A GEOLOGICAL EVALUATION OF MINERALIZATION AT MINERAL MOUNTAIN, WASHINGTON COUNTY, UTAH

by

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STATEMENT BY AUTHOR

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ABSTRACT

Mineral Mountain is a leucocratic quartz monzonite porphyry intrusion located along the eastern margin of the Basin and Range province in Washington County, Utah. The intrusion is one of many igneous masses in southwestern Utah which have been localized along a N. 60° E.-trending Laramide overthrust anticline, the Iron Springs Gap structure. Pennsylvanian carbonate rocks overlying the intrusion have been forcefully domed and tilted during uplift, so that they lie in a crudely concentric manner around Mineral Mountain. The carbonate rocks make up an allochthonous block of a post-Laramide thrust sheet. Limestone adjacent to the intrusion has been converted into low-grade skarn and marble. Analyses from selected geochemical rock samples indicate that Cu-Zn and Pb-Mo affinities exist along the skarn zones. Vast sheets of pyroclastic rocks derived from nuée ardente eruptions are exposed at the base of Mineral Mountain. The spatial relationships of the pyroclastic rocks preclude the possibility that volcanism preceded plutonism. Age for the plutonism is estimated at 40 m.y.; at that time the magma was iron poor.

CHAPTER 1

INTRODUCTION

Mineral Mountain, Washington County, Utah is a leucocratic quartz monzonite porphyry intrusion located in a relatively primitive mining area in southwestern Utah. The intrusion is unusual because it has been emplaced into an allochthonous block of Pennsylvanian limestone. Skarn alteration is weakly developed in the limestones adjacent to the intrusion, but little, if any, ore-grade rock has been mined from the area. An established iron ore district is located about 45 miles northeast at Iron Springs; Mineral Mountain may qualify as a precursor to igneous intrusion at Iron Springs.

The method of approach in this study involved large-scale geologic mapping, geochemical rock sampling, and an examination of published aeromagnetic data. The objects of the study were to determine the source of the thick section of Pennsylvanian limestones, to estimate the relative age of igneous intrusion, to estimate the ages of a thick sequence of pyroclastic rocks exposed at the base of Mineral Mountain, and to determine the interrelationships between each rock type in order to make an overall geologic evaluation.

Location

The study area is located in the southwestern corner of Utah, approximately 4 miles from the Utah-Nevada border (Fig. 1). It includes 6 square miles in the southwestern part of the Bull Valley mining district,

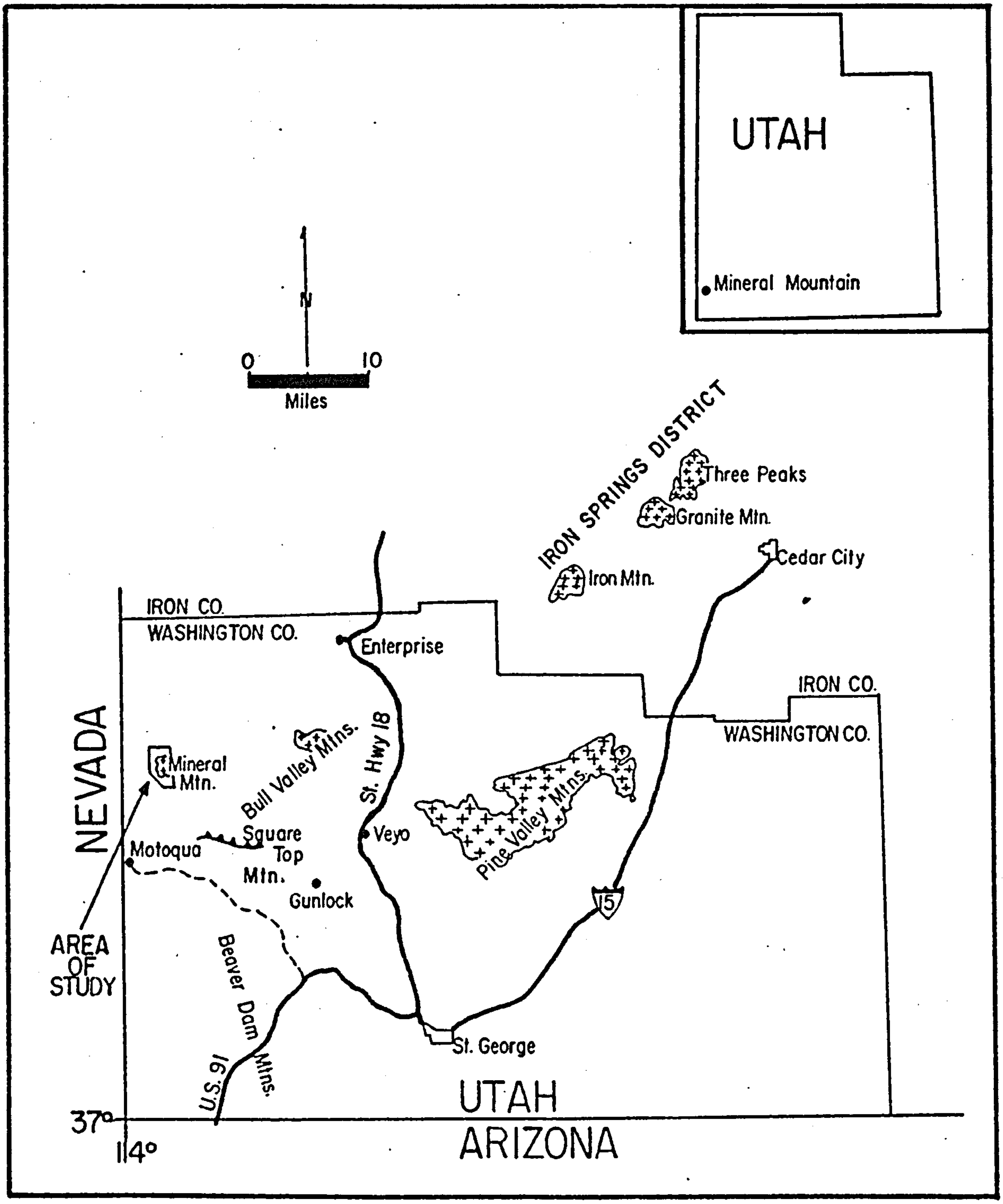


Figure 1. Location map showing geographical location of Mineral Mountain and its relation to the Bull Valley, Pine Valley, and Iron Springs areas.--Modified after Stokes and Heylmun (1963)

in Washington County, Utah, nearly centered on Mineral Mountain, a small, irregularly shaped intrusion, measuring more than 2 miles in diameter. Minteral Mountain is bounded on the west by Slaughter Creek and on the east by Butcher Knife Canyon (Fig. 2, in pocket). The old Emma copper prospect and Potters Peak mark the northern and southern limits, respectively. The area is accessible from U.S. Highway 91 at a turnoff located 18 miles west of St. George, Utah. A dirt road extends from this turnoff 22 miles to Motoqua and then 10 miles northerly along Slaughter Creek to the property.

Previous Work

In spite of its geologically interesting character, little information has been published regarding the Mineral Mountain area. Cook's (1960) Geologic Atlas of Utah: Washington County lists little more than a summary of the salient physical features of the intrusion. Crawford and Buranek (1948) suggested that the Beauty Knoll halloysite deposit, associated with andesitic volcanics a mile or more east of Mineral Mountain, may have formed from hydrothermal solutions given off by the intrusion or one of its apophyses. Mackin (1960) indirectly alluded to the Mineral Mountain mass by suggesting that several intrusions in western Washington County are aligned along the Laramide Iron Springs Gap structure.

Much of southwestern Utah to the east and northeast of Mineral Mountain has been the subject of a good deal of geologic study by investigators from the University of Washington. Areas mapped in this region include the Bull Valley Mountains (Blank, 1959), the

Gunlock-Motoqua area (McCarthy, 1959), the Pine Valley Mountains (Cook, 1954), and the Iron Springs district (Mackin, 1960, 1968) (Fig. 3).

Procedure

The only topographic base map available of the Mineral Mountain area at the time of field mapping was the 1:250,000 scale Cedar City, Utah, AMS sheet. As it was not possible to use such a small scale map with any degree of accuracy, field mapping was done directly on aerial photographs that had been enlarged to an approximate scale of 1:6,000. The aerial photography was flown in June 1972 by the U.S. Geological Survey. Preliminary 7 1/2-minute topographic sheet of the Gunlock NW quadrangle was made available through the U.S. Geological Survey during the later part of 1973. This 1:24,000-scale quadrangle sheet was enlarged fourfold to an exact scale of 1:6,000, thus closely matching the scale of the aerial photographs. Geology was transferred from the aerial photographs to the enlarged topographic quadrangle sheet, which, in addition, served as an elevation control from which the cross sections were constructed.

Regional Geologic Setting

Throughout the course of this paper, references and comparisons will be made to the Bull Valley, Pine Valley, and Iron Springs areas (Fig. 3). These have many structural and stratigraphic similarities to the Mineral Mountain area. Each area is characterized by mid-Tertiary plutonism, some of which is correlative temporally and spatially with the extensive silicic volcanism of southwestern Utah. Igneous masses

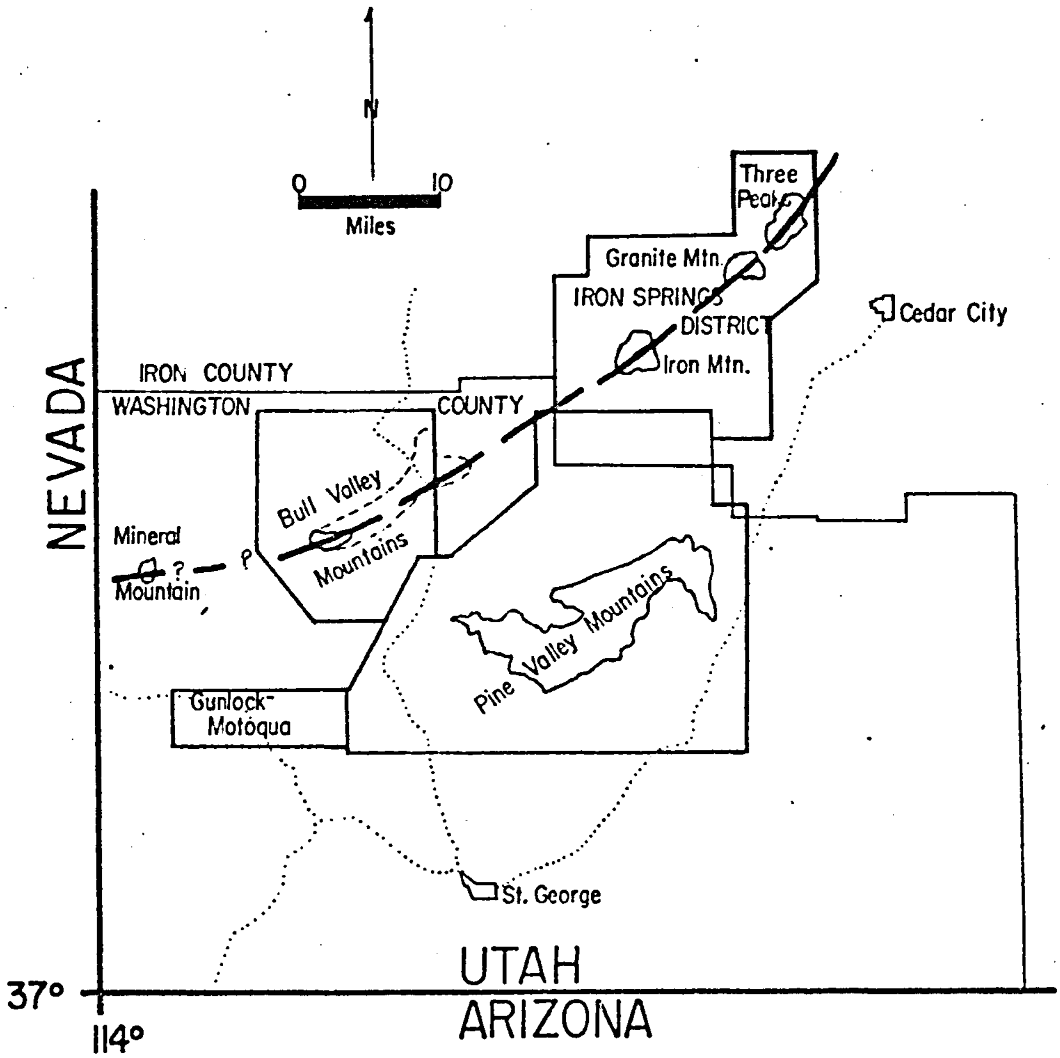


Figure 3. Areas mapped in southwestern Utah

The general trend of the Iron Springs Gap structure is shown by the heavy dashed line.

in the Bull Valley Mountains and the Iron Springs district have been emplaced as concordant to semiconcordant cupolas derived from a deep-seated parent magma chamber. The cupolas, which strongly resemble laccolithic intrusions, have been localized along the axial portion of a Laramide overthrust anticline (Blank, 1959; Mackin, 1960). This Laramide anticline was first recognized by Mackin in the Iron Springs region and was so named the Iron Springs Gap structure. The Iron Springs Gap structure extends southwesterly from Iron Springs through the Bull Valley Mountains and very likely into the Mineral Mountain area (Fig. 3). The Pine Valley Mountains intrusion, which is not localized along the Iron Springs Gap structure, is a deroofed laccolith whose hypabyssal depth of emplacement typifies the intrusive bodies in Washington County. A brief sketch of the Bull Valley, Pine Valley, and Iron Springs areas follows.

Bull Valley Mountains

The Bull Valley Mountains, located in western Washington County, Utah, consist of silicic welded tuff units and hypabyssal quartz monzonite porphyry intrusions. Aeromagnetic and diamond drill data largely substantiate that the region is wholly underlain by a northeast-trending igneous mass, localized along the Iron Springs Gap structure (Blank, 1959; Cook, 1960). Exposures of quartz monzonite porphyry in the Bull Valley Mountains represent upward bulges or cupolas from the underlying igneous mass.

Mid-Tertiary silicic volcanics form an extensive and integral part of the Bull Valley Mountains. Blank (1959) traced a latite crystal tuff, the Rencher formation, directly into a quartz monzonite porphyry center, thus establishing the consanguinity between intrusive and extrusive rocks. Iron deposits are also found in the area, but they are not of sufficient grade or tonnage to be commercially mined.

Pine Valley Mountains

The Pine Valley Mountains intrusion in Washington County is the largest of several intrusive masses located in the transition zone between the Colorado Plateau and the Basin and Range province. The intrusion is characterized by a distinct concordancy of emplacement and is, in fact, regarded as the world's largest laccolith (Cook, 1960). Structural evidence indicates that the intrusion is Oligocene, magma having spread between the Eocene Claron formation and a thick sequence of mid-Tertiary silicic volcanic rocks.

Late Cretaceous folding in the Pine Valley Mountains resulted in local thrusting with minor eastward displacement (Cook, 1954). No correlation, however, has been made between this gentle thrusting in the Pine Valley Mountains and the similar, though much larger scale, thrusting along the Iron Springs Gap structure. There have been no commercial discoveries of iron ore deposits in this area.

Iron Springs District

Three quartz monzonite porphyry laccoliths are exposed in the Iron Springs district in Iron County. Each laccolith has been concordantly emplaced along the axial portion of the Iron Springs Gap structure, and the intrusive horizon is, without fail, concordant to a basal siltstone member of the Carmel Limestone. Perhaps the single most important characteristic of the Iron Springs district is the commercial production of iron ore since the 1920's. Iron ore bodies occur as replacement deposits of magnetite and hematite in Jurassic Carmel Limestone dipping off the flanks of the intrusions.

K-Ar dates of the laccoliths range from 22 m.y. for the Iron Mountain intrusion to 20.9 m.y. for the Three Peaks and Granite Mountain intrusion (Armstrong, 1970). Plutonism is closely related both spatially and temporally and postdates a good deal of the widespread pyroclastic activity common to southwestern Utah.

Local Geologic Setting

Mineral Mountain may be regarded as the "protagonist" in the geologic history of the mapped area. The intrusion was emplaced into a thick mass of Pennsylvanian Callville Limestone during Eocene(?) time, locally converting the carbonate rock into marble and skarn. The Callville Limestone makes up part of an allochthonous thrust sheet of Late Cretaceous(?)-Eocene age, known as the Castle Cliff thrust. The eastward-advancing Castle Cliff thrust overrode a Laramide erosion surface before it was later intruded by the Mineral Mountain mass. A massive section of limestone dips moderately away from the southern flank of Mineral Mountain (Fig. 4), while lesser isolated outcrops of limestone are inclined in a crudely concentric fashion around its other flanks. A few outcrops of limestone are left as roof pendants resting on the intrusion. The craggy brownish cliffs of the intrusion contrast sharply with the light-colored limestone and rise markedly between two southerly flowing drainages, Slaughter Creek on the west and Butcher Knife Creek on the east. Total relief in this dry, semiarid region exceeds 1,800 feet.

Figure 4. Block of light-colored Callville limestone dipping off the southern flank of Mineral Mountain

The areal extent of limestone exposures is limited by an extensive cover of mid-Tertiary welded tuffs and flows. Prior to erosion, the volcanic rocks must have been draped over much of the mapped area, but today they merely lap onto the flanks of the intrusion. Subsequent normal faulting, presumably in response to Basin and Range tectonism, has modified the topography in the region.

CHAPTER 2

GENERAL GEOLOGY

The principal features at Mineral Mountain are sedimentary, volcanic, and intrusive igneous rocks. The intrusive rock is here designated the Mineral Mountain quartz monzonite porphyry.

Sedimentary Rocks

Callville Limestone

The Callville Limestone was named by Longwell (1921) for thrusted blocks of Pennsylvanian sedimentary rock exposed in the Muddy Mountains of Clark County, Nevada. These Pennsylvanian rocks were originally deposited in the Paleozoic miogeosyncline of the eastern Great Basin region of Nevada and Utah. Segments of Callville Limestone exposed as overthrust blocks at Mineral Mountain were probably derived from the same miogeosynclinal rocks as those overthrust blocks exposed in the Muddy Mountain range. Within the mapped area, the Callville makes up an overthrusted segment of the Castle Cliff thrust sheet. The carbonate rocks making the allochthonous block of the thrust have been domed by the intrusion of the Mineral Mountain mass and have been converted to marble and skarn for approximately 200 feet away from the igneous contact. Exposures of limestone within the field area are lithologically very similar to the Callville section exposed in the Beaver Dam Mountains (Reber, 1951).

Stratigraphy. The rocks of the Callville Formation in the Mineral Mountain area include approximately 800 to 1,000 feet of limestone, dolomites, and quartzites, conformably overlain by 200 to 300 feet of calcareous sandstone. The light-gray to light-tan limestone is typically fine to medium crystalline, containing chert lenses, a few millimeters to several centimeters thick, along bedding planes. Cherty nodules and irregularly shaped cherty "blobs" are scattered through the rock and are not necessarily restricted to bedding planes. Locally, the limestone is well laminated, although massive, dense layers make up a large part of the section. Cliff-forming units of limestone easily measure from 20 to 50 feet in thickness. The upper parts of the carbonate sequence include a succession of fossil-bearing limestone and dolomite units. Brachiopod shells and crinoid stems are mixed with fossil debris and give the dark-gray rock a particularly fetid odor. Chert is also quite abundant within these fossiliferous units, especially along bedding planes.

Massive, fine-grained quartzite layers, about 25 feet thick, are interbedded with the carbonate rocks. The hard, resistant quartzite units commonly serve as ledge formers capping limestone ridges. Carbonaceous debris have formed dark discontinuous bands in the quartzite, principally along bedding surfaces. The banding is a primary depositional feature in the rock, although it does transect bedding planes. Sandwiching of quartzite between limestone layers refelects the contemporaneous deposition of both sand and lime in adjacent subaerial facies. The quartzite may have been originally deposited on the ocean floor as a fine-grained sand bar or shoal, well worked by wave action so that intergranular mude was carried away. Subsequent limestone deposition on top of the sandstone may have occurred in response to regressing or transgressing seas.

Two to three hundred feet of fine- to medium-grained calcareous sandstone make up the uppermost member of the Callville formation in the mapped area. Lithologically, the sandstone is a perfect match for an upper sandstone member of the Callville formation that Reber (1951) measured in the Beaver Dam Mountains. The rock is best exposed in Butcher Knife Canyon where it stratigraphically overlies the limestone section, but a thin sliver of sandstone is also exposed along a fault zone located north of Potters Peak (Fig. 2). Contacts between sandstone and underlying limestone are conformable, as both rocks are interbedded in layers less than 25 feet thick. The sugary textured sandstone is moderately well sorted, friable, and forms massive units. Marvelously tortuous, orange, brown, tan, and purple liesegang bands give the rock a striking appearance. An absence of fossils and the buff colors suggest that it was a product of a continental rather than marine environment.

In Butcher Knife Canyon, a sandy cobble conglomerate caps almost every ridge in the sandstone section and also commonly crops out along many of the slopes. The sedimentary conglomerate was probably deposited during Paleozoic time in the eastern Great Basin, as a miosynclinal rock, prior to the advent of the Castle Cliff thrust. The underlying quartzite rock interbedded within the carbonate section of the Callville Limestone may have served as the source for the sandy conglomerate. Reber (1951) made no mention of a similar sandy conglomerate in the Callville section exposed in the Beaver Dam Mountains. Erosion has truncated the upper Callville sandstone member down to the level of this conspicuous conglomeratic unit. Over 50 percent by volume of the cobbles in the conglomerate consist of unsilicified sandstone resting in a friable sandy matrix. Silicified cobbles and matrix do make up a substantial volume percentage of the conglomerate, giving it a resistant character. Most cobbles tend to be subrounded to rounded, attaining ellipsoidal or even equidimensional shapes. Sandy cobbles, similar to those exposed in the conglomerate occur along fault zones in Butcher Knife Canyon. However, fragments in the fault zones are generally subangular, and those that are rounded are commonly silicified. Extensive silicification along the fault zones has also preserved many well-developed slickensides.

The preservation of the conglomeratic sands may well be a function of the degree of silicification the rocks have undergone. The effects of silicification are obvious, but the source of the silica is not apparent. Silicification of matrix and cobbles along the fault planes was probably a result of fluids liberated during the emplacement of the Mineral Mountain mass. With the necessary fracturing, hydrothermal silicification of the sedimentary conglomerate could have also occurred on an extensive scale. However, silicified cobbles in the conglomerate are in contact with sandy cobbles, and both rest in a sandy matrix. Such spatial relationships suggest a delicate control over silicification processes rather than wholesale hydrothermal introduction of fluids along throughgoing fractures. Therefore, mobilization of silica from the heat, pressure, and water generated by the intrusion would seem to be more of an effective way to silicify only a portion of the sandstone cobbles. The sandstone itself would certainly supply a ready source of silica which could be mobilized. Sandstone with the best porosity would more easily and efficiently accommodate an introduction of silica. Calcite between quartz grains would be driven away and replaced by the silica. It is quite apparent from field observation that a later stage of fracturing developed throughout the sandstone section. These younger fractures are linearly continuous and transect both friable and silicified cobbles and matrix. Clearly this stage of fracturing postdates silicification but may coincide with fracturing developed within the younger volcanic rocks.

Age Relationship. The blocks of limestone exposed at Mineral Mountain have been referred to as Pennsylvanian Callville(?) (Cook, 1960). In an effort to determine the age of the carbonate section more precisely, various fossils were collected but no positive identification could be made. However, following a suggestion by D. Schumacher (oral commun., 1973), samples of the limestone were dissolved in acetic acid in order to free possibly diagnostic conodont microfossils. The procedure involved dissolving the limestone in an approximate 15 percent acetic acid solution, separating and collecting the remaining residue, and examining it under low magnification with the binocular microscope.

The microscopic inspection revealed skeletal fragments of the conodont genus Adetognathus, which is widely recognized in Pennsylvanian rocks but has also been identified in Lower Permian Wolfcampian rocks. However, the absence of additional Permian conodonts and the fact that the stratigraphically closest Permian carbonate sequence in southwestern Utah is the Upper Permian Kaibab Limestone strongly suggest that the conodonts were indeed indigenous to a Pennsylvanian formation, the Callville Limestone.

Claron Formation

The Claron formation in the Bull Valley and Pine Valley Mountains and the Iron Springs district is divisible into three members: a basal conglomerate, a middle red siltstone, and an upper gray limestone interbedded with the Needles tuff pyroclastics (Blank, 1959). Mackin (1960) ascribed a lacustrine or fluvial origin to Claron sediments at Iron Springs. Exposures of the Claron in the Colorado Plateau region are also believed to have been deposited in a fresh-water environment. Claron conglomerate in western Washington County, however, is recognized as an erosional product of the Paleozoic limestone and sandstone units making up the Castle Cliff thrust. Consequently, thrust-derived sedimentary rocks of the Claron formation lie stratigraphically above the Callville Limestone. Neither the middle siltstone nor the upper limestone members of the Claron formation are present above the basal conglomerate in the mapped area.

Stratigraphy. The Claron formation, although well exposed throughout southwestern Utah, is limited in outcrop extent in the study area. In Butcher Knife Canyon, the poorly sorted fine to coarse pebble conglomerate was derived from the overriding block of the Castle Cliff thrust and unconformably rests along the toe of the once eastward-advancing Callville block. The conglomerate consists of a subangular jumble of quartzite and limestone pebbles set in a predominantly calcareous matrix. The rock varies in color from light tan to orange brown and is transected by 0.5 to 2 mm calcite veinlets. Limestone fragments within the conglomerate range from a few millimeters to a meter wide. Erosion of the upper sandstone member of the Callville formation has contributed sandstone and quartzite pebbles to the Claron. More extensive erosion has cut into the thick carbonate section below the sandstone, thereby supplying a source for the limestone and chert pebbles. The best evidence that the conglomerate is thrust derived rather than thrust overridden is shown by the character and relative position of the rock units as seen in Butcher Knife Canyon. Surficial deposits of rock, if thrust overridden, should be brecciated and striated. The conglomerate is exposed in front of (east of) the thrust sheet, it overlies the upper sandstone member of the Callville formation, and the pebbles are not unduly brecciated; this evidence indicates that the sediments in this conglomerate was thrust derived.

Position in Time. The age of the Claron formation in southwestern Utah remains enigmatic, although it is considered by Mackin (1960) as a stratigraphic equivalent to the Wasatch or "Pink Cliffs Wasatch" formation of the Colorado Plateau. He has also dated the sedimentary rocks of the Wasatch Formation in the Colorado Plateau as Eocene on the basis of fresh-water shell material. The basal or red Claron exposed at Iron Springs cuts structures made up of Cretaceous and Jurassic sedimentary rocks and is clearly a post-Laramide depositional product (Mackin, 1960). The Needles tuff, interbedded within the upper Claron limestone member, is equivalent to a 34 m.y. pyroclastic formation in central Nevada (Cook, 1960). Consequently, Claron deposition may span a long period of time, ranging from earliest Eocene to middle Oligocene.

The age of the Claron formation would, of course, serve to date the time of eastward advance of the Castle Cliff thrust. At Square Top Mountain, 7 miles southeast of the study area, the thrust sheet has overridden sandstone which is equivalent to the Upper Cretaceous Kaiparowits Formation (Cook, 1960). Basal Claron beds derived from the Square Top Mountain portion of the thrust rest on Kaiparowits Formation equivalents with little disconformity. Eastward, fresh-water Claron conglomerate rests on a Jurassic erosion surface, indicating that over 5,000 feet of rock had been removed prior to Claron deposition. If thrust-derived and fresh-water Claron are considered stratigraphic equivalents, then Claron deposition must have been quite variable, spanning a large amount of time. Mackin (1960) was careful to point out that the eastern Great Basin was a single fluvial and lacustrine plain during Claron time. If "Claron time," as interpreted by Mackin, is post-Castle Cliff thrusting, then remnants of the thrust served as probable sources from which sediments were shed easterly into the depositional basin. Under such circumstances, segments of thrusted Callville Limestone extended farther east into Utah than the exposures in western Washington County and were destroyed as they contributed to the Claron formation conglomerate. Those segments of the thrust that were not destroyed have been concealed by a cover of younger silicic volcanic rocks.

Intrusive Igneous Rocks

The only intrusive rock exposed in the study area is the Mineral Mountain quartz monzonite porphyry. This rock is leucocratic, containing virtually no mafic minerals. Pyroxenes and amphiboles are extremely rare, and biotite and magnetite make up less than 3 percent by volume of the rock. In hand specimen, the Mineral Mountain quartz monzonite porphyry varies from light gray to light tan. Quartz, feldspar, and shreddy biotite grains are set in a gray to tan aphanitic (0.05 mm) groundmass, composed primarily of interlocking grains of K-feldspar and K-feldspathized plagioclase (65%) and quartz (30%). Average composition of the quartz monzonite porphyry is

Groundmass		60.0%
Phenocrysts		39.5%
Plagioclase	25.0%	
Quartz	12.0%	
Biotite	2.5%	
Magnetite		0.5%

The most striking textural feature of the rock is the elliptical to ovoid quartz phenocrysts that range from less than 1 to 12 mm in diameter. The quartz grains stand out as "eyes" and give the rock its porphyritic texture. Each quartz grain is fractured and has poikilitic inclusions of magnetite, biotite, iron oxides, feldspar, pyroxene(?), and commonly accessory minerals along the fractures (Fig. 5). These impurities cause a darkening of the typical clear, glassy appearance of the quartz. Normally, a sufficient amount of magnetite and iron oxide is present to give each phenocryst an orange or gray color. Most grains exhibit unit extinction; therefore, each quartz phenocrysts is an individual grain and not an aggregate of segmented quartz grains. All quartz "eyes" examined in thin section have been resorbed from bipyramidal to elliptical

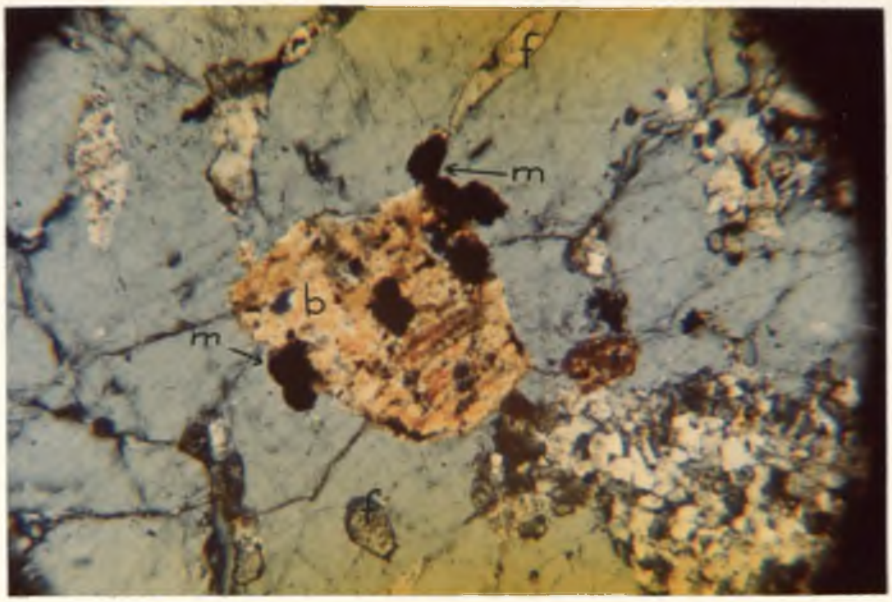


Figure 5. Photomicrograph of a quartz phenocryst from Mineral Mountain quartz monzonite porphyry

Note poikilitic inclusions of magnetite (m), biotite (b), and feldspar (f). Groundmass material has resorbed the quartz grain along fractures. Crossed nicols, X10.

shapes. Fracturing of each grain was probably due to a sudden chilling of the magma; magmatic crystallization was not completed because fractures do not extend into the groundmass. Proof of disequilibrium between groundmass and crystals exists where groundmass material has eaten into the margins and fractures of the grains (Fig. 5).

Feldspar phenocrysts, including both plagioclase (An_{18}-An_{35}) and potassic feldspars, are typically blocky or lath shaped. The phenocrysts vary in color from creamy white to light tan and average 2-3 mm in length but may reach 5 mm. In hand specimen, the phenocrysts appear both as closely spaced clusters of grains and as single grains set in the groundmass. Many grains are fresh, having withstood the effects of alteration, and their well-developed crystal faces brilliantly reflect light. Blocky-shaped voids and cavities indicate the former presence of feldspar grains which were probably altered to clay minerals.

Biotite, pyroxenes, and other mafic minerals, with the exception of magnetite, are rarely observed in hand specimen samples collected from the interior zone of the intrusion. Thin section examination reveals that biotite is disseminated as ragged flecks and stringers within the groundmass of the rock. Biotite fragments average 0.5-1.0 mm in longest dimension and make up only 1 to 2 percent by volume of the rock. The wispy, fine-grained nature of the biotite is suggestive of formation by secondary or hydrothermal processes. However, the biotite does not occur within the other crystals, as it would if it were replacing them. Instead, the biotite grains have their own crystal boundaries and are located between other mineral grains. Furthermore, the hydrothermal breakdown of feldspar should form sericite prior to the formation of alteration biotite. For example, alteration of K-feldspar follows the hydrolysis reaction (Hemley and Jones, 1964):

$$3KAlSi_3O_8 + 2H^+ = KAl_3Si_3O_{10}(OH)_2 + 6SiO_2 + 2K^+.$$

K-feldspar sericite quartz

Because sericite is essentially absent from the interior zones of the intrusion, it seems unlikely that the biotite formed as an alteration mineral. The low percentage of mafic minerals implies that alteration did not involve addition of ferric minerals.

K-feldspar is the dominant alteration mineral formed in the quartz monzonite porphyry. The observed limits of this alteration vary from veinlet-controlled to pervasive modification of plagioclase. Quartz is not affected by the K-feldspathization. Plagioclase feldspar grains within the interior zones of the intrusion have been k-feldspathized primarily along fractures. Figure 6 is an excellent example of veinlet-controlled K-feldspathization destroying the twin planes of a well-formed plagioclase grain. Figure 7 shows K-feldspathization of albite grains, also along fractures. Fractures transecting the feldspar grains usually do not continue into adjacent groundmass material. The groundmass itself consists of over 50 percent by volume K-feldspar, but no distinction can be made between primary (magmatic) and secondary K-feldspar.

Extrusive Igneous Rocks

A thick succession of post-intrusive silicic pyroclastic rocks is exposed around the flanks of Mineral Mountain. The volcanic rocks, which probably once draped over the intrusion, were deposited from high-temperature, gas-charged nuées ardentes. Similar deposits have been

Figure 6. Photomicrograph of veinlet-controlled K-feldspathic alteration destroying twin planes of a plagioclase phenocryst

Crossed nicols, X10.

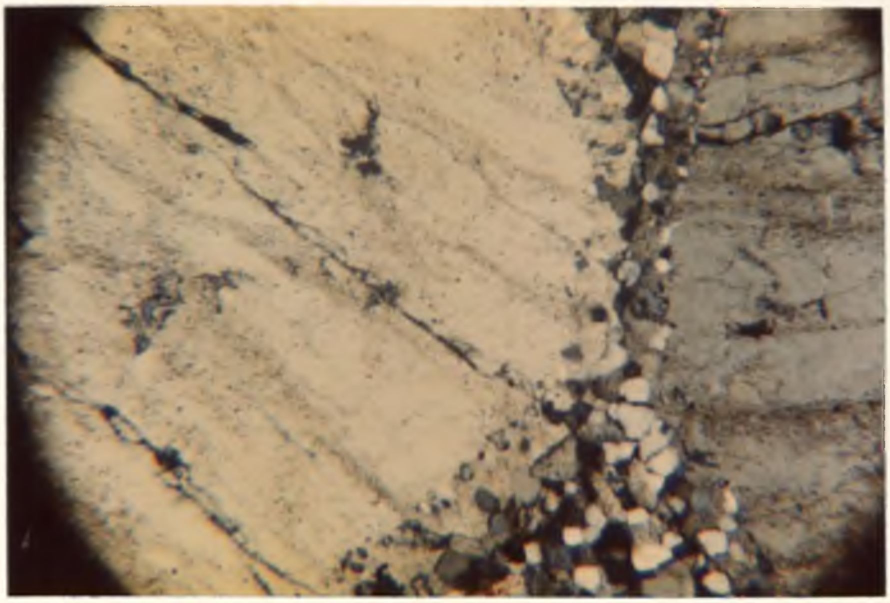


Figure 7. Photomicrograph of veinlet-controlled K-feldspathic alteration in albite phenocrysts

Crossed nicols, X10.

described in the Bull Valley and Pine Valley Mountains (Blank, 1959; Cook, 1954). Nuée ardente eruptions give rise to thick deposits of material variously termed ignimbrites, welded tuffs, or ash flows, which exhibit the characteristics of both lava flows and material ejected into the air. The nature of nuée ardente eruptions is discussed at length by MacDonald (1972). A comprehensive description of ignimbritic rocks in the Bull Valley and Pine Valley Mountains is given by Blank (1959) and Cook (1954), respectively.

The extrusive rocks exposed at Mineral Mountain include a thick succession of ignimbrites and flows. In Butcher Knife Canyon, approximately 4,000 feet of ridge- and slope-forming pyroclastics strike to the northwest and dip generally 20°-30° NE. The northwest strike of the volcanics is so marked that this trend clearly dominates the structural grain in the area around Mineral Mountain. There is no recognized source of pyroclastic eruption at Mineral Mountain, but the considerable thickness of exposed cover implies derivation from nearby fissures or vents. Potters Peak may represent a vent phase upwelling along a fissure, as it is intersected by a strong N. 50° W.-trending lineament. The symmetrical shape of Potters Peak and the presence in thin section of 20-25 percent by volume lithic fragments (commonly porphyritic) also strongly suggest a source of upwelling magma. If so, Quichapa formation pyroclastics were derived from the Potters Peak "vent." The oldest volcanic unit in the study area, the Isom formation, is the equivalent of a 25 m.y. tuff located south of Iron Springs (Armstrong, 1970).

Formation names at Mineral Mountain are taken from correlative units exposed in the Bull Valley Mountains. The distinction between separate units is based largely on petrographic and compositional differences between rock types. In the following discussion of the volcanic stratigraphy at Mineral Mountain, pyroclastic units are listed chronologically.

Isom Formation

Vesicular Flow. Overlying the Claron conglomerate and Callville Limestone in Butcher Knife Canyon is a bluish-gray to purple volcanic unit approximately 300-400 feet thick. On the basis of physical and petrographic characteristics, this rock is correlative with the vesicular flow member of the Isom formation exposed in the Bull Valley Mountains. Blank (1959) recognized two additional members of the Isom formation overlying the vesicular flow in Bull Valley, both of which are missing in Butcher Knife Canyon. The rock breaks into angular platy chips and was therefore given the field designation "slate flow." Elongate vesicles, filled with silica, are aligned northwesterly in the flow direction. Phenocrysts are rare, predominantly consisting of plagioclase (An_{33}-An_{35}). The cryptocrystalline to glassy groundmass makes up 90 to 95 percent of the rock. Minute grains of secondary chlorite make up 30-40 percent of the groundmass. The rock is pervasively stained with hydrous iron oxides and contains tiny specks of magnetite. Blank classified the vesicular flow in Bull Valley as andesite, an appropriate designation for the similar rock at Mineral Mountain.

Hole-in-the-Wall Tuff. A salmon-colored rock exposed west of Potters Peak is correlative with the Hole-in-the-Wall member of the Isom formation in Bull Valley. Because only a very small portion of the

Hole-in-the-Wall tuff was mapped in the southwest corner of the study area (Fig. 2, in pocket), its thickness at Mineral Mountain is unknown. The Hole-in-the-Wall tuff underlies Quichapa ignimbrites west of Potters Peak but is not exposed in Butcher Knife Canyon. Phenocrysts are very rare, constituting less than 5 percent of the rock. Elongate vesicles, aligned along the flow direction, and thin veinlets are filled with secondary silica. The rock is a lithic crystal vitric tuff.

Quichapa Formation

The Quichapa formation is a widespread series of ignimbrites and flows recognized throughout southwestern Utah (Blank, 1959). The formation consists of four members in the Bull Valley Mountains, two of which are exposed at Mineral Mountain. These two lower members, the Leach Canyon tuff and the overlying Bauers tuff, crop out over a large part of the southern and eastern halves of the study area. Potters Peak may represent a source vent from which Quichapa volcanics were derived. Total exposed thickness of Quichapa volcanics at Mineral Mountain is approximately 1,700 feet. Leach Canyon pyroclastics in Butcher Knife Canyon overlie both the vesicular flow member of the Isom formation and the upper sandstone member of Callville limestone. West of Potters Peak, Leach Canyon volcanics overlie the Hole-in-the-Wall tuff. Although it is possible to distinguish the Leach Canyon from the Bauers tuff, both units are treated as one unit on the geologic map (Fig. 2). A third member of the Quichapa formation, the Little Creek breccia, possibly overlies Bauers pyroclastics between Slaughter Creek and Mineral Mountain. The rock compositionally and texturally differs from the Bauers tuff, but positive correlation was not made with Little Creek equivalents exposed at Bull Valley.

Leach Canyon and Bauers Tuffs. The Leach Canyon tuff in the Mineral Mountain area is a purple to red rock, given the field designation "purple porphyry." The rock is a poorly to moderately welded quartz latite lithic vitric crystal tuff. Dark-red lithic inclusions, commonly porphyritic and averaging 1 to 5 mm in diameter, are a common characteristic. The purple porphyry grades into a texturally similar rock of lighter color, given the field designation "white porphyry." White porphyry, also a quartz latite lithic vitric crystal tuff, seems to represent a bleached phase of the purple porphyry. The most convincing evidence that white porphyry is indeed bleached purple porphyry can be seen along fractures and joints in the darker rock. Fluids have altered the rock to a flesh or orange-tan color for 1 to 6 inches on either side of the joints. There is no regularity between white and purple porphyry contacts. The rocks may grade into each other or overlie one another, and, in general, their spatial relationships preclude the possibility that they are separate flows.

The white porphyry is generally a slope former in Butcher Knife Canyon, being sandwiched between the more resistant ridges of purple porphyry (Fig. 8). However, white and purple porphyries are not exclusively restricted to slope- or ridge-forming units. Both rocks are well foliated, commonly showing eutaxitic structure.

Bauers tuff can likewise be described in terms of purple or white porphyritic units, but this rock is characterized by bronze- or copper-colored polygonal biotite flakes about 1 mm in diameter. Bauers

Figure 8. Color contrast between ridge-forming "purple porphyry" and slope-forming "white porphyry" units in Butcher Knife Canyon

Photograph taken looking north along Butcher Knife Canyon.

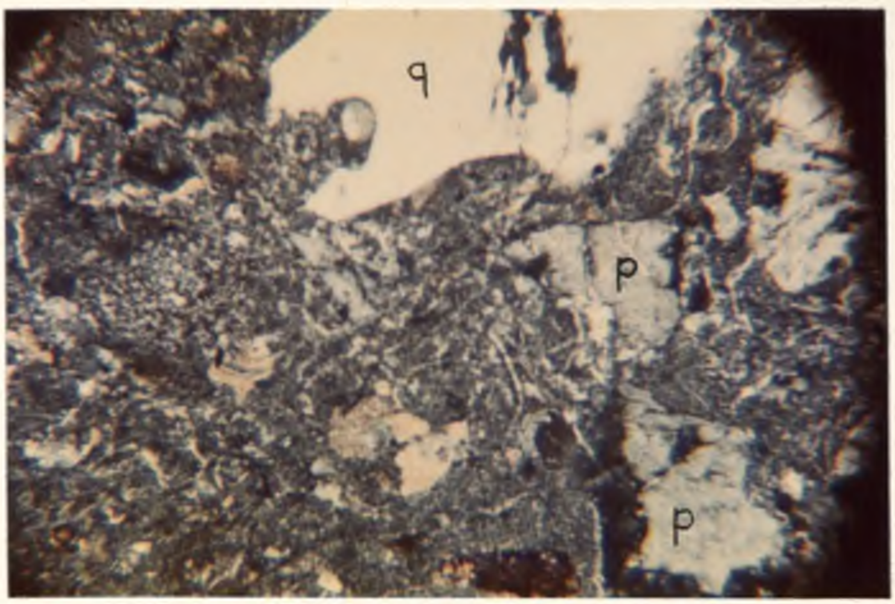


Figure 9. Photomicrograph of strongly resorbed quartz phenocryst (q) and broken plagioclase grains (p) set in a glassy to microcrystalline groundmass

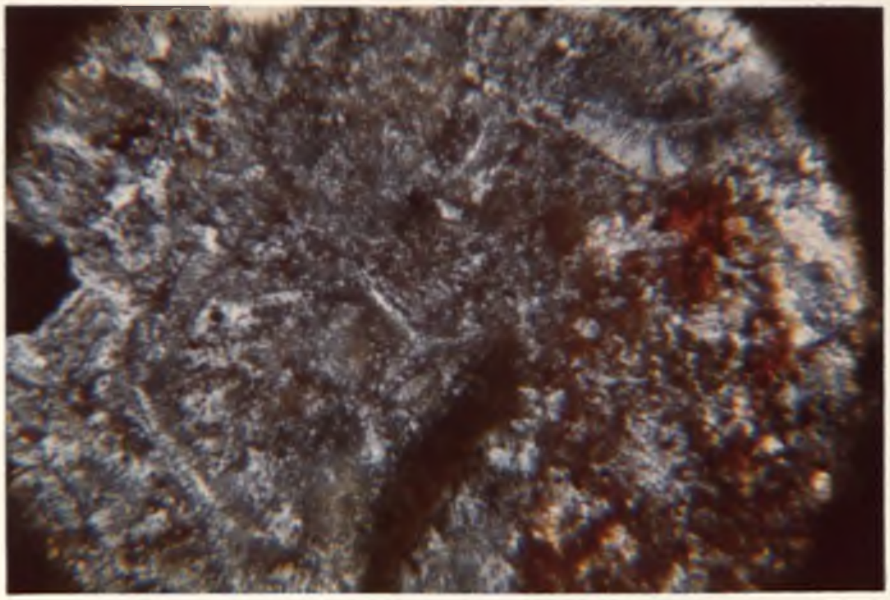
Specimen collected from Quichapa formation in Butcher Knife Canyon. Crossed nicols, X10.

pyroclastics overlie the Leach Canyon tuff, but no distinction was made on the geologic map (Fig. 2). Eutaxitic texture of Bauers tuff is not as well developed at Mineral Mountain as it is in correlative Bull Valley rocks. This may reflect a lateral change in the character of the tuff between the two localities.

In thin section, the Leach Canyon and Bauers tuffs are dominated by crystal fragments set in a matrix with tortuous flow structure. Poor crystal sorting suggests that the rocks were deposited under turbulent conditions. Resorbed quartz phenocrysts and plagioclase grains (An_{24}-An_{34}) make up most of the crystal fragments (Fig. 9). Corroded, shreddy biotite flakes and disseminated magnetite are commonly present. The cryptocrystalline to glassy groundmass makes up 50-70 percent of the rock. Both curviplanar- and tricuspate-shaped glass shards in the matrix have devitrified to chlorite (Fig. 10). In thin section, straight and twisted devitrified shards appear to enclose linearly fibrous material growing normal to the shard boundaries (Fig. 11). This texture is known as axiolitic structure (Ross and Smith, 1961) and is diagnostic of the Quichapa pyroclastics at Mineral Mountain. Most shards are poorly welded (Fig. 10a), indicating that the rock has a good deal of porosity.

A light-colored, crystal-poor tuff exposed in Butcher Knife Canyon (SW1/4 sec. 3) was mapped as an interbed within the Quichapa formation. The rock resembles white porphyry, except that it contains only 10-15 percent phenocrysts, predominantly plagioclase. Flattened and elongate cavities coated with iron oxide or filled with silica are aligned along northwesterly trending foliation planes. Plagioclase grains (An_{32}-An_{37}) are set in a glassy to microcrystalline groundmass that is

A



B

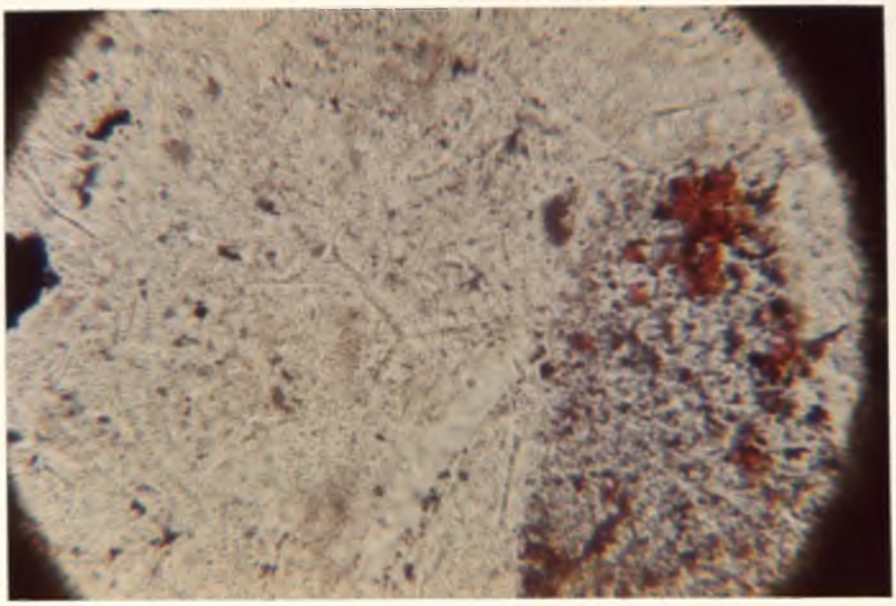


Figure 10. Photomicrographs of tricuspate and curviplanar shards from the Quichapa formation in Butcher Knife Canyon

A. Poor welding of the rock is exhibited by the open structure of the tricuspate shard centered in the figure. Crossed nicols, X45.

B. Glass shards have devitrified to light-green chlorite. Plain light, X45.

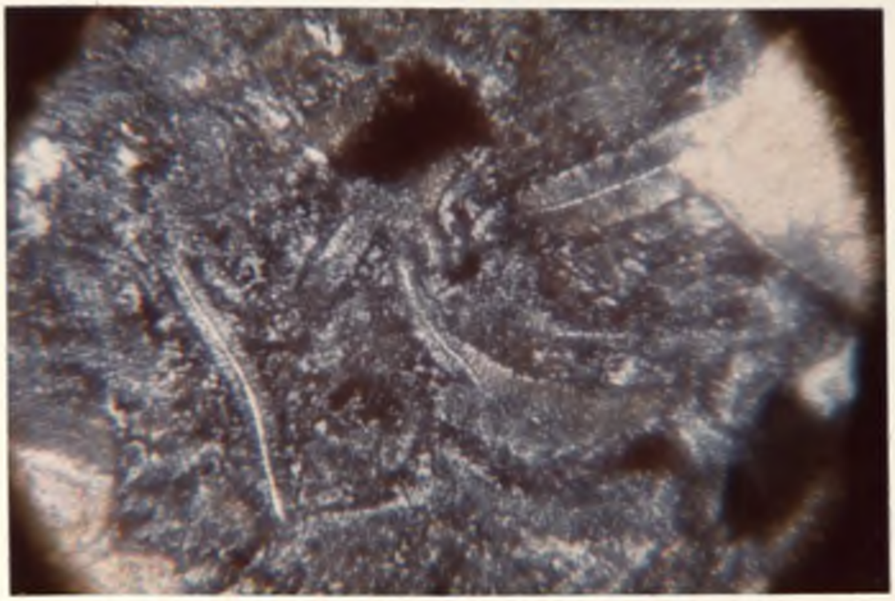


Figure 11. Photomicrograph depicting axiolitic texture of devitrified glass fragments

Parallel intergrowths of chlorite are arranged normal to the outline of each fragment. Crossed nicols, X45.

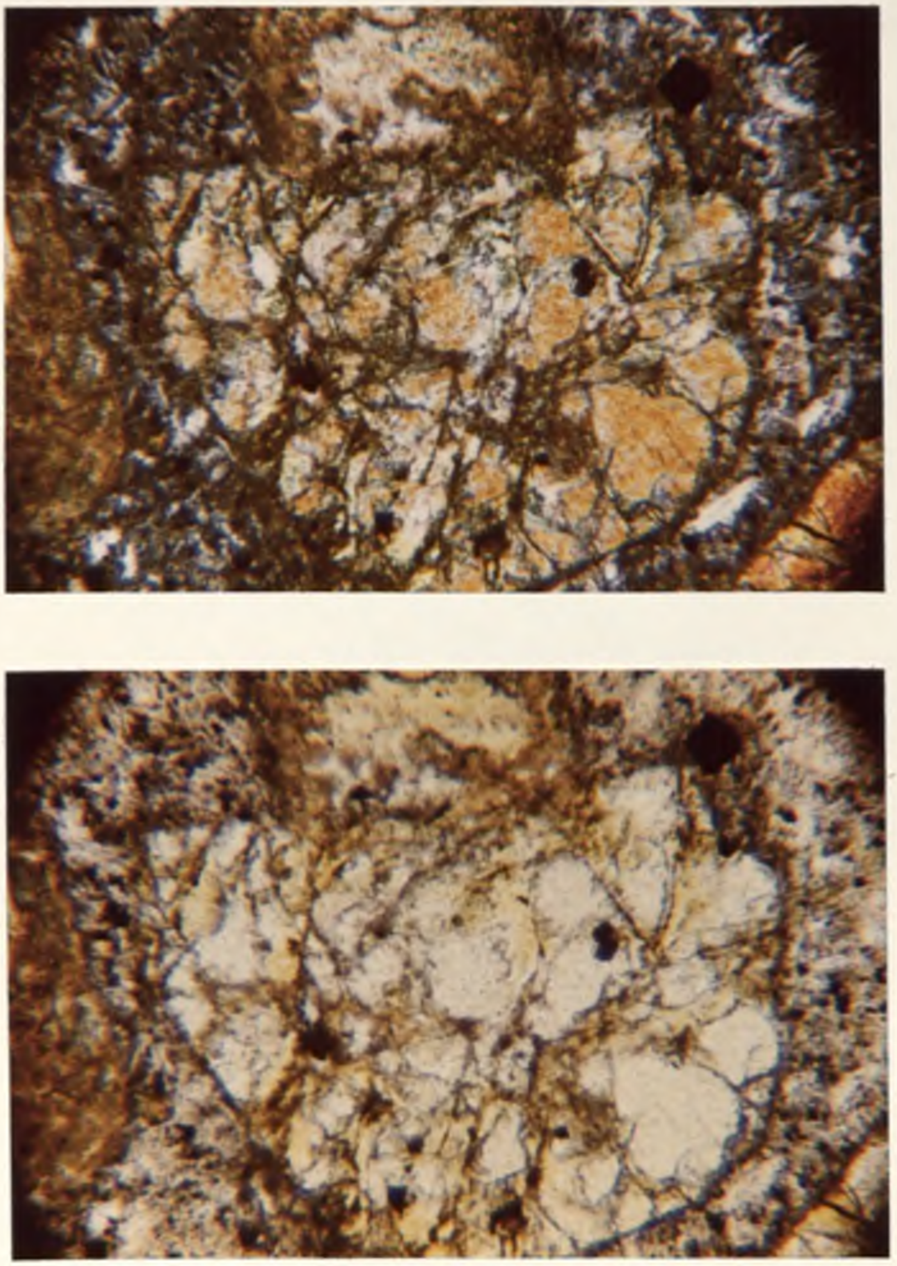
characterized by tiny blebs of iron oxide. Locally, the groundmass is very dense and in hand specimen looks like porcelain.

Little Creek Breccia. A light to dark-green, medium-grained crystal tuff overlies Leach Canyon and Bauers tuffs on the west side of Mineral Mountain. This rock visually resembles the basal Quichapa pyroclastics underlying it, except for the complete absence of quartz.

Plagioclase phenocrysts (An_{27}-An_{40}) make up 25-40 percent of the rock and are blocky to lath-shaped, ranging in size from 4 to less than 0.5 mm. Most of the grains are altered to K-feldspar(?), but many have well-developed, sharp twin planes. Biotite, magnetite, and other unidentified mafic minerals are present, generally in minor amounts. The glassy to microcrystalline groundmass is typical of all the volcanic units in the study area. Secondary chlorite makes up most of the groundmass. On the basis of stratigraphic position and texture, this rock is correlated with the Little Creek breccia member of the Quichapa formation exposed at Bull Valley.

Basalt Member

The youngest volcanic rock exposed in the study area is a very coarse grained olivine basalt. This flow is only locally exposed in the SW1/4 sec. 3, and no estimation of thickness was attempted. The dark-gray to black rock is crystal rich, consisting of grains of plagioclase (An_{34}-An_{51}), olivine, augite, and hypersthene(?). Approximately 1-3 percent pyrite and magnetite are disseminated in the rock. Vesicles are filled with quartz and calcite, with pyrite also preferentially localized in vesicles. The rock is diagnostic in hand specimen, containing twinned feldspar laths averaging 4 to 5 mm in length. Olivine grains, ranging from 0.5 to 8 mm in diameter, are altered to brown iddingsite along their margins and along fractures (Fig. 12). The groundmass constitutes about 50 percent of the rock and consists of glass and secondary chlorite. This unit is probably correlative with the Pilot Creek or Enterprise basalts in Bull Valley. However, neither of the two flows in Bull Valley are comparable in grain size or sulfide content with the pyritiferous, coarse-grained basalt in the study area.



A

B

Figure 12. Photomicrographs of coarse-grained olivine phenocryst with poikilitic inclusions of magnetite (black specks)

A. Crossed nicols, X10.

B. Note olivine grain altered to brown iddingsite along fractures and rim of crystal. Plain light, X10.

CHAPTER 3

STRUCTURAL GEOLOGY

Major orogenic structures in Washington County are products of late Mesozoic and early Tertiary thrust faulting. Pre-mid-Tertiary rocks have, in addition, been dissected by younger normal faulting, presumably in response to Basin-and-Range tectonism. Orogenic activity commenced during Late Cretaceous Laramide time producing two large asymmetric overthrust anticlinal folds. Planation of the Laramide structures was followed by the eastward advance of a younger thrust sheet, active during Eocene(?) time. Both periods of thrusting were followed by extensive plutonism and volcanism, temporally and spatially correlative.

Thrust Faulting in Washington County

Iron Springs Gap and Kanarra-Virgin Anticlines

The earliest recognized orogenic structures in Washington County developed in response to thrusting during Laramide time. Two northeasterly trending structures, one a southwestern extension of the Iron Springs Gap structure and the other the Kanarra-Virgin anticline roughly aligned along Interstate Highway 15 between Cedar City and St. George, developed as large foreland anticlinal folds during Late Cretaceous time. The western limbs of both asymmetric anticlinal structures, acting as competent masses, were thrust southeasterly over the

Cretaceous foreland surface. The Iron Springs Gap anticline trends southwesterly from the Iron Springs area toward Mineral Mountain, but it has been largely obscured by the localization and emplacement of several intrusive bodies and by volcanic cover. This overthrust structure developed along an older zone of demarcation between the Cretaceous foreland to the east and a basin to the west. The large, asymmetric, and locally overturned Kanarra-Virgin anticline made the same southeasterly reverse movement as the Iron Springs Gap anticline. Evidence for large-scale thrusting is presently not apparent on the Kanarra fold because two periods of normal movement have been superimposed along it, reflected in the offset taken up by the Hurrican fault. The present-day Virgin anticline is regarded as a southwestern extension of the now obscured Kanarra fold. Erosional planation of both Laramide structures was followed by the eastward advance of the Eocene(?) Castle Cliff thrust.

Castle Cliff Thrust

The Castle Cliff thrust was originally named and described by Dobbin (1939). Segments of the thrust roughly delineate the eastern boundary of the Basin and Range province in Washington County. The thrust was first recognized in the Beaver Dam Mountains, where Pennsylvanian Callville Limestone has overridden Precambrian and Cambrian rocks. Several segments of the thrust plate possibly crop out along the northwestern margins of the Beaver Dam Mountains where Mississippian Redwall Limestone rests on Precambrian rocks. Farther north, small segments of Callville Limestone derived from the thrust overlie younger rocks. The largest exposure of the thrust plate is located at Square Top Mountain, a klippe of Permian Supai-Coconino sandstones and Callville Limestone. The northernmost recognized exposure of the thrust sheet in Washington County is located at Mineral Mountain, where quartz monzonite porphyry has intruded a thick section of Callville Limestone in the overriding plate of the thrust. The thrust plane dips about 5° W. in the Beaver Dam Mountains and steepens to about 25° W. in exposures farther north. Measurements cannot always be made directly from the poorly exposed thrust plane, but instead must be approximated from bedding above the sole of the thrust.

The base of the thrust is nowhere exposed within the mapped area. Segments of the overriding limestone lie in a crudely concentric manner about Mineral Mountain and are largely obscured by talus from the igneous mass and by pyroclastic cover. Limestone blocks dipping away from the eastern and western flanks of the intrusion offer few exposures for examination. Other contacts of the limestone are either normally faulted (north of Potters Peak) or are unconformably overlain by Claron conglomerate (in Butcher Knife Canyon). Unconformable contacts exposed between limestone and Claron conglomerate do not represent the thrust surface.

An isolated remnant of limestone, exposed on the western bank of Butcher Knife Creek, overlies Claron conglomerate (Fig. 2). The limestone is obscured by volcanic cover to the east, and the contact between conglomerate and limestone is only locally exposed. The limestone may represent the upper member of the Claron formation, but the middle siltstone member is absent if this is true. The limestone may also represent a segment of the Castle Cliff thrust, which has locally overridden the conglomerate. If so, a later (minor ?) period of thrusting postdating Claron conglomerate deposition must be associated with Castle Cliff movement. If the limestone does indeed represent a segment of the Castle Cliff thrust, it may be part of a much larger klippe obscured by volcanic cover. A smaller isolated outcrop of limestone exposed on the west bank of Butcher Knife Creek is probably part of the Callville section. This relationship is diagrammatically shown on cross section A-A' (Fig. 13, in pocket).

Interpretation. Despite its relatively young age, little evidence of the Castle Cliff thrust is preserved in the geologic record. Erosion, volcanic cover, and dislocation by normal faulting have combined to destroy or conceal large portions of the thrust sheet. Attempts made to date accurately the Castle Cliff thrust are clouded with uncertainty. The thrust can be no older than the Laramide structures it truncates nor can it be any younger than the 30 m.y. pyroclastic rocks which drape over it. The basal Claron conglomerate derived from the overthrust block is closely related temporally to the thrust, while limestone members making up the upper Claron formation are interbedded with the 29.7 m.y. Needles tuff member (Armstrong, 1970). In addition, the lower part of the Claron formation is considered a stratigraphic equivalent of the Eocene Wasatch Formation of the Colorado Plateau (Mackin, 1960). These data certainly suggest a period of active thrusting during Eocene time or at least prior to or synchronous with the deposition of the lower member of the Claron. However, if the entire Claron formation was deposited in a period spanning a few million years, the Castle Cliff thrust may have advanced eastward in Oligocene time, possibly between 40 to 30 m.y. ago. The Needles tuff interbedded within the upper Claron limestone member demands that the Claron deposition be sustained through mid-Oligocene time (30 m.y.). Silicic pyroclastics overlying the Claron formation clearly postdate the time of thrusting.

Movement on the thrust resembles eastward overthrusting that occurred along the Iron Springs Gap structure and the Kanarra-Virgin anticline. Dobbin (1939) regarded the overriding block of the thrust as the competent segment of an anticline that was thrust eastward, gliding on basal beds of Callville limestone. The thrust subsequently overrode an erosion surface consisting of both older and younger sediments. Lithostatic pressure during the advance of the thrust consisted only of the weight of the overthrust block itself. These conditions were not conducive to a high degree of heat generation, thus brittle fracture rather than flow characterized the thrust sheet during movement.

Lateral Extent. Prior to concealment by silicic volcanics and dislocation by normal faulting, the Castle Cliff thrust may have been laterally continuous throughout a much greater area than is exposed today. The thrust sheet disappears beneath a cover of volcanic rocks at Mineral Mountain. Only two miles to the south, the Square Top Mountain segment of the thrust is exposed. Lower Quichapa volcanics, particularly the Leach Canyon tuff member, outcrop in the intervening area, very possibly concealing subsurface exposures of the thrust sheet. It is probable that subsurface exposures of the thrust may extend southwestward from Washington County to the Mormon and Muddy ranges of southern Nevada, where Callville limestone is exposed. Basal Claron conglomerate, derived from the overthrust block, generally marks the farthest eastward advance of the thrust into Utah. The thrust sheet would probably be concealed by volcanics at Mineral Mountain too were it not for the seemingly fortuitous emplacement of the intrusion into the thrust sheet.

A complete section of Paleozoic rock, including the Callville Limestone, is exposed along U.S. 91 in southern Washington County (Fig. 1). Sedimentary beds follow a north-northwesterly strike but bend sharply to the west in the region between the Beaver Dam Mountains and the study area. Isolated segments of Callville Limestone, mapped as part of the overthrust sheet, crop out alongside of Callville rocks believed to have been depositionally derived. Obviously overthrust segments of Callville Limestone could be easily confused with depositional Callville if thrust-related features were not preserved. The Callville section exposed at Mineral Mountain might also be regarded as part of the depositionally derived Callville section were it not for the thrust-derived Claron conglomerates exposed in Butcher Knife Canyon. The point behind this discussion is simply that thrusted segments of limestone could easily be misinterpreted for depositionally deposited limestone and vice versa. Thrust-related features, such as the thrust-derived Claron conglomerates, provide the only real clue regarding the origin of the Callville Limestone. The extensive volcanic cover has a great deal to do with complications and possible misinterpretations regarding Callville outcrops.

Post-Laramide Igneous Intrusion at Mineral Mountain

Development of the Mineral Mountain Laccolith

The sequence of events culminating in the emplacement of the Mineral Mountain quartz monzonite intrusion closely parallels the development of other laccolithic bodies in southwestern Utah. Igneous activity commenced with the tapping of the same deep magma chamber that fed the Iron Springs and Bull Valley intrusions and possibly the Pine Valley intrusion. Deep fracturing along preexisting zones of weakness, accompanied by a decrease in pressure, allowed calc-silicate magma to begin an upward ascent into the crust. The magma rose until it encountered the weak Iron Springs Gap structure and was localized along it. The sequence of events is hereafter obscured, as the magma was guided by subsurface structural and stratigraphic relations that can only be inferred. However, igneous emplacement in the Iron Springs and Bull Valley districts can be regarded as a paradigm to the emplacement of the Mineral Mountain laccolith.

Intrusive magma at Iron Springs and Bull Valley has consistently expanded along a thin basal siltstone member of the Jurassic Carmel Formation (Mackin, 1968; Blank, 1959). The upward-bulging laccoliths are always in semiconcordant to concordant contact with this same stratigraphic horizon. The intrusions have a strict proclivity for following the Carmel siltstone member because this horizon served as the sole for the Laramide thrusting (Mackin, 1968). An ascending magma would naturally expand along such a zone where confining pressures are minimized.

Aeromagnetic data suggest that an extension of the Laramide Iron Springs Gap anticline is present beneath Mineral Mountain. This concept will be discussed later. Accordingly, ascending magma, destined to crystallize as the Mineral Mountain mass, bulged upward upon encountering the basal Carmel siltstone present in the core of this overthrust anticline. Overlying sediments were pushed aside as the "mushroom" shaped laccolith began to develop. The involvement of only Callville limestone from the Castle Cliff thrust in the doming process precludes the existence of Mesozoic sedimentary rocks above the basal Carmel siltstone. This means that much of the Mesozoic section, including the upper Carmel limestone, was planed off prior to intrusion, because Mesozoic sedimentary rocks have not been exposed during uplift. Therefore, the basal Carmel siltstone, which accommodated subsurface overthrust movement in Laramide time, was itself subsequently overridden by the Castle Cliff thrust prior to ascent of the magma. The only rock overlying the upwelling magma was the allochthonous block of Paleozoic sedimentary rocks in the thrust. Without the cover of the overlying thrust segment, magma would probably have erupted as a pyroclastic rock rather than crystallizing as a hypabyssal mass.

It is difficult to assign a horizon of intrusion if an extension of the Iron Springs Gap anticline does not exist beneath Mineral Mountain. Cook (1954) concluded that the Pine Valley Mountains laccolith was localized between Claron sedimentary rocks and overlying pyroclastic units. Conduits from the Hurricane fault zone acted as feeders for the magma. However, pyroclastic units postdate intrusive uplift at Mineral Mountain and must be ruled out as an intrusive horizon.

Based on the assumption that the magma was first localized and emplaced along the basal siltstone member of the Carmel formation, the further development of the Mineral Mountain mass may have continued as follows. Upwelling magma began to expand like a fluid wedge upon encountering the Iron Springs Gap structure, forcing apart the basal Carmel and the overlying sedimentary rocks. Suprajacent sedimentary rocks were upflexed and shouldered aside, as in a forceful mode of intrusion. As upwarding bulging progressed, the magma crystallized along the periphery of the intrusion, forming a fine-grained chilled margin. Flowage along the margins of the magma chamber laminated the peripheral rock. With continued upwelling of magma, pieces of the chilled margin were broken from the peripheral shell and incorporated as inclusions in the still viscous magma. Fragments of the peripheral shell were rounded by attrition and by resorption with the magmatic fluid. Fragments of igneous rock derived from the feeder vents below the laccolith were rounded during their ascent to almost perfect spheres, 3 to 4 feet in diameter. The absence of limestone xenoliths in the interior of the intrusive mass may be explained either by (1) the solidification of the peripheral shell prior to intrusion of the carbonate rocks of the Castle Cliff thrust sheet or (2) the complete resorption of limestone fragments by the magma. The magma continued swelling until it finally crystallized in its entirety, attaining dimensions quite similar to those observed today.

From the preceding description, it is obvious that Mineral Mountain can be classified as a forceful intrusion. Its semiconcordant roof (cross section B-B', Figure 13), its attitudes with adjacent sedimentary rocks, and its fine-grained chilled margin are all consistent with forceful injection. A dearth of cross-cutting igneous rock types, coupled with the absence of assimilated and stoped country rock, further attests to a forceful mode of intrusion. While the floor of the intrusion is nowhere exposed in the study area, the mushroom shape of the intrusion is typical of a laccolithic body.

Level of Emplacement. Tertiary intrusions in southwestern Utah are characterized by a hypabyssal depth of emplacement. Several thousand feet of synchronous pyroclastic tuffs and flows bear witness that many of the shallow plutons have breached surface rocks during their emplacement. Mineral Mountain has no recognized extrusive equivalent rocks, but it too has crystallized in a shallow subvolcanic environment. Well-developed zones of endoskarn permit an estimate of the probable level of intrusive emplacement at Mineral Mountain and supply permissive evidence as to how much igneous rock has been removed since the time of intrusion.

Endoskarn alteration is best exposed in the NE1/4 sec. 5 in the northwest part of the study area along the contact between igneous and carbonate rock (Fig. 2). Alteration effects in the igneous rock extend for one to two hundred feet away from the contact. Similar well-developed alteration zones are exposed on the west slope of Mineral Mountain in the NW1/4 sec. 9 and SE1/4 sec. 4 as isolated light-greenish patches of porphyritic rock. The isolated endoskarn outcrops are remnants of a once continuous sheet of igneous rock which covered the roof of the intrusion. If the thickness of this overlying altered igneous rock was roughly equivalent to the thickness of outcropping endoskarn zones, then it would not be unreasonable to assume that one to two hundred feet of altered igneous rock have been removed from the roof of the intrusion. These data strongly suggest that the original dimensions of Mineral Mountain have been only slightly modified by erosion since the time of crystallization. However, it is more difficult to estimate the thickness of Callville Limestone overlying the igneous rock that has been removed by erosion. Judging from the present inclination of the limestone, perhaps 500 feet of carbonate cover would not be an unreasonable estimate. The topographic surface presently exposed was apparently emplaced at a remarkably shallow depth, very likely beneath 1,000 feet of overlying rock.

Associated Faulting. During the intrusive process, lobes of upwelling magma within the pluton rose at different rates. Consequently, the roof of the pluton was stretched and often breached in order to accommodate the swelling magma. When breaching occurred during late-stage crystallization, the magma was viscous enough to preserve the effects of faulting. Evidence for faulting is recognized at Mineral Mountain as north to northwesterly trending structures, commonly confined in areal extent to the igneous rock. The fault zones range from 50 to 100 feet in width and in some places may reach 150 feet. These zones are characterized by extensive silicification, brecciation, and hydrous oxide staining. Attrition of rock fragments in the fault zones has commonly turned angular fragments into rounded cobbles. Extensive silicification has made the fault zones more resistant so that they project as ridges above adjacent rock.

A nearly north-south-trending fault zone locate in the NW1/4 sec. 4 was given the field designation "silicified limestone breccia dike." Rocks along this zone have been extensively silicified so that they project as a "dike" above adjacent rock. This silicified zone transects both limestone and pyroclastic rock and is traceable for approximately 1,500 feet along the western margin of the igneous mass (Fig. 2). Brecciated limestone fragments in the fault zone were derived from the overlying Callville formation. Silicification of the fragments in the fault zone was probably a result of late magmatic processes.

Two northwesterly trending fault zones bounding the east and west sides of the southernmost massive Callvile block (Fig. 2) have apparently formed as a result of the intrusive uplift. The N. 30° W.-trending fault zone located north of Potters Peak transects a thin sliver of the upper sandstone member of the Callville formation. Callville limestone on the eastern upthrown block lies in fault contact with the sandstone units on the western downthrown block. The dip of the fault is steep, averaging 75° E. Younger pyroclastic rock has obscured the southern extension of the fault, thereby substantiating a pre-volcanic period of movement. To the north, the fault simply seems to disappear within the limestone as if it were hinged on its end. However, a marked topographic relief still exists between limestone and pyroclastics where the trace of the fault can no longer be recognized. Most of the tectonically rounded sandstone cobbles in the fault zone have been pervasively silicified. Silica is probably hydrothermally derived but may have been remobilized from the silica available in the thin sliver of outcropping sandstone. Extensive iron oxide staining of the rock along the fault zone also suggests that hydrothermal processes were operative during displacement.

In Butcher Knife Canyon, another generally northwesterly trending intrusive fault has offset the upthrown limestone block on the west from the downthrown sandstone member of the Callville formation on the east (Fig. 2). This fault is steeply dipping, and its northerly extension also seems to disappear within the limestone section. The southerly extension of the fault may bend to the east along a wash, but the offset is difficult to recognize. The tectonically rounded cobbles within the fault zone are silicified, mostly likely in response to hydrothermally derived silica.

The northwest-trending fault forming the northern boundary of the study area is a Basin and Range fault and not an intrusive fault. This structure can be traced on aerial photographs across pyroclastic and intrusive rocks and obviously postdates igneous intrusion and pyroclastic eruption.

Spatial confinement within the igneous mass provides the best evidence that faults are a product of intrusive and not Basin and Range activity. Faults related to the doming process probably developed in the area of greatest curvature (inflection area) along the igneous contact. Extensive silicification along fault zones implies that hydrothermal processes probably were operative during the time of faulting. An ideal time for the silicification process to have occurred would have been during the crystallization of the igneous mass, because fluids could have been readily partitioned from the magma. However, there is no reason to suspect that silica-bearing fluids derived from some unknown source did not follow fractures created during Basin and Range tectonism. Perhaps it is best to conclude that faults which are restricted areally to the igneous mass most likely developed in response to intrusive uplift. Silica introduced along these faults was probably a differentiate from the crystallizing magma. Later Basin and Range faulting, although creating conduits along which fluids passed, was probably not largely responsible for these particular silicification processes.

Space-Time Relationships of Plutonism at Mineral Mountain

Tertiary igneous rocks in Washington County lie roughly within a 10-20 m.y. orogenic zone surrounding a core area in east-central Nevada (Armstrong et al., 1969). The intrusive centers in the Iron Springs district range from 22-20 m.y. in age, slightly younger than the 24-21 m.y. Quichapa volcanics (Armstrong, 1970; Mackin, 1960). Blank (1959) concluded that igneous intrusion in the Bull Valley Mountains followed extravasation of the Quichapa volcanics. Emplacement of the Pine Valley Mountains laccolith also postdates Quichapa volcanics.

The Mineral Mountain intrusion does not temporally fit the 10-20 m.y. age designation of orogenic activity in southwestern Utah. Structural evidence indicates that the Mineral Mountain mass was uplifted after the eastward advance of the Castle Cliff thrust sheet and prior to the onset of silicic volcanism. Uplift may be crudely bracketed between Eocene (40-60 m.y.) movement along the thrust and pyroclastic eruption beginning about 30 m.y. ago. Within these rather broad limits, and without the benefit of an absolute age date, the uplift may assumed to have occurred about 40 m.y. ago. The exact date of intrusion is relatively important, since the assumed date shows that Mineral Mountain is several million years older than its sister intrusions in southwestern Utah.

Gravity slide blocks provide the best evidence that uplift at Mineral Mountain preceded volcanism. Original flat-lying layers of Callville limestone constitute the only rock type that has been effected by the doming process. Blocks of limestone dip away from the crest and flanks of Mineral Mountain and rest in sharp contact against the peripheral shell of the intrusion. If volcanic rocks had been deposited over the Callville Limestone prior to uplift, both rock types would have been affected by the doming process. In the Bull Valley and Iron Springs districts, volcanism preceded intrusion, allowing mid-Tertiary pyroclastic rocks to undergo gravity gliding. Under these circumstances, crescent-shaped wedges of older rock have slid over younger rock, which, in turn, rest on older rocks. In addition, chaotic mixtures of fractured, incompetent rock have accumulated at the base of the slide surface where volcanic and sedimentary rock units converged. The superposition of wedges of older Mesozoic sedimentary rocks resting upon younger pyroclastics at Iron Springs and Bull Valley proves that both rocks were deposited before intrusive doming. No such features are present at Mineral Mountain.

The doming process at Mineral Mountain with subsequent gravity sliding can be outlined as follows. The klippe of Callville Limestone overrode a Laramide erosion surface, creating a topographically high relief feature. The substantial relief difference was further augmented by upwelling magma as the igneous dome started to grow. The overlying limestone sheet was broken and segmented during uplift. Apparently, the klippe did not cover a large areal extent and limestone blocks were not confined along the downdip apron of the intrusion. Therefore, the blocks were free to slide along a glide surface dipping generally 40^{o}-50^{o} off the intrusion; the limestone was not folded because there was no barrier at the base of the upwelling dome. Sliding from the crest and flanks of the intrusion occurred mainly in response to oversteepened slopes. This sliding did not occur on a large scale because roof pendants of limestone remain on the intrusion. There is little evidence to suggest that the sliding was sudden or of great magnitude. Instead, a gradual sliding contemporaneous with doming is suggested. Rocks in contact with the slide surfaces were brecciated, but the effects are minor and generally restricted to a narrow zone along the contact. The overall paucity of folding in the limestones may also be attributed to an insufficient lithostatic pressure during the sliding process. However, two small folds exposed in a prospect pit did develop in response to gliding. The fold axes (b-lineation direction) are oriented parallel to the igneous contact. Ductile behavior of the limestone was probably a consequence of heat liberated from the intrusive body.

The implications of pre-volcanic uplift at Mineral Mountain are more far reaching than merely furnishing a rough estimate for the time of igneous intrusion. The Mineral Mountain intrusion was probably derived from the same deep-seated parent magma as the intrusions at Bull Valley, Iron Springs, and possibly Pine Valley. Intrusion at Mineral Mountain may predate intrusion at Bull Valley and Iron Springs because of an early structural break or weakness along the southwestern part of the Iron Springs Gap structure. Aeromagnetic data indicate that all of these intrusions seem to have developed as cupolas above the underlying magma chamber. Each of the igneous bodies or laccoliths share many basic similarities, including structural, textural, petrologic, and lithologic qualities. In fact, the description of one intrusion may with little modification be applicable to all others with one fundamental but most important difference--content of mineralization. The three laccolithic plugs at Iron Springs (24-20 m.y.) produced viable iron ore bodies. Iron mineralization is also associated with the Bull Valley Mountains intrusion (22 m.y.). Mineral Mountain, presumably localized along the same Laramide structure as these Oligocene iron-bearing intrusions is perhaps twice as old but is devoid of iron mineralization.

The development of the Mineral Mountain intrusion is therefore interpreted as representing an early barren stage of magma crystallization. The earliest upward-bulging cupolas in southwestern Utah were simply formed at a time when the parent magma was iron poor. Given another 20 million years, the magma had sufficient time to partition out an ore-bearing fluid. By then, any upward-bulging cupola was more likely to tap the accessible metal-rich fluid reservoir which had accumulated in the magma. The Iron Springs and Bull Valley laccoliths bear witness to this.

The formation of the Beauty Knoll halloysite deposit within andesitic volcanics indicates that late-stage hydrothermal solutions were also active in the Mineral Mountain area. The Beauty Knoll deposit should not be regarded as having formed from hydrothermal solutions given off by the Mineral Mountain intrusion, as Crawford and Buranek (1948) suggest. Instead Beauty Knoll should be considered a late-Tertiary deposit because its host rocks are surely younger than 25 m.y. However, the hydrothermal source for the halloysite could possibly be a result of regeneration of magmatic fluids derived from an apophysis of Mineral Mountain. Obviously, the source of the fluids is speculative so it is best to conclude that the halloysite formed from post-volcanic fluids derived from an unknown hydrothermal source.

Aeromagnetic Studies

Aeromagnetic maps of southwestern Utah and southeastern Nevada were obtained from U.S. Geological Survey open-file maps released in 1972 and 1973. The magnetic data were compiled from flight paths flown in a north-south direction, spaced one to two miles apart. Much of the magnetic response in western Washington County is probably derived from a thick pile of mid-Tertiary volcanic rocks which typically cause spurious anomalies or obscure important anomalies. However, magnetic highs elongated in a southwesterly manner from Iron Springs to Bull Valley indicate that a largely continuous mass of igneous rock may underlie much of this region. The magnetic highs are conveniently situated along the trend of the Iron Springs Gap structure. Diamond drilling in the Bull Valley Mountains has confirmed that igneous rocks do underlie this area, presumably emplaced along the Iron Springs Gap structure (Cook, 1960). A magnetic anomaly elongated roughly N. 60° E.

over the Mineral Mountain intrusion coincides with a southwesterly extension of the Iron Springs Gap anticline. Magnetic contours taper off appreciably toward the Bull Valley Mountains. The magnetic trough between Mineral Mountain and Bull Valley may indicate a greater depth of burial for the igneous rock mass or even the complete absence of igneous rock in that region.

Magnetic closures occur frequently on the magnetic map of western Washington County. These closures represent three-dimensional anomalies, which ideally should exhibit the same cross-sectional shape for any plane passing through the center of the closure. Consequently, three-dimensional closures are usually characteristic of intrusive bodies with two equal dimensions very much less than the third. Because the intrusions in Washington County probably represent cupolas derived from a deeper igneous mass, the three-dimensional magnetic anomalies can be substantiated.

Aeromagnetic profiles flown on quarter-mile spacings over the Iron Mountain laccolith in the Iron Springs district also describe a three-dimensional anomaly (Blank and Mackin, 1967). Interpretation of the magnetic anomaly over the Three Peaks laccolith at Iron Springs suggests that this body is floored at a shallow level, less than 5,000 feet below the surface (Blank and Mackin, 1967). Mineral Mountain may likewise be floored at a depth not exceeding 5,000 feet, as it is structurally similar to the intrusions at Iron Springs.

Bullock (1970) noted that a magnetometer survey revealed a small anomaly over the Emma prospect on the northern edge of the study area. The response was probably from an iron occurrence in the metamorphosed carbonate rocks with an estimated ore potential of less than 1,000 tons. Because ore at the Emma prospect visually represents the best mineralization around Mineral Mountain, it is unlikely that any stronger magnetic anomaly exists in the area.

CHAPTER 4

ECONOMIC GEOLOGY

Mining activity in the Mineral Mountain area most likely dates back to the 19th century but certainly has not been commercially rewarding. The most important activity in the area was directed toward the recovery of halloysite and alunite at Beauty Knoll, located a mile or more northeast of Mineral Mountain. The deposit was the subject of an investigation conducted by the U.S. Bureau of Mines in a search for refractory minerals during World War II (Crawford and Buranek, 1948). In the early 1960's, alunite was mined by Rocky Mountain Refractories and shipped to their plant in Salt Lake City. Exact figures on the tonnage mined are not known as the refractory material was used for in-house operations (R. V. Wyman, 1974, personal commun.).

Iron mineralization is best exposed in the old Emma prospect located on the north end of Mineral Mountain. Replacement and vein deposits of iron and copper occur in a limestone roof pendant (cross section D-D', Fig. 13), resting on the igneous rock. The Emma prospect was abandoned after a few shallow shafts were sunk and an adit was driven for approximately 150 feet.

Mining activity has been quite prolific along the contact metamorphic zones which developed adjacent to the intrusive mass. Many small prospect pits and adits have been worked, mainly for copper, iron, or gold, with little success. A minor amount of marble has been quarried from contact zones around the base of Mineral Mountain. Some of the marble is brightly colored with orange, red, and purple bands, thereby making the rock more prized for its ornamental value rather than its use as a building stone.

The major deterrant to mining at Mineral Mountain is the extreme inaccessibility of the region. Narrow dirt roads from the north and south provide the only access to the area. Alunite mined from the Beauty Knoll deposit was trucked for a considerable distance over dirt roads that have so deteriorated that they are now almost impassable. The nearest paved road, either U.S. Highway 91 to the south or State Highway 18 to the east, is at least a two-hour travel time from the area. Clearly, a viable mining operation in this region must be of high unit value or of large tonnage or high grade.

Mineralization at Mineral Mountain

Mineralization in the Mineral Mountain area occurs in three forms: as very minor quantities of magnetite within the intrusive rock, as disseminated pyrite in the peripheral shell of the intrusion, and as skarn mineralization in the altered limestone adjacent to the intrusion. Combined magnetite and pyrite do not amount to more than three percent by volume of the constituent minerals in rock from the interior zone of the porphyry. The peripheral shell rock contains the greatest percentage of magnetite (up to 15 percent) of any igneous rock. Skarn alteration in the limestone is weakly developed, but vein and replacement iron and copper ores represent the best mineralization in the study area.

Peripheral Shell Rock

Description. Minor pyrite mineralization is ubiquitously disseminated in the fine-grained peripheral shell rock bounding the Mineral Mountain intrusion. Wherever the thin (4 to 25 feet thick) peripheral zone is in contact with metamorphosed limestone, the igneous rock seems to be speckled with pyrite. Thin section examination of the rock reveals that sodic plagioclase grains (An_{18}-An_{33}) are grouped in radial glomeroporphyritic masses within the rock (Fig. 14). Radial clustering of plagioclase grains may have formed in response to sudden changes in temperature, local or regional stresses, or replacement processes. A sudden chilling of the peripheral shell might have caused plagioclase grains to become radially aligned due to their opposing electrical charges. The plagioclase grains would then be preserved as they are seen today. Another method by which the radial plagioclase textures could have formed is through pseudomorphic replacement. Pyroxene and amphibole minerals forming in metamorphic environments are typically grouped in radial aggregates. Therefore, it may not be unreasonable to assume that the breakdown of these minerals would supply the necessary Ca, Na, and SiO_2 to form plagioclase as an alteration mineral. Glomeroporphyritic texture is also visible both in hand specimen and thin section from inclusions located within the interior zone of the porphyry. Obviously, the inclusions have been derived from the peripheral shell rock. Radial clustering of the plagioclase grains has imparted a crude foliation to many of the inclusions. When the foliation is coupled with the reddish colors of the inclusions, the igneous fragments resemble layered sedimentary rock fragments, which, of course, is not true.

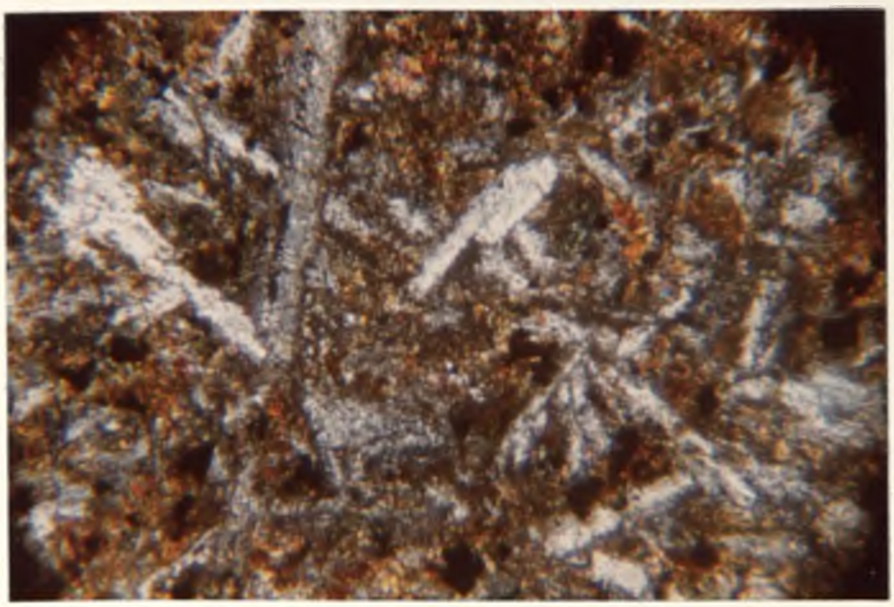


Figure 14. Photomicrograph of radially clustered plagioclase phenocrysts poikilitically intergrown with biotite and magnetite

Crossed nicols, X10.

Rock in the peripheral shell bounding Mineral Mountain is much fresher and certainly contains a greater percentage of mafic minerals, particularly pyroxenes, than rock in the interior of the intrusion. Compositionally, the peripheral shell is essentially devoid of quartz and is classified as a diorite. Compositional differences between diorite in the peripheral shell and quartz monzonite in the interior zones may be a result of contamination of the original magma. However, this means that as the magma ascended through the sedimentary section prior to forceful injection into the Callville Limestone, it was contaminated on its contacts with adjacent country rock but was relatively unaffected in its interior. Blank (1973, personal commun.) regards the fine-grained peripheral shell which formed around the Bull Valley complex as an impermeable membrane through which fluids from the interior of the intrusion could not pass. Quick quenching of the rock without subsequent fracturing prevented iron-bearing solutions from escaping into overlying limestone units. Somewhat similar circumstances occurred during the crystallization of the Mineral Mountain intrusion. The peripheral shell did not fracture after cooling so that magmatic fluids were unable to penetrate and alter the fresh peripheral rock. Biotite and pyroxene minerals were consequently preserved in the peripheral shell.

The peripheral shell around Mineral Mountain is best exposed in a gully and in two adits located in the NW1/4 sec. 9 (Fig. 2). Mineralized calc-silicate breccia fragments, derived from overlying altered limestone layers, are trapped within the peripheral shell. Recrystallized limestone is exposed between and above the peripheral shell, leaving the impression that the peripheral shell rock crops out as a series of northerly trending dikes. Cross section C-C' (Fig. 13) shows that an "igneous dike" is, in reality, the exposed part of an undulating flank of the intrusion.

Figure 15 is a plan view of the underground workings along the contact between the peripheral shell and the altered limestone that clearly illustrates the real economic worth of the poorly mineralized peripheral rocks. Notice that a drift was advanced along the peripheral shell for approximately 80 feet where mining stopped abruptly in favor of advancing the workings toward the west into faulted and fractured limestone and skarn. The prospectors abandoned the idea of chasing the slightly mineralized and most likely unprofitable peripheral shell rock in favor of mining the more profitable skarn mineralization.

Petrography and Alteration. Thin section examination reveals that the peripheral shell rock is strikingly fresh when compared to the rock of the interior zones of the porphyry. Fine-grained pyroxene minerals, including enstatite, are common constituents of the peripheral zones. Biotite is disseminated within the rock, but iron oxides are particularly abundant, over 25 percent by volume of the rock. Magnetite grains (<1 mm) are commonly rimmed by orange and red iron oxides, as are many of the pyroxene and biotite grains. Texturally, the glomeroporphyritic habit of the plagioclase crystals is peculiar to the peripheral shell rock. Radially clustered plagioclase grains are, however, better developed in the inclusions than in the peripheral zones. Curiously, the inclusions contain a great deal more quartz than the peripheral shell from which they were derived. The inclusions are also coarser grained and are classified as a holocrystalline fine-grained (<1 mm) seriated quartz

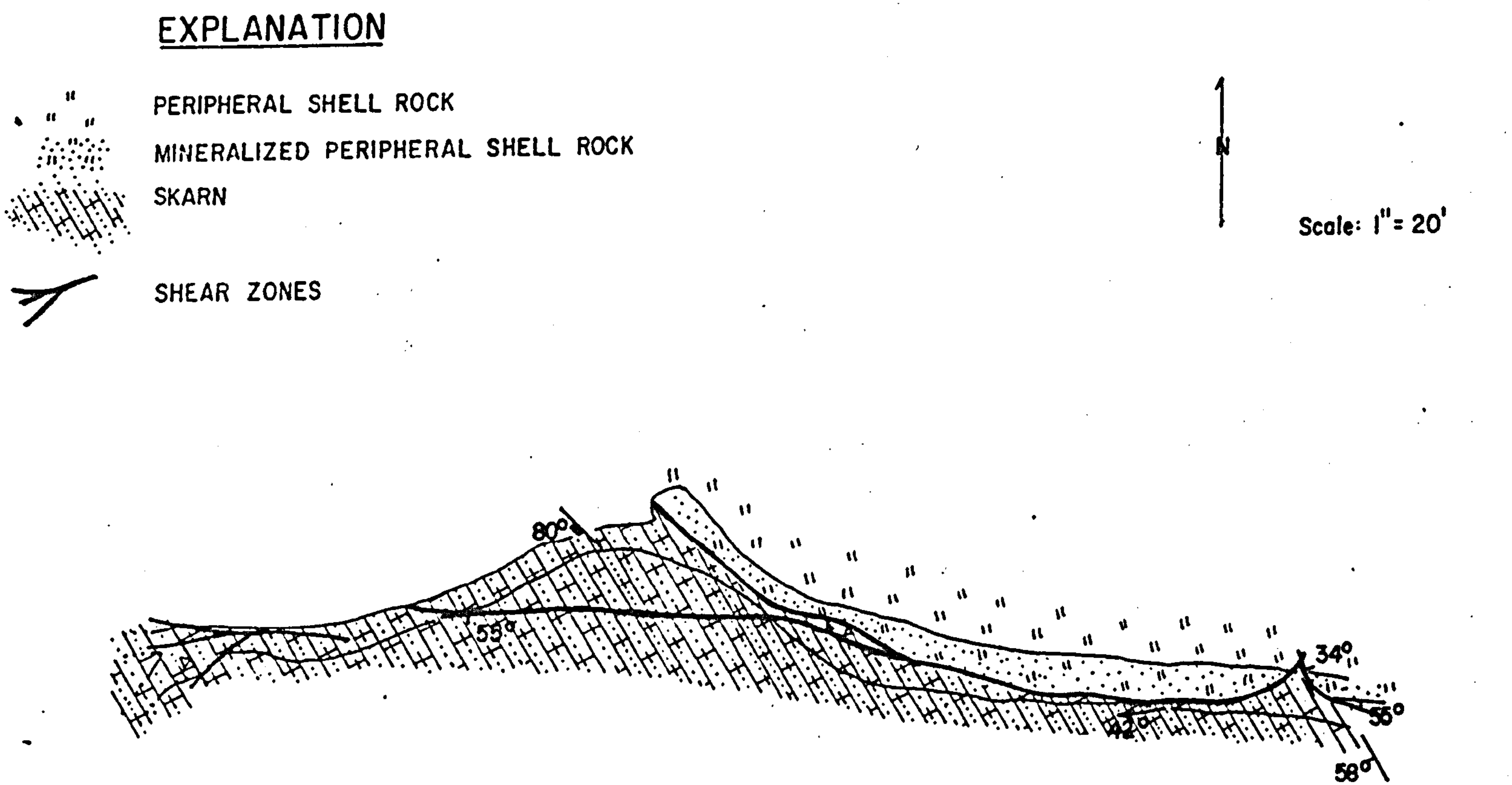


Figure 15. Simplified plan view of underground mine workings, NW1/4 sec. 4

monzonite. The peripheral shell rock is classified as a fine-grained seriate diorite due to the absence of quartz.

Plagioclase grains in the peripheral shell have been pervasively but not extensively K-feldspathized. Those grains that have escaped alteration indicate that the original plagioclase feldspar was sodic, varying between oligoclase and andesine. K-feldspar appears to be dusted over some of the plagioclase grains but does not appear to be veinlet controlled. Calcite, epidote, and chlorite were probably formed because of the ready supply of calcium and magnesium in the adjacent carbonate rocks. Iron oxides, of course, have formed from the breakdown of magnetite, biotite, and iron-bearing pyroxene minerals.

Contact Metamorphosed Rock

Skarn-type alteration effects in the mapped area are clearly a product of metamorphism incurred when the Mineral Mountain mass intruded the overlying Callville Limestone. Skarn zones have developed in the limestone adjacent to the intrusion for a maximum of perhaps 200 feet. In many places, the limestone has not been altered to skarn but has instead been converted into marble and coarsely crystalline limestone. Apparently both the skarn and marble have formed with equal facility from solutions derived from the intrusion. Marble was preferentially formed in those regions where the limestone units were relatively pure with little fossil debris or with a minor MgO content. On the other hand, impure limestone units or dolomitic units were probably more reactive and susceptible to skarn-type alteration.

Endoskarn zones without sulfide or oxide mineralization also developed in response to metamorphism. Mineralogically, epidote makes up more than 50 percent by volume of the endoskarn. Figure 16 shows saussuritized plagioclase grains replaced by tiny grains of epidote. The texture of the endoskarn, including quartz phenocrysts, is masked by the pervasive saussuritization. Alteration of the igneous rocks demonstrates that the quartz monzonite porphyry solidified before the metamorphic processes were completed.

Gangue mineralogy of the contact metamorphic aureole in the skarn zones includes garnet, epidote, fluorite, quartz, chlorite, minor calcic pyroxenes, and calcite. Garnet-bearing skarns are well banded, as is common to these rocks. The garnet crystals observed in thin section are aggregates of very fine grained crystals with poorly developed crystal faces. A few of the garnet grains do exhibit excellent cleavage and sharp zoning. Irregular, poorly developed calcite grain boundaries indicate that the calcite is a late-stage mineral of the skarn assemblage (Fig. 17). Disseminated magnetite grains are present in most skarn zones. Veinlets of magnetite are best developed in samples from the Emma mine and from the skarn zone located in the NE1/4 sec. 5. Geochemical assays indicate that very little tungsten mineralization occurs in the skarn zones, although lamping for scheelite was not done.

Comparison of Mineral Mountain and Iron Springs Intrusions

The geologic setting at Mineral Mountain seems to be quite ideal for the formation of a pyrometasomatic ore body. The middle Tertiary quartz monzonite porphyry intrusion has invaded a thick section of Pennsylvanian carbonates, converting some to marble and some to skarn. A strikingly similar situation exists in the Iron Springs district where

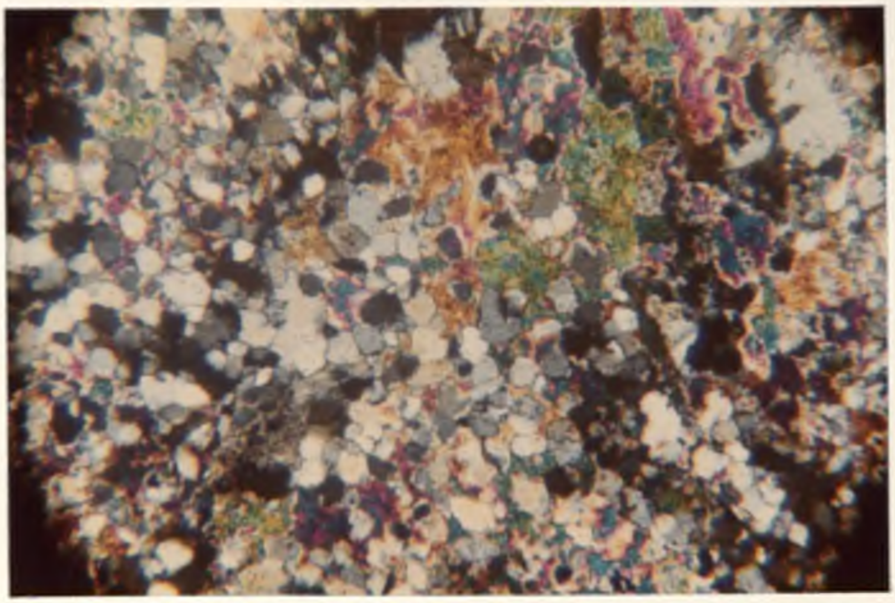


Figure 16. Photomicrograph of typical sample of endoskarn with highly birefringent epidote replacing plagioclase

Crossed nicols, X10.

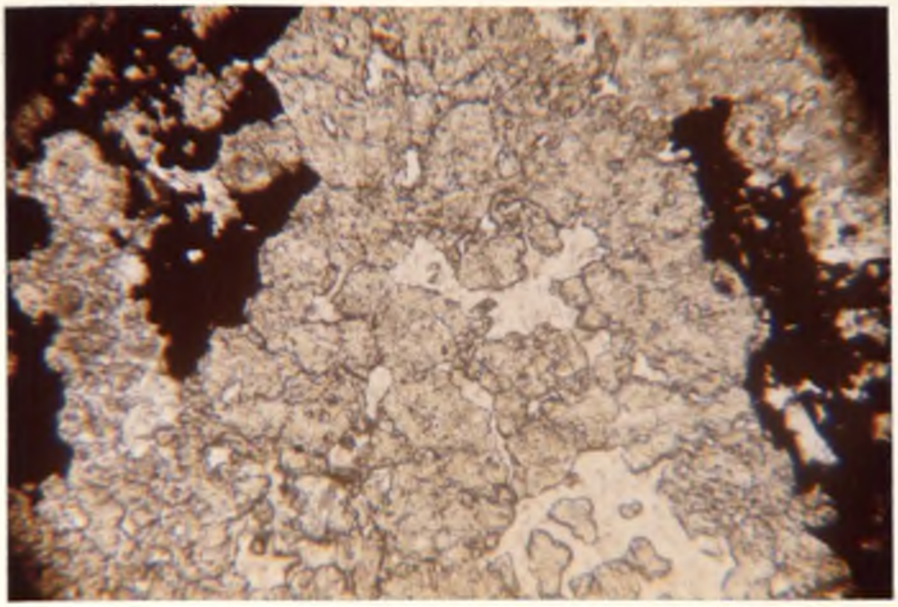


Figure 17. Photomicrograph of typical skarn sample with fine-grained garnet crystals (high relief) and irregular calcite grains (black)

Plain light, X45.

three quartz monzonite porphyry laccoliths have invaded a thick section of Jurassic limestone. Mackin (1968) concluded that iron had been deuterically leached from the Iron Springs laccoliths and deposited into the adjacent limestone. If Mackin's assumptions about the dueteric release hypothesis are correct, the Mineral Mountain certainly suggests that a mafic-poor intrusion is not capable of deuterically releasing iron-bearing fluids. However, the chemical differences between the two limestone units may well be responsible for the development of replacement ore bodies regardless of the composition of the magma.

In addition to the replacement deposits at Iron Springs, iron ore also occurs in selvage zones along fractures and veins in the intrusive rocks themselves. The many similar physical features of the Iron Springs laccoliths and the Mineral Mountain laccolith again invite some explanation for the lack of mineralization in selvages at Mineral Mountain. Mackin (1968) proposed that the iron trapped in the selvages at Iron Springs was originally present in hydroxyl-bearing mafic minerals convecting through the magma. The iron was deuterically released from the mafic minerals and migrated as an ore fluid at a critical late stage of crystallization. The magma at this time was still molten but was rigid enough to hold open a crack. Late distention of the intrusions (laccoliths) allowed the iron-bearing fluids to escape into dilated fracture zones where the iron was trapped as selvages. The rock around each selvage zone is leached and altered, having supplied the iron that had migrated to the dilated fractures.

The selvage zones at Iron Springs have been formed in radial, concentric, and oblique joints which converge below the laccoliths. A limited amount of fracture data collected at Mineral Mountain indicates that radial and concentric joint patterns also exist within this extensively fractured intrusion. However, the joints and fractures at Mineral Mountain obviously have not trapped any iron-bearing fluids.

The mafic minerals from which iron may have been derived are conspicuously absent from the rocks of the interior zone of the Mineral Mountain intrusion. The absence of iron-bearing mafics indicates that these minerals either did not crystallize from the magma or were destroyed during an iron-leaching process. Because selvage zones of iron ore do not occur at Mineral Mountain, any iron leached from preexisting(?) mafic minerals probably escaped through the extensively fractured peripheral shell of the intrusions. Under such circumstances, the supra-jacent Callville Limestone should have been replaced by ore, which of course did not occur. The lack of iron mineralization along joints and fractures or in the overlying limestone, coupled with an absence of mafic minerals in rock from the interior of the intrusion, reinforces the observation that the Mineral Mountain pluton is iron deficient.

CHAPTER 5

GEOCHEMICAL ROCK SURVEY

During the field mapping, 97 geochemical samples were collected from fault zones, contact metamorphic zones, and volcanic rocks. Almost all of the geochemical samples were collected as rock chips and the remainder were soil and dump samples. The geographic location of the samples are shown on Figure 18. The samples were analyzed either by semi-quantitative colorimetric or emission spectrographic techniques. Atomic absorption methods were used for gold analyses. Colorimetrical analyses included determinations for Cu, Mo, Pb, and Zn, as well as determinations for Ag when requested. All samples analyzed by emission spectrography also included determinations for Cu, Mo, Pb, Zn, and Ag as part of a 31-element analysis.

The limited number of geochemical samples did not permit a statistical treatment. The small sample populations are further reduced significantly because three different rock types, skarn, extensively silicified sandstone along fault zones, and silicic pyroclastics, were sampled and each type was treated separately. Furthermore, laboratory analyses involved two analytical methods, emission spectrography and colorimetry. The former extracts more metal from a sample than the latter. Therefore, lithologic and analytic effects would have had to be evaluated before the geochemical data could have been considered suitable for contouring or statistical treatment. Rather it was decided not to

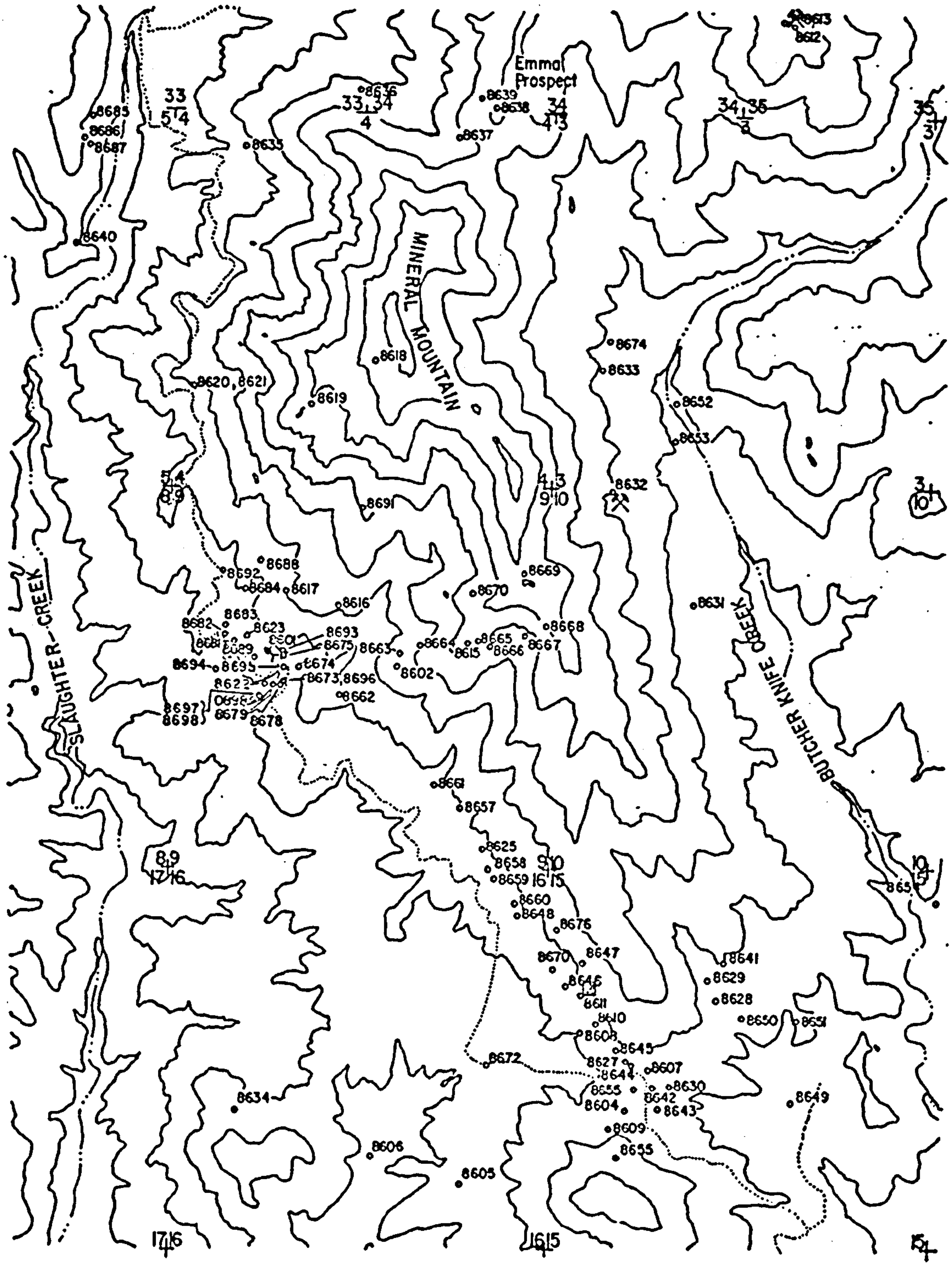


Figure 18. Geographic location of samples collected for geochemical analysis

evaluate all of the geochemical data as a homogeneous sum but to present comparisons of metal enrichment for each rock type sampled. In addition, Cu, Mo, Pb, and Zn are discussed individually. Geochemical values for these elements are given in the appendix.

Geochemical Distribution by Rock Type

Metal enrichment in the following discussion means geochemical values greater than the threshold value as determined for the study area. High and low will be used to mean greater or less than the threshold values given in the discussion of each element.

Limestone samples collected from the contact metamorphic zones with high concentrations of Cu (200-4900 ppm) were generally enriched in Zn (500-3300 ppm). Similarly, skarn samples with high concentrations of Pb (40-175 ppm) were generally enriched in Mo (20-100 ppm). The highest concentrations of Ag (up to 7.6 ppm) occurred in skarn samples with Cu-Zn enrichment. Tungsten analyses, surprisingly, exhibited anomalously low geochemical values in samples collected from skarn zones.

Silicified fault breccia and silicified fault cobbles collected along the fault zones were enriched in Mo (34-440 ppm) without corresponding Pb, Zn, or Cu enrichment. Two silicified fault cobbles collected along the intrusive fault zone north of Potters Peak had high concentrations of Mo and were also enriched in Au (0.17 and 0.85 ppm).

Samples collected from the volcanic rocks exhibit no metal concentrations above threshold values for Cu, Mo, Pb, Zn, Ag, or Au. Most of these samples were collected from iron-stained rock along joints and within fractured areas. Apparently the fracturing had little influence on metal distribution within the rock.

No abnormal concentrations of trace elements were found in any of the rock types sampled. In fact, most of the trace elements probably present have geochemical values below the sensitivity of the analytical method used. One possible exception is tin, with values of 50, 50, and 70 ppm in three skarn samples. No conclusions can be drawn from the limited amount of trace element data.

Copper

The average abundance of copper in limestone is given as 4 ppm by Turekian and Wedepohl (1961) and by Horn and Adams (1966) and as 5 to 20 ppm by Hawkes and Webb (1962). Threshold value for Cu in the Mineral Mountain area is 70-90 ppm. Approximately 25 percent of the skarn samples have Cu concentrations higher than the threshold value. Most of these enriched samples were collected from skarn zones located in the NE1/4 sec. 5. Samples collected from skarn zones near the two adits in the NW1/4 sec. 4 are Cu rich. Fault gouge from the peripheral shell shows a high Cu concentration. Only 10 percent of the geochemical samples collected had values above the threshold value.

Molybdenum

The predicted average abundance of molybdenum in limestone ranges from 0.4 ppm (Turekian and Wedepohl, 1961) to 0.4-1.1 ppm (Horn and Adams, 1966). Hawkes and Webb (1962) give a range of 0.1-0.5 ppm for Mo in limestone. Threshold for molybdenum in the Mineral Mountain district is approximately 20 ppm. Four of the five skarn samples with values greater than threshold were collected from the area near the two adits in the NW1/4 sec. 4. One sample collected from the skarn zone in the NE1/4 sec. 5 contained 100 ppm Mo. Samples collected from the Emma prospect had Mo concentrations well below threshold. Skarn samples with low molybdenum values characteristically exhibit higher Cu-Zn concentrations.

Ten percent of the total number of samples collected have values above an overall threshold value of approximately 26 ppm. Four samples collected from the intrusive fault zone north of Potters Peak have high Mo concentrations. These samples represent about 20 percent of the samples collected along the intrusive fault and this finding should be considered significant.

Lead

The average abundance of lead in limestone is given as 5 to 10 ppm and 9 ppm by Hawkes and Webb (1962) and Turekain and Wedepohl (1961), respectively. Horn and Adams (1966) give an average of 16.5 ppm for lead in limestone. Threshold for lead, regardless of rock type, averages from 25 to 45 ppm in the Mineral Mountain area, but the threshold for Pb in the skarns is slightly lower, between 20 and 40 ppm. Samples with high concentrations of Pb were collected from the skarn zone in the NW1/4 sec. 4. Six of these samples contained 55, 70, 75, 100, 150, and 175 ppm Pb. Samples collected from the intrusive fault zone north of Potters Peak had Pb values above the threshold.

<u>Zinc</u>

The abundance of zinc in limestone is given as 20 ppm by Turekian and Wedepohl (1961), 4-20 ppm by Hawkes and Webb (1962), and 13-50 ppm by Horn and Adams (1966). Because the lower limit of detection for samples analyzed by emission spectrography is 200 ppm, threshold for the study area could not be accurately determined. The threshold value for those samples analyzed by semi-quantitative colorimetric means appears to be about 90 ppm, similar to the threshold for Cu values. This number is also in accordance with the affinity Cu and Zn show for one another in enriched skarn samples. Eight of 11 samples which have zinc concentrations above 500 ppm were collected from the skarn zones.

Threshold values for Cu, Mo, Pb, and Zn, which are above the crustal abundance for each element in limestone, indicate the introduction of metal ions during skarn-forming processes. These results are not in themselves significant. Metal values above threshold in samples collected along the intrusive fault zones, particularly Mo and Au, are significant and warrant further investigation.

CHAPTER 6

GUIDES TO FUTURE EXPLORATION

The weak mineralization in the contact metamorphic aureole around Mineral Mountain will undoubtedly not achieve the status of an ore deposit under existing technology and economics. However, an understanding of the geologic structure and stratigraphy at Mineral Mountain is of definite value to the exploration geologist working in southwestern Utah; it provides important concepts for exploration in similar geologic environments. Much of the geologic history of the eastern Great Basin can be unraveled within a 4-5 square mile area bounding Mineral Mountain. Evidence of post-Laramide thrust faulting, middle Tertiary igneous intrusion, and mid-early Tertiary volcanism are all present within the region.

If future exploration were to be considered in the immediate vicinity of Mineral Mountain, the focus would be on intrusion-related events. Detailed geochemical sampling along the fault zones might reveal metal enrichment related to the igneous mass. Ground magnetic surveys along the contact metamorphic aureole would be useful only where carbonate rocks occur. In areas of volcanic cover, ground magnetics would most likely reflect conditions related to the volcanic rocks rather than magnetite in the skarn zones. The leucocratic nature of the Mineral Mountain porphyry does not favor its being an ore-bearer.

However, apophyses or satellitic intrusions derived from the intrusion may contain sulfide mineralization.

On a regional scale, an examination of the possible southwesterly extension of the Iron Springs Gap structure into Nevada would be important in an exploration program. An aeromagnetic pattern with closures in the area southwest of Mineral Mountain suggest that intrusive bodies may indeed be localized along a zone of structural weakness. An examination of the area between Mineral Mountain and the Bull Valley Mountains along the trend of the Iron Springs Gap structure would also be in order. However, magnetic data indicate that an intrusion located between the two regions would probably be deeply buried. A possibility exists that other segments of the Castle Cliff thrust besides the exposures at Mineral Mountain may be present beneath the cover of volcanic rocks. Igneous intrusion into one segment could well develop into a pyrometasomatic ore body if the intrusion was mafic rich. Locating a concealed segment of the thrust would require detailed geologic mapping; geophysical or geochemical techniques would probably not be effective because of the geologically complex basis for response from the volcanic rocks. Clearly, the volcanic cover is a complicating factor in studying the geological history of southwestern Utah.

CHAPTER 7

CONCLUSION

The important points of the geologic study at Mineral Mountain can be summarized as follows. The thick section of Callville Limestone is recognized as a segment of the Castle Cliff thrust sheet, which advanced eastward into Utah during Eocene(?) time. Claron conglomerates derived from the overthrust block provide the best evidence that the limestone is indeed an allochthonous block. Aeromagnetic data suggest that the Iron Springs Gap structure, a Laramide overthrust anticline, underlies the study area; the Mineral Mountain intrusion was probably localized along this structure. Mineral Mountain was forcefully emplaced into the thrust sheet, converting adjacent limestone into marble and skarn. The forceful intrusion caused blocks of limestone to slide off the growing laccolithic dome. Plutonism was followed by silicic volcanism; Potters Peak may represent a source vent for the pyroclastic rocks deposted around the base of Mineral Mountain. Analyses of selected geochemical rock samples demonstrate a Cu-Zn and a Pb-Mo affinity along skarn zones. Mo-Au enrichment occurs along silicified fault zones. The ore potential of the region seems extremely small, whether replacement ore bodies in the limestone or a porphyry-type deposit within the intrusive mass is considered.

APPENDIX

GEOCHEMICAL DATA

Sample No.	Cu (ppm)	Mo (ppm)	Pb (ppm)	Zn (ppm)	Remarks
8601	200	3	50	500	skarn
8602	50	2	20	200	skarn
8603	7	2	10	200	Quichapa volcanics
8604	3	3	15	200	Quichipa volcanics
8605	10	2	20	200	Quichipa volcanics
8606	20	2	10	200	Hole-in-the-Wall volcanics
8607	7	2	10	200	fault breccia
8608	2	15	10	200	fault breccia
8609 [a]	20	4	20	35	Quichapa volcanics
8610 [a]	25	34	5	25	fault breccia
8611 [a]	20	100	20	750	fault breccia
8612	5	2	15	200	endoskarn
8613 [a]	10	2	15	180	skarn
8614 [a]	5	8	15	260	skarn
8615	70	2	15	200	skarn
8616 [a]	5	2	5	30	skarn
8617	3	2	10	200	limestone breccia
8618	10	10	10	200	endoskarn
8619	20	2	50	200	intrusive breccia
8620 [a]	100	12	50	3300	skarn
8621	500	100	15	2000	skarn
8622	15	5	15	200	fault breccia
8623 [a]	15	6	5	25	fault breccia
8624 [a]	35	2	15	140	Quichapa volcanics

Sample No.	Cu (ppm)	Mo (ppm)	Pb (ppm)	Zn (ppm)	Remarks
8625[a]	20	2	10	35	Quichapa volcanics
8626[a]	105	10	5	230	skarn
8627	5	20	10	200	fault breccia
8628[a]	10	4	5	3000	limestone, along fault
8629[a]	5	90	5	620	limestone, along fault
8630	3	2	10	200	quartzite
8631	15	2	10	200	quartzite
8632	2	2	10	200	fault breccia
8633	5	2	50	200	fault breccia
8634[a]	5	2	10	30	Quichapa volcanics
8635[a]	10	4	35	130	intrusive porphyry
8636[a]	10	2	5	15	intrusive porphyry
8637	15	2	10	200	skarn
8638[a]	3750	2	15	1000	skarn
8639[a]	55	2	5	900	skarn
8640[a]	35	4	10	800	skarn
8641	3	30	10	200	sandstone cobbles
8642[a]	10	6	5	15	fault breccia
8643[a]	5	16	5	5	fault breccia
8644	2	20	10	200	fault breccia
8645[a]	15	6	10	15	Quichapa volcanics
8646	2	2	10	200	silicified fault cobble
8647[a]	5	6	5	5	Quichapa volcanics
8648	5	5	10	200	limestone breccia
8649[a]	5	6	5	5	sandstone
8650[a]	10	2	5	5	fault breccia
8651	51	5	10	200	sandstone cobbles
8652	70	7	10	200	basalt
8653[a]	5	6	5	130	Quichapa volcanics
8654[a]	5	2	5	20	conglomerate

Sample No.	Cu (ppm)	Mo (ppm)	Pb (ppm)	Zn (ppm)	Remarks
8655	15	2	10	200	silica veinlets in volcanics
8656 [a]	5	50	60	10	fault breccia
8657 [a]	5	2	5	30	limestone
8658 [a]	10	6	5	10	fault breccia
8659 [a]	10	2	5	10	quartzite
8660	10	2	10	200	Quichapa volcanics
8661 [a]	5	2	5	20	limestone breccia
8662	5	2	10	200	silicified limestone
8663 [a]	10	6	5	10	skarn
8664 [a]	10	4	5	15	skarn
8665 [a]	20	6	15	20	skarn
8666 [a]	10	4	40	45	skarn
8667 [a]	5	2	15	60	skarn
8668	2	2	10	200	quartzite
8669 [a]	20	2	10	10	peripheral shell rock
8672 [a]	10	2	14	25	Quichapa volcanics
8673 [a]	50	22	55	40	skarn
8674 [a]	40	4	25	25	peripheral shell rock
8675 [a]	1100	80	35	45	shear in limestone
8676 [a]	135	10	150	55	shear in limestone, sampled underground (NW1/4 sec. 9)
8677 [a]	60	8	15	90	shear in limestone, sampled underground (NW1/4 sec. 9)
8678 [a]	30	40	175	150	peripheral shell rock
8679 [a]	40	20	75	50	skarn
8680 [a]	15	2	5	30	limestone breccia
8681 [a]	180	2	5	190	skarn
8682 [a]	25	4	10	20	fault breccia
8683	90	2	5	100	limestone breccia
8684	2	2	10	200	limestone breccia
8685 [a]	4900	2	5	2100	skarn

Sample No.	Cu (ppm)	Mo (ppm)	Pb (ppm)	Zn (ppm)	Remarks
8686 [a]	435	46	120	1100	skarn
8687 [a]	35	10	5	25	endoskarn
8688 [a]	10	2	5	10	endoskarn
8689 [a]	35	8	25	35	fault breccia
8690 [a]	5	440	5	10	fault breccia
8691	5	2	15	200	igneous inclusions
8692	3	2	20	200	intrusive porphyry
8693	50	2	20	200	peripheral shell rock
8694	40	2	70	200	skarn
8695	50	7	50	200	skarn
8696	50	70	100	200	peripheral shell rock
8697 [a]	45	14	35	75	skarn
8698 [a]	70	26	35	220	skarn

a. Colorimetric determination.

Analyses by Skyline Labs, Inc., Wheat Ridge, Colorado.

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2 maps

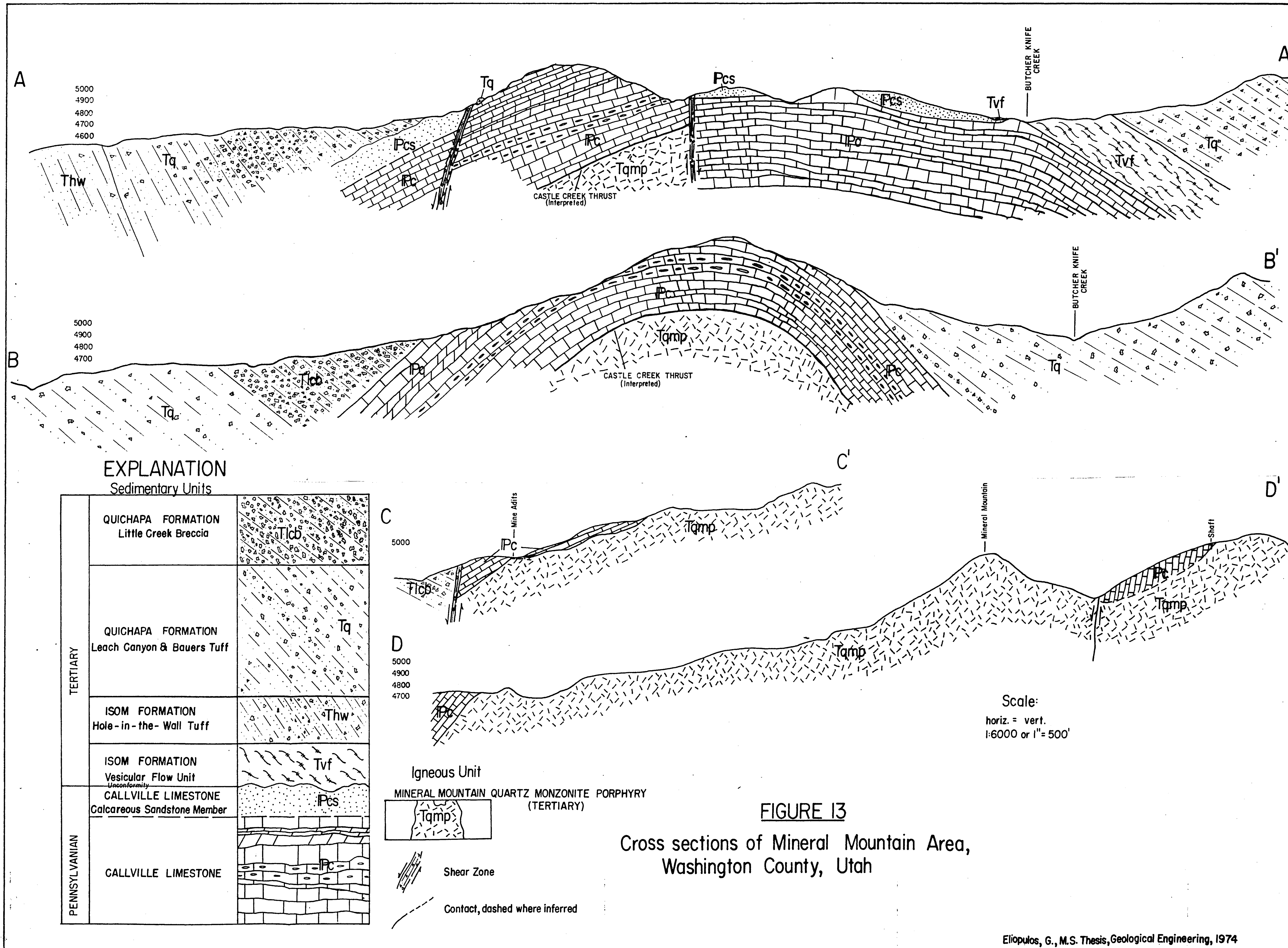


FIGURE 13

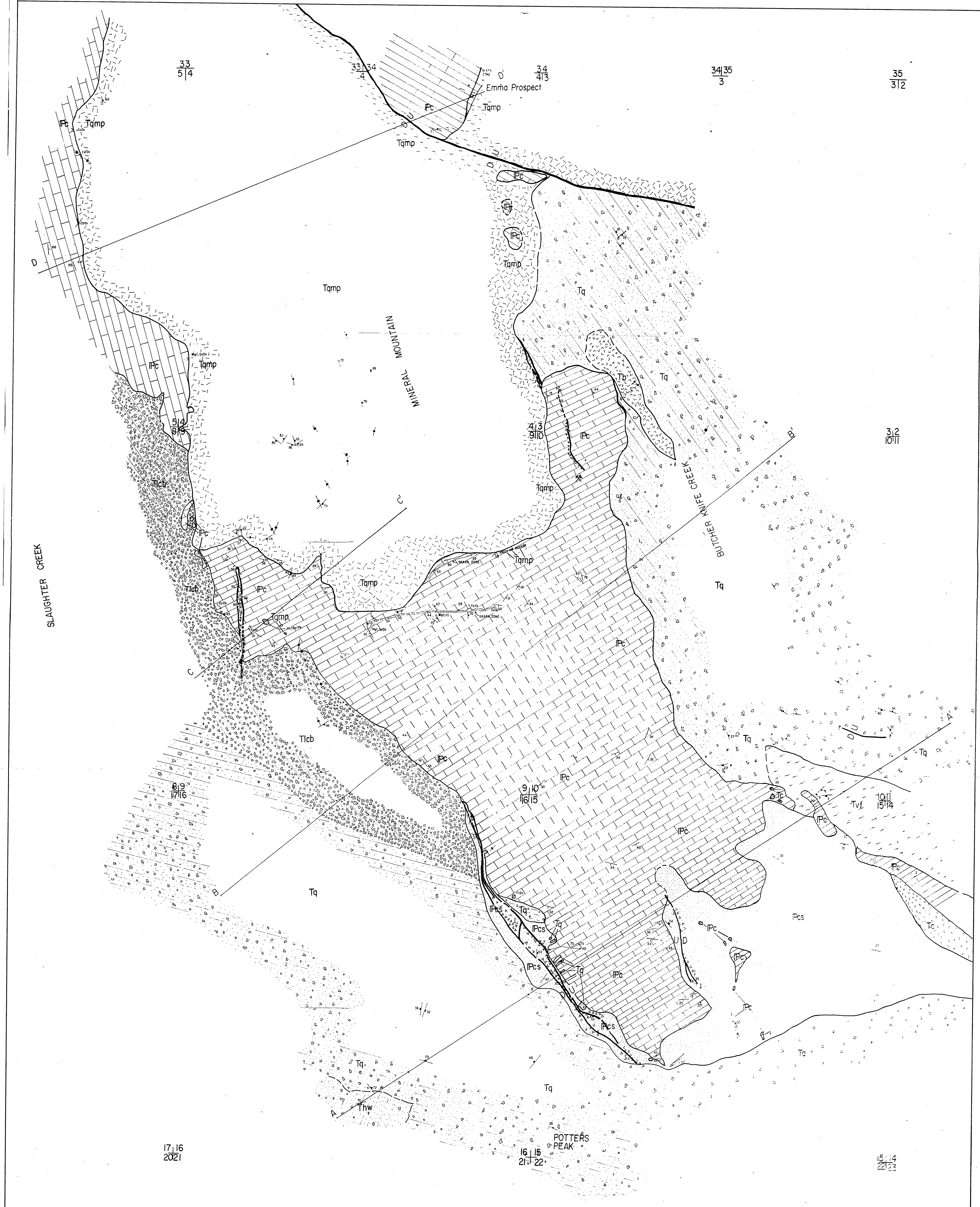
Cross sections of Mineral Mountain Area, Washington County, Utah

EL10 pulos 1971 #160 cy 2

FIGURE 2

Geologic Map of Mineral Mountain Area

Washington County, Utah



EXPLANATION

SEDIMENTARY ROCKS

TERTIARY		Basalt Member	Tb
TERTIARY	Quichapa Formation	Little Creek Breccia	Tlcb
TERTIARY	Quichapa Formation	Leach Canyon & Bauers Tuff	Tq
TERTIARY	Isom Formation	Hole-in-the-Wall Tuff	Thw
TERTIARY	Isom Formation	Vesicular Flow	Tvf
TERTIARY	Claron Formation		Tc
	UNCONFORMITY		
PENNSYLVANIAN	Callville Limestone (Skarn Zone)		IPc

IGNEOUS ROCKS

Mineral Mountain Quartz Monzonite Porphyry	Tqmp

Contact; dashed where inferred

Brecciated Fault Zone

Fault; dashed where inferred

Doubtful or probable fault

Strike and Dip of bedding

Strike and Dip of planar structure

Strike and Dip of jointing

Adit x Prospect Pit Quarry

A ——— A' Cross Section

0 500 1000 1500 FEET

SCALE: 1:6000

Eliopulos G., MS Thesis,

Geological Engineering, 1974