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Geology of North Craters of the Moon National Monument, Idaho

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The map area is located within Craters of the Moon National Monument at the southern margin of the Pioneer Mountains, in Blaine and Butte Counties, Idaho. Steep maturely dissected slopes in older rocks and recent lava flows and cinder cones of the Snake River Plain characterize the area.

The Mississippian Drummond Mine Limestone and Scorpion Mountain Formations are the oldest rocks in the area. The Drummond Mine Limestone has an exposed thickness of 100 ft

(30 m). The non-carbonate clastic rocks of the Scorpion Mountain Formation of the Copper Basin Group have an exposed thickness of 1600 ft (490 m). Thrusting from the west during the Late Mesozoic Sevier orogeny has caused northwest-trending inclined folds, which have widths of 1.5 mi (2.4 km) and amplitudes of 1000 ft (300 m). Anticlines plunge to the northwest and southeast.

Unconformably overlying these Paleozoic sedimentary rocks are the Eocene Challis volcanic rocks which have an exposed thickness of at least 3875 ft (1180 m). The Challis volcanic rocks compose a sequence of interbedded rhyodacite tuff-breccia, tuff, and lava flows. Individual units are lenticular and variable in thickness. A welded tuff bed unconformably caps the sequence.

The strata of Challis volcanic rocks are gently folded in a northwest-trending arch. They are intruded by stocks of biotite granite, hornblende quartz monzonite, and by small plutons and dikes of hornblende leucogranite porphyry, granite pegmatite and aplite, hornblende quartz syenite, and biotite-hornblende dacite, ranging in age from 35 to 58 m.y. Shattering of country rock near the intrusions has formed favorable hosts for sulfide mineralization. A hornsfel aureole of albite-epidote facies surrounds the margins of the stocks.

Deformation has continued into the Holocene. Undetermined thicknesses of olivine basalts have issued from Grassy

Cone, Sunset Cone, and North Crater, which are aligned on the northwest-trending Great Rift Zone of Craters of the Moon National Monument. This rift appears to follow older structures in the Pioneer Mountains. Holocene alluvium partly fills the major drainages of Big Cottonwood Creek and Little Cottonwood Creek.

GEOLOGY OF NORTH CRATERS OF THE MOON NATIONAL MONUMENT, IDAHO

by

William C. Sidle

A thesis submitted in partial fulfillment of the
requirements for the degree of

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TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

The members of the Committee approve the thesis of William C. Sidle presented April 18, 1979.

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CHAPTER I

INTRODUCTION

Purpose and Scope

The purpose of the investigation was to map the geology of the north end of Craters of the Moon National Monument and surrounding area. A stratigraphic sequence of Late Paleozoic sedimentary and Tertiary volcanic rocks was compiled and the structures of these rocks and contact relationships with intrusions were delineated. Grade and facies of contact metamorphism were defined. The Snake River Plain basalts were also mapped. The sources of these flows were determined where possible. Preexisting structures and relationships of vents to earlier faulting were explored in ascertaining extensions of the Great Rift Zone into the Pioneer Mountains. Petrographic descriptions of the rock units were completed. Study of the economic geology was not undertaken. The interested reader is referred to Nelson (1969) for descriptions of the mineral deposits in the Lava Creek Mining District.

Field and Laboratory Procedures

Data and conclusions presented in this report are based on both field work and petrographic study. Field work was conducted from April to September, 1978. Geology was mapped at 1:24,000 scale on preliminary topographic base sheets of Inferno Cone and Blizzard Mountain South Quadrangles with the aid of air photos. Reconnaissance mapping was undertaken in portions of Grouse Quadrangle to the north. Contacts were walked out wherever possible and stratigraphic relationships determined. A Jacob staff was used to measure a small section of Paleozoic rocks. Rock color descriptions follow Goddard (1963).

Petrographic study of 49 thin sections complements field observations. A Zeiss research microscope was utilized in the petrographic analysis. Mineral determinations were made optically; refractive indices of a few minerals were determined by standard immersion techniques in index oils using white light. Plagioclase composition was determined by the a-normal method (Kerr, 1959). Identification of K-feldspars was facilitated by staining both slabs and thin sections with sodium cobaltinitrate solution using the method of Williams (1960). Percentages of minerals were determined modally by the Swift automatic thin-section point-counter.

Modal analyses and location of representative samples are given in the Appendix. The rock classification adhered to is the IUGS. Criteria used for the classification of fragmental rocks are from Wentworth and Williams (1932), O'Brien (1963), Fisher (1961, 1966), and Blyth (1940).

Previous Work

Umpleby (1917), of the United States Geological Survey, made the first reconnaissance survey of the Lava Creek Mining District, including detailed mapping of various mining claims. Stearns (1938) and Murtaugh (1961) completed detail mapping of the Quaternary basalt flows. Bedrock geology to the west of the thesis area was mapped by Larsen (1974).

Several geologists of the United States Geological Survey are now engaged in mapping the regional geology. B. A. Skipp is continuing a study of Grouse Quadrangle and segments of Blizzard Mountain South Quadrangle. M. A. Kuntz, R. H. Lefebvre, and D. A. Champion are completing a survey of the Quaternary flows in the Craters of the Moon Lava Field.

Location and Access

Craters of the Moon National Monument is located in southeastern Idaho. It is about 10 mi (16 km) southwest of Arco and 18 mi (29 km) northeast of Carey on U.S. Alternate Highway 93 and 87 mi (140 km) from Idaho Falls (Figure 1).

The mapping area is bounded in the west by the eastern drainage of Big Cottonwood Creek and in the east by Alternate Highway 93 and lies within T. 2 N., R. 23, and 24 E. It includes the northern end of Craters of the Moon National Monument. It covers approximately 28 sq mi (73 sq km), and

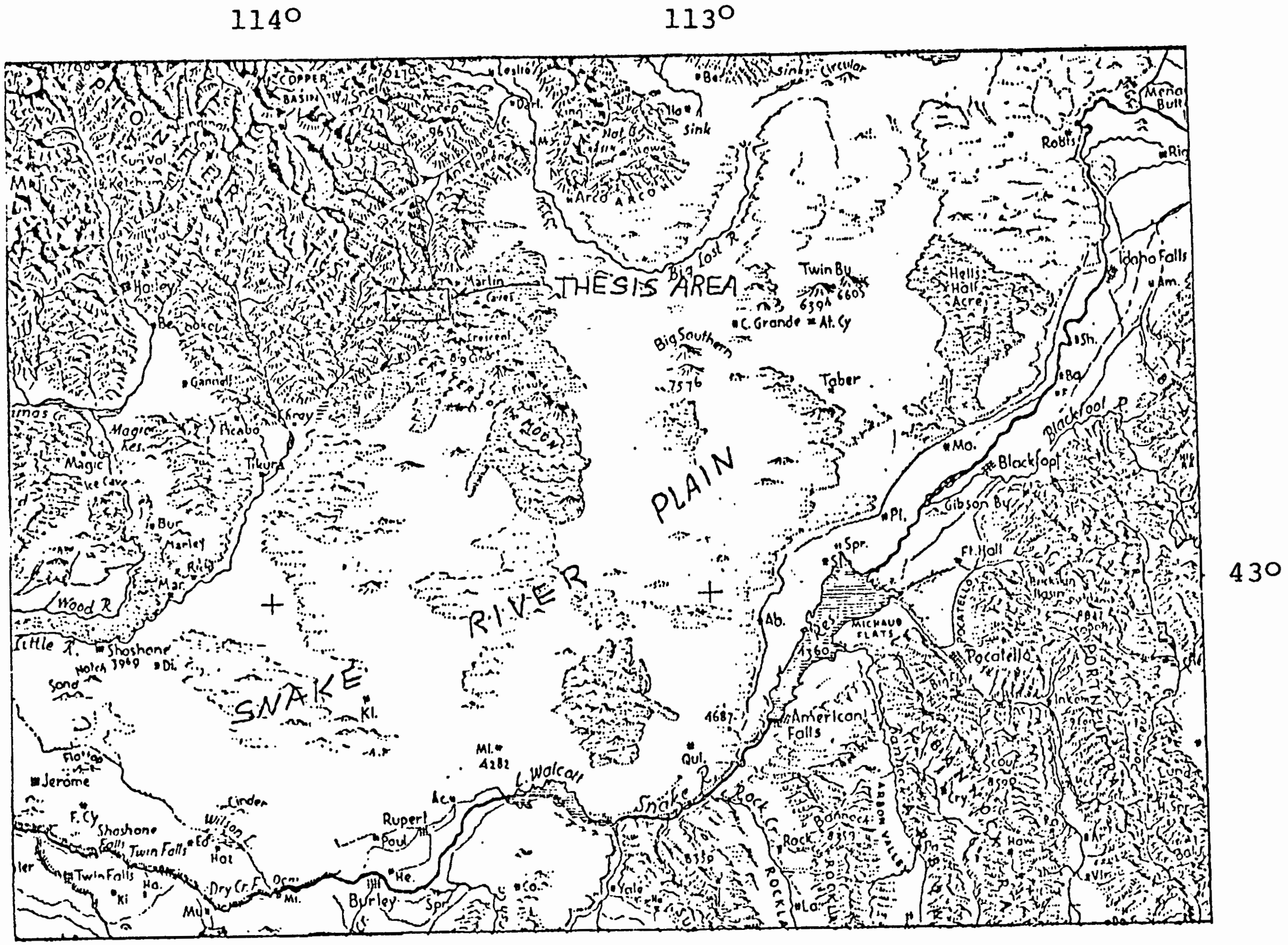


Figure 1. Location map (modified after Raisz, 1941).

lies within Inferno Cone and northeastern Blizzard Mountain South 7½-minute Quadrangles in Butte and Blaine Counties.

Relief and Drainage

The map area lies at the southern margin of the Pioneer Mountains and the northern edge of the Snake River Plain (Figure 2). The relief averages 1600 ft (490 m) and reaches a maximum of 3510 ft (1070 m) on Blizzard Mountain in the northwestern corner of the map area (Plate I), at an elevation of 9313 ft (2839 m). These mountains are maturely dissected and the most remarkable characteristic of the topography is the degree of dissection which has produced a great number of ridges and gullies.

Flowing springs and streams are numerous in the mountains, many supplying large volumes of water. Most drainage leads to the Snake River Plain through Big Cottonwood Creek and Little Cottonwood Creek. Big Cottonwood Creek has the greatest discharge, receiving a considerable part of its flow from melting snow on Blizzard Mountain. Little Cottonwood Creek has sufficient flow to be piped into the campground in Craters of the Moon National Monument. Both creeks disappear into the gravels before reaching the lava flows on the plain.

Climate and Vegetation

The region is semi-arid and similar to that character-

Figure 2. Looking north toward the maturely dissected frontal portion of Pioneer Mountains, embayed by Holocene basalt lavas. Note blocked drainage of Little Cottonwood Creek in middle distance. Skyline is 3 mi (4.8 km).

izing much of the Snake River Plain. The amount of precipitation is variable. The mean annual precipitation is 43 cm, most of which falls during the winter months of December and January as snow, and as rain in May. Slight rainfall occurs in July and August during thunderstorms. The prevailing wind direction is from the southwest, and high wind velocities are frequent. Average summer temperatures reach a high of 26°C and low of 8°C. Average winter temperatures have a high of 1°C and a low of -10°C.

The mountainous area is characteristically covered with giant sagebrush and russian thistle. The upper slopes support rye grasses. Small patches of ponderosa pine and Douglas fir grow in protected places high on the mountain slopes and in gullies where snow lingers. Forest cover is sparse below 8000 ft (2444 m).

Vegetation is sparse on the Snake River Plain. Major vegetation types includes giant sagebrush, rubber rabbitbrush, antelope bitterbrush, limber pine, and various wildflowers.

CHAPTER II

REGIONAL GEOLOGIC SETTING

The area mapped overlaps the Basin and Range Province and the Snake River Plain. Folded Paleozoic strata appear in north-south block faulted mountains both north and south of the Snake River Plain. Late Paleozoic strata north of the Plain is overlain unconformably by Challis volcanic rocks of Eocene age (Armstrong, 1974, 1976). The Challis volcanic rocks are warped and block faulted. The Snake River Plain transects the regional structure, and is a depression of late Cenozoic age.

Late Paleozoic sedimentary rocks are exposed through the volcanic cover in the Pioneer Mountains and occur as rare xenoliths in the Holocene lavas of the Snake River Plain. The Late Paleozoic strata includes micritic limestone of the Drummond Mine Limestone, which grades upward and is overlain by pebble to granule conglomerate with interbedded quartzite of the Scorpion Mountain Formation. Intense shearing is evident in these Paleozoic rocks which have been thrusted eastward and warped into broad-scale northwest trending folds with widths of 1.5 mi (2.4 km) and amplitudes of 1000 ft (300 m).

Deformation is probably related to the Sevier orogeny of Late Jurassic age (Skipp and Hall, 1975). Large valleys were carved in these older sedimentary rocks before deposition of the Tertiary volcanic rocks.

Unconformably overlying these deformed strata is a thick sequence of Tertiary volcanic rocks which was originally assigned informally to the Challis Volcanics by Ross (1927, 1937). The original definition included all assemblages of dominantly volcanic rocks in the eastern part of south-central Idaho. The Challis volcanic rocks is now restricted to dominantly volcanic strata of early Tertiary age within central Idaho lying north of the Snake River Plain and south of the westward-flowing segment of the Salmon River near latitude 45°30' N (Ross, 1962a). Armstrong (1974) gives ages of the volcanic strata ranging from 35 to 50 m.y. The Challis volcanic rocks thus represent most Eocene deposits of south-central Idaho. Subsequent erosion has largely removed the volcanic cover but old lava-filled valleys displaying inverse topography remain.

Intrusions younger than the Cretaceous Idaho Batholith are known in south-central Idaho. These younger intrusive rocks were first recognized by Ross (1927) and since then similar bodies have been discovered elsewhere. Among these are the intrusions of Big Cottonwood Creek and Little Cottonwood Creek in the study area. They include stocks of granite and quartz monzonite with related dikes and intrude the Challis volcanic strata. An age of 48 ± 1.2 m.y. is known for the Big Cottonwood Creek stock (Skipp, 1978, written communication). Armstrong (1974) gives ages ranging from 38 to 55 m.y. for nearby intrusives.

The youngest rocks are basalt lava flows of the Snake River Plain. Quaternary volcanism was widespread in the Snake River Plain, a volcano-tectonic depression, bordering the Basin and Range Province in southeastern Idaho. Viable hypotheses for the origin of the Plain are downwarping (Kirkham, 1931) and tensional rifting (Hamilton, 1963). Holocene rifting transects both provinces and may reflect earlier structural lineaments. The most evident rifting occurs within Craters of the Moon National Monument (Stearns, 1938, 1963) and Lava Creek (Russell, 1902). The Lava Creek vents are located 6 mi (9.6 km) on strike northwest of the Great Rift in the Monument.

Recent alluvium is present in some stream valleys and on the margins of the Plain where basalt flows have obstructed the drainage.

CHAPTER III

STRATIFIED ROCK UNITS

Oldest rocks in area occur west of Big Cottonwood Creek (Plate I) and belong to the Drummond Mine Limestone and Scorpion Mountain Formation (Skipp, 1978, personal communication). The stratigraphic relationship of these sedimentary units within the Copper Basin Group is shown in Figure 3. They are overlain unconformably by Eocene volcanic rocks, basalt lava flows of the Snake River Plain, alluvium, and intruded by granitic silicic plutons.

Drummond Mine Limestone (Mldm)

Distribution and Thickness

The Drummond Mine Limestone is recognized in sections 25 and 31 along Big Cottonwood Creek. In section 25 the limestone is in fault contact with the Big Cottonwood stock of biotite granite. The lower contact was not observed and the upper contact with the overlying Scorpion Mountain Formation is gradational upwards over 32 ft (10 m). The upper contact is drawn where float of the Drummond Mine Limestone ceases. Exposed thickness is estimated to be 100 ft (30 m). North of the map area thicknesses of 650 ft (200 m) occur.

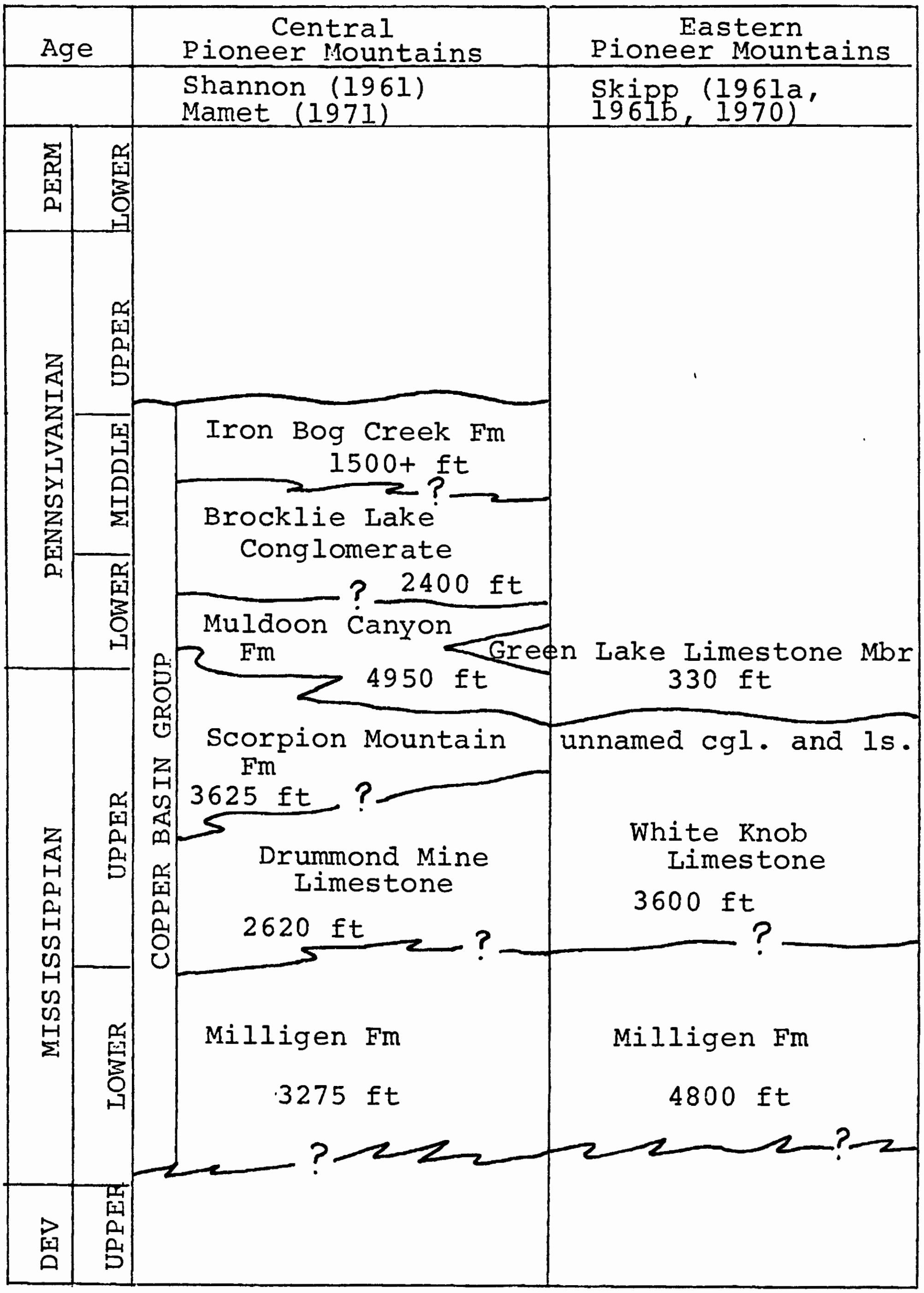


Figure 3. Upper Paleozoic stratigraphic nomenclature in Pioneer Mountains.

Character

The Drummond Mine Limestone is a micritic limestone (Pettijohn, 1975) with occasional small interbeds of argillite and quartzite (Figure 4). The limestone is medium dark gray (N4) to medium gray (N5) and weathers medium light gray (N6) to light gray (N7) and light olive gray (5Y 6/1). Bedding thickness ranges from 0.6 ft (0.2 m) to 3 ft (0.9 m) with 0.1-0.25 in (3-6 mm) interbeds of black cherty argillite. Scattered authigenic euhedral pyrite occurs.

Age

Conodont samples collected by Skipp (1978, personal communication) were identified as Early Mississippian (Kinderhookian).

Scorpion Mountain Formation (Mlsm)

Distribution and Thickness

The Scorpion Mountain Formation underlies all of Blizzard Mountain, with an exposed thickness of 1600 ft (490 m). Along the eastern side of the mountain, strata are intruded by the Big Cottonwood stock of biotite granite, whose contact is exposed on top of Blizzard Mountain. The lower contact is gradational with the Drummond Mine Limestone.

Character

The Scorpion Mountain Formation is a thick sequence of

Figure 4. Rhythmically bedded micrit limestone of Drummond Mine Limestone. Located in the NE ¼ sec. 25, Blizzard Mountain South 7½ minute Quadrangle.

dark pebble to granule conglomerate with interbedded quartzite (Figure 5). The rocks are medium light gray (N6) to medium dark gray (N4) and thickness of bedding ranges from 0.8 ft (0.2 m) to 6.2 ft (1.9 m). One section identified as Z-Z' in Plate I was measured in SE ¼ sec. 25. It is described in Figure 6.

Age

No fossils were found in the map area or to the north. The Scorpion Mountain Formation lies conformably above the Drummond Mine Limestone. The underlying Drummond Mine Limestone is late Kinderhookian; the Scorpion Mountain Formation is considered to be Osagean (Skipp, 1978, written communication).

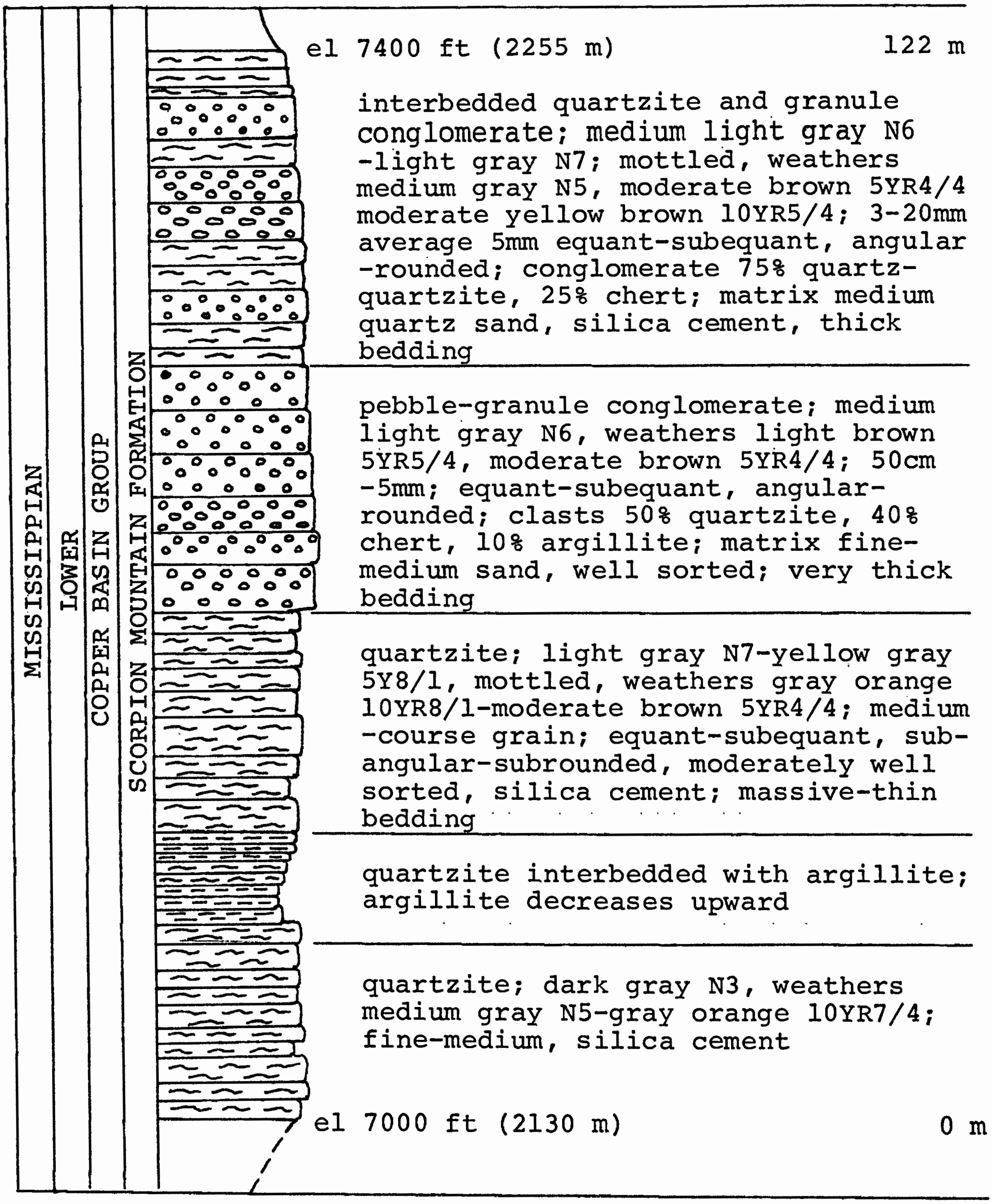
Challis Volcanic Rocks

Eocene Challis volcanic rocks cover a major part of the map area (Plate I). Total thickness exposed is 3875 ft (1180 m). No individual volcanic units or marker horizons could be traced through the area. Individual thicknesses vary and units are lenticular. Lava flows are most easily traced laterally and serve to separate stratigraphic parts of the volcanic sequence (Figure 7). Units are described in stratigraphic order.

Lower Tuff Breccia with Tuff Interbeds (Tcvl)

A lower tuff breccia with tuff interbeds, forming the

Figure 5. Quartzite interbedded with granule conglomerate of Scorpion Mountain Formation. At base of hammer handle is lense of argillite. Located in the SE ¼ sec. 25, Blizzard Mountain South 7½ minute Quadrangle.



interbedded quartzite and granule conglomerate; medium light gray N6 -light gray N7; mottled, weathers medium gray N5, moderate brown 5YR4/4 moderate yellow brown 10YR5/4; 3-20mm average 5mm equant-subequant, angular -rounded; conglomerate 75% quartz-quartzite, 25% chert; matrix medium quartz sand, silica cement, thick bedding

pebble-granule conglomerate; medium light gray N6, weathers light brown 5YR5/4, moderate brown 5YR4/4; 50cm -5mm; equant-subequant, angular-rounded; clasts 50% quartzite, 40% chert, 10% argillite; matrix fine-medium sand, well sorted; very thick bedding

quartzite; light gray N7-yellow gray 5Y8/1, mottled, weathers gray orange 10YR8/1-moderate brown 5YR4/4; medium -course grain; equant-subequant, sub-angular-subrounded, moderately well sorted, silica cement; massive-thin bedding

quartzite interbedded with argillite; argillite decreases upward

quartzite; dark gray N3, weathers medium gray N5-gray orange 10YR7/4; fine-medium, silica cement

Figure 6. Measured section Z-Z' (Plate I) of Scorpion Mountain Formation in SE ¼ sec. 25 of Blizzard Mountain South 7½ minute Quadrangle.

Tcv6	welded tuff 190 ft (58 m)
Tcv5	upper tuff breccia 740 ft (226 m)
Tcv4	upper lava flows 655 ft (200 m)
Tcv3	middle tuff breccia with tuff and lava flow interbeds 1310 ft (399 m)
Tcv2	lower lava flows 735 ft (224 m)
Tcvl	lower tuff breccia with tuff interbeds 245 ft (75 m)

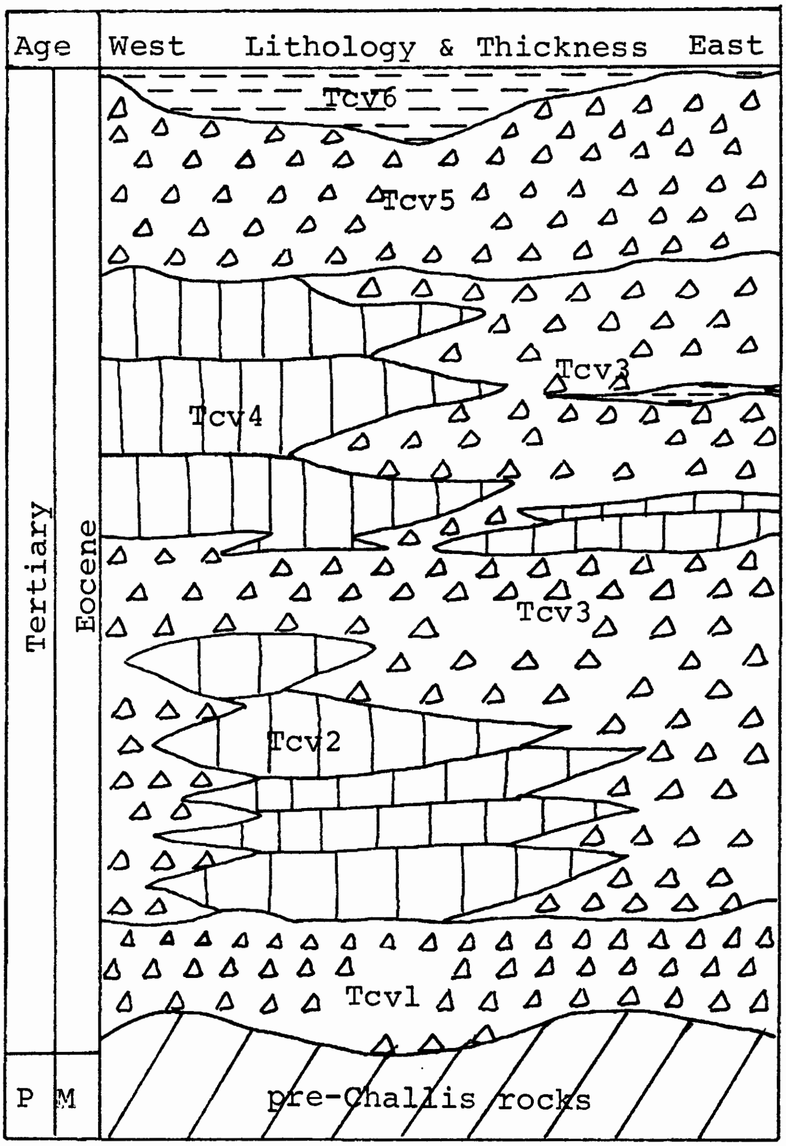


Figure 7. Stratigraphic relationships and average thicknesses of Challis volcanic units in the map area.

lowest exposed stratigraphic unit, occurs in the SW ¼ sec. 27. The maximum thickness exposed is 245 ft (75 m). It is overlain conformably by the lower lava flows (Tcv2) and intruded by an apophysis of the biotite granite of Big Cottonwood Creek.

Tuff-breccias and interfingering lenses of crystal-vitric tuffs have a greenish color ranging from grayish green (5 G 5/2), pale green (10 G 6/2), grayish green (10 Y 5/2), greenish gray (5 B 5/1), dark greenish gray (5 G 4/1), to medium bluish gray (5 B 5/1).

The modal composition of the tuff-breccia averages 65 percent lithic fragments, of which 14 percent are pumiceous, 23 percent crystals, and 12 percent partly devitrified glass (Appendix, Table II). The tuff interbeds average 5 percent pumiceous fragments, 15 percent lithic fragments, 40 percent crystals, and 40 percent glass (Appendix, Table III).

Lithic fragments in the tuff-breccia range in size from 2 mm to 2 m, averaging 45 mm. They are heterolithologic, and were apparently derived from either earlier deposited or equivalent lavas. Subangular fragments in the breccia predominate. Subrounded fragments may be due to hydraulic churning of the angular fragments (Parsons, 1969). Vesicular fragments are rare. Most fragments are glassy and slightly porous. Grains of pumice are common in the matrix and have been compacted to form elongate particles. Some beds display weak incipient compaction foliation while others have well developed foliation. These tuff-breccias are unsorted and generally display weak stratification.

This unit probably originated from ash flows and breccia flows issuing out of eruptive centers north of the map area during Eocene time.

Lower Lava Flows (Tcv2)

The lower lava flows occur in the NW ¼ sec. 30 and make up a part of the ridge west of Little Cottonwood Creek in sections 27 and 28. Maximum thickness is 735 ft (224 m). The unit conformably overlies the lower tuff breccia (Tcv1) and interfingers with the middle tuff breccia (Tcv3) (see cross-section C-C, Plate I). Overlapping of individual lava flows gives the interfingering relationship. The unit is intruded by the Big Cottonwood Creek stock of biotite granite.

The lavas are composed of porphyritic rhyodacite and contain alternating bands of glassy and cryptocrystalline bands 2-10 cm wide. The banding is superficial, being confined to the outer 3-4 mm of an exposed face of the outcrop. This weathering feature serves to separate this unit from the upper lava flows (Tcv4). Megascopically, the aphanitic rocks range in color from dark gray (N4) to grayish black (N2). They weather medium bluish gray (5 B 5/1), greenish gray (5 G 6/1), brownish gray (5 YR 4/1), and light brownish gray (5 YR 6/1).

This unit may represent a small domal complex of Eocene block lavas filling a basin between the breccia flows.

Middle Tuff-Breccia with Tuff and Lava Flow Interbeds (Tcv3)

The middle tuff-breccia with tuff and lava flow interbeds is the thickest and most widespread of the fragmental units. This unit is thickest east of Little Cottonwood Creek where it totals 1310 ft (400 m). Lenses of lava are exposed in the SE ¼ sec. 22 and SE ¼ sec. 15. Beds of crystal-vitric tuff are intercalated throughout this unit. Individual thicknesses vary considerably. The unit interfingers with both the lower lava flows (Tcv2) and upper lava flows (Tcv4). It is intruded by the Big Cottonwood stock of biotite granite and the Little Cottonwood stock of hornblende quartz monzonite.

The unit is lithologically similar to the lower tuff-breccia (Tcvl). Figure 8 illustrates a characteristic sample of the unit. Lithic fragments resemble the rock of the upper lava flow (Tcv4).

Reconnaissance mapping north of the map area indicates that this unit is lobate to fan-shaped. It may have originated as pyroclastic flows from fissure nuee ardente-type explosions (Rittman, 1962) from eruptive centers presumably located to the north during Eocene time.

Upper Lava Flows (Tcv4)

Rhyodacite lava flows of wide extent make up this unit.

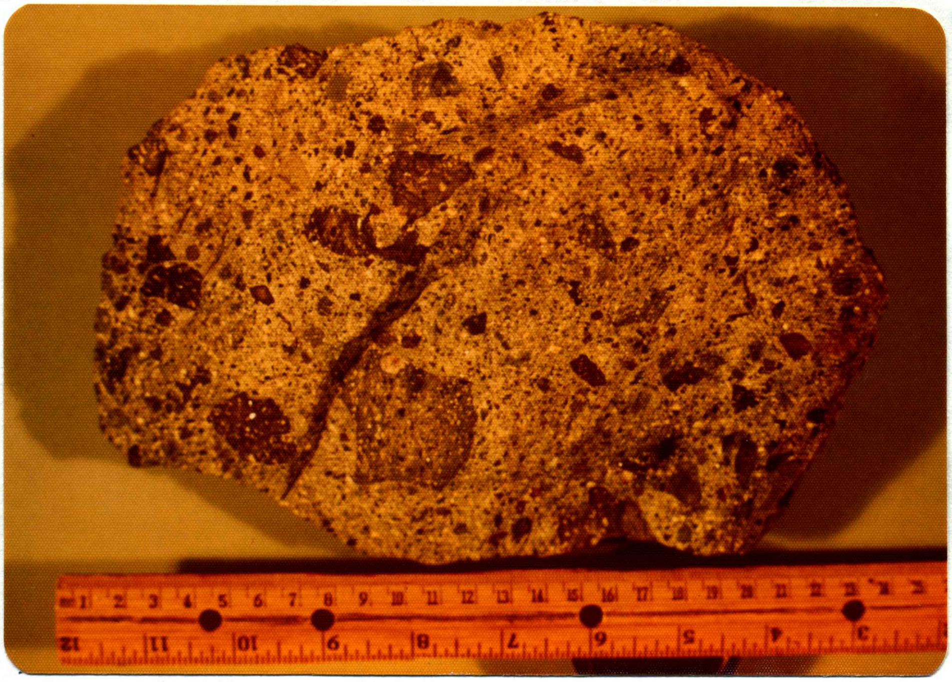


Figure 8. Pumiceous lithic-crystal lapilli tuff-breccia of middle tuff breccia (Tcv3). Note angularity of lithic fragments. Located in 19-23-2N-24E.

Total thickness ranges up to 655 ft (200 m). Thicknesses of individual flows are variable. Overlapping lava flows interfinger with the middle tuff-breccia (Tcv3). These flows are intruded by the Big Cottonwood and Little Cottonwood stocks.

Lithology is similar to the lower lava flows (Tcv2) with the notable absence of glassy bands. These rocks may have originated as a domal complex of block flows filling in a basin during Eocene time.

Upper Tuff-Breccia (Tcv5)

The upper tuff-breccia extends from the summit of Blizzard Mountain eastward into section 21 west of Little Cottonwood Creek. Its maximum thickness is 740 ft (225 m). Individual thicknesses of beds are variable. The basal and top contacts are irregular. The unit is overlain unconformably by the welded tuff (Tcv6). The lithology is identical to the other tuff-breccia units.

Welded Tuff (Tcv6)

A remnant of a probable formerly extensive welded-tuff sheet occurs in the NW ¼ sec. 21. Thickness of the welded tuff is at least 190 ft (58 m). It rests unconformably upon the upper tuff-breccia (Tcv5).

The rock is colored medium dark gray (N4), dark gray (N3), and grayish black (N2). It weathers medium dark gray

(N4). Block size pumice fragments are common; their colors range from light brownish gray (5 YR 6/1), moderate orange pink (5 YR 8/4), to moderate pink (5 R 7/4) (Figure 9). Silica veinlets and lenses permeate this unit.

The welded tuff is an ash-flow deposit that may represent the culminating volcanic activity during Eocene time.

Petrography

The rhyodacite composition of the pyroclastic units is revealed by modal analysis (Appendix, Tables II, III). Abundant equant orthoclase, anhedral quartz, and tabular crystals of plagioclase (An_{26-32}) can be readily recognized. In some samples nearly half of the crystals are broken and shattered, yet enclosed in a vitrophyric matrix, having occasional microlites presumably of the same minerals. The feldspars are commonly rounded and partly resorbed. In general the tuffs show much alteration. The feldspars are rarely clear but consist of fine aggregates of sericite. The greenish color of the rock is due to abundant chlorite and minor epidote developed from very fine-grained ferromagnesian minerals in the groundmass, probably biotite and hornblende, which occur as unaltered isolated phenocrysts elsewhere in the rock. Epidote locally fills small fractures. Magnetite is the chief accessory mineral. Tuffs altered near hydrothermal sulfide deposits have been converted to aggregates of chlorite, pyrite, secondary quartz, chalcedony,

Figure 9. Welded pumiceous crystal-vitric tuff of welded tuff (Tcv6) with block size pumice, silica lenses, and silica veinlets. Length of hammer handle 11 in (28 cm). Located in 7-21-2N-24E.

calcite, and a little rhodochrosite.

Modal analysis (Appendix, Table IV) of representative samples of the lava flow units show these rocks to be hornblende-biotite rhyodacites, containing 10-16 percent subhedral plagioclase (An_{20-42}), partly sericitized and chloritized, commonly as weakly aligned phenocrysts, and 16-28 percent kaolinized orthoclase. About 20 percent anhedral quartz is present. The ferromagnesians averaging 11 percent include hornblende and tabular biotite, commonly pseudomorph after hornblende, and poikilitically enclosing magnetite. Minor amounts of opaques and clinopyroxenes occur in a pilotaxitic to trachytic matrix of appressed alkali microlites and quartz grains. The rocks are weakly altered except in the vicinity of hydrothermal mineral deposits where chlorite and secondary quartz are abundant.

Age

Potassium-argon age determinations indicate an Eocene age for the Challis volcanic rocks. Armstrong (1974, 1976) gives ages of 35-50 m.y. for Challis volcanic rocks and 38-55 m.y. for related intrusives. Ages of volcanic rocks near the map area (Plate I) are approximately 48 ± 1.2 m.y. from the Big Cottonwood Creek stock on Boyle Mountain 3/4 mi (1.2 km) north of Blizzard Mountain (Skipp, 1978, written communication). It is not known how much older these volcanic rocks are than the intrusives in the map area.

CHAPTER IV

INTRUSIVE ROCK UNITS AND METAMORPHISM

General Features

Intrusions form small stocks and dikes covering 3.5 sq mi (9.3 sq km). The major intrusions are the biotite granite of Big Cottonwood Creek, dikes and small bodies of hornblende leucogranite porphyry and the hornblende and quartz monzonite of Little Cottonwood Creek with granite pegmatite aplite, and hornblende quartz syenite dikes. Biotite-hornblende dacite also occurs in isolated dikes. They are discussed in this order.

No contact was observed between the Big Cottonwood stock of biotite granite and the Little Cottonwood stock of hornblende quartz monzonite. Hornblende leucogranite porphyry appears to be younger than the biotite granite, cutting it in the NE ¼ sec. 25. The Little Cottonwood stock is intruded by granite pegmatite and aplite, and hornblende quartz trachytite. One biotite-hornblende dacite cuts the biotite granite in the NW ¼ sec. 33. No cross-cutting relationships were observed between these dikes. All dike rocks are considered to be younger than the biotite granite and hornblende quartz monzonite plutons.

These intrusive rocks are chiefly medium to coarse grained with hypabyssal varieties in dikes and along margins of the stocks. Along these margins the volcanic rocks have been subjected to low grade contact metamorphism.

Biotite Granite of Big Cottonwood Creek (Tig)

A medium to coarse grained massive biotite granite extends from Boyle Mountain northwest of the map area southward across Blizzard Mountain lying principally within the drainage of Big Cottonwood Creek. This elongated stock is approximately 5.9 mi (9.5 km) long averaging 0.5 mi (0.8 km) wide.

The Big Cottonwood stock has in many places intruded the Mississippian sedimentary rocks and the Challis volcanic rocks along fault contacts. A particularly well-defined fault contact with the Drummond Mine Limestone is located in the NE ¼ sec. 25. The intrusive rocks here occur in a down-dropped block, which is the site of the Paymaster Mine. Another major fault contact is in the NE ¼ sec. 33 where the biotite granite abruptly cuts the Challis lower lava flows (Tcv2).

On fresh surfaces the dominant color is pale red purple (5 RP 6/2) with pinkish gray (5 YR 8/1), and grayish orange pink (5 YR 7/2). The granite weathers very light gray (N8) and pale pink (5 RP 8/2). Bleached samples are pale greenish yellow (10 Y 8/2). The massive granite is typically equigranular, occasionally micropegmatitic.

Spheroidal weathering is common.

The biotite granite of Big Cottonwood Creek is comprised of weakly granophyric sericitized and argillitized orthoclase, anhedral quartz, and subordinate plagioclase and chloritized biotite.

Orthoclase makes up 23-46 percent of the rock (Appendix, Table V). Some are as large as 35 mm in diameter and occur as subhedral equant prisms with quartz inclusions. The orthoclase is cloudy with incipient alteration consisting of clays. Plagioclase (An_{5-20}) makes up 7-10 percent. The crystals are invariably euhedral with myrmekitic intergrowths and are unaltered in contrast to the orthoclase. Anhedral quartz averaging 15 mm forms 30-47 percent of the rock. Biotite and weakly pleochroic hornblende are the only mafic minerals recognized, accounting for 6-12 percent. The biotite appears greenish as a result of nearly complete conversion to chlorite. Magnetite and rutile are the most common accessories.

Hornblende Leucogranite Porphyry (Tigp)

A small body of hornblende leucogranite porphyry occurs in section 19. Elsewhere it occurs as dikes cutting the Mississippian sedimentary rocks and Challis volcanic rocks. In the NE ¼ sec. 25 it intrudes the Big Cottonwood Creek stock.

These massive rocks are distinctly light colored ranging from light gray (N7), pinkish gray (5 YR 8/1) to very pale orange (10 YR 8/2) weathering very light gray (N8). The small intrusion is composed of medium grained equigranular to slightly porphyritic rocks; dikes are fine grained.

The rock is a hornblende leucogranite porphyry, (Appendix, Table VI), consisting of 40-55 percent rounded embayed phyric quartz (Figure 10), ranging up to 20 mm in diameter, 35 percent sericitized orthoclase, 8 percent plagioclase (An_{12-31}), and 6 percent chloritized strongly pleochroic hornblende, forming an equigranular to felsophyric matrix.

Hornblende Quartz Monzonite of Little Cottonwood Creek (Tiqm)

An irregular shaped stock of hornblende quartz monzonite, covering about 0.6 sq mi (1.6 sq km), occurs at the head of Little Cottonwood Creek. The stock is entirely bounded by the Challis volcanic strata which it intrudes. Numerous faults are present along the periphery where the rocks have been shattered by the pluton. No contact relation between the hornblende quartz monzonite and biotite granite was observed.

Fresh surfaces range from very light gray (N8), light gray (N7), pinkish gray (5 YR 8/1), to dark greenish gray (5 G 4/1). The rock weathers yellowish gray (5 Y 8/1), pale greenish yellow (10 Y 8/2), and light gray (N7).

The rock is a weakly foliated medium-grained equigranular, sericitized-chloritized hornblende-quartz monzonite.

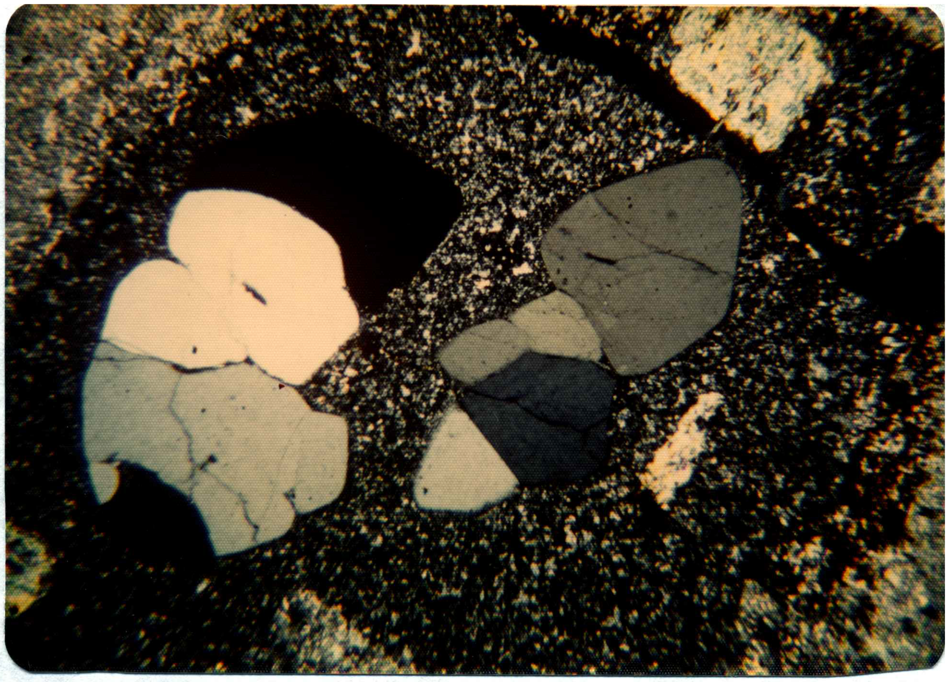


Figure 10. Rounded and embayed 1 mm phenocrysts of quartz in felsophyric groundmass of hornblende leucogranite porphyry dike. Silica veinlet appears in upper right. 3.4 mm x 2.1 mm. Crossed polarized light. Sample W-139 located in 1-30-2N-24E.

White to pale green plagioclase forms 33-46 percent of the rock (Appendix, Table VII). Two generations of plagioclase having a composition of An_{9-18} and An_{31-48} respectively. The oligoclase occurs in reverse zoned crystals that are albitized in the core. The andesine forms well-developed finely twinned laths containing abundant clinozoisite and sericite. Orthoclase makes up 19-27 percent and is microperthitic, sericitized, and argillitized. Subhedral to anhedral quartz, averaging 5 mm in size, accounts for 10-23 percent of the quartz monzonite. Mafic minerals contribute 9 percent with chloritized hornblende dominant. Magnetite and pyrite are ubiquitous.

Granite Pegmatite (Tipg) and Aplite (Tiap)

Several pegmatite dikes and lenses occur in the hornblende quartz monzonite of Little Cottonwood Creek and the surrounding Challis volcanic strata. Some have well-defined walls and others are gradational. These rocks have pegmatitic textures and are orange pink (10 R 7/4). Quartz crystals up to 4 cm in diameter account for at least 25 percent of the rock. Orthoclase and albite account for the bulk of the pegmatite with biotite and magnetite the only other minerals identified.

Light red (5 R 6/6) and moderate pink (5 R 7/4) aphyric aplitic dikes as small as a few centimeters thick cut the stock. No cross-cutting relationships are seen in the granite pegmatite. These aplites display typical sugary texture. Mineralogy consists almost entirely of quartz and presumably alkali feldspars. No ferromagnesian minerals were seen in thin section.

Hornblende Quartz Trachytite (Tisy)

One dike of hornblende quartz trachytite cuts the hornblende quartz monzonite in the SW ¼ sec. 15. The massive fine-grained rock is pinkish gray (5 YR 8/1). Modal analyses (Appendix, Table VIII) indicates that the rocks contain 13 percent orthoclase, 4 percent plagioclase (An_{5-12}), 3 percent quartz, 7 percent brown prismatic hornblende, all occurring as phenocrysts in 70 percent unresolvable felsophyric groundmass.

Biotite-Hornblende Dacite (Tid)

Fine grained aphyric biotite-hornblende dacite intrudes Challis volcanic strata in the SW ¼ sec. 23, NE ¼ sec. 27, and SE ¼ sec. 15. A dacite dike also cuts the biotite granite in the NW ¼ sec. 33.

Fresh surfaces are medium dark gray (N3) to dark gray (N3). These rocks weather to olive gray (5 Y 3/2), grayish olive green (5 GY 3/2), dusky yellow green (10 GY 3/2), and dusky green (5 G 3/2).

Petrography shows the biotite-hornblende dacite containing up to 29 percent plagioclase (An_{32-54}) laths with moderately abundant epidote inclusions. Orthoclase occurs as chalky white equant crystals totaling 1-6 percent of the rock. Quartz makes up 15-25 percent as fractured anhedral grains. Biotite and hornblende average 13 percent of the dacite. Occasionally the strongly pleochroic hornblende contains granules of colorless pyroxenes. Up to 56 percent of the 80 percent total groundmass is glass streaked in shades of gray and crowded with trichites of feldspar and ferromagnesian minerals. Brown spherulites of quartz and feldspar are common. The chief accessory is euhedral magnetite oxidized to hematite. Modal analysis is given in Appendix, Table IX.

Age of Emplacement

All intrusions cut the Challis volcanic strata. An age of 48 ± 1.2 m.y. was determined from the biotite granite of Big Cottonwood Creek 3/4 mi (1.2 km) north of Blizzard Mountain (Skipp, 1978, written communication). Armstrong (1974) gives a range of 38-58 m.y. for intrusions occurring in the Challis volcanic strata.

Metamorphism

The intrusions of Big Cottonwood Creek and Little Cottonwood Creek are encircled by a low-grade contact metamorphic aureole never more than 150 ft (45 m) thick.

In general the volcanic rocks have been altered to a dense fine-grained hornsfels, a grayish to greenish assemblage often without recognizable minerals. Colors range from dusky blue green (5 BG 3/2), medium bluish gray (5 B 5/1), to dark greenish gray (5 G 4/1). Some are faintly spotted as though outlining former minerals or inclusions.

Under the microscope, a granoblastic texture of plagioclase (An_{10-21}), quartz, biotite, epidote, and actinolite can be seen. Modal analysis (Appendix, Table X) reveals that biotite is the dominant replacement mineral. The mineral assemblage is quartz-albite-actinolite-biotite and albite-actinolite-biotite-epidote(±chlorite), indicating the albite-epidote hornsfel facies (Hyndman, 1972).

The degree of metamorphism in the sedimentary rocks bordering the Big Cottonwood stock was not examined in detail. Field inspection of the Drummond Mine Limestone revealed no skarn minerals. Only recrystallization is present in the rocks of this formation as well as in the Scorpion Mountain Formation.

CHAPTER V

QUATERNARY EXTRUSIVE ROCKS

Basalt lava flows occur in the southern part of the map area, comprising part of the Craters of the Moon Lava Field of the Snake River Plain (Plate I). The stratigraphic succession of the basalt flows in northern Craters of the Moon National Monument are shown in Figure 11. Informal names are applied to each flow except the previously named Highway Flow.

The basalts range from scoreaceous types to dense aphanitic lava. Their colors vary from grayish black (N2) to black (N1). Weathered surfaces are pale reddish brown (10 R 5/4) and moderate reddish brown (10 R 4/6). An unusual blue glassy crust coats portions of the pahoehoe flows. This moderate blue (5 B 5/6) glass is due to electron processes near included magnetite crystals (Lefebvre, 1977).

Grassy Flow (Qbla) - Sunset Northeast Flow (Qblb)

The summit of Grassy Cone rises 450 ft (137 m) above the Snake River Plain. The cone is ½ km wide and 1½ km long with the long axis southwest-northeast. The asymmetric shape was evidently caused by strong southwesterly winds during most of the eruptions. The cone has a thick mantle of cinders.

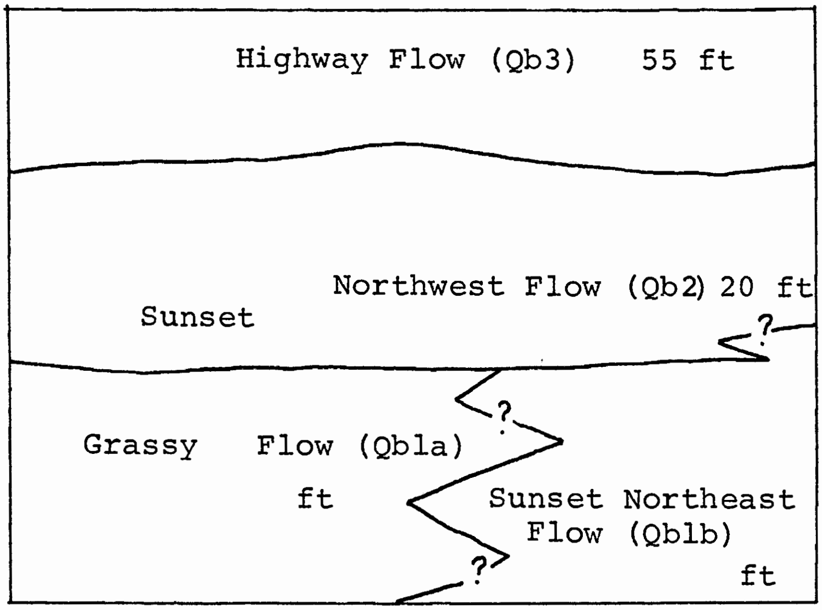


Figure 11. Stratigraphy of basalt lava flow units in North Craters of the Moon National Monument.

The Grassy Flow erupted from vents on the north flank of Grassy Cone. Pahoehoe flows from two vents merge imperceptibly, suggesting simultaneous eruptions on the north side. The flow tops are reddish brown. A network of lava tubes, including an accessible tube 30 ft (9 m) in diameter and at least 150 ft (50 m) long, extend out from the north side of the cone. The contact of the Grassy Flow with the Sunset Northeast Flow could not be located because of cover.

Sunset Cone rises 590 ft (180 m) above the Plain. The cone was formed by multiple eruptions. One formed a deep crater on its western slope and the red and purple shades of scoria of the walls gives this crater its name. The crater rim is crescent-shaped and its lack of symmetry is attributed to strong winds during the eruption. An undrained depression about 50 ft (15 m) deep forms the bottom of the crater. On the northeast side, the breached crater has deposited a thick mantle of cinders on the projecting spurs of Challis volcanic rocks to the north. Finer lapilli has accumulated in the gulches northeastward.

The Sunset Northeast Flow issued from the breached crater on the northeast side of the cone. The Park Service Group Campground is located in this crater. The flow is pahoehoe near the vent and is characterized by pressure ridges and tumuli.

Sunset Northwest Flow (Qb2)

The Sunset Northwest Flow is made up of aa lava that has issued from a parasitic cone on the northwest slope of Sunset Cone. The flow is about 20 ft (6 m) thick and overlies the Grassy Flow.

Highway Flow (Qb3)

The well-defined Highway Flow is the youngest in the area. Also called the North Crater AA Flow, it lies between Sunset Cone and Grassy Cone atop flows from these cones. The flow is a mixture of aa, large segments of pahoehoe, and blocks. The surface is braided with channels 10-20 ft (3-6 m) deep. The crenulate lobate flow margins range from 10 to 55 ft (3-15 m) thick. Kipukas of cinders are frequent as are pressure ridges and longitudinal fractures paralleling the flow direction.

Petrography

All lava flows are olivine basalts containing mostly microlites of plagioclase (An_{54-71}), small grains of olivine, and euhedral magnetite in an alternating hyalopilitic and vitrophyric matrix of brown to black glass charged with numerous small granules of iron oxides.

Labradorite phenocrysts are lath-shaped and make up only 9 percent of the rock (Appendix, Table XI). Another 10 percent of recognizable plagioclase occurs as flow-aligned microphenocrysts commonly in glomeroporphyritic intergrowths with olivine and clinopyroxene. Olivine accounts for 4 percent of the rock. It occurs as bipyrmidal microlites or rarely rounded seriate microphenocrysts. The olivine is colorless and slightly altered to serpentine. Minor amounts of augite and hypersthene are present. Finely disseminated magnetite and other iron ores probably contribute to the opaque brown to black glass.

Age

Age of the flows is Holocene, derived from Carbon 14 dates and paleomagnetic dates (Champion, 1975).

CHAPTER VI

SURFICIAL SEDIMENTARY DEPOSITS

The Big Cottonwood Creek and Little Cottonwood Creek are filled with 0 to 100 ft (0-30 m) of alluvium. The alluvium contains rounded to subangular granite, quartz monzonite, and rhyodacite pebbles and sand. Alluvial fans have built up at the mouths of these drainages where obstructed by lava flows. Stream flow disappears at the margin of the Pioneer Mountains and the Snake River Plain.

An older stream terrace occurs in the Big Cottonwood Creek drainage. Also a few patches of colluvium resulting from sheetwash have accumulated.

CHAPTER VII

STRUCTURES

Folds

A large northwest-trending anticline is mapped east of Big Cottonwood Creek (Plate I). This fold is traced from Late Paleozoic rocks north of the map area southward into the Challis volcanic strata. The Late Paleozoic rocks west of this anticlinal axis dip 40-50 degrees southwest. To the north beds dip 20-30 degrees southwest. East of the anticlinal axis beds dip 50-55 degrees northeast. The anticline is domal with the beds closing to both the northwest and southeast. The width of this fold is near 1½ mi (2.4 km) and its amplitude approaches a maximum of 1000 ft (300 m).

Immediately west of this anticline is a syncline of minor amplitude. On the ridge west of Big Cottonwood Creek are an anticline and syncline having an irregular northwest trend and which involve principally pre-Challis rocks. The Big Cottonwood Creek stock intruded along this anticlinal axis. Mapping farther west by Skipp (1975) reveals broad-scale folding accompanied by thrusting.

The Challis volcanic rocks have been gently uparched north of the map area.

Faults

All rock units are cut by faults. Normal faults in the Mississippian rocks parallel the anticline west of Big Cottonwood Creek and the Big Cottonwood Creek intrusion.

Many faults trend N45°E to N55°E; some strike between N60°W and N70°W; others have no definite trends, intersecting or abruptly transecting each other. Some steeper dips probably were caused by tilting of fault blocks. The Challis volcanic rocks range in dip from 8-35 degrees. Lack of stratigraphic marker beds prevents determination of sense and amount of displacement. Small-scale faults exposed in prospect adits have normal displacement in the magnitude of tens of feet.

A few faults cut the plutons. They are especially well exposed in the Little Cottonwood Creek stock (Plate I).

Holocene faulting is exhibited by the Great Rift Zone in Craters of the Moon National Monument. The Great Rift Zone, part of the Idaho Rift System (Prinz, 1970), is a 54 km long, north to northwest-trending fissure zone that crosses the eastern Snake River Plain, and continues 6 mi (9.6 km) northward into the Pioneer Mountains at least as far as the Lava Creek vents (Russell, 1902). The general trend of the Great Rift Zone parallels the large anticline east of Big Cottonwood Creek. One possible extension of a rift, aligning with Grassy Cone, is a normal fault marked by prospects and springs and the bounding margin of an outlier of the Big Cottonwood Creek stock in sections 28 and 33. This fault can be traced only a short distance into the Pioneer Mountains. Another possible fault extends from the rift of Big Craters through North Crater and the Highway Flow into a small biotite granite intrusion in section 27. Contrary to Russell's belief no lineaments are observed to continue northward through the map area into Lava Creek.

Intrusions

Intrusions include the Big Cottonwood Creek stock, 2.9 sq mi (7.5 sq km), Little Cottonwood Creek stock, 0.6 sq mi (1.6 sq km), and smaller intrusives and dikes.

The elongated (2.4 x 0.5 km) Big Cottonwood Creek stock was intruded along the east limb of the anticline on the ridge west of Big Cottonwood Creek. Emplacement of the pluton caused fracturing of the rocks especially along fault contacts. The biotite granite of Big Cottonwood Creek is intruded by a hornblende leucogranite porphyry. Some dikes trend parallel to the Big Cottonwood Creek stock. Others have a generally northeast trend.

The Little Cottonwood Creek stock is an irregular body of hornblende quartz monzonite, surrounded by numerous faults, possibly the result of its emplacement. Granite pegmatite and aplite dikes trend predominantly northeasterly. No contact relationship is observed between the Little

Cottonwood Creek and Big Cottonwood Creek stocks.

Age of Deformation

Three major episodes of deformation are present in the rocks. Strongest deformation during the Sevier orogeny of Late Jurassic age compressed the Mississippian beds into broad-scale folds (Skipp, 1975). Presumably this same orogeny folded the Mississippian strata just west of Big Cottonwood Creek.

A second deformation, probably a result of rising plutons, was less intense, warping the Challis volcanic rocks into gentle folds. Emplacement of plutons appears to have followed the northwest-trending folds and is associated with the northwest faulting. Northeast faulting occurred with emplacement of dikes.

CHAPTER VIII

SUMMARY OF GEOLOGICAL HISTORY

During Mississippian time cratonic sea encroachments deposited at least 100 ft (30 m) of the Drummond Mine Limestone and 1600 ft (490 m) conglomerates and quartzites of the Scorpion Mountain Formation of the Copper Basin Group in the area. No evidence of Mesozoic deposits appears in the area which suggests that by this time the area was emergent.

Orogenic movements including the emplacement of the Idaho Batholith occurred in Mesozoic time and resulted in broad-scale folding and faulting as the region was rapidly uplifted. The folds were developed along northwest axes and under great compression some were overturned and others broken by overthrusts. The Sevier orogeny of Jurassic age, representing one stage in the northern Rock Mountain tectonic evolution, is responsible for the folding of the Mississippian rocks (Skipp, 1975).

A long period of erosion followed and the terrain was carved into broad valleys. Volcanism began during Eocene time, filling the valleys with Challis rhyodacite block lava flows and pyroclastic rocks, the latter are believed to be lobate to fan-shaped deposits which cascaded down the flanks of large eruptive centers located to the north. Most of the tuffs and tuff-breccias probably erupted as pyroclastic flows from fissure nuee ardente-type explosions (Rittman, 1962). Eventually over 3875 ft (1180 m) of volcanic rocks covered the entire landscape.

Concurrent with this volcanic activity, small plutons gently uparched the rocks. Northwest and northeast-trending faults accompanied the emplacement of the biotite granite of Big Cottonwood Creek and the hornblende quartz monzonite of Little Cottonwood Creek. These intrusions, along with the episode of silicic volcanism, may have been occurring with Basin and Range faulting which is present in the region.

After a long quiescence, Snake River Plain mafic volcanism began in Quaternary time. The Snake River Plain may represent a tensional rift that transects continental structure and has resulted from crustal thinning. In the eastern plain, thinning and foundering of the sialic rocks has occurred as the Idaho Batholith is drifting slowly northwestward as an unbroken mass, in the lee of which the Snake River depression is produced by tensional thinning of the crust (Hamilton, 1965). Filling of this depression by volcanic rocks derived from the earth's mantle accounts for the present aspect of the Snake River Plain. The latest extrusions occurred about 2000 years ago in the Craters of the Moon Lava Field.

CHAPTER IX

CONCLUSIONS

Conclusions reached from this thesis research are based upon mapping in the Challis volcanic rocks observed in the map area. Also, the extensions of the Great Rift Zone into the Pioneer Mountains is postulated.

Field mapping conducted in the Challis volcanic rocks indicates these rocks can be subdivided. Rhyodacite tuffs, tuff-breccias, and lava flows were mapped at 1:24000 scale. Tuff-breccias presented the most difficult problem in mapping. Their overall mineralogical composition, distribution of fragments, cementation, and alteration appear uniform throughout the map area. However, thick block lava flows which apparently fill previous basins, aid in separating each tuff-breccia unit. In addition, welded and nonwelded tuffs are confined to the lower and middle tuff-breccia units helping to distinguish the upper tuff-breccia unit. This upper tuff-breccia unit is also separated by an erosional unconformity with a welded tuff unit containing pumice blocks. These stratigraphic relationships are essential to subdivide the Challis volcanic rocks exposed in the map area. They include the lower tuff-breccia with tuff interbeds, lower lava flows, middle tuff-breccia with tuff and lava flow interbeds, upper lava flows, upper tuff-breccia, and welded tuff units.

Extension of the 54 kilometer long Great Rift Zone into the Pioneer Mountains was earlier speculated upon by Russell (1902) to include the Lava Creek vents located on strike 6 mi (9.6 km) north of Craters of the Moon National Monument. However, no lineament extending through the Pioneer Mountains has been confirmed which would connect these vents. But mapping of a large anticlinal fold just east of Big Cottonwood Creek indicates the fold is in line with the Great Rift Zone. One rift passing through Silent Cone and Grassy Cone continues into a fault contact between the Big Cottonwood Creek pluton and the lower lava flows unit. A more speculative possibility is that a rift passes through Big Craters into an apophysis of biotite granite at the western margin of Little Cottonwood Creek. Both of these rifts, if extended, lie on the steep east limb of this large anticline. The entire Great Rift Zone reflects an earlier structural weakness occurring with the anticline.

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APPENDIX

TABLE I

LOCATION OF SAMPLES

No.	Rock Type	Location	El. ft
W-1	Rhyodacite Tuff	12-27-2N-24E	6280
W-3	Biotite-Rhyodacite Tuff Breccia	13-22-2N-24E	6900
W-10	Hornblende-Biotite Rhyodacite	19-23-2N-24E	6600
W-15	Hornblende-Biotite Rhyodacite	34-16-2N-24E	7580
W-16	Tuff Breccia	19-23-2N-24E	6600
W-18	Hornblende Quartz Syenite	29-15-2N-24E	7360
W-19	Hornblende-Biotite Rhyodacite	17-19-2N-24E	7840
W-26	Hornblende-Biotite Rhyodacite	18-27-2N-24E	6080
W-28	Hornblende-Biotite Rhyodacite	31-27-2N-24E	6929
W-33	Biotite-Hornblende Dacite	26-15-2N-24E	7200
W-35	Hornblende Quartz Monzonite	28-22-2N-24E	6280
W-40	Hornblende Quartz Monzonite	31-15-2N-24E	7560
W-46	Rhyodacite Tuff	33-27-2N-24E	6300
W-47	Rhyodacite Tuff	33-27-2N-24E	6300
W-50	Hornblende Quartz Monzonite	7-22-2N-24E	7060
W-51	Hornblende Quartz Monzonite	17-22-2N-24E	6740
W-52	Biotite Hornsfel	11-22-2N-24E	7200
W-53	Rhyodacite Tuff	33-27-2N-24E	6140
W-61	Hornblende Quartz Monzonite	11-22-2N-24E	7240
W-67	Rhyodacite Tuff	4-27-2N-24E	6080
W-68	Rhyodacite Tuff	22-28-2N-24E	6680
W-70	Rhyodacite Tuff	10-27-2N-24E	6120
W-72	Rhyodacite Tuff	31-22-2N-24E	6500
W-79	Hornblende Quartz Syenite	29-15-2N-24E	7300
W-80	Hornblende Quartz Syenite	29-15-2N-24E	7280
W-87	Biotite-Hornblende Dacite	3-27-2N-24E	6320
W-88	Biotite-Hornblende Dacite	3-27-2N-24E	6400
W-90	Hornblende Leucogranite Porphyry	35-18-2N-24E	7960
W-92	Hornblende Leucogranite Porphyry	15-19-2N-24E	7400
W-94	Hornblende Leucogranite Porphyry	20-25-2N-23E	8466
W-95	Biotite Hornsfel	32-15-2N-24E	7260
W-96	Biotite Hornsfel	3-22-2N-24E	7370
W-100	Biotite-Hornblende Dacite	17-33-2N-24E	6340
W-101	Rhyodacite Tuff	15-28-2N-24E	6880
W-103	Biotite Granite	34-24-2N-23E	7580
W-104	Biotite Granite	25-24-2N-23E	7400
W-105	Rhyodacite Tuff	1-30-2N-24E	6700
W-107	Biotite Hornsfel	17-29-2N-24E	6400
W-110	Biotite Granite	32-13-2N-23E	9313
W-116	Hornblende Leucogranite Porphyry	10-30-2N-24E	6640
W-117	Biotite Granite	5-32-2N-24E	6463
W-119	Biotite Granite	13-32-2N-24E	6020
W-130	Olivine Basalt	28-34-2N-24E	6000
W-132	Olivine Basalt	13-34-2N-24E	6050
W-139	Hornblende Leucogranite Porphyry	1-30-2N-24E	6720
W-140	Hornblende Leucogranite Porphyry	7-19-2N-24E	8520
W-141	Biotite-Hornblende Dacite	29-23-2N-24E	6140
W-145	Olivine Basalt	23-27-2N-24E	6020
W-146	Olivine Basalt	15-26-2N-24E	6000

TABLE II

PETROGRAPHIC DESCRIPTION OF BIOTITE RHYODACITE TUFF BRECCIA

Sample W-3

65%	Lithic fragments:	subangular-subrounded; size range 2 mm - 2 m, averaging 45 mm in diameter; 51.2% rhyodacite, hyalopilitic, vitrophyric, microgranular; some vitrophyre with patchy polarization; phenocrysts include plagioclase, orthoclase, hornblende, biotite, magnetite; few broken anhedral quartz; 13.8% pumiceous vitrophyre with phenocrysts of plagioclase, biotite, and magnetite set in pale yellowish brown altered glass segmented by chloritic globulites.
23.3%	Crystals:	some euhedral but most broken and angular; size range 0.5-5 mm. 6.1% plagioclase (An_{20-36}); altered to sericite and epidote; inclusions of glass and apatite. 11.8% K-feldspar; subhedral equant prisms broken; perthitic and sericitized. 4.3% biotite; tabular to columnar; pleochroic yellow brown; chlorite pseudomorph; inclusions of zircon apatite, magnetite, and hematite. 1.1% hornblende; X=pale brown, Y=green, Z=brown; columnar broken; poikilitic with magnetite; rimmed with yellow green fibrous chlorite.
11.7%	Matrix:	size less than 0.5 mm; indistinguishable fragments in pale dusky green chloritic glass occluded by fine granular epidote (?); glass pumiceous in places; crystallites common.

TABLE III

MODAL ANALYSIS OF RHYODACITE TUFF

		Tcvl samples					Tcv3 samples			
	W-46	W-47	W-53	W-1	W-70	W-67	W-105	W-101	W-72	W-68
Pumice % (black) < 4mm	9.5	6.0	3.2	tr	5.6	9.0	12.1	6.6	6.1	35.5
Crystals % < 4mm	35.9	27.0	49.1	60.3	30.2	30.9	55.0	47.7	52.1	22.1
Quartz	17.9	4.3	5.2	1.8	6.7	12.2	24.8	9.0	30.1	5.7
Plagioclase (An_{26-32})	1.1	5.6	11.8	29.2	12.9	7.5	15.3	20.2	0.5	4.9
K-feldspar	16.0	13.9	28.0	26.5	9.4	6.0	12.7	6.0	14.6	1.9
Femics[1]	—	1.0	4.0	1.6	1.2	4.2	2.2	12.5	0.9	9.6
Opaques[2]	0.9	2.2	tr	1.2	tr	1.0	tr	tr	tr	tr
Lithics % < 4mm	10.3	16.5	18.9	53.1	4.2	31.1	8.7	9.6	18.2	6.5
Accessory	9.1	16.0	17.3	2.0	4.2	30.1	8.7	7.3	16.1	6.5
Accidental	1.2	0.5	1.6	—	—	1.0	—	2.3	2.1	—
Vitric % (brown)	43.2	51.1	30.6	38.1	53.7	40.0	25.5	38.2	24.5	37.4
Totals % 1000 pts.	98.9	100.6	100.0	99.6	100.8	101.3	101.5	101.2	100.6	100.1

[1] biotite, hornblende

[2] magnetite

TABLE IV

MODAL ANALYSIS OF HORNBLENDE-BIOTITE RHYODACITE

Samples	W-15	W-28	W-26	W-10	W-19
Plagioclase (An_{28-42}) ave. 2mm	12.6	9.5	13.1	22.0	12.5
Orthoclase ave. 4mm	1.0	2.6	5.9	7.7	7.5
Phenocryst Totals	13.6	12.1	19.0	29.7	20.0
Plagioclase (An_{20-35})	3.7	0.8	2.9	0.6	5.5
Orthoclase	21.1	14.2	9.8	8.5	21.3
Sanidine	tr	2.1	tr	1.6	0.9
Quartz	31.0	20.7	34.0	25.7	22.8
Biotite	9.1	4.2	3.8	5.2	7.1
Hornblende	5.0	3.9	7.7	4.6	6.5
Diopside-Augite	tr	tr	tr	tr	tr
Hypersthene	—	tr	tr	—	—
Zircon	—	—	tr	—	—
Apatite	tr	1.0	tr	0.7	tr
Opaques[1]	1.2	0.9	1.5	1.5	1.0
Unresolvable Groundmass	14.1	38.0	21.0	21.2	13.0
Groundmass Totals <10.5mm	85.2	85.8	80.7	69.6	78.1
Alteration[2]	2.0	1.0	0.9	0.9	1.6
Totals 1000 pts	100.8	98.9	100.6	100.2	99.7

[1] magnetite, rutile, leoxene, hematite, pyrite

[2] chlorite, sericite, clays

TABLE V

MODAL ANALYSIS OF BIOTITE GRANITE

equigranular ave.1cm Samples	W-103	W-104	W-110	W-117	W-119
Plagioclase (An_{5-20})	9.1	7.0	14.2	7.6	10.4
Orthoclase	45.5	42.8	43.9	39.0	23.5
Quartz	29.6	31.6	30.1	35.2	47.1
Biotite	6.2	7.0	7.1	12.2	8.5
Hornblende X yellow green Y olive green Z dark green	3.2	2.3	1.0	1.0	1.1
Epidote	tr	tr	tr	tr	tr
Zircon	—	tr	—	—	tr
Apatite	1.0	tr	tr	tr	tr
Opaques[1]	1.7	0.9	0.9	1.0	1.7
Alteration[2]	4.4	9.2	2.5	5.2	8.6
Totals 1000 pts.	100.7	100.8	99.7	101.2	100.9

[1] magnetite, sphene, rutile, leoxene, garnet

[2] chlorite, sericite, clays, clinozoisite

TABLE VI

MODAL ANALYSIS OF HORNBLENDE LEUCOGRANITE PORPHYRY

equigranular ave. 3mm Samples	W-116	W-90	W-94	W-92	W-140
Plagioclase (An_{12-31})	10.7	8.2	12.1	0.9	7.1
Orthoclase	39.1	35.7	27.6	42.7	32.0
Quartz	40.0	46.2	55.5	39.8	51.6
Biotite	1.0	tr	—	tr	tr
Hornblende X yellow green Y olive green Z dark green	7.6	6.0	3.6	5.1	5.5
Apatite	tr	0.9	tr	tr	tr
Opaques[1]	tr	1.0	0.7	3.3	1.3
Alteration[2]	2.2	3.2	1.8	7.9	3.1
Totals 1000 pts.	100.6	101.2	101.3	99.7	100.5

[1] magnetite, sphene, shalerite, garnet, pyrite

[2] chlorite, sericite

TABLE VII

MODAL ANALYSIS OF HORNBLENDE QUARTZ MONZONITE

equigranular ave.5mm Samples	W-50	W-51	W-61	W-35	W-40
Plagioclase (An_{9-18})	33.2	25.6	29.2	35.8	29.0
Plagioclase (An_{31-48})	8.6	14.1	13.4	10.0	3.9
	41.8	39.7	42.6	45.8	32.9
Orthoclase	25.5	18.8	27.1	19.6	25.7
Quartz	10.2	15.5	19.6	15.2	23.4
Biotite	2.1	0.9	1.2	1.3	tr
Hornblende X pale brown Y green Z dark green	9.8	9.2	7.1	8.1	6.0
Augite	—	0.9	—	—	1.1
Apatite	0.6	tr	tr	tr	tr
Epidote	tr	2.7	tr	1.0	tr
Zircon	tr	—	—	—	—
Calcite	tr	tr	tr	—	tr
Opaques[1]	1.0	1.0	0.4	tr	1.1
Alteration[2]	9.7	12.1	3.4	9.2	10.3
Totals 1000 pts.					

[1] chlorite, sericite, zoisite, clinozoisite

[2] magmetite, rutile, sphene, leoxene, pyrite, hematite, shalerite, galene

TABLE VIII

MODAL ANALYSIS OF HORNBLENDE QUARTZ TRACHYTITE

aphanitic Samples	W-18	W-80	W-79
Plagioclase (An$_{5-12}$) ave. 1mm	3.9	3.7	6.0
Orthoclase ave. 1mm	12.7	18.1	10.1
Quartz ave. 0.8mm	3.1	1.9	3.5
Hornblende ave. 5mm	9.0	7.8	4.1
Phenocryst Totals	28.7	31.5	23.7
Biotite	tr	tr	tr
Apatite	tr	tr	tr
Opaques[1]	tr	2.8	tr
Unresolvable Groundmass	70.1	65.8	76.3
Groundmass Totals $<$0.5mm	70.1	68.6	76.3
Alteration[2]	0.9	1.2	1.1
Totals 1000 pts.	99.7	101.3	101.1

[1] magnetite, pyrite, sphalerite

[2] chlorite, sericite, clinozoisite

TABLE IX

MODAL ANALYSIS OF BIOTITE-HORNBLENDE DACITE

aphanitic Samples	W-141	W-33	W-87	W-88	W-100
Plagioclase (An$_{32-54}$) ave. 1mm	8.0	11.1	6.2	11.2	3.6
Orthoclase ave. 0.8mm	0.9	2.0	—	—	—
Biotite ave. 0.8mm	2.0	0.9	2.5	4.1	1.7
Hornblende ave. 0.8mm X pale yellow Y yellowish green Z olive green	1.8	4.1	5.0	3.6	2.0
Phenocryst Totals	12.7	18.1	13.7	18.9	7.3
Plagioclase (An$_{36-47}$)	1.6	18.2	22.5	3.3	0.9
Orthoclase	0.9	1.1	6.3	—	tr
Quartz	23.0	18.9	15.1	19.0	24.7
Biotite	3.0	3.9	4.1	2.6	5.6
Hornblende	7.1	1.8	2.6	0.9	3.0
Augite	tr	tr	tr	—	tr
Hypersthene	tr	tr	—	—	—
Olivine	tr	—	—	—	—
Apatite	tr	tr	tr	tr	tr
Opaques[1]	0.8	2.0	1.9	2.1	0.9
Unresolvable Groundmass	43.9	33.0	30.5	50.9	56.5
Groundmass Totals $<$0.5mm	80.3	78.9	83.0	78.8	91.6
Alteration[2]	8.1	4.2	2.6	3.0	2.2
Totals 1000 pts.	101.1	101.2	99.3	100.7	101.1

[1] magnetite, pyrite, hematite

[2] chlorite, sericite, epidote, zoisite

TABLE X

MODAL ANALYSIS OF BIOTITE HORNSFEL

fine grain

Samples	W-52	W-107	W-96	W-95
Plagioclase (An_{10-21})	32.7	20.0	35.2	12.1
Orthoclase	tr	tr	tr	tr
Quartz	8.1	6.7	7.2	4.3
Biotite	8.6	9.4	6.7	4.8
Hornblende	1.4	tr	tr	1.2
Epidote-Zoisite	9.7	6.8	4.8	3.4
Diopside	0.9	0.9	1.1	0.8
Actinolite	2.1	3.4	2.1	2.9
Opaques[1]	1.1	1.1	0.9	tr
Unresolvable Groundmass	30.7	47.5	40.2	67.7
Alteration[2]	5.6	4.7	2.0	1.9
Totals 1000 pts.	100.9	100.5	100.2	99.1

[1] magnetite, spinel

[2] chlorite, sericite

TABLE XI

MODAL ANALYSIS OF OLIVINE BASALT

aphanitic Samples	W-145	W-146	W-130	W-132
Plagioclase (An$_{54-71}$)	6.8	9.2	7.5	12.4
Phenocrysts Totals ave. 0.8mm	6.8	9.2	7.5	12.4
Plagioclase (An ?)	5.7	8.2	10.1	16.1
Olivine	1.9	4.0	2.4	6.6
Augite	2.1	1.0	1.2	1.2
Hypersthene	tr	1.1	2.1	1.2
Apatite	tr	tr	tr	tr
Opaques[1]	3.1	2.0	2.1	1.6
Unresolvable Groundmass	67.9	69.2	59.3	46.1
Groundmass Totals 0.5mm	80.7	85.5	77.2	72.8
Vesicles	12.7	5.9	14.2	15.3
Alteration[2]	0.8	tr	tr	0.6
Totals 1000 pts.	101.0	100.6	98.9	100.9

[1] magnetite, rutile, spinel

[2] epidote, cliozoisite, serpentine, iddingsite

PLATE I