, most of the fractures plotted in the first quadrant are barren.

Around the mouth of Iron Gulch, there is a set of highly mineralized joints in the aplite parallel the contact. They are filled with molybdenite, quartz, and small amounts of fluorite and pyrite. The width is 5 inches at the maximum. Their average strike is N17°E; the dip is 36°W (Plate 9). The same joints are prominently present at the north margin of the Log Cabin granite with no molybdenum mineralization. They are clearly marginal fissure-type joints, outward dipping, which usually occur along the margins of the stock (Balk, 1937).

### VI. 2. 3 Veins controlled by local faults

The area most complex geologically lies between Iron and upper Sulphur Gulch around the Questa mine. Volcanic rocks have been intruded by granite porphyry and the branches of satellite dike, and then by the aplite. Various types of faulting are associated with the intrusions. Mineralization in the andesite is of the fissure filling-type (Figure 19). Molybdenite occurs associated with quartz and calcite, together with small amounts of fluorite, chlorite, and pyrite. The molybdenite in the aplite is partly in a single vein, filled with clay minerals, quartz, and fluorite, and is partly in stockwork veinlet with quartz. At the north end of the main tunnel level, about 950 feet below the surface, strong mineralization occurs within a certain zone in the aplite. The mineralization consists of fissure filling and is partly of the stockwork-type. The major constituents are molybdenite, quartz, fluorite, biotite, clays, pyrite, chalcopyrite, sphalerite, and galena. The fracture system is shown in Figure 20.

There is a great similarity of pattern in the two figures (Figures 19 and 20) despite the great differences in geology. In a fracture system trending northeast (Plate 10), the surface shows two spots of more than 6 per cent area. One strikes N45°E and dips 85°NW; the other strikes N31°E and dips 96°NW. But one area of more than 4 per cent has an average strike of N38°E while changing dip from 80°NW to 90°SE, whereas the main tunnel has a center at N30°E and 84°SE. On the northwest fracture system, the surface has no clear center of concentration. A moderately concentrated area ranges from N45°W, dipping 35°SW, to N15°E, dipping 80°SW. The main tunnel has an eye at N27°W and dipping 38°SW, and these bearings are similar to the strike and dip of two large faults observed on the

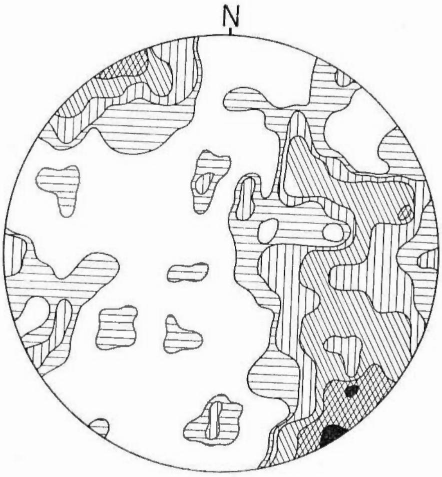

Figure 19 Projection (lower hemispheric) of fractures, upper Sulphur Gulch.
154 points. Contours more than 0, 1, 2, 4, and 6 per cent; 1 per cent counter.

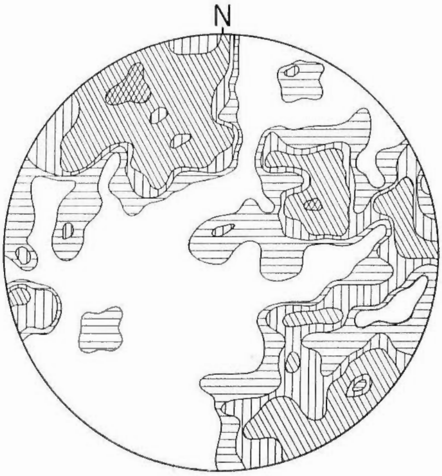

Figure 20 Projection (lower hemispheric) of fractures, Questa mine tunnel.
239 points. Contours more than 0, 1, 2, 4, and 6 per cent; 1 per cent counter.

surface (Figure 3).

Adits of the glory hole level supplied the highest grade ore throughout the history of the mine. Similar mineralization to that in the adits is present just north of the glory hole (Plate 11). Here molybdenite is formed along a set of east-west faults dipping steeply north or south. A fault considered one of the largest faults around the Questa Mine aplite dislocates the contact at least 7,000 feet at the point where the fault passes through the eastern margin of the aplite. The north wall of the fault was moved relatively to the west or downward or in both directions.

### VI. 3 Wall-rock Alteration

Alteration accompanying the formation of molybdenite veins affects only a relatively small volume of rock. The alteration can be classified into the two groups–contact metamorphism and hydrothermal alteration.

#### VI. 3. 1 Contact metamorphism

Contact metamorphism is observed as a halo around intrusive bodies. Intrusives of the type apparently forcefully injected–granite porphyry, for example–have a wider halo than those around intrusive bodies not forcibly injected, such as the Questa Mine aplite. The granite porphyry has a halo up to 500 feet wide at the northern margin of the main plug and where dikes are distributed east of the plug. The original rock in the halo is hornblende andesite (AI). The metamorphosed rock consists of two types; one is "spotted rock," the other is biotitized rock.

The spotted rock is located along faults or tips of dikes of the granite porphyry. It has a porphyritic texture in a matrix of unequigranular-granoblastic-mosaic. The apparent "phenocrysts" are composed of plagioclase and biotite "clots." The plagioclase, up to 4 by 8 mm, is everywhere "dirty" in appearance because of a fine dust made up of specks of sericite and chlorite. On some crystals the plagioclase has been replaced by potash feldspar.

In the "spotted" rock, biotite "clots," up to 1.6 by 3 mm in size, consist of fine-grained aggregates of biotite and magnetite with small amounts of pyrite. The forms of the clots are prismatic or angular. Few of the clots show a banding, caused by a preferred orientation of biotite with opaque minerals. They seem to be originally assimilated shale; the banding may show the original S-surface.

Few euhedral crystals of quartz are present in the "spotted" rock. The matrix of the rock consists of mosaic crystals of plagioclase, potash feldspar, and quartz, together with scattered specks of biotite, apatite, and opaque minerals.

Since the plagioclase of the "phenocrysts" in the "spotted" rock is dirty and is replaced by the later minerals, it can not have been porphyroblastic, produced during metamorphism. The composition, $An_{27}$ to $An_{31}$, is more sodic than that in the original rock, andesite, but is very similar to that in the granite porphyry. The occurrence of this type of rock is limited to permeable zones such as faults or shear zones. This fact leads to the conclusion that the rock was formed by contamination of fragments of the andesite and by sulutions of granitic composition during the intrusion of the granite porphyry.

In sharp contrast to the "spotted" rock just described, which is relatively rare, most of the halo of alteration is composed of biotitized rock. This type of alteration usually preserves the original hyalopilitic texture of the andesite. Phenocrysts of prismatic and lath-shaped plagioclase have been replaced by fine specks of biotite and sericite, and small amounts of apatite and opaque minerals. Mafic minerals have been completely changed to biotite or to opaque minerals.

The matrix of the rock is covered by a mat of biotite and a little sericite, apatite, sphene, and opaque minerals. Small amounts of pyroxene–probably augite–occur in the matrix rich in biotite.

The rocks have suffered hydrothermal alteration after the metamorphism. The alteration is present along fractures or small faults. In this situation, both the phenocrysts of plagioclase, and the matrix are highly replaced by sericite, making a network in some cases. Biotite is altered to chlorite. Quartz veinlets, consisting of mosaic crystals, cut through the rock along fractures. Calcite, chlorite, pyrite, and small amounts of molybdenite accompany the silicification. Veinlets composed of adularia and calcite are present.

The Questa Mine aplite has a halo of alteration up to 100 feet in width, but this widens where the host rock is andesite tuff (AII). No spotted rock was formed in the halo. The original texture is destroyed in most places, and its place is taken by an inequigranular-granoblastic-mosaic texture with islands of relict plagioclase. The plagioclase has been almost completely replaced by sericite and very small amounts of calcite. The outlines become blurred because of encroachment by the matrix of recrystallized minerals. No original mafic minerals remain; they are now represented by scattered crystals of biotite, chlorite, and opaque minerals. Few blebs of xenolithic material are present. They consist of an aggregate of relict, dirty plagioclase, together with sericite, biotite, and chlorite. The biotite and chlorite show a subparallel arrangement which could represent the S-surface of the original rock. The matrix of the rock is composed of anhedral crystals of quartz, potash feldspar, albite, biotite, chlorite, apatite, and opaque minerals.

In some places, biotitized rock contained andalusite. The andalusite is now in irregularly rounded forms because of its strong replacement by sericite. It has many inclusions of carbonaceous matter and quartz. The birefringence is weak; the interference color ranges up to first-order orange. The extinction is parallel in most crystals. Columnar crystals show an orientation of length-fast. The 2V is very large (close to 90°) and negative. The andalusite is buried in a matrix consisting of a mat of sericite and small amounts of opaque minerals (mostly organic matter and little pyrite), hematite, and quartz which contains liquid inclusion and organic dust along cracks.

Originally this rock was probably an argillaceous sediment - possibly the late Paleozoic shale reported by Schilling (1960), the overlapping hydrothermal alteration of which has erased its original petrographic character, which could tell the story of its origin.

Since flooding of potassium over country rocks around the intrusives is extreme, it may not be feasible to adopt the regular facies idea of contact metamorphism. Biotite, which is a common metamorphic mineral in a contact metamorphic aureole, is present throughout the halo. Augite and andalusite occur in certain spots. This mineral assemblage suggests a pyroxene hornfels facies for contact metamorphism around the intrusives.

### VI. 3. 2 Hydrothermal alteration

The most prominent wall-rock alteration of the aplite is silicification and sericitization. In the rocks of the later phases of alteration of the Questa Mine aplite there is a tendency especially to increase the silica content. The quartz appears in granular aggregates or veinlets. In wall-rock alteration, the silicification occurs along small barren quartz veins, and less commonly along molybdenite quartz veins.

Most of the feldspars in the phenocrysts of the aplite have been completely altered to sericite and a little kaolinite. The color is white or pale grass green. This alteration is confined to narrow zones along veins or fractures. A white gouge, consisting mostly of sericite, is common along faults or fractures. Dissemination of pyrite is associated with chloritized biotite. In the surrounding rocks, hydrothermal alteration is limited and occurs chiefly along faults, fractures, or joints. An extreme phase of such alteration appears as quartz veins in the case of silicification and as masses of clay minerals in the case of argillization. The latter consists of pale greenish and white clays. X-ray study indicates that the green mass is composed of sericite with accessories of kaolinite and quartz. The white masses are the more pure sericite.

A rock next to the veins or fractures has inequigranular-granoblastic-mosaic texture. The original texture is completely destroyed. The rock consists of quartz, sericite, potash feldspar, albite, and pyrite, and accessories of apatite, limonite, and carbonaceous matter. The quartz tends to aggregate as veinlets or in irregular patches.

Slightly altered rock far from the faults or fractures reflects the composition of the original rock in the assemblage of the alteration products – that is, calcite is developed after calcic plagioclase, chlorite after biotite or hornblende, or the like. It seems likely that the composition of the intensely altered rocks is also greatly dependent on the kind of hydrothermal solution.

### VI. 3. 3 Alteration related to mineralization

As far as we know, molybdenum mineralization is not related to regional alteration but rather wall-rock alteration. Geochemical exploration indicates that soil samples from the hydrothermal pipes showed higher values (up to 3,000 ppm) than those from propylitized andesite or latite. However, no minable deposits are found associated with the pipes. The contact metamorphic aureole is associated with molybdenum mineralization. The mineralization is poor on the surface at the upper part of Sulphur Gulch, but rich in the lower part underground and in Log Cabin Canyon. Disseminated molybdenite is rarely present in rocks in the aureole. Molybdenite mostly occurs in veins with quartz. Therefore the main stage of the mineralization is later than the stage of the contact metamorphism. In other words, the location of the metamorphosed rocks, furnishing a physical change or "contact", had more influence on the location of mineralization than did any specific physicochemical condition.

The hydrothermal alteration extends to a zone around the contact. Molybdenite is present in the altered zone. It also occurs in veinlets along joints or cracks in fresh aplite, or as a rock-forming mineral in the rocks of the latest phase of the aplite. However, the greater part of the molybdenite is concentrated as vein material with various hydrothermal minerals, or as a film in the fault gouge. This indicates that alteration is not an absolute necessity but a usual prerequisite for the mineralization.

An example of molybdenum mineralization in relation to hydrothermal alteration is shown in Figure 21. A bore-hole (No. XXIV) was drilled vertically on upper Sulphur Gulch; it passed through the aplite close to the contact. The mineralization here is controlled by local faults and partly by flat-lying joints. The alteration is mostly sericitization.

As can be seen in the figure, some of the strongly altered zone has a low content of $MoS_2$, while some has a high content. Similar phenomena are observed in many places.

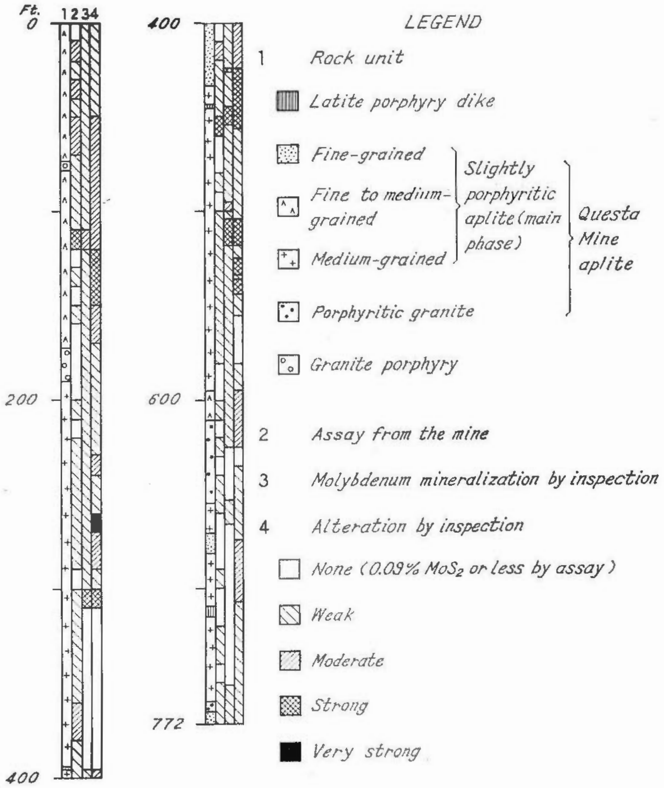

Figure 21 Molybdenum mineralization in relation to hydrothermal alteration and rock unit.

## VI. 4 Vein-forming Minerals

Most of the veins are largely composed of quartz, clays, and molybdenite. The kinds of vein-forming minerals and their sequence are shown in Figure 22.

### VI. 4. 1 Gangue minerals

Quartz and sericite are the most abundant gangue minerals. In order of abundance, fluorite, biotite, calcite, kaolinite, rhodochrosite, adularia, and topaz are locally present. Gypsum is common at the outcrop or in the adit above groundwater level.

The biotite is associated with quartz and molybdenite. It has a paler brown color than those in contact metamorphic rocks and aplite. It has been chloritized in places. The miners consider the presence of the biotite to be an indicator of rich ore because it is abundant in the ore shoots. Fluorite, calcite, and rhodochrosite fill re-openings of the molybdenite-quartz veins. They are more common in the margins of ore shoots than in the shoots themselves. Fluorite sometimes occurs along with molybdenite-quartz veins within the shoots. Calcite and rhodochrosite contain fragmental fluorite in places. There are two kinds of calcite; one is white, the other brown. The brown mineral that appeared to be dolomite showed a calcite pattern by X-ray diffraction. Kaolinite occurs with sericite in the fault gouge.

### VI. 4. 2 Ore minerals

Molybdenite is the most abundant ore mineral in the veins. Pyrite is fairly common, associated with the molybdenite. Small amounts of chalcopyrite, sphalerite, and galena fill re-opened fractures in veins, together with fluorite, calcite, and rhodochrosite.

In the oxidized zone are such oxidation products as ferrimolybdite, ilsemanite, jordisite (?), chalcocite, covellite, malachite, hematite, akaganeite, limonite, and manganese oxides.

Molybdenite is found widely distributed in distinct veins and even in disseminations throughout much of the wall-rock. The molybdenite is usually present in irregular aggregates in the vein, and less commonly in a banded structure with quartz. It is intergrown with quartz and biotite. Lenticular masses of quartz in the veins are covered with molybdenite films, looking like pure masses of molybdenite (Plate 12). Molybdenite is also frequently found alone as thin coatings or films along faults or fractures ("moly-paint"). Such films cut all other minerals. This may indicate that the film formed as the very latest stage of mineralization or was made by dragging molybdenite, the previously precipitated, along the fault plane.

Small amounts of molybdenite also occur along re-opened fractures with pyrite, sphalerite, chalcopyrite, and galena. Under the microscope, the molybdenite mostly occurs in the gangue minerals, especially in quartz. It is in slender flakes or aggregates of fine subhedral crystals. The flakes are usually curved (Plate 18). Chalcopyrite encloses the molybdenite and partly replaces it. Veinlet-like galena cuts the flakes. Pyrite tends to occur with chalcopyrite, microscopically considered. The pyrite is in large masses with many cracks which are filled with quartz, chalcopyrite, sphalerite, or galena. The pyrite is present in cubic form. Pyrite replaces molybdenite and vice versa (Plate 19). In general, molybdenite and pyrite are the earliest in the sequence of the sulphides.

Sphalerite generally occurs as large masses always containing exsolution "dots" or rounded masses of chalcopyrite. The "dots" are concentrated only at the margins of some crystals. No "dots" are found in the smaller crystals. Sphalerite is cut through by veinlets of chalcopyrite or galena. In addition to its occurrence in the small "dots", chalcopyrite appears as irregular masses which show mutual boundaries with the sphalerite. The chalcopyrite "dots" are probably contemporaneous with the sphalerite or in part somewhat later in view of the presence of veinlet-like patterns of "dots". Chalcopyrite usually replaces pyrite. It occurs along the cleavage planes of galena, whereas galena invades chalcopyrite along the margin of the chalcopyrite.

Galena is present as large masses with many triangular pits. Some crystals show stress effects by curved rows of the pits (Plate 21). Galena has a mutual boundary with the sphalerite or boundaries that indicate that the galena is later. Islands of relict galena are also present in chalcopyrite. All of the features reported above are crossed by veinlets of chalcopyrite and covellite. The highly generalized sequence is shown in Figure 22.

Using the faces 333, 044, 135, 026, and 335, the lattice constant of sphalerite was measured by X-ray diffraction. The method of Bradley and Jay was used for averaging. One was $a_0 = 5.4135_1$Å (FeS 9% mole.); the other $5.4155_4$Å (FeS

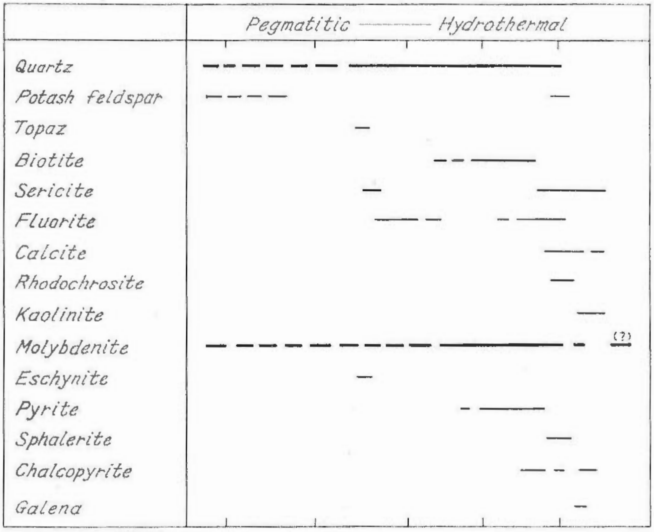

Figure 22 Sequence of the vein-forming minerals.

13% mole.). However, the sphalerite was not crystallized with pyrrhotite under equilibrium conditions. Besides, recent experimental studies are making clear complexity and difficulty of sphalerite geothermoter (SHIMAZAKI, 1966), so that no further interpretation is described here.

It should be noted here occurrence of two strange minerals – eschynite and akaganeite. The eschynite was found at an old discovery pit, located just north side of Red River around the mouth of Sulphur Gulch, when the author was a guide to a gentleman from the Forest Service of New Mexico. The location of the pit is the southern margin of the Questa ore deposits, where only barren or poorly mineralized quartz veinlets are distributed in the Questa Mine aplite. An excellent crystal occurred in a nearly flat-lying quartz vein of two inches wide. The vein contained very small amounts of molybdenite and accompanied "pneumatolytic" alteration halo of about an inch wide.

The crystal is 18 by 7 by 6 mm in dimensions and is pitch black (Plate 13). The color of streak is dark brown. The specific gravity measured by using a 1 mililiter pycnometer is 5.11. Morphological data measured by a two-circle goniometer, are given in Table 11. The faces of 001, 010, 110, and 021 are well developed,

Table 11 Faces measured by a two-circle goniometer.

| | | $\rho$ | $\varphi$ |
|---|---|---|---|
| c | (001) | 0° | — |
| a | (100) | 90° | 90° |
| p | (111) | 56°1/2 | 65°3/4 |
| p′ | ($1\bar{1}1$) | 56° | 116° |
| *b′ | ($0\bar{1}0$) | 90° | 180° |
| m′ | ($1\bar{1}0$) | 90° | 116° |
| m′′ | ($\bar{1}\bar{1}0$) | 90° | 244° |

*Standard face for the measurements. Measured by Dr. K. Sakurai, National Science Museum, Tokyo.

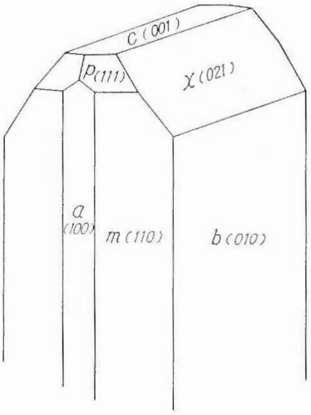

Figure 23 Projection (Parker's method) of the eschynite crystal.

while that of 111 is very poor (Figure 23). The morphology gives an idea that the crystal is eschynite (DANA, 1946 and SOBOLEVA, 1961). The eschynite was highly radioactive and metamict. Since eschynite has exothermic peak at about 775 °C (KERR, 1951), the crystal was heated at 900 °C in air for two hours. In Table 12 the X-ray pattern after the heating is shown together with the data of ASTM No. 11627 and of a specimen from Hitteroe, Norway, a collection of Columbia University. Eschynite is orthorhombic. It is one of the rarest multiple oxides; its chemical formula is (Ce, Ca, Fe, Th)$_6$(Ti, Nb)$_2$O$_6$.

Dana(1946) gives specific gravity of 5.19±0.05 for eschynite and 4.95±0.10 for priorite. On this point the Questa eschynite seems to be eschynite-side of a mineral eschynite-priorite, which agrees to the X-ray diffraction pattern. No chemical analysis has been made on the eschynite, except niobium that has been considerably detected by X-ray fluorescence method. Data based on face measurement are not perfectly reliable, because the mineral was cracked and even partly chopped off when it was taken off from its host minerals. Columbia collections levelled as eschynite from four localities in the United States were tested by X-ray diffraction. All failed to be eschynite, so that around that time – end of 1963, Manley Hot Springs in Alaska was the only occurrence of the mineral reported from the United States.

In recent years a few studies on secondary molybdenum minerals in new approaches have been worked out (KERR et al., 1963, and TITLEY, 1963). A part of similar studies at Questa mine by Dr. Bappu of New Mexico Bureau of Mines and Professor Carpenter, a new occurrence of akaganeite around molybdenite quartz veins should be introduced here. The mineral, β–FeOOH, first identified at Akagane mine in Japan (NANBU, 1959, and MACKAY, 1962), occurs in close association with ferrimolybdite in oxidized halos of molybdenite quartz veins. Generalized pattern in the halos is reported注4) from center to outward side as follows; ore vein ($MoS_2+FeS_2+SiO_2$) – Blank zone (4 inches thick) – ferrimolybdite zone (5 inches) – akaganeite zone (2 inches) – lepidocrosite zone (thicker than 1 foot). The akaganeite shows a high Mo content. It is considered that the mineral contains molybdenum as $HMoO_4^-$ in the crystal structure.

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注4) Lecture by Professor Carpenter at the Association of Japanese Mining Industry in Tokyo on July 6, 1965.

Table 12 X-ray powder spacing data for eschynite.

| I | | II | | III | | |
|---|---|---|---|---|---|---|
| d(Å) | I/I₁ | d(Å) | I/I₁ | d(Å) | I/I₁ | |
| 5.43 | 18 | 5.47 | 29 | 5.46 | 20 | |
| | | 4.74 | 10 | 4.76 | 20 | (4.70 20d) |
| | | | | 4.65 | 20 | |
| 4.39 | 16 | 4.40 | 16 | 4.40 | 25 | |
| 4.33 | 8 | 4.30 | 12 | | | |
| 4.02 | 14 | 4.00 | 16 | | | |
| 3.74 | 8 | | | | | |
| | | 3.46 | 12 | | | |
| 3.32 | 10 | 3.36 | 13 | | | |
| 3.08 | 20 | 3.07 | 36 | 3.06 | 35 | |
| 3.01 | 70 | 3.00 | 77 | 2.98 | 80 | |
| 2.94 | 100 | 2.92 | 100 | 2.92 | 100d | (2.91 99<br>2.93 100) |
| 2.79 | 16 | 2.78 | 24 | 2.79 | 30 | |
| 2.66 | 25 | 2.63 | 30 | 2.59 | 25 | |
| 2.57 | 14 | 2.56 | 18 | 2.53 | 30 | |
| 2.50 | 6 | 2.48 | 7 | | | |
| 2.43 | 8 | 2.42 | 16 | | | |
| 2.31 | 6 | | | | | |
| 2.28 | 16 | 2.25 | 17 | 2.23 | 15 | |
| 2.21 | 10 | 2.20 | 12 | 2.20 | 15 | |
| 2.15 | 8 | 2.14 | 10 | | | |
| 2.07 | 8 | 2.05 | 10d | | | |
| 2.01 | 20 | 1.997 | 24 | 1.986 | 15d | (1.977<br>1.994) |
| 1.96 | 14 | 1.949 | 18 | 1.938 | 20 | |
| 1.90 | 8 | 1.897 | 9 | 1.897 | 18 | |
| 1.87 | 16 | 1.858 | 21 | | | |
| 1.84 | 6 | 1.837 | 18 | 1.837 | 25 | |
| 1.78 | 10 | 1.772 | 10 | 1.793 | 35 | |
| 1.72 | 6 | 1.725 | 11 | 1.769 | 20 | |
| 1.70 | 14 | 1.689 | 17 | | | |
| 1.64 | 5 | 1.629 | 10 | 1.631 | 15 | |
| 1.59 | 25 | 1.579 | 25 | | | |
| | | 1.570 | 19 | 1.565 | 20d | |
| 1.54 | 18 | 1.522 | 16 | 1.527 | 30d | |
| 1.50 | 8 | 1.498 | 12 | 1.501 | 15 | |
| 1.47 | 8 | 1.468 | 11 | 1.462 | 15 | |
| 1.41 | 4 | 1.420 | 6 | 1.429 | 10 | |
| 1.37 | 6 | 1.390 | 7 | | | |
| 1.34 | 6 | 1.348 | 10 | | | |
| 1.30 | 4 | 1.285 | 9 | | | |
| 1.25 | 6 | 1.264 | 9 | | | |
| 1.21 | 10 | 1.200 | 14 | | | |
| | | | | 1.161 | 15 | |

I: ASTM Card, II: Questa Mine, Norelco 40kv–30mA, 4–1–4, 1–.006–1, III: Hitteroe, Norway.

## VII. Trace Elements Study by Spectrographic Method

Prior to the author went into this field work, preliminary examination was made of the trace elements in samples from the ore deposits area, using a semi-quantitative spectrographic method at the Colorado School of Mines. The standard plate with 1–2–5 divisions was prepared for 43 elements.

The samples of various kinds are classified into four large groups; they are fresh aplites, altered aplites, biotitized rocks, and vein-forming materials. Most of these samples were taken underground and from drilling cores by Prof. R. H.

Carpenter. The analyses are shown in Table 13. The total number of the samples is not large enough to speak with confidence about the geologic significance of their distribution; however, two purposes of the study are indicated in Figures 24 and 25.

One of the characteristics of the intrusive bodies here studied is that, as mentioned already, the ratio between plagioclase and potash feldspar is changeable, the potash feldspar increasing during the process of magmatic evolution. Content of strontium and barium which can act as substitutes for the calcium and potassium positions in feldspars may be compared with the petrographic characteristics, as indicated in what follows. It is known that strontium and barium are concentrated in certain igneous rocks that can be regarded as residuals from fractional crystallization; such rocks are like the Questa Mine aplite. As calcium and strontium belong to the same type of ion (inert gas type), the sequence of their entrance into a crystal lattice in the course of decreasing temperature will depend on their radii (1.06 Å for Ca, 1.27 Å for Sr). During the cooling of the magma the dominant calcium ions will be more strongly bonded than the larger strontium ions, because of the dependence of electrostatic forces upon inter-ionic distances. It is expected, therefore, that minerals in the aplite that contain calcium (such as plagioclase or apatite) must be high in strontium.

Table 13 General tendency of distribution of trace elements in three rock units.

| Elements | Vein | Altered aplite | Biotitized rock |
|---|---|---|---|
| Mo | high | low | low (excluding ore-vein) |
| Pb | high | high | low |
| Zn | variable | low | high |
| Cu | variable | low | high |
| Ti | low | moderate | high |
| V | low | low | high |
| Ni, Co | Very similar to V; high in some veins through later mineralization ( ? ). | | |
| Mn | high | low | moderate |
| Ba | low | moderate | high |
| Sr | variable<br>(Very high in calcite veins) | low | high |

If the two ions of similar radius and similar ionic type (such as strontium and potassium (1.33 Å), with one ion (Sr) divalent and the other (K) univalent) are considered, then the increase in electrostatic attraction between opposite charges in the lattice leads to a preferential capture of the elements with the higher valence in the earliest fractions of crystallization.

Chemical analyses of the intrusive show that the calcium content of any rock of the latest stage (such as the Goat Hill porphyry for the monzonite sequence and the dense aplite for the Questa Mine aplite) is very low. Following their crystrochemical natures and the analyses, one may easily expect a hyporbolic curve rather than a linear one to express correctly the distribution of strontium and barium in the intrusives. There is, however, a liner relation in Figure 24. Although numbers of the samples are small, this is because the concentration of barium is most probably connected with the collection of the early crystallization of potash feldspars.

Figure 25 shows the relation between lead and zinc. Molybdenite veins are sometimes associated with such sulphides as chalcopyrite, sphalerite, and galena. They are generally later than the main stage of the molybdenum mineralization.

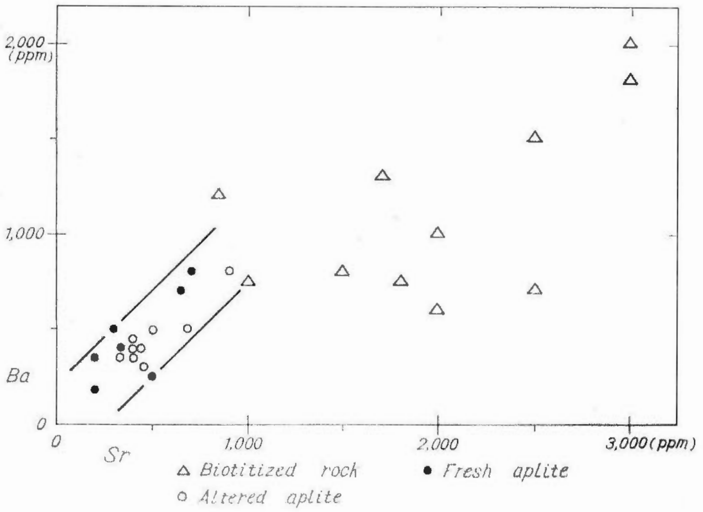

Figure 24 Distribution of strontium and barium. Solid circle: fresh Questa Mine aplite, open circle: altered Questa Mine aplite, open triangle: biotitized rock (andesite (AI)).

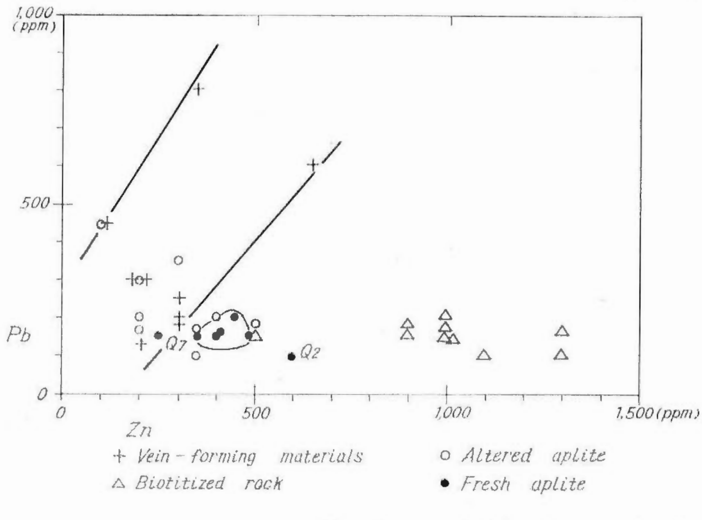

Figure 25 Distribution of zinc and lead. Solid and open circle, and open triangle are the same as those of Figure 24. Cross: vein-forming material. Q2 and Q7 contain well digested xenolith to make the composition more mafic, so that they can not be counted as standard fresh aplite.

Even microscopically the galena is present with the sphalerite. However, the figure shows an interesting point that, except for veins containing visible sphalerite and galena (these are not plotted in the figure) the ratio of lead and zinc in the veins has a proportional relation, while that in altered aplite shows a random distribution or even an inproportional relation. These considerations may offer an explanation for the fact that its ionic radius ($Pb^{2+}$ 1.32 Å) makes it possible for lead to replace strontium (1.27 Å), barium (1.43 Å), potassium (1.33 Å), and in certain minerals even calcium (0.99 Å). Instead of lead being precipitated as galena in the altered aplite, it has substituted for the elements mentioned above in feldspars or micas.

The content of zinc in the altered aplite decreases, compared with that in fresh aplite. Zinc in rocks and minerals of magmatic origin follows the ferrous iron in oxides, and magnesium and ferrous iron in the solid solution represented by ferromagnesian silicates. Microscopic studies indicate that all the ferromagnesian silicates in the altered aplite have been changed to chlorite, sericite, and iron oxides. Most of the zinc might have lost its position in the minerals.

## VIII. Summary of Igneous Activities and Molybdenum Mineralization

So far as known the igneous activities in the Questa region were started by the eruption of the andesite (AI); then followed by more differentiated rocks. A generalization is shown in Figure 26. The effusive rocks are distributed in a narrow depressed belt with an approximate thickness of 3 kilometers in total. It is supposed for the thick deposits and structural movement that the eruption and depression have been reciprocally repeated through the igneous activities. If so, there would

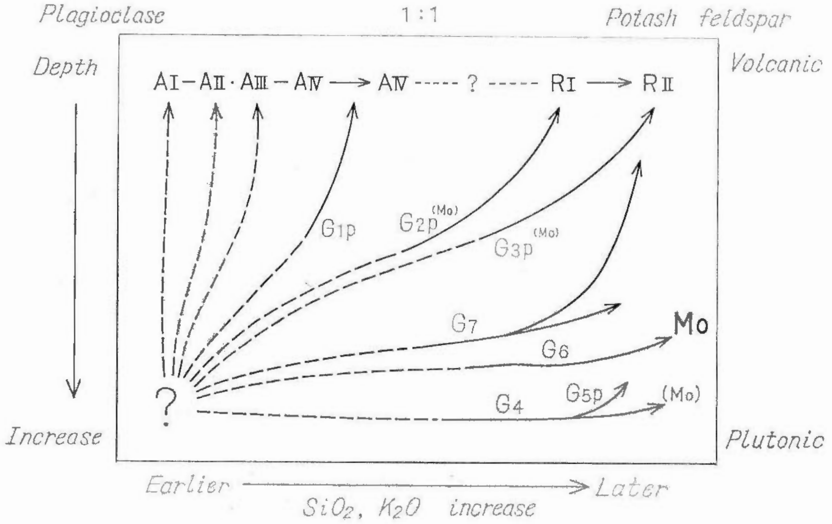

Figure 26 Generalized Miocene igneous activity in relation to molybdenum mineralization, Questa mine area.
G1p: (Quartz) monzonite porphyry, G2p: Granite porphyry, G3p: Goat Hill quartz porphyry, G4: Log Cabin granite, G5p: Columbine aplite porphyry, G6: Questa Mine aplite, G7: Red River aplite. Mo: Strong molybdenum mineralization, (Mo): Weak molybdenum mineralization.

be a possibility to exist more basic magma than that of the andesite (AI). However, this has not been observed at the geologically lowest horizon according to drilling and surface mapping. Compositionally the igneous rocks show somewhat alkalic character in the M–F–A diagram. They point a normal alkali basalt, though they get very rich in silica in the end of the magmatic differentiation.

The igneous rocks are stratigraphically correlated to those in Miocene. Two dated biotite locating them in lower Miocene support this estimation. Since no causes that would make argon leakage have been found on the samples, these two figures should be valid. They are 23 million years for the mineralization stage at the Log Cabin granite, and 21 million years for that of the Questa Mine aplite. It is obvious that the extrusion and intrusion proceeded the mineralization. Although the whole time range has not been detected, it may not be as long as for an example of 7 or 8 million years reported in the Boulder Bathylith (KNOPF, 1964) for such a small scale activity at Questa region, but within a few million years. In this assumption, the earliest part of the activities would have been around the end of Oligocene, which is 26± 1 millions year in Holmes time scale (MATSUMOTO, 1965).

Nearly the end of the magmatic activity, the partial magma would have been enriched in molybdenum. There are a few ore veins in the altered andesite (AI) around the northern rim of the main plug granite porphyry (G2p). Molybdenum mineralization around underground Goat Hill porphyry dikes may be partly due to the porphyry intrusion. They are well fractionated ones among dike-forming intrusive rocks. Practically almost all molybdenum are concentrated at the west flank of the Questa Mine aplite. There are weak molybdenum mineralization observed in relation to the Log Cabin granite. One at the west flank of the granite is as

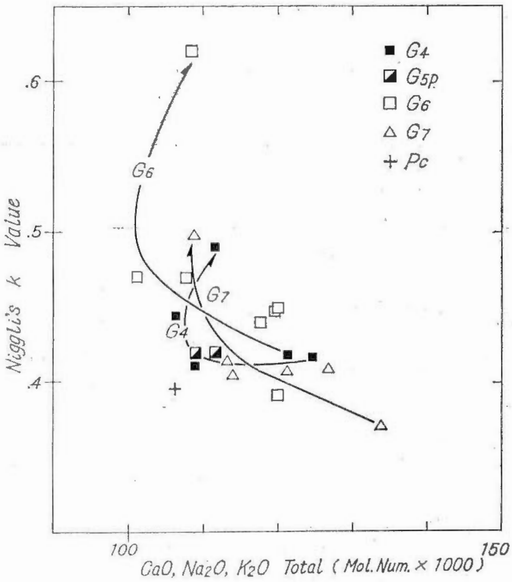

Figure 27 Variation diagram showing evolution trends of the Log Cabin granite, Questa Mine aplite, and Red River aplite.
G4: Log Cabin granite, G5p: Columbine aplite porphyry, G6: Questa Mine aplite, G7: Red River aplite, PC: Precambrian granite. The arrows indicate each trend.

fairly large scale as it could be minable. No molybdenum mineralization has been so far found related to the Red River aplite.

As described in the CaO–$Na_2O$–$K_2O$ diagram (Figure 9), these three granitic stocks are highly differentiated, and moreover in later phases the differentiation is best demonstrated in the alkali ratio. In Figure 27, the Niggli's k value is plotted against the total lime and alkali. Here the Red River aplite starts at the lowest; then the Log Cabin granite and Questa Mine aplite follow it. The Red River aplite and Log Cabin granite end at the lowest; while the Questa Mine aplite does at the highest. This may indicate that degree of magmatic differentiation could have been important for the strong molybdenum concentration at Questa mine.

There have been no detailed studies on how large amounts of molybdenum would be contained in original magmas. However, it must be as very low as below 1 ppm (KURODA & SANDEL, 1954). Behaviour of the molybdenum in magmatic fractionation is uncertain. It may be feasible to assume that the molybdenum will be concentrated in residual liquids, because there are no suitable positions for the molybdenum (possibly quadrivalent) in major rock-forming minerals of igneous rocks. The basic support for this assumption is the "Goldschmidt Rule," which is partly revised (SHAW 1953, RINGWOOD 1955, and NOCKOLDS 1966) but still works for the element. It is also supported by trace element studies by Kuroda (1954), which indicate that molybdenum does not closely follow any single major constituent of igneous rocks.

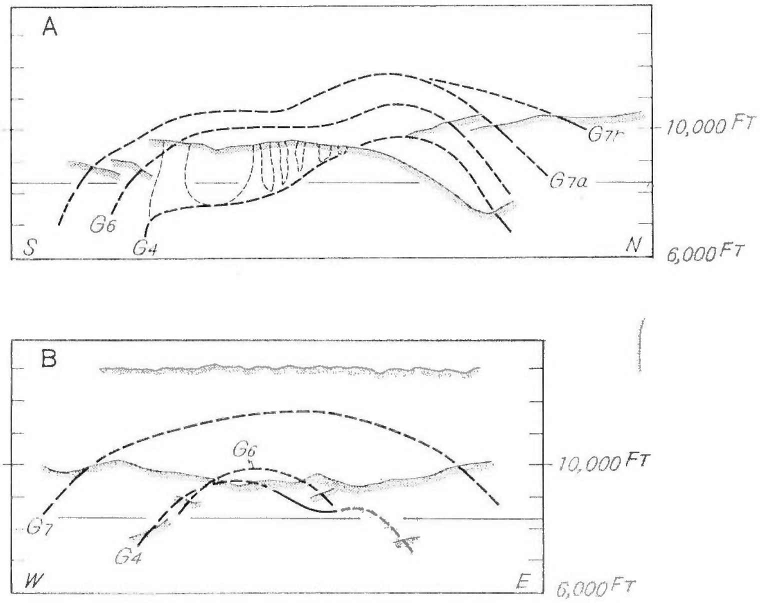

Figure 28 Sections of the three granitic stocks along Red River Valley.
A: The whole topography is of the Log Cabin granite (G4). Directions of sections are G4–N2°W, G6 (Questa Mine aplite)–N7°W, and G7–N12°E. G7a: Edge of main phase Red River aplite; G7r: or rhyolitic part of the Red River aplite B: The whole topography is of the Red River aplite. Directions are parpendicular to those in A, roughly E–W. A waved line in B indicates the estimated paleo-surface at the intrusion of the Questa Mine aplite.

The molybdenum, concentrated in probably liquid and gas phases of the residual magma, should have been precipitated in fractures after certain stage of the solidification of the granitic stocks. The Questa Mine aplite has no branched or satellite dikes, and the surrounding rocks are all the lowest effusive rock, andesite (AI). This means that the magma intruded into a somewhat closed environment where no rifts or weak zones were distributed, and warped gently the basal andesite upward. This kind of environment possibly served enough time to precipitate molybdenite from the molybdenum bearing ore fluid.

The Log Cabin granite accompanies satellite dikes. Even such an upper horizon rock as welded tuff (RIIa) is included in the surrounding rocks. Besides, the structure of the volcanic rocks are disturbed at the western edge of the Taos Range, where the granite is located. These indicate that the Log Cabin granite intruded into a faulted area where the ore fluid would have leaked out easily. Although no detailed mapping has been done on the Red River aplite, it is known that the aplite intruded at the highest horizon among three stocks (Figure 28). The aplite has a rhyolite phase in the northern margin, so that it could be extruded onto surface or very close to the situation, which would affect the associated ore solution similarly to the case of the Log Cabin granite. This mode of the intrusions may be another importance on the formation of the Questa molybdenum deposits.

In underground it is known that Goat Hill quartz porphyry dikes cut the Questa Mine aplite. The quartz porphyry is probably vent to the welded tuff (RIIa), and a similar dike of Hot'ntot quartz porphyry is possibly that to the welded tuff (RIIa & RIIb). Therefore thickness of andesite (AI) and quartz latite (AIII) above the stocks indicate depth of the upper limit of the stocks. In the example of Questa Mine aplite, it is estimated 1,000 to 1,300 meters, which is a sum of a mean thickness – 500m (max. 700 m) of the quartz latite and unintruded part – 500m of the andesite (Figure 2). Then the present known ore bodies are included in such a shallow zone as the depth between 1 and 1.6 km.

The sequence of the intrusive rocks used for the above estimation could be a local phenomenon. It may have erupted rhyolitic rocks up to welded tuff (RIIb) before the intrusions. If these rhyolitic rocks are added, the sum goes up to 2 kilometers. In consideration of these approximate calculation of the depth and rhyolitic phase of the Red River aplite, the granitic stocks and molybdenum deposits are possibly formed in relatively shallower horizon than general understanding to formation of granitic stocks and related ore deposits of lithophile elements.

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(Originaly written in January of 1964 at Columbia University, New Yoru, and revised in 1966 in Tokyo.)

Appendix Localities of samples used for further studies.

| Symb. | Sam. No. | Locality |
|---|---|---|
| PC | SI–242 | "Columbine", cutting at big curve, north side highway 38. |
| AI | SI–141 | About a mile east of old moly camp, north side highway 38. |
| AIV | SI–211 | Very upper Goat Hill Gulch, end of old road, between ADX and ADY survey points. |
| RIIb | SI–135 | Southern slope Sawmill Mtn., along jeep road. |
| $G_{1}p$ | SI–140 | About a mile west the town of Red River, north side highway 38. |
| $G_{2}p$<br>(Granite porphyry) | SI–9 | Upper Iron Gulch, nearly center of the main plug. |
|  | SI–10′ | Upper Sulphur Gulch, nearly north margin of the main plug. |
|  | SI–172 | Upper Sulphur Gulch, tip of a small granite porphyry dike (1″–50′ map #6). |
|  | SI–173 | Ridge between Iron and Sulphur Gulch, small dike (1″–50′ map, #6). |
|  | SI–233 | Underground, No. 1 Cross Cut North. |
| $G_{3}p$<br>(Quartz porphyry) | SI–25 | Underground Goat Hill porphyry dike, from mine dump. |
|  | SI–181 | South (foot) Eagle Rock, small dike, north side highway 38, curved point. |
|  | SI–184 | East side Goat Hill, air photo 2–61. |
|  | SI–185 | West side Goat Hill, air photo 2–61. |
|  | SI–232 | Underground, DDH (diamond drilling hall) 45, 197′. |
| $G_{4}$<br>(Log Cabin granite) | SI–174 | Bear Canyon, near its mouth. |
|  | SI–175 | Almost north edge of Log Cabin granite, north side highway 38. |
|  | SI–176 | In old Log Cabin prospect, 350′ from its portal. |
|  | SI–177 | In old Log Cabin prospect, face of the main drift. |
|  | SI–180 | 350′ west from Log Cabin discovery put #12. |
|  | SI–240 | Near mouth of Bear Canyon, north side highway 38. |
|  | SI–241 | 10′ east from an old prospect at south side Red River. |
| $G_{5}p$ | SI–35 | Haulage adit side of a small ridge, Columbine. |
|  | SI–36 | The other side (west side) of the ridge. |
| $G_{6}$<br>(Questa Mine aplite) | SI–186 | Behind old moly camp, ridge, at survey point #1 (8752.54′). |
|  | SI–187 | At mouth of Spring Gulch, southeast side. |
|  | SI–188 | Upper Spring Gulch, next to survey point 2–45–1, 9293.84′. |
|  | SI–189 | Middle Sulphur Gulch, 8,500′ elevation, south side. |
|  | SI–192 | Very upper Blind Gulch, 400′ south DC–20 drill hole. |
|  | SI–193 | Same as above. |
|  | SI–234 | Underground, No. 3 Cross Cut South, 3212+8′. |
|  | SI–235 | Underground, Questa main tunnel, dike. |
|  | SI–236 | Underground, No. 1 Cross Cut North. |
|  | SI–237 | Ridge between Blind and Spring Gulch, 600′ southeast of Blind Gulch adit. |
|  | SI–238 | 200′ east of Sulphur Gulch mouth, north side highway 38. |
|  | SI–239 | Opposite, Sulphur Gulch mouth, south side Red River. |
| $G_{7}$<br>(Red River aplite) | SI–64 | Middle Mallette Creek, nearly center of Red River aplite. |
|  | SI–65 | Mallette Creek, close to mouth of a branch to Bonito Canyon. |
|  | SI–66 | Mallette Creek, near SI–65, lower side. |
|  | SI–67 | Mallette Creek, close to SI–65, lower side. |
|  | SI–69 | Near mouth of Mallette Creek. |
|  | SI–197 | Near discovery pit of Oak #25. |

# ニュー・メキシコ州クェスタ鉱山のモリブデン鉱化作用

## ――モリブデン鉱床形成における岩漿の進化度の重要性――

石原　舜三

## 要　旨

クェスタ鉱床はニュー・メキシコ州北部のサングレ・ド・クリスト山塊中，海抜約3000mの高所にある。この山塊はおもにララマイド期に東方のプレーリーにつき上げたプレカンブリア系からなる。この地塊運動に付随して火成活動が中新世の初期にあり，クェスタ地域では幅約5km, N 75°E にのびる陥没帯に各種の火成岩類が分布している。

火成活動は安山岩の噴出に始まり，より酸性な岩石に移行した。初期は熔岩，中期は降下性堆積物，末期は火砕流の活動で特徴ずけられる。すなわち下位より角閃石安山岩 (A I) → 安山岩質凝灰岩 (A II) → 閃雲（石英）ラタイト → 黒雲母（石英）ラタイトと同質砕屑岩 (AIV) → 流紋岩 (R I) → 流紋岩質熔結凝灰岩 (R II) である。

これら噴出岩類の化学成分上の変化は一般のカルク・アルカリ岩系の特徴を示すが，個々の酸化物については $K_2O$ に非常に富み，$SiO_2$ と MgO にやや富む，$Na_2O$ と $TiO_2$ にややと $FeO_3$ と FeO および CaO に非常に乏しいなど，ややアルカリ岩の特徴を示している。CaOの異常に低い傾向は岩脈類にもみられ，両者を通じて著しく非平衡の条件下で同結したと思われる岩石でその傾向が強い。

貫入岩として岩脈またはプラグ状の閃雲（石英）モンゾニ岩 ($G_1$p)，黒雲母花崗斑岩 ($G_2$p), 石英斑岩 ($G_3$p) などがある。これらは（石英）ラタイト (A IV) 以後の噴出岩類の噴出口と考えられ，化学成分上も対比されるそれぞれに類似している。

小岩株状の貫入岩が石英斑岩 ($G_3$p) を除く上記諸岩類に貫入し，西からログ・キャビン花崗岩 ($G_4$), クェスタ鉱山アプライト ($G_6$), レッド・リバーアプライト ($G_7$) と呼ばれる。ログ・キャビン花崗岩は 1.3×3 km で東西にのび，断層運動により基盤がブロック化した所に貫入したもので，派生岩脈が多い。弱いモリブデン鉱化作用が岩体の周縁，とくに西縁に存在する。

クェスタ鉱山アプライトは 3.3×1.5 km で南北にのび，基盤を特ち上げて貫入している。貫入水準はログ・キャビン花崗岩とほぼ同じで，岩体の頂部は地表下 1～1.3 km 程度と推定される。岩体西縁にクェスタ鉱床が存在する。その形成時の深さは 1～1.6 km の比較的浅所であったらしい。レッド・リバーアプライトは直径ほぼ 4.5 km, 3岩体中もっとも高所まで貫入し，一部は地表に溢流したかも知れない。モリブデン鉱化作用を伴わない。

これら花崗岩類は化学成分上，岩漿分化が進んでおり，D I 値で主岩相が93～95，後期相が96～97である。最末期相で斜長石をカリ長石が交代し，またカリウム量が増加する。3岩体中，クェスタ鉱山アプライトがそれぞれの相で分化の程度がもっとも進んでいる。

噴出岩類は多少ともいわゆる自変質作用を蒙り，べつに鉱床形成後の水蒸気活動によると思われる熱水変質ハロを伴う。これら地域的な変質作用のほか，貫入岩による局部的な接触変質作用がある。岩脈状貫入岩の周辺で著しく，最厚幅約 150m である。クェスタ鉱山アプライトの西縁では幅約30mの接触変質帯があり，カリウムと珪酸の添加で特徴ずけられる。これは鉱化作用と密接に関係している。

クェスタ鉱床はクェスタ鉱山アプライトが西に張り出す部分にあり，南北走向の境界面が急激に西に曲がる付近で鉱況がよい。鉱床はこの境界面沿いに約35°の傾斜で西南西に落ち，海抜約 3000 m の露頭部から約 2400 m まで確認されている。鉱化作用は一般に安山岩 (AI) とアプライトとの境界面付近でもっとも強く，離れるに従って弱くなる。アプライト側がより広く鉱化作用をうけ，母岩として好ましい。

鉱床は裂か充填鉱床で，輝水鉛鉱が各種の割れ目を埋める。部分的に鉱染鉱床や，母岩がアプライトの場合に輝水鉛鉱-石英細脈による網状鉱脈鉱床がある。富鉱部の鉱脈は境界面上かアプライト側に15m以内の範囲で，境界面にほぼ平行なものが多い。境界が極端にうねる場合には鉱脈は直線的に走る傾向がある。一般に傾斜より走向方向によく発達する。最大脈幅は約 2 m であるが，膨縮に富み，容易に皮膜に移りかわる。このほか鉱化作用は局部的な断層とそれに伴われる小裂か，およびアプライトの周縁節理に規制されている。前者は東西系と東北—南西系で急傾斜，後者はほぼ南北，西に緩傾斜である。

鉱脈を形成する脉石鉱物はおもに石英と絹雲母で，ほかに蛍石・黒雲母・方解石・カオリン・菱マンガン鉱・氷長石・トパズなどがある。黒雲母は富鉱部中心の鉱脈中に多く産出し，蛍石・方解石・菱マンガン鉱などは周縁部で鉱脉中の割れ目を埋め，複合鉱脉を作る。

鉱石鉱物はほとんど輝水鉛鉱で，全般的に少量の黄鉄鉱を伴う。ほかに微量の黄銅鉱・閃亜鉛鉱および方鉛鉱が産出し，蛍石-炭酸塩鉱物脉など後期の諸鉱物におもに伴われる。輝水鉛鉱は 1) 石英脉や 2) 粘土などに伴われるものが多く，少量は 3) 硫化物-蛍石-炭酸塩鉱物に伴われ，また 4) 割れ目に沿い皮膜として産出する。主鉱化期は中温熱水期よりやや低温と推定され，鉱化作用の時期は中新世初期である。

露頭部では鉱脉の周辺に水鉛華が発達し，そのさらに外側は赤金鉱で，これは $HMoO_4^-$ の形でモリブデンを含んでいるらしい。アメリカ本土新産の Eschynite が発見された。

# PLATES
# AND
# EXPLANATIONS

(with 21 Plates)

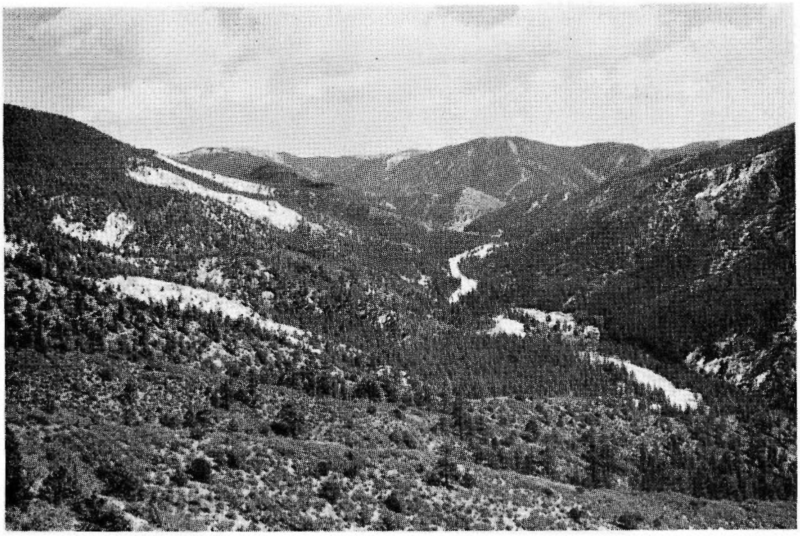


Plate 1 A view of the upper Red River Valley, at the east end of the moly camp looking toward east. White spots at left hydrothermal pipes, August, 1962.

Plate 2 Granite porphyry (G2p) plug, rough surface, standing on the ridge between Iron Gulch (left) and Sulphur Gulch (right), July, 1963.

Plate 3

Mineralized parts Sulphur Gulch and Z tunnel mine dump ; andesite (AI), dark grey and smoose, intruded by the Questa Mine aplite (G6), lighter colored and rocky. White : hydrothermal pipe, July, 1963.

Plate 4

A part of the old moly camp, a small floatation plant in center and tailings, August, 1963.

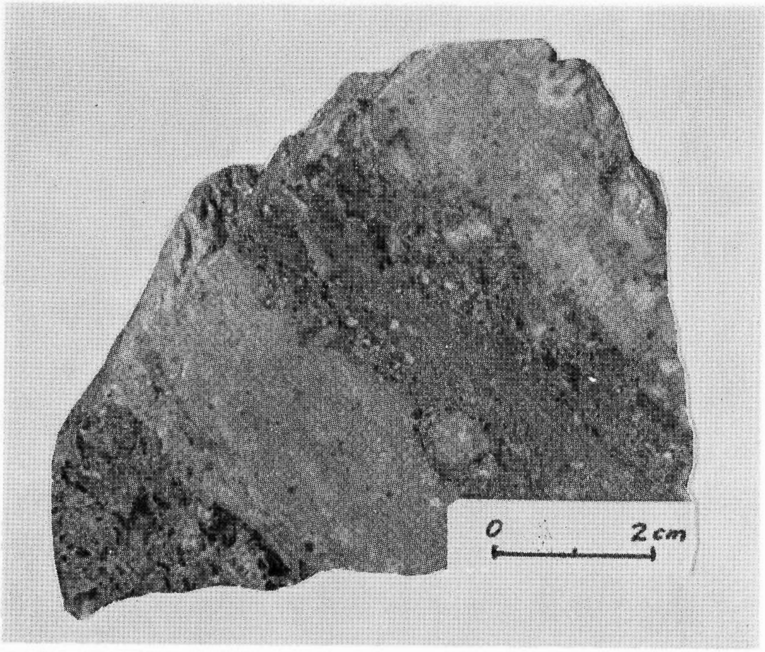


Plate 5 Coarse-grained rhyolitic welded tuff (RIIa) with alteration bands (white). (SI–162, near the ridge between Sulphur and Goat Hill Gulhc).

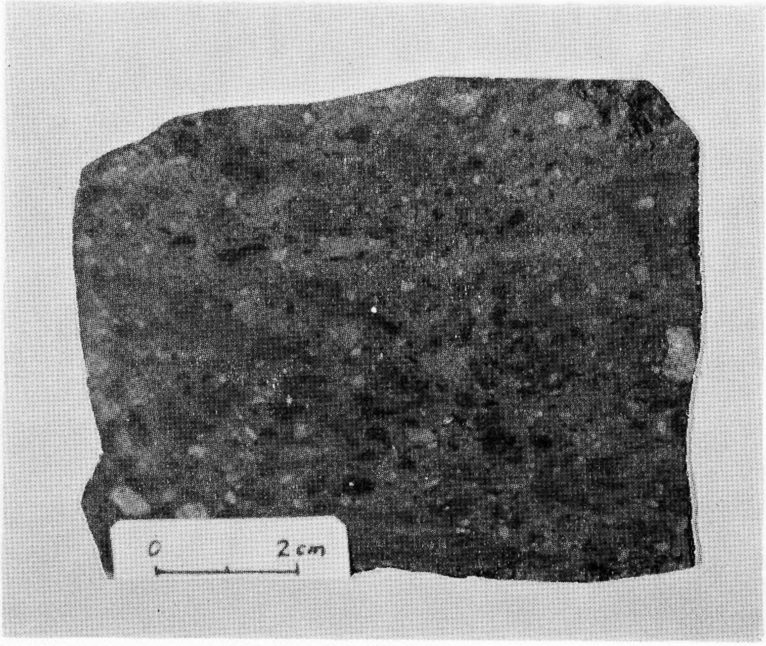


Plate 6 An example of the lower unit of fine-grained rhyolitic welded tuff (RIIb). (SI–135).

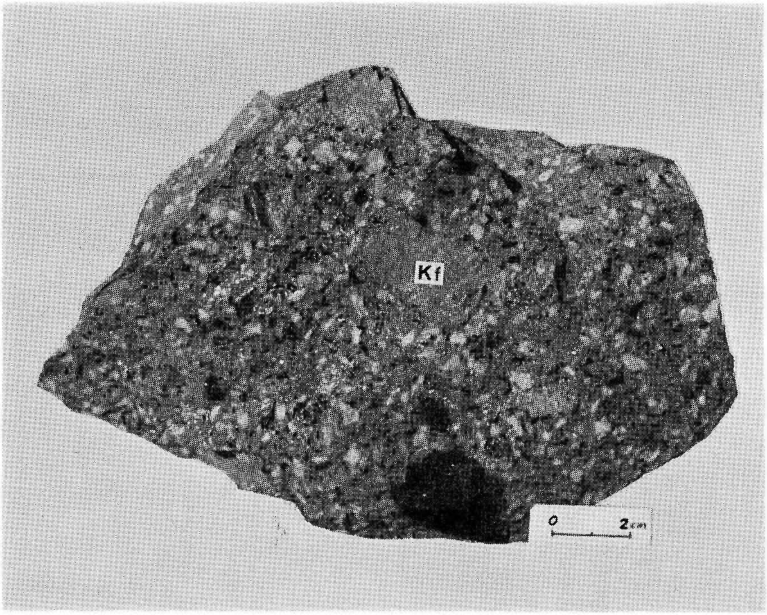
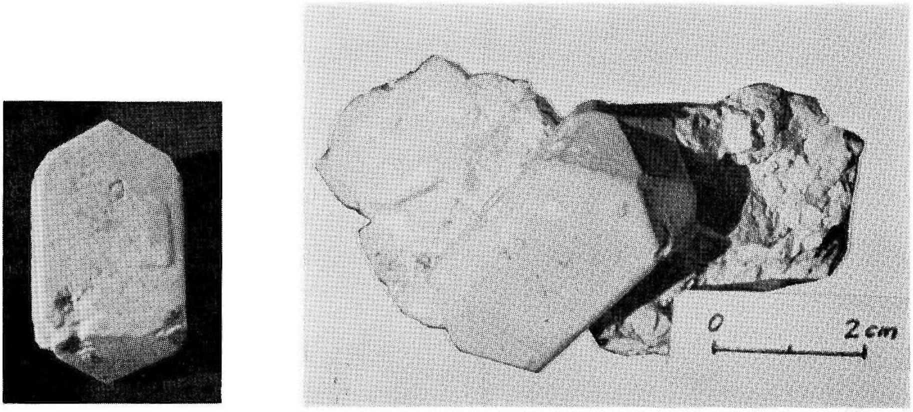
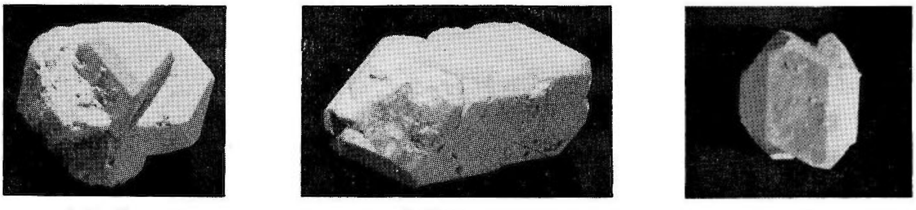


Plate 7 Monzonite porphyry (G1p) with large sanidine (Kf) phenocrysts. (SI-140)



a) Untwinned b) Manebach



c) Breihaupt d) Baveno e) Carlsbad

Plate 8 Phenocrysts of twinned sanidine in the monzonite porphyry, Goat Hill Gulch. Collected and classified by Mr. K. H. Rippere.

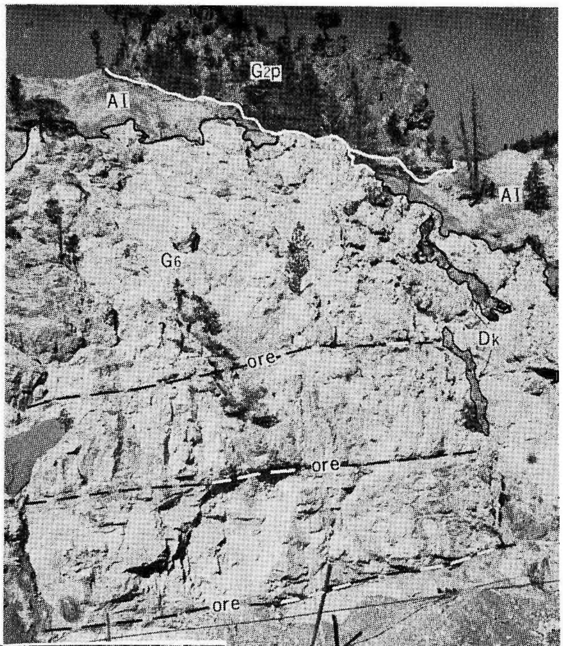


Plate 9

Mineralized flat-lying fractures at margin of the Questa Mine aplite (G6).
AI : Hornblende andesite. $G^2p$ : Branches of the granite porphyry main plug. Dk : Post-aplite dike. Looking westward at the upper Sulphur Gulch.

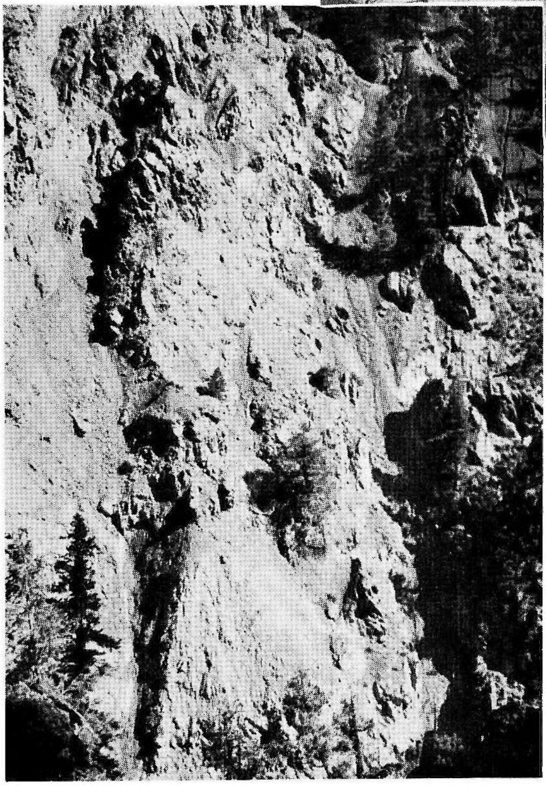


Plate 10

Mineralized local faults of NE direction at the upper Sulphur Gulch. Looking toward N20°E.

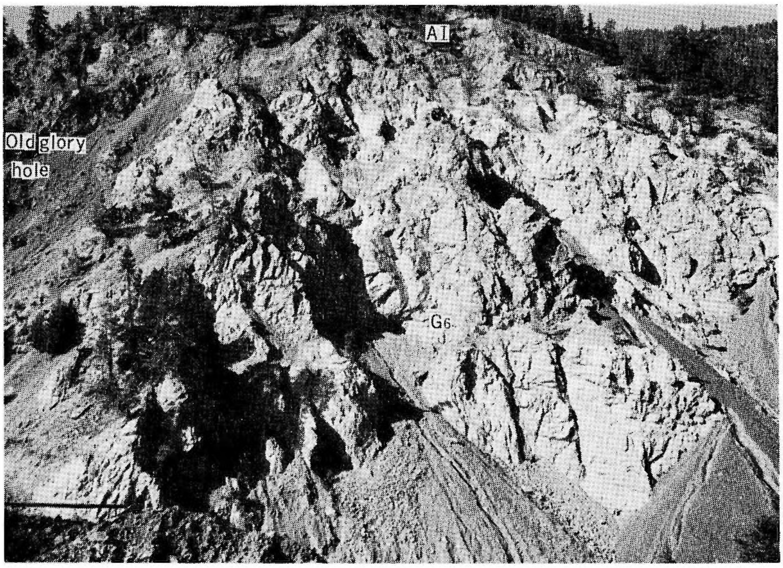


Plate 11 Mineralized steeply dipping faults (E–W) at margin of Questa Mine aplite. Looking westward at the middle Sulphur Gulch.

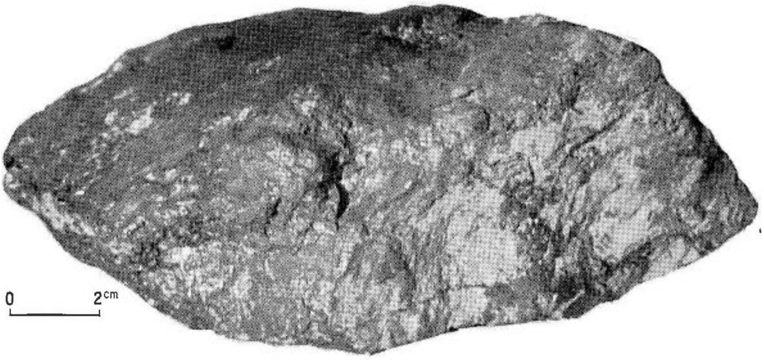


Plate 12 High grade massive ore, a part of molybdenite-quartz vein.

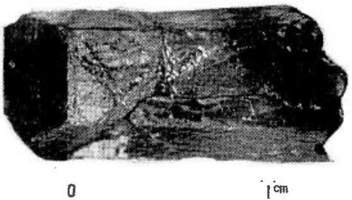


Plate 13

Euhedral eschynite crystal found at the southern end of the Questa ore deposits.

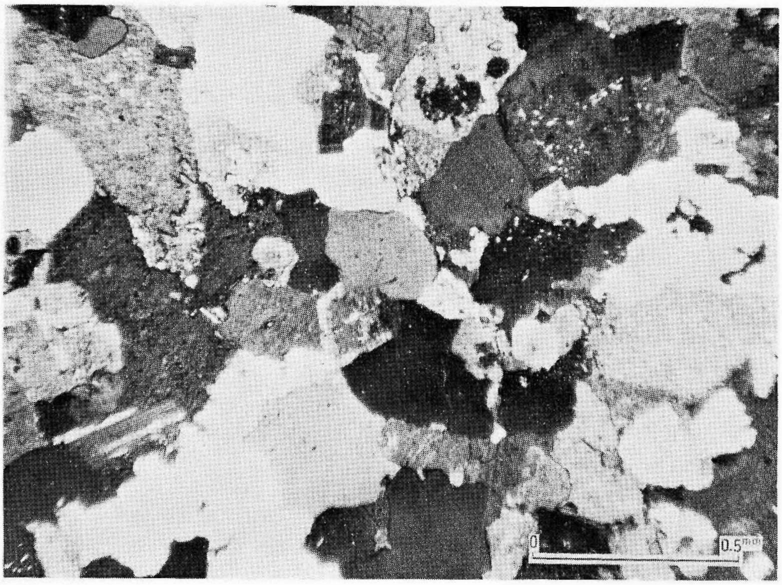


Plate 14 General appearance of the main phase of the Questa Mine aplite (SI–188, crossed nicols).

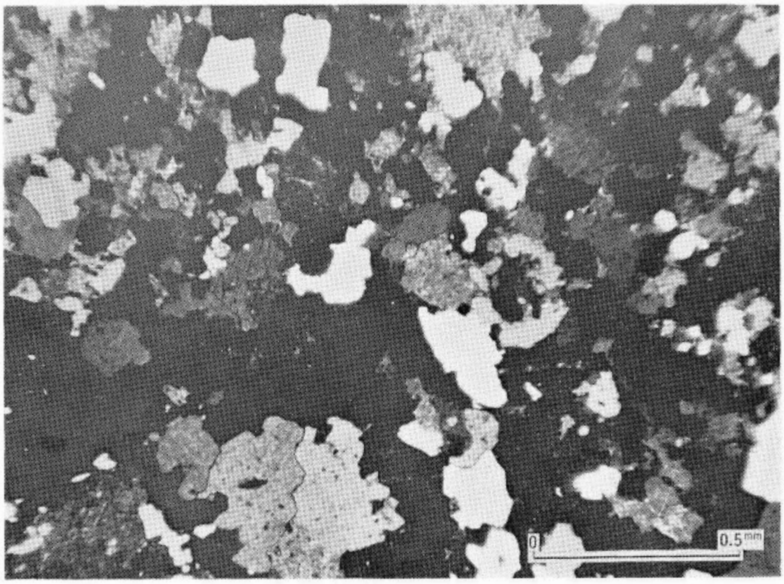


Plate 15 General appearance of the dense aplite, probably the latest phase of the Questa Mine aplite (SI–236, crossed nicols).

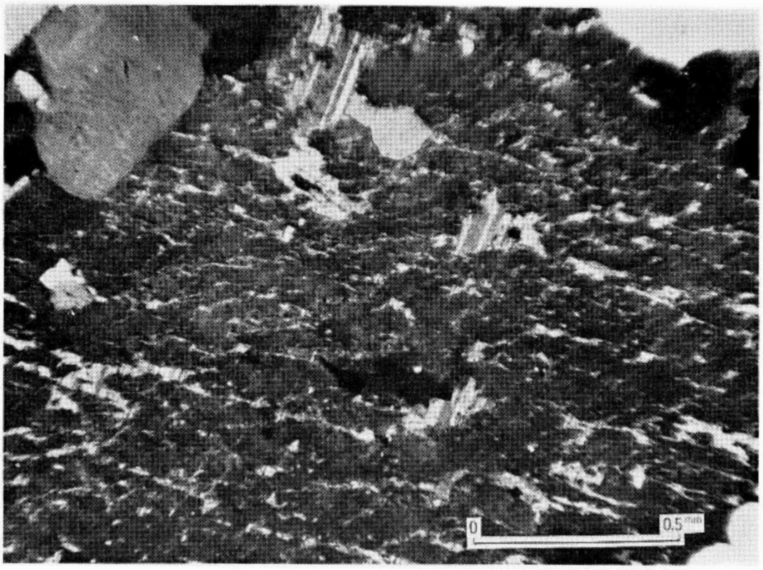


Plate 16 Plagioclase almost completely replaced by potash feldspar showing a perthite structure. This replacement phenomenon over plagioclase by potash feldspar is a characteristic in the latest phases of the Log Cabin granite and Questa Mine aplite (SI–236, crossed nicols).

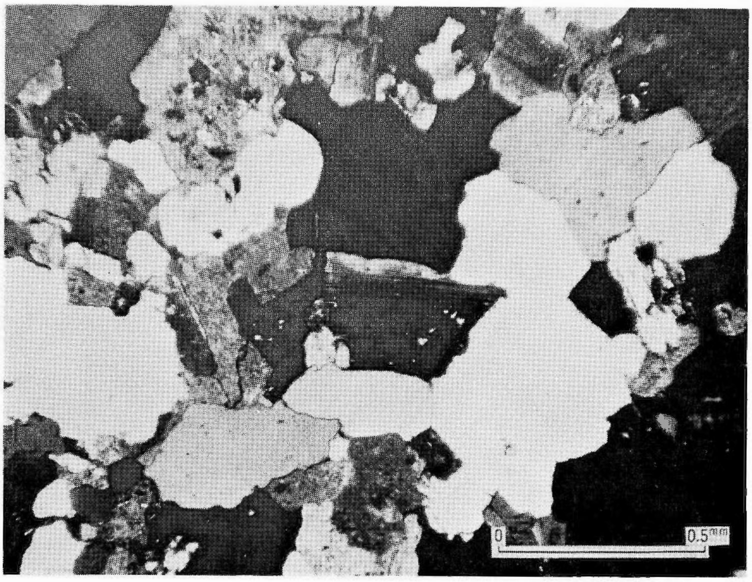


Plate 17 Albite rim of plagioclase, often seen at the contact with potash feldspar. This is probably due to albitization during the late magmatic stage (SI–188, crossed nicols).

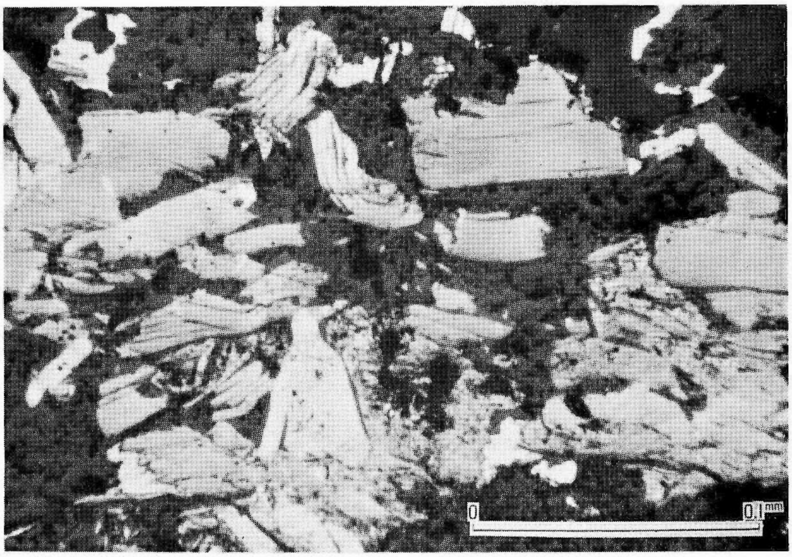


Plate 18 Molybdenite flakes occurring, with a little pyrite (white and irregular-shaped crystals), in quartz, carbonates, and other gangue minerals. (SI–228, No. 2 Cross Cut North 40′).

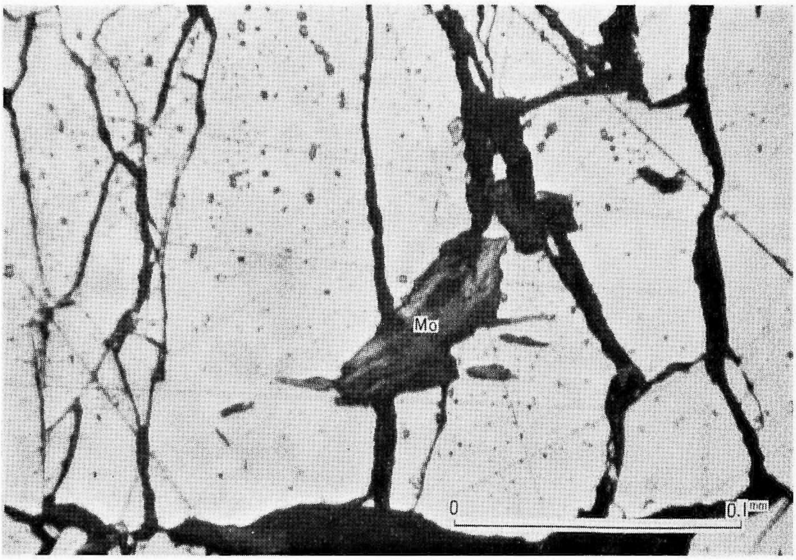


Plate 19 Cracked pyrite filled with carbonates. Molybdenite (Mo) shows a replaced figure, and it is not cut by the carbonates veinlets (SI–230, Main Tunnel, G 243+20.5′).

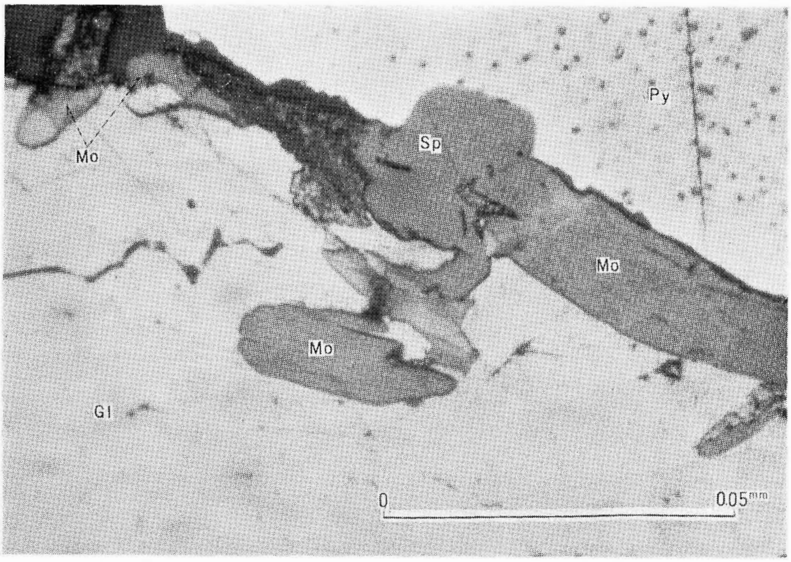


Plate 20 Molybdenite (Mo) and sphalerite (Sp) with exsolution "dots" of chalcopyrite, occurring in two large masses of pyrite (Py) and galena (Gl). The sphalerite has invaded the pyrite rim where lesser inclusions are distributed (SI–231, Drilling core, DDH–XX 521′).

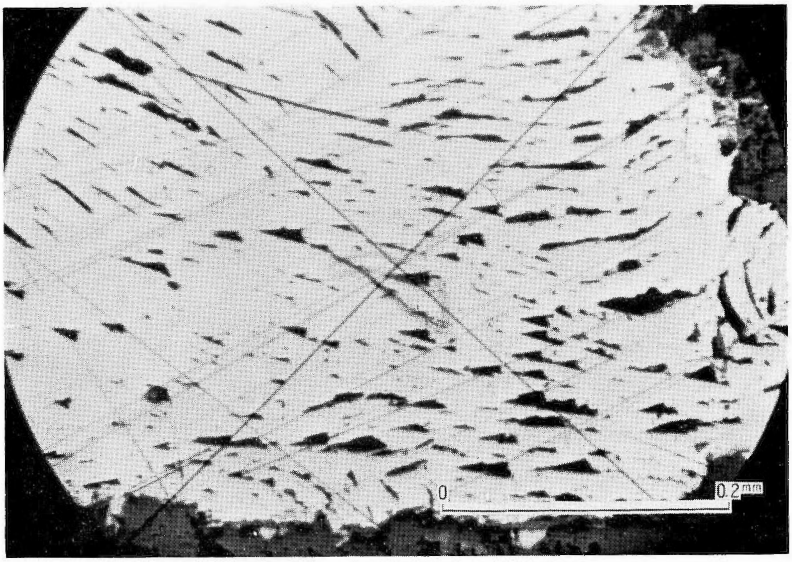


Plate 21 Curved rows of triangle pits in galena. The rows roughly parallel to an edge of gangue minerals in some cases (here at bottom); however, no general regularity has been found (SI–227, Blind Gulch Tunnel, 17 m from the 2nd turn).

地質調査所報告は１報文について報告１冊を原則とし，その分類の便宜のために，次のようにアルファベットによる略号をつける。

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  - b．岩石・鉱物
  - c．古生物
  - d．火山・温泉
  - e．地球物理
  - f．地球化学
- B．応用地質に関するもの
  - a．鉱　床
  - b．石　炭
  - c．石油・天然ガス
  - d．地下水
  - e．農林地質・土木地質
  - f．物理探鉱・化学探鉱および試錐
- C．その他
- D．事業報告

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Ishihara, S.

### Molybdenum Mineralization at Questa Mine, New Mexico, U.S.A.

Shunso Ishihara
地質調査所報告, No. 218, 1967
28 illus., 21 pl., 13 tab.

Two summer vacations were spent for basic geological mapping, examination of drilling cores, geochemical exploration, and claim evaluation at Questa, Taos County, New Mexico, U.S.A. Additional treatment in laboratories is added to the field results; then it is emphasized important factors for the formation of the Questa molybdenum deposits. They are degree of magmatic fractionation and mode of the intrusions of the ore-bringers. The deposits may have been formed in such a shallow horizon as a kilometer in depth.

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