An Abstract of the Thesis of

Richard C. Hook for the degree of Master of Science.

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Approved:

Edward M. Taylor

Steens Mountain is a major horst block near the northern terminus of the Basin and Range geomorphic province of southeastern Oregon. A section of Miocene volcanic rocks totaling 5000 feet in thickness are exposed in a fault escarpment on the eastern side of Steens Mountain. These include: the Pike Creek Formation, consisting of rhyolite and dacite flows and tuffs about 1000 feet in thickness, including one rhyolite ignimbrite locally 900 feet thick; the Andesite Series (also known as Steens Mountain Volcanics), a sequence of andesite and basaltic andesite flows totaling about 1500 feet in thickness; Steens Basalt, a series of 15 million year old high-alumina olivine basalt flows totaling about 3000 feet in thickness, which crop out extensively in southeastern Oregon. Steens Basalt also crops out in the Mickey Hot Springs area, 16 miles east of Steens Mountain, where it is overlain by a thin, continuous ignimbrite and a younger basalt, here informally named Mickey basalt.

The basalts of Steens Mountain were compared to those of the Mickey Hot Springs area. Correlation is established on the basis of a paleomagnetic reversal observed in the two areas, and supported by petrologic observations and chemical analysis.

A large circular fault basin north of Mickey Hot Springs is suggestive of a collapsed caldera structure. The great thickness of a rhyolite ignimbrite in the Pike Creek formation may have been deposited in a rhyolite-flood eruption associated with a caldera collapse, creating a structure such as the one north of Mickey Hot Springs.

THE VOLCANIC STRATIGRAPHY OF THE MICKEY HOT SPRINGS AREA, HARNEY COUNTY, OREGON

By Richard Hook

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APPROVED

Redacted for privacy

Major Professor

Redacted for privacy

Chairman, Department of Geology

Redacted for privacy

Dean of the Graduate School

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typed by Lisa Oberste

for Richard Hook

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THE VOLCANIC STRATIGRAPHY OF THE MICKEY HOT SPRINGS AREA, HARNEY COUNTY, OREGON

INTRODUCTION

Problem and Purpose

The purpose of this study is to record and describe the volcanic sequence exposed on Steens Mountain in southeastern Oregon and correlate it with a similar sequence to the east of Steens Mountain in the Mickey Hot Springs area. The study is of interest because it demonstrates the areal extent of a portion of the Steens Basalt. It also provides a basis for more precise stratigraphic correlation and a better understanding of the structure of the area. An understanding of the volcanic stratigraphy and structure in the area is of value to the geothermal exploration currently underway there.

Methods

Field mapping was done on nine-inch by nine-inch aerial photographs at a scale of 1:20,000. This information was transferred to U.S.G.S. 7-1/2 minute topographic sheets including Alberson 3 Northeast, Alberson 3 Northwest (advance prints) and Wildhorse Lake (1968). A Brunton compass and Thommen altimeter were used to determine locations in the field. Stratigraphic sections were measured by using a Brunton clinometer as a level.

Samples of all lithologic types were taken and prepared for petrographic and whole-rock oxide analysis. Seventy specimens were prepared in thin section and examined with a petrographic microscope. The Michel-Levy method for plagioclase determination was used. Forty samples were prepared for anhydrous whole-rock oxide analysis. The analyses were done by Dr. E.M. Taylor, using x-ray fluorescence spectrometry for FeO, TiO_2, CaO, K_2O, SiO_2, and Al_2O_3. Atomic absorption spectrophotometry was used for analysis of Na_2O and MgO. In the Steens Basalt 50 samples which were not highly porphyritic or vesicular were selected for paleomagnetic interpretation. The position of magnetic north and the horizontal were marked on each sample before it was removed from outcrop. Analysis of paleomagnetic polarity was done in the lab using a California Electronic Model 70 fluxgate magnetometer.

Borehole cuttings were obtained from two exploratory geothermal wells in the area. Ten foot grab samples were examined with a binocular microscope and their descriptions used to construct sample logs.

Location and Accessibility

The study area includes roughly the northern two-thirds of Township 33 South, Ranges 34 and 35 East, and the northern two-thirds of the west half of Township 33 South, Range 35 East. This constitutes a strip of land three to four miles wide, beginning at the crest of Steens Mountain and extending east across the northern end of the Alvord Desert into the Sheepshead Mountains some 15 miles distant. The highest point in the area is Steens Mountain at an elevation of 9,639 feet. The lowest point is in the Alvord Desert near Mickey Hot Springs at an elevation of 3,994 feet.

Access to the western part of the study area is provided by the Steens Mountain Loop Road, which leads east from the town of Frenchglen on Oregon Route 205 to the summit of Steens Mountain. The central part of the area can be reached on a Harney County road which connects Oregon Route 78 at Follyfarm, Oregon, with Nevada Route 140 at Denio, Nevada. The eastern part of the area is accessible via a network of dirt roads connecting the county road with the Mickey Hot Springs area. Nearly all of the study area is in public ownership.

Climate and Vegetation

Because of its great elevation, Steens Mountain is cooler and receives more precipitation than does the semi-arid Alvord Desert. Steens Mountain is snow-covered from November through April. Small patches of snow remain in protected areas near the summit throughout the summer. Steens Mountain receives most of its precipitation in the winter and spring. Summers are mostly dry but late afternoon thunderstorms are not uncommon. Average precipitation in the Alvord Desert is less than 10 inches per year. Temperatures are mild, ranging from 20° to 40°F in winter and 45° to 85°F in summer.

As a result of the dry climate vegetation in most of the area is sparse and small in size. Trees are found in protected canyons high on Steens Mountain with cottonwood and aspen the most common varieties. Unprotected areas on Steens Mountain are covered with grasses and low bushes. Vegetation in the Alvord Desert is very sparse and includes sagebrush, greasewood, grasses and cactus.

Regional Geology

Steens Mountain is the largest topographic feature in southeastern Oregon (Figure 1). Inspired by its sharp rise from the floor of the

Figure 1. Steens Mountain Viewed from the Alvord Ranch.

Alvord Desert, Howell Williams termed it "unrivaled in grandeur" (Williams & Compton, 1953). Steens Mountain, together with the Pueblo Mountains to the south, form a continuous north-trending range roughly 20 miles wide and 100 miles long. Located near the northern limit of the Basin and Range geomorphic province, Steens and the Pueblo Mountains comprise a major horst-block, flanked by the grabens of the Catlow Valley to the west and the Alvord Basin to the east. The central part of the range is a westward-dipping horst known as High Steens, which creates a gentle dip-slope from the summit west to the Catlow Valley. To the east, a tremendous normal fault caused a 5,000 foot scarp, plunging to the flat Alvord Basin below.

In the Pueblos, the section exposed in the east-bounding fault scarp consists of Paleozoic and Mesozoic metamorphic and intrusive rocks, overlain by a series of Tertiary volcanic rocks. The Paleozoic and Mesozoic rocks do not crop out as far north as Steens Mountain, but are inferred to lie beneath the Tertiary rocks found there. The Tertiary rocks exposed in the Pueblo Mountains are, in part, correlative with the Pike Creek Formation and the Steens Basalt exposed in the scarp of Steens Mountain.

The entire section exposed in the eastern scarp of High Steens is composed of Miocene volcanic, volcanoclastic, and epiclastic rocks. These include, from base to top, the Pike Creek Formation, the Alvord Creek Beds, the Basic Andesite Series, the Upper Andesite Series, and the Steens Basalt. Two other informal rock units which do not crop out on Steens Mountain, but are found in the Alvord Desert area, are the Mickey ignimbrite and the Mickey basalt.

The Pike Creek Formation consists of pyroclastics and flows of rhyolite and dacite. It crops out along the base of High Steens for a distance of about six miles both north and south of Big Alvord Creek. It also crops out 12 miles south of High Steens in the area west of Alvord Lake, and 35 miles south in the Pueblo Mountains near Red Point. In its type section along Pike Creek, the Pike Creek Formation consists of 1,500 feet of pyroclastics and flows of rhyolite and dacite. These lithologies are very localized, showing rapid lateral changes and making correlation within the unit difficult. A new date presented in this study places the age of the Pike Creek Formation at 23.7 ± 1.3 million years (Vance, personal communication, 1980). Because of the large local thickness of pyroclastics, it may be inferred that the Pike Creek Formation is continuous in subsurface throughout the area.

The Alvord Creek Beds apparently are a restricted unit which crops out mainly along Big Alvord and Little Alvord Creeks, at the base of the Steens Mountain scarp. They are predominately well-bedded tuffaceous rocks but some flow and pyroclastic rocks are found near the top of the unit. Flows in the Alvord Creek Beds have been radiometrically dated at 21.3 million years (Evernden and James, 1964). The Alvord Creek Beds occupy the same stratigraphic interval as the Pike Creek Formation, in the sense that both underlie the "Basic" Andesite. The Alvord Creek Beds appear to lie conformably beneath the andesite, whereas the Pike Creek Formation lies unconformably beneath it. This relationship is supported by the dates which show the Alvord Creek Beds to be younger than the Pike Creek Formation. The lateral contact between the Alvord Creek Beds and the Pike Creek Formation is not exposed. Wilkerson

(1958) and Baldwin (1976) considered the two units to interfinger. In light of the dates presented here such interfingering appears unlikely.

Unconformably above the Pike Creek Formation and the Alvord Creek Beds is the Andesite Series of Fuller (1931). The "Basic" Andesite Series consits of three locally thick andesite flows in the area between Big Alvord Creek and Cottonwood Creek. The largest of these, called the "Great Flow", reaches a thickness of 900 feet. Resting conformably on these flows is the "Upper" Andesite Series. In the central part of the range this unit consists of blocky andesite flows averaging about 40 feet in thickness with a total thickness of 1,000 feet. The andesite is predominately aphanitic. Rubbly flow-margin breccias and ash interbeds are also characteristic of this series. Near the southern end of Steens other lithologies, including basalt and rhyolite, are reported within this part of the section. To this interval the name Steens Mountain Volcanic Series is applied (Williams and Compton, 1953). The "Upper" Andesite Series crops out continuously along the eastern scarp of Steens Mountain but is not seen elsewhere in the area.

Disconformably above the "Upper" Andesite series is the Steens Basalt. This sequence consists of 3,000 feet of similar flows of porphyritic high-alumina olivine basalt averaging roughly 20 feet in thickness (See Figure 2). Many of the flows contain phenocrysts of plagioclase as large as 50 mm, which comprise up to 20 percent of the rock. Steens Basalt has been dated at 15.1 ± .3 million years (Watkins, et. al., 1967). It is recognized over a large area on the basis of lithologic characteristics and position in the sequence. Steens Basalt caps the entire length of Steens Mountain and most of Pueblo Mountain. It is

Figure 2. Steens Basalt along Willow Creek near the summit of Steens Mountain.

reported as far west as the Warner Rim, a distance of 80 miles (Fuller, 1931). To the east, immediately across the Alvord Basin, it crops out extensively in the Sheepshead Mountains and has been found as far east as the Owyhee River Canyon (Baldwin, 1976). The Owyhee Basalt occupies a similar stratigraphic position and is equivalent in age, but is dissimilar lithologically. The Columbia River Basalt Group, which covers a large part of northeastern Oregon, is also age-equivalent but lithologically different.

Steens Basalt is the youngest stratigraphic unit exposed on High Steens, but elsewhere in the region younger volcanics are found. Two younger units crop out in the Sheepshead Mountains and are described in this paper. These are informally named the Mickey basalt and the Mickey ignimbrite. These units show a conformable relationship with Steens Basalt.

Several Pliocene rhyolitic ash-flow tuffs have been described in the region (Green, 1973). These include the Devine Canyon ash-flow tuff in the Harney Basin and the Trout Creek Ignimbrite in the Trout Creek area. These young ignimbrites have not been identified within the study area.

The Steens Mountain area is in the northern part of the Basin and Range Province near its termination against the Brothers Fault Zone (Lawrence, 1976). The major structures in the region are range bounding normal faults which generally trend north-south, as seen in the eastern scarp of Steens Mountain (Figure 1). The scarp appears to be in an active zone of long-lived crustal weakness. Dikes and eruptive centers are well exposed in the scarp suggesting that this same zone was exploited by rising magma during Miocene time, probably before significant displacement had occurred. A subordinate set of normal faults in the area trends roughly northwest-southeast, crossing the north-south faults at about 45° (Figure 3). Faults of this orientation are seen best on horst blocks such as Steens Mountain, and are generally parallel to the Brothers Fault Zone and the Eugene-Denio Lineament (Lawrence, 1976). The block comprising High Steens is a discrete horst terminated to the north and south by two of these northwest-trending faults which cross the range in a transverse fashion.

East of Steens Mountain the north-trending structual grain is expressed in the Alvord Desert, which is a linear graben bounded to the east by a low scarp. This grain continues to the north, but in the Sheepshead Mountains the north-south trend becomes subordinate to an east-west grain, as seen in Figure 3. Displacements along the normal faults in the Alvord Desert and Sheepshead Mountain area are generally much less than those seen near Steens Mountain.

Previous Work and Stratigraphic Nomenclature

The pioneer work on the Steens Mountain section was done by Fuller in 1931. He applied the names Alvord Creek Beds, Pike Creek Volcanic Series (restricting it to the rhyolite and dacite flows and pyroclastics from Pike Creek south to Indian Creek), "Basic" Andesite, "Upper" Andesite Series and Steens Mountain Basalt. These names were based on a study of the High Steens scarp, principally between Pike and Willow Creeks in the central part of the range.

In 1953 Williams and Compton published a paper dealing with cinnabar prospects in the rhyolitic and dacitic rocks of the Pike Creek

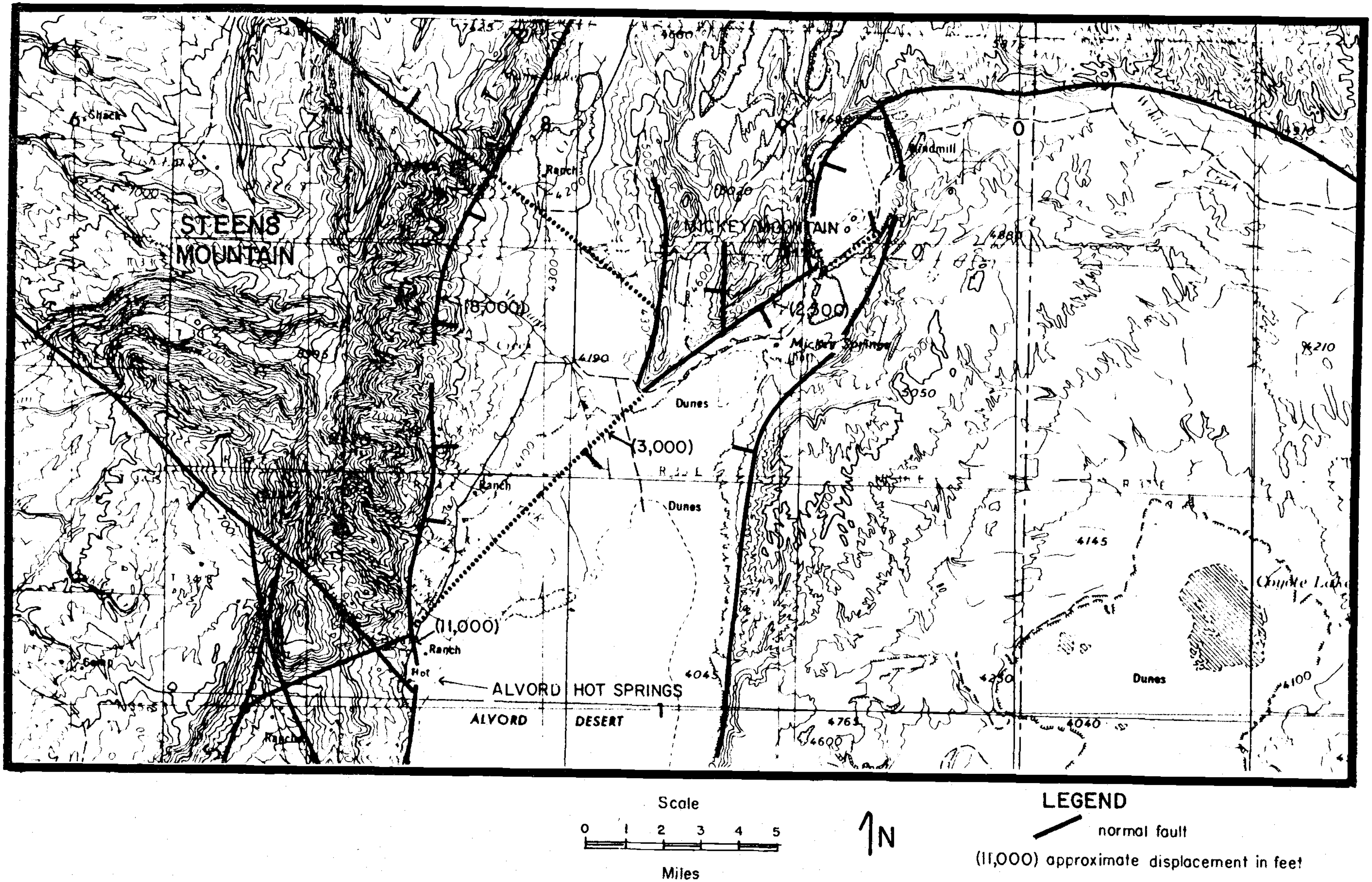


Figure 3: Regional Tectonic Map Of The Steens Mountain Area.

Formation. Their study was geographically restricted to the eastern scarp of southern Steens Mountain and the northern Pueblo Mountains, from Red Point north to Indian Creek. They found that the unit between the Pike Creek Formation and the Steens Basalt included several different rock types ranging from basalt to rhyolite. Due to this petrologic variation they proposed the name Steens Mountain Volcanic Series to replace the "Upper" Andesite Series of Fuller. The use of two names has resulted from the fact that the two studies were centered in different areas. In the scarp of High Steens where Fuller worked, the section is essentially all andesite; where Williams and Compton worked, the petrologic variety required a broader name (see Figure 4).

The use of the name Steens Mountain Volcanic Series (or Steens Mountain Volcanics) has been continued by Wilkerson (1958) in his masters thesis, as well as by Walker and Repenning (1965) on their reconnaissance geologic map of the area. Wilkerson worked in the scarp of High Steens as had Fuller, but mistakenly identified the andesite as basalt, and applied the term Steens Mountain Volcanic Series, following Williams and Compton. While this name is valid, in that the unit in question is certainly volcanic, it is inappropriately broad. All of the rocks exposed on the eastern scarp of Steens Mountain are volcanic, but only a distinct sequence are andesitic. Because this study is concerned with the section along the northern part of the High Steens scarp where only these andesites are present, the terms "Basic" Andesite and "Upper" Andesite Series are followed here. The reader should note the term "Basic" Andesite refers only to the stratigraphic position and not the composition of the rocks it is intended to describe.

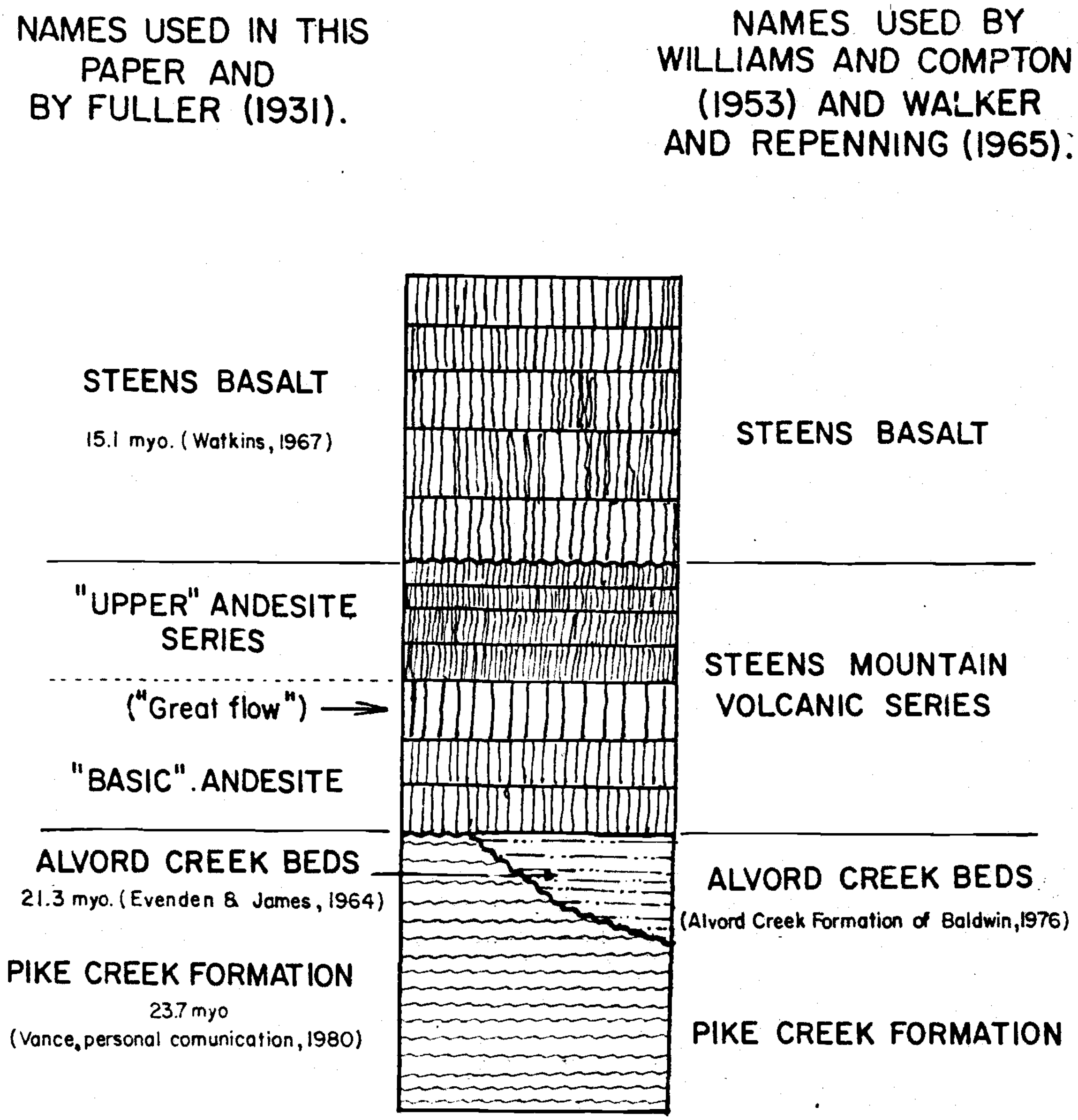


Figure 4: Stratigraphic Column Showing Various Names Used In The Steens Mountain Area.

Wilkerson also used the name Alvord Creek Formation, as did Baldwin (1976). As mentioned above, the Alvord Creek Beds are similar to, and enclosed within the Pike Creek Formation. Walker and Repenning (1965) included them in the Pike Creek Formation on their reconnaissance geologic map. Although they do constitute a mappable lithologic unit, it seems better to denote this unit as the Alvord Creek Beds of the Pike Creek Formation until its extent and stratigraphic relationship is better understood.

STRATIGRAPHY

The stratigraphic section exposed in the study area includes all of the rock units exposed in the Steens Mountain scarp. Two other units found within the area are younger than the Steens section and are exposed only in the Sheepshead Mountains near Mickey Hot Springs. The section described includes (oldest to youngest): Pike Creek Formation, "Basic" Andesite, "Upper" Andesite Series, Steens Basalt, and the informal units here named Mickey ignimbrite and Mickey basalt (see Figure 4).

Pike Creek Formation

Within the study area the Pike Creek Formation crops out continuously along the base of the eastern scarp of High Steens, but is not seen elsewhere. It is exposed best along Cottonwood and Willow Creeks, where it consists entirely of densely welded rhyolite ignimbrite (Figure 5). Exposure is poor on the scree-covered slopes between the canyons but abundant rhyolite float suggests the rhyolite is present there also. Fuller (1931) restricted his Pike Creek Volcanic Series to exposures of rhyolite and dacite south of Big Alvord Creek along the scarp, with the type section along Pike Creek. Walker and Repenning (1965) expanded the unit to include all of the rhyolite rocks exposed along the eastern scarp of Steens Mountain, and applied the term Pike Creek Formation. Fuller did not correlate the rhyolites along Cottonwood Creek with his Pike Creek Volcanic Series, citing a high degree of alteration and lack of continuous exposure. The present author feels that based on lithologic similarity and stratigraphic position, the rhyolites are correlative, and the name of Pike Creek Formation is applied here.

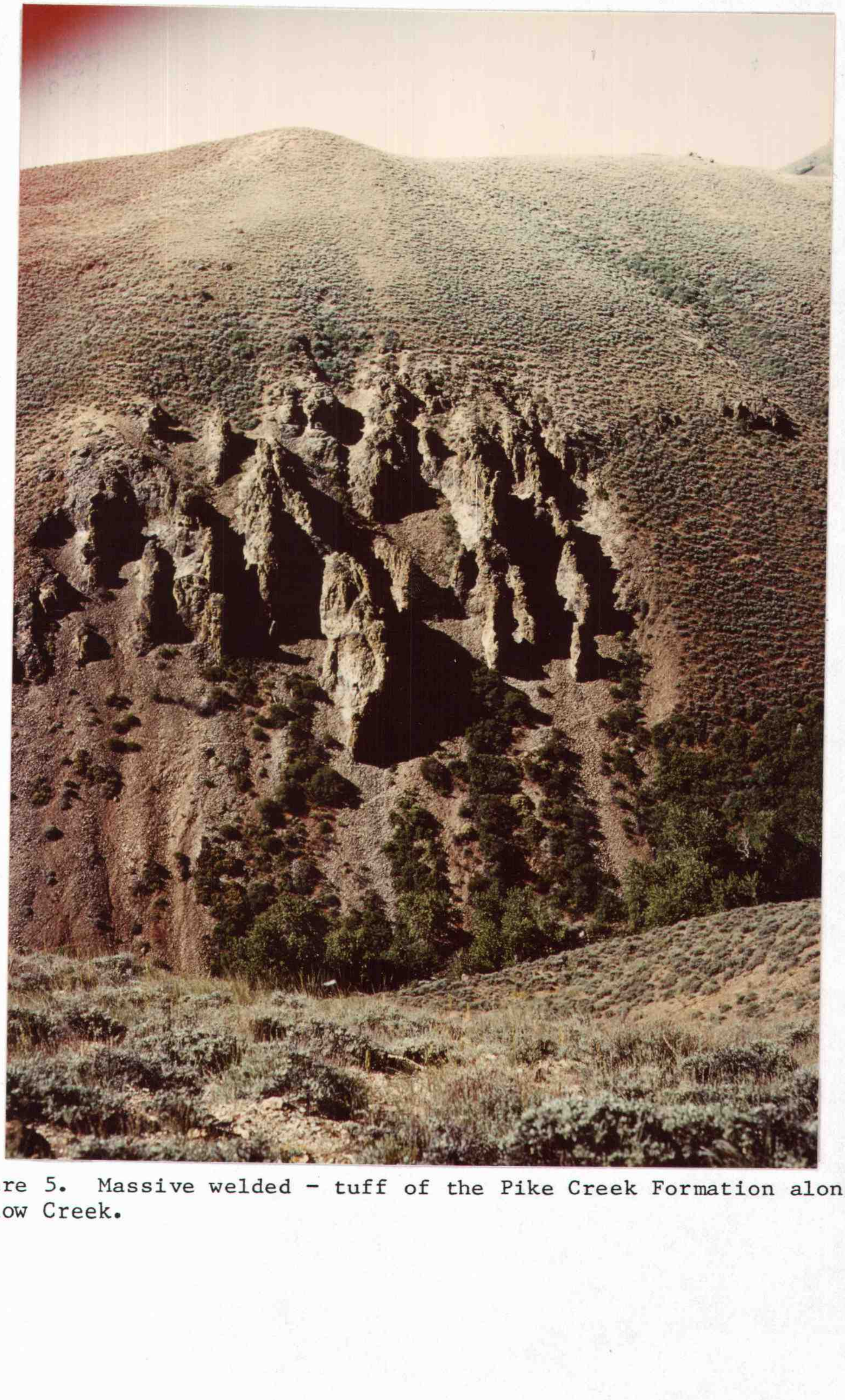


Figure 5. Massive welded - tuff of the Pike Creek Formation along Willow Creek.

The base of the Pike Creek Formation is not exposed along the Steens scarp. A maximum thickness of 900 feet is exposed in the Cottonwood Creek canyon. The slight northward dip of the Steens block causes this thickness to decrease northward along the base of the scarp. In the Pueblo Mountains, 30 miles south of Steens Mountain, a similar pyroclastic rhyolite rests directly on the pre-Tertiary intrusive and metamorphic rocks exposed there. This suggests that the Pike Creek Formation is the base of the Tertiary section in the Steens Mountain area, but such a relationship cannot be demonstrated on the surface. Just south of the study area, in the canyon of Big Alvord Creek, the rhyolites of the Pike Creek Formation are not seen and in their place is an 800 foot-thick sequence of lacustrine sediments known as the Alvord Creek Beds. These beds have limited outcrop in the canyon of Cottonwood Creek, where they can be seen to underlie the andesites in the scarp of a minor north-south fault. The relation between the Alvord Creek Beds and the Pike Creek Formation is not clear. Both units directly underlie the Basic Andesite in places, but the contact between Pike Creek and Alvord Creek Beds is not seen. A radiometric date of 21.3 million years has been reported for the Alvord Creek Beds (Evenden and James, 1964). A new fission track date on zircon (Vance, personal communication, 1980) indicates the rhyolite ignimbrite along Willow Creek (Pike Creek Formation) to be 23.7 ± 1.3 million years old. This shows the Pike Creek Formation to be older and suggests that the lacustrine Alvord Creek Beds were deposited on an erosional surface of Pike Creek rhyolite ignimbrite. This relationship is supported by the fact that the upper part of the Alvord Creek Beds are conformable and interbedded with the overlying Basic Andesite. In contrast, the Pike Creek rhyolites show slight disconformity along the contact with the overlying andesites.

In outcrop the Pike Creek Formation is light grey to buff. It is highly jointed and fractured. Reddish oxide stains along these fractures give the rock a pinkish cast when viewed from a distance. Along the walls of the canyons the Pike Creek Formation crops out as imposing cliffs, sometimes with sheer vertical faces as much as 400 feet high. Textures typical of a rhyolite ignimbrite, such as collapsed pumice shards and rock fragments are noted in the fresher outcrops but most of the unit is hydrothermally altered, making textural features difficult to see. Such alteration includes devitrification of the glass and deposition of secondary quartz, calcite, and zeolites. Locally a greenish color is noted, presumably due to clay, but most altered outcrops are grey to rusty brown.

Vertical traverses through the unit indicate it is a single, homogeneous, ash-flow tuff. Local variations in the abundance of phenocrysts, rock fragments, and pumice shards are noted, as well as varying degrees of alteration which appear gradational. No internal cooling surfaces within the unit were identified. Although not previously reported in the Steens Mountain section, thick rhyolite ignimbrites are well documented in the Basin and Range province of Nevada (Smith, 1960). Alteration may have masked the presence of multiple cooling units within this part of the Pike Creek Formation, but it appears to be a single flow.

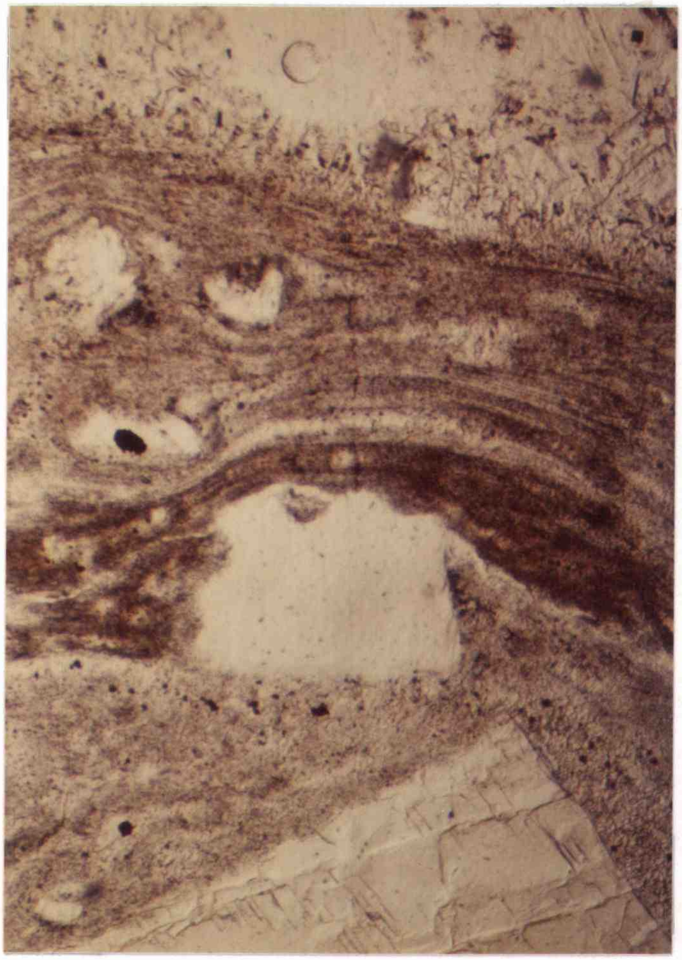


Figure 6. Eutaxitic texture in welded-tuff of the Pike Creek Formation (X20, plane-polarized light).

Petrology and Chemistry

The name rhyolite is applied on the basis of both mineralogy and major oxide chemistry. Phenocrysts of sanidine and quartz indicates that the rock is a sanidine rhyolite. Silica values of 74 to 79 percent, and K_2O of 5.7 to 6.35 percent support this classification. Sanidine and quartz are the only phenocryst phases noted. Typically the rock contains 15 to 20 percent subhedral to euhedral laths and equidimensional phenocrysts of sanidine up to 3 mm in length. Quartz is rare, but occurs as small, subhedral phenocrysts up to 2 mm in size. The remainder of the rock consists of devitrified glass, minor pumice, rock fragments, and accessory magnetite and zircon. In less altered samples there is a pronounced eutaxitic texture resulting from compaction (Figure 6). In more altered samples this texture is obscured, but faint ghosts of shards, and evidence of compaction can be seen. Devitrification of the glass is complete, and spherulites and axiolites are present in all samples.

Alteration effects commonly include secondary silica replacing devitrified glass shards and filling open vugs and veinlets. Other secondary minerals include calcite, zeolites, and clays. The most highly altered samples show abundant calcite replacing sanidine and axiolites of devitrified glass (Figure 7). Microlites of secondary pyrite and magnetite are noted in quartz veinlets in highly altered samples.

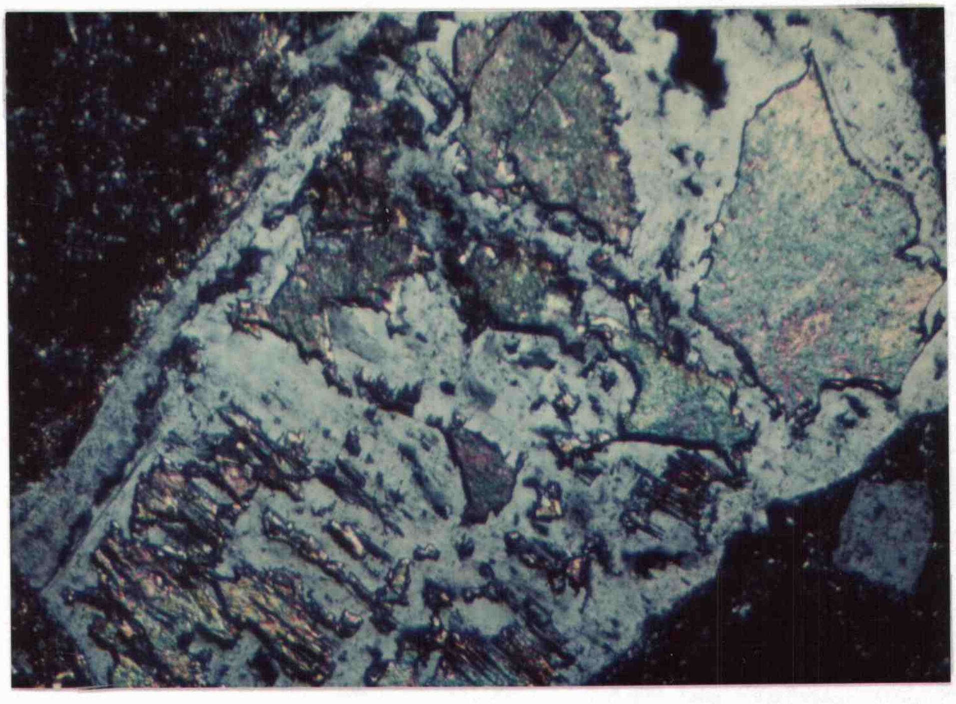


Figure 7. Calcite replacing sanidine in altered ash-flow tuff of the Pike Creek Formation (X50, cross-polarized light).

Four samples of Pike Creek Formation rhyolite ignimbrite were analyzed for major oxide chemical composition, including two samples from the Cottonwood Creek Canyon (CW-2, CW-8), and two from the Willow Creek Canyon, some two miles north (W-1 and W-10). The results are shown in Table 1. Sample W-1 was taken from the lowest exposures along Willow Creek. Sample W-10 came from an outcrop about 400 vertical feet higher, approximately half way through the Pike Creek section. The similarity of these two analyses suggests vertical homogeneity of the unit along Willow Creek. CW-8 came from a highly altered outcrop along a fault scarp, and this is reflected by the high content of CaO and and low content of Al_2O_3, FeO, and Na_2O. CW-2 came from near the top of the rhyolite outcrop along Cottonwood Creek, and is very similar to the two Willow Creek samples. Overall, the analysis of the three unaltered samples supports the conclusion that the Pike Creek Formation mapped within the study area is a single, thick rhyolite ignimbrite.

	Pike Creek Rhyolite				"Basic" Andesite			"Upper" Andesite Series
	CW-2	CW-8	W-1	W-10	CW-9	C-1	CW-5	M-4
SiO_2	72.5	77.9	76.7	76.4	55.3	57.3	63.8	58.7
Al_2O_3	14.8	9.0	12.8	13.0	17.8	17.4	16.7	18.1
FeO	1.5	0.8	1.2	0.9	8.4	7.1	4.1	6.0
CaO	0.2	5.5	0.1	0.1	6.4	6.2	4.2	5.3
MgO	0.2	0.1	0.1	nil	3.2	3.8	1.5	2.7
K_2O	5.60	6.20	5.55	5.50	2.10	2.35	3.15	2.80
Na_2O	4.4	0.2	3.8	4.0	4.0	3.8	4.0	3.8
TiO_2	0.50	0.20	0.20	0.30	1.25	1.05	0.60	.85
Total	99.70	99.90	100.50	100.25	98.45	99.20	98.05	98.25

Table 1. Oxide analyses of rhyolites and andesites in percent.

The Andesite Series

Above the Pike Creek Formation is a thick section of andesites, which includes three unusually thick flows at the base and a series of 25 relatively thin, highly brecciated flows above (Figure 8). The lower thick flows are termed the "Basic" Andesite and the upper thin flows the "Upper" Andesite Series following Fuller (1931). Because the two andesites are quite different in characteristics they are discussed separately.

The "Basic" Andesite

The "Basic" Andesite consists of three flows totalling 800 feet in thickness, ranging in composition from basaltic andesite (55.3% SiO_2) to andesite (63.8% SiO_2). Within the study area they crop out only along Cottonwood Creek although they are well exposed along Big Alvord Creek to the south, where they reach a maximum thickness of over 1,000 feet. North of Cottonwood Creek in the canyon of Willow Creek the "Basic" Andesite is absent, suggesting that in spite of their great thickness the flows are of limited areal extent. The depositional site could have been in an areally restricted basin. Such a basin may also have been the site of deposition for the Alvord Creek beds, prior to the eruption of the andesite.

The underlying Alvord Creek Beds have been dated at 21.3 million years (Evendon and James, 1964). Above the entire Andesite Series, the Steens Basalt is dated as 15.1 1.3 million years (Watkins, 1967). Because the "Basic" Andesite is conformable and adjacent to the Alvord Creek Beds, similar age is assumed for them. The angular unconformity between the Andesite Series and the Steens Basalt suggests that the basalt is much younger.

Only 40 feet of the lowermost "Basic" Andesite flow is exposed within the study area. Above it, separated by a tuff resembling the Alvord Creek Beds, is an identical flow about 200 feet thick, which is completely exposed. These two lower flows consist of dark grey, dense, aphyric and aphanitic andesite, resembling basalt in hand specimen. It is resistant and forms vertical cliffs along the canyon walls. The uppermost flow is by far the thickest. Fuller (1931) dubbed it the "Great Flow", based on exposures along Big Alvord Creek where it is 900 feet thick. Along Cottonwood Creek it is about 500 feet thick, forming high cliffs with well developed columnar jointing in the canyon walls.

The presence of visible phenocrysts, particularly in the upper part of the "Great Flow", makes it distinct from the lower two flows. Small black hornblende phenocrysts, as well as rare plagioclase can be seen in hand specimen. Otherwise, the rock is aphanitic and dense, resembling the lower flows. It is separated from the middle flow by a bed of air-fall tuff about 15 feet thick consisting primarily of andesite rock fragments and ash. As with the lower flows, there is no breccia at the base of the "Great Flow", and it appears to have quietly erupted into a great lava lake and slowly cooled. Columnar joints are evident in these thick flows. Between the flows minor beds of air-fall tuff consisting mainly of ash and andesitic rock fragments are seen, suggesting that violent volcanic activity occurred at the beginning or end of each eruption.

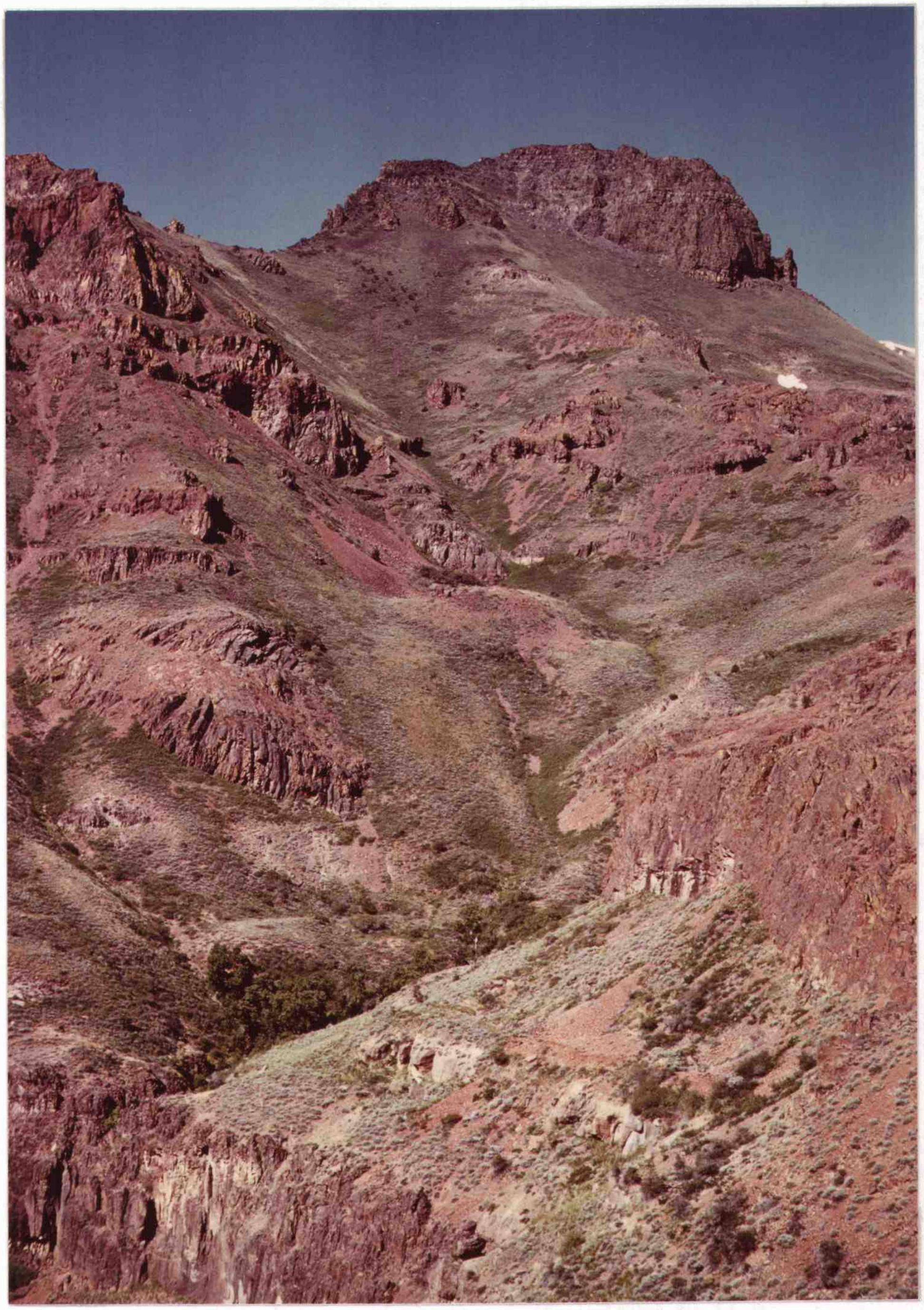


Figure 8. Andesites along Cottonwood Creek.

Petrology and Chemistry

In thin section the "Basic" Andesite flows are seen to be slightly porphyritic. Plagioclase (labradorite) is present in laths up to 2 mm in length. Clinopyroxene is seen in embayed and eroded crystals up to 2 mm in size. The groundmass consists of needle-like microlites of plagioclase, with intergranular to subophitic clinopyroxene. A faint, sub-parallel alignment of microlites in the groundmass is seen in some samples. Euhedral magnetite is disseminated throughout. Secondary calcite and zeolites are present as open space fillings.

Chemically the lower two flows are basaltic andesite in composition the "Great Flow" is andesite. Table 2 shows the major oxide composition for one sample of each flow. When plotted on a Peacock Diagram (Figure 9) the analyses of the "Basic" Andesite flows and the "Upper" Andesite Series flows are similar to calc-alkaline andesites of andesite belts. The high alumina and low silica values obtained from some samples are reminiscent of andesites and basaltic andesites of the Cascade Range of Oregon.

In thin section the groundmass of the Great Flow is seen to consist of small laths of andesine showing faint sub-parallel orientation with intergranular clinopyroxene locally present. Magnetite is disseminated throughout. Hornblende occurs as roughly equidimensional phenocrysts up to 1 mm in length, which have been corroded. Magnetite forms a reaction rim around most hornblende crystals. Andesine (An44) forms lath shaped phenocrysts up to 3 mm in length which show oscillatory zonation. Also present, but rare, are small phenocrysts of clinopyroxene. Small vesicles near the top of the flow are filled with calcite and zeolites.

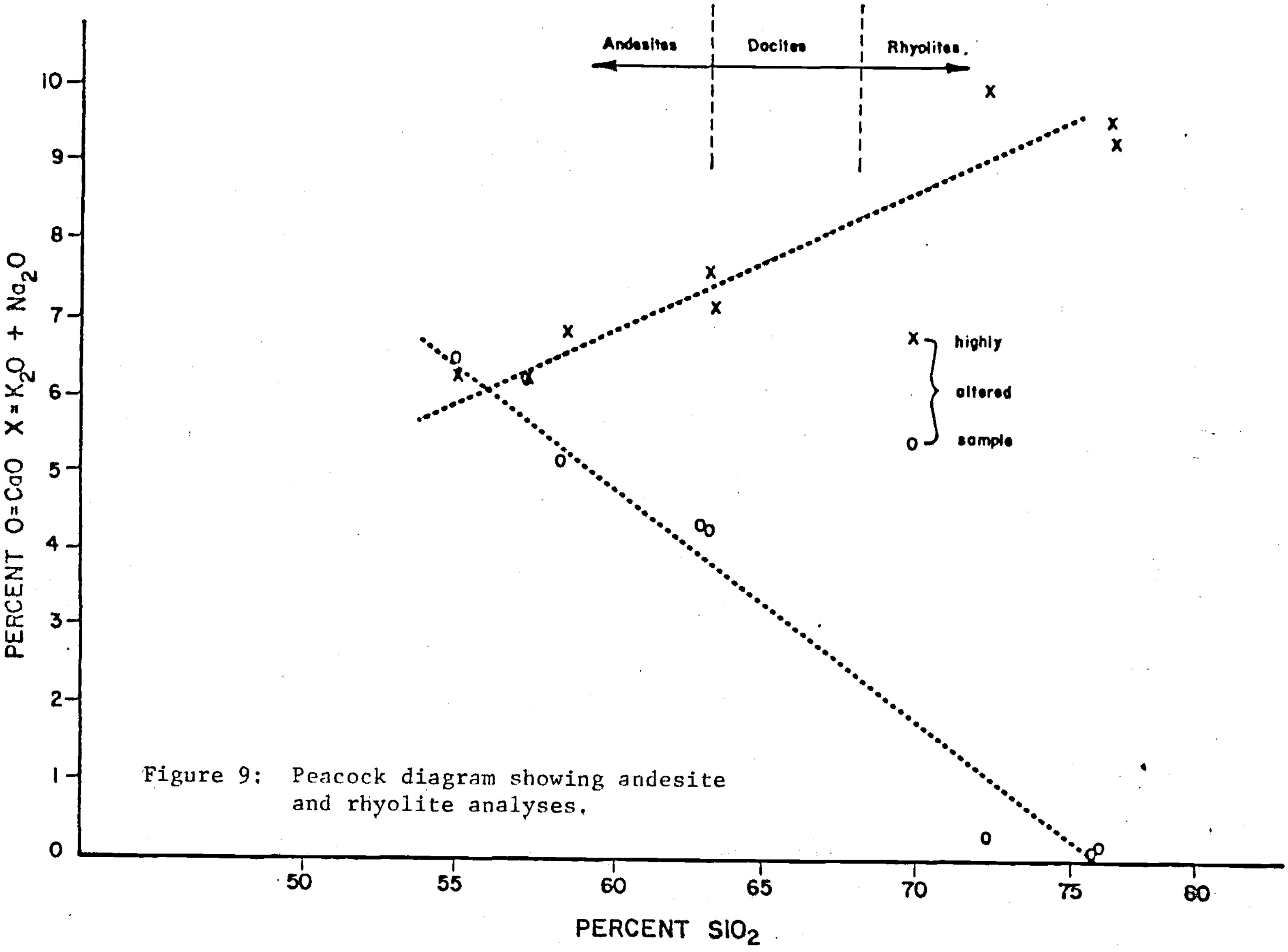


Figure 9: Peacock diagram showing andesite and rhyolite analyses.

Upper Andesite Series

In contrast to the "Basic" Andesite, the "Upper" Andesite Series is composed of about 25 relatively thin, blocky flows. In the study area the flows average approximately 25 feet thick, and locally may be as much as 200 feet thick. The total thickness is about 1,000 feet.

The "Upper" Andesite appears to rest conformably upon the "Great Flow", where the "Great Flow" is present. In the north part of the study area the "Upper" Andesite Series rests with slight angular unconformity and major disconformity on the Pike Creek Formation. The flows of the "Upper" Andesite Series are widespread in the area, cropping out nearly continuously along the eastern scarp of Steens Mountain from south of Follyfarm to the Fields area. The blocky, highly brecciated, flows do not appear to have been very fluid, so it is assumed they did not flow great distances. They appear to have erupted from the area of the present-day scarp. No vents are preserved in the study area, but the reminants of cinder cones have been reported both to the north and south (Fuller 1931). Several dikes cut the "Upper" Andesite Series but they are basaltic in composition and not related to the andesite.

In outcrop, the flows of the "Upper" Andesite Series consist of thick, blocky, flow-margin breccias enveloping the denser central portion of the flows. This central portion is usually dark grey, aphyric andesite with characteristically platy jointing. Locally the denser flow-center material has been injected into the breccias to form squeeze-ups and auto-injection breccias. Some flows are blocky throughout. The dense flow-centers sometimes are vesicular in their upper part. The vesicles are filled with a greenish material presumed to be a clay. The breccias are generally composed of vesicular scoriaceous material containing abundant blocks of denser rock, up to several feet in size. Oxidation of the iron minerals in the breccias give it a dark reddish color. When viewed from a distance, these thick breccias make the "Upper" Andesite appear reddish.

Petrology and Chemistry

In thin section most "Upper" Andesite flows are seen to be aphyric. Some are slightly porphyritic, and differ from the "Basic" Andesite by containing both clinopyroxene and minor orthopyroxene, as well as plagioclase phenocrysts. In at least one flow the pyroxene is dominant over the plagioclase phenocrysts, which is unusual for andesite. Clinopyroxene phenocrysts occur as anhedral crystals up to 3 mm in length. Orthopyroxene phenocrysts are more rare, occurring as embayed anhedral crystals about 1 mm in length. The plagioclase is andesine (An48), and occurs as laths up to 3 mm in length. Total phenocryst content is less than 5 percent. The groundmass consists of tiny interlocking laths and microlites of plagioclase, with minor intergranular clinopyroxene arranged in a pilotaxitic texture. There appears to have been some glass in the rock but this is now devitrified and altered to a dusty gray substance, presumed to be clay.

Only one sample of the "Upper" Andesite Series was analyzed for major oxide composition (see Table 1). The results show a typical andesite. This composition is included in the Peacock diagram (Figure 9), and plots with the other andesites and rhyolites in a manner similar to those of the Oregon Cascades.

Steens Basalt

The Steens Basalt is a thick sequence of high-alumina olivine basalt, which is widespread in southeastern Oregon. The name was formalized by Fuller (1931) and is taken from Steens Mountain, where its spectacular outcrops comprise the upper one-third of the eastern scarp. Steens Basalt is found all along the length of Steens and Pueblo Mountains. To the west it has been correlated with a series of flows exposed some 50 miles distant in the Warner Rim (Fuller 1931). East of Steens, the basalt is exposed along several of the fault scarps in the eastern side of the Alvord Desert and in the Sheepshead Mountains, where it lies beneath a younger basalt, informally called Mickey basalt. Steens Basalt crops out as far east as the canyon of the Owhyee River. The Owhyee Basalt and part of the Columbia River Basalt Group are similar to Steens Basalt in age but both are different in appearance and distribution. Steens Basalt has been dated at 15.1 .3 million years (Watkins, 1967).

The base of the Steens Basalt is exposed only along the eastern scarp of Steens Mountain, where it rests on an erosional surface of the "Upper" Andesite Series. This disconformity is shown best in the study area along the south side of Willow Creek, where flows of Steens Basalt lap onto a paleo-slope of andesite (Figure 10). The basalt is more resistant than the andesite and forms towering outcrops in the canyons and cirques on the upper part of Steens Mountain.

A swarm of dikes trending roughly north-south along the eastern scarp of Steens Mountain are believed to have fed a series of elongate fissure vents from which most of the basalt was extruded (Figure 11). In the Mickey Hot Springs area a few more north-trending basalt dikes

Figure 10. Steens Basalt resting disconformably on the "Upper" Andesite along Willow Creek.

Figure 11. Basalt dikes cutting Steens Basalt near the summit of Steens Mountain.

are exposed, suggesting that eruption was not restricted to the area of the present day scarp.

Several factors suggest that the basalt was extremely fluid. Individual flows average ten feet in thickness with a range from 2 to 150 feet. They are usually bounded only by a minor cooling rind, with no breccias present. Most flows are dense or diktytaxitic with vesicular zones commonly near the top. Even thin flows can be traced laterally for several hundred yards along the scarp, and presumably could be traced many miles if access permitted. The flows are often massive, but in thick flows a crude columnar jointing can be seen. The Steens Basalt flows appear to have accumulated rapidly; at no place within the study area was evidence of an inter-flow soil horizon found. Indeed, the near absence of a cooling rind between some flows suggests they were not even cool when covered by successive flows.

The total thickness of basalt exposed on Steens Mountain is about 3,000 feet. This figure represents nearly the total thickness deposited there, with only a minor amount having been removed by erosion. In the Mickey Hot Spring area the base of the basalt is not exposed, but on the basis of paleomagnetic stratigraphy discussed below, a greater thickness, on the order of 4,000 feet, was deposited there.

Steens Basalt ranges from dark grey and dark brown to nearly black. Phenocrysts of olivine and plagioclase are seen in most flows. The olivine occurs in roughly equidimensional crystals up to 4 mm in size. Olivine generally makes up one to four percent of the rock, but in exceptional flows may be as high as twenty percent. The plagioclase occurs as long laths and tablets. Most flows have in excess of 10 percent plagioclase, with 20 to 30 percent not uncommon. They range in size from 4 mm to 50 mm. These flows, rich in large plagioclase phenocrysts, are the most characteristic type of Steens Basalt. Also noted in some flows are visible clinopyroxene crystals. Aphyric flows are present but are not common. Diktytaxitic texture can be seen in the fine vesicular zone occurring near the top of most flows. When viewed with a hand lens, tiny laths of groundmass plagioclase can be seen protruding into open vesicles. Glomeroporphyritic plagioclase is also common.

Petrology

In thin section Steens Basalt is usually porphyritic with a subophitic groundmass. Less common aphanitic flows have a subophitic to ophitic texture. Phenocryst phases, in order of abundance, include plagioclase, olivine, and clinopyroxene. These are often randomly dis-

Figure 12. Laths of plagioclase showing diktytaxitic texture in Steens Basalt (X20, cross-polarized light).

seminated throughout the rock, but may be found in clots. The diktytaxitic texture is best developed in coarsely crystalline, finely vesicular flows and can be better seen with a hand lens than in thin section, due to destruction of the delicate feldspar laths during grinding. Groundmass minerals include plagioclase, clinopyroxene, olivine, and magnetite.

The plagioclase phenocrysts are zoned labradorite ranging in composition from An53 to An70, with an average of An63. The plagioclase phenocrysts range in size up to 50 mm in length and show normal oscillatory zonation. They occur as subhedral laths and are often bent or broken, presumably due to deformation during eruption and flow. The plagioclase phenocrysts generally show a random orientation, but in many cases a preferred orientation resulting from flow can be seen. Often the large phenocrysts are seen to contain small inclusions of olivine and clinopyroxene. Alteration effects are rare and not noted in most samples.

Olivine is the most abundant mafic phenocryst phase, making up as much as 20 percent of some flows. It occurs in roughly equidimensional grains up to 6 mm across, and often shows a bimodal size distribution. Olivine is commonly subhedral, with grains showing evidence of corrosion and alteration to iddingsite. The crystals of olivine appear colorless in plain light, and the characteristic cleavage, and ubiquitous rimming of brown iddingsite make it easily identifiable. As with plagioclase, some large crystals are bent or broken due to flow.

Clinopyroxene occurs as anhedral phenocrysts and ranges up to 3 mm in size. It may constitute up to 5 percent of the rock and is generally unaltered. In addition to occuring as discrete grains, clinopyroxene is

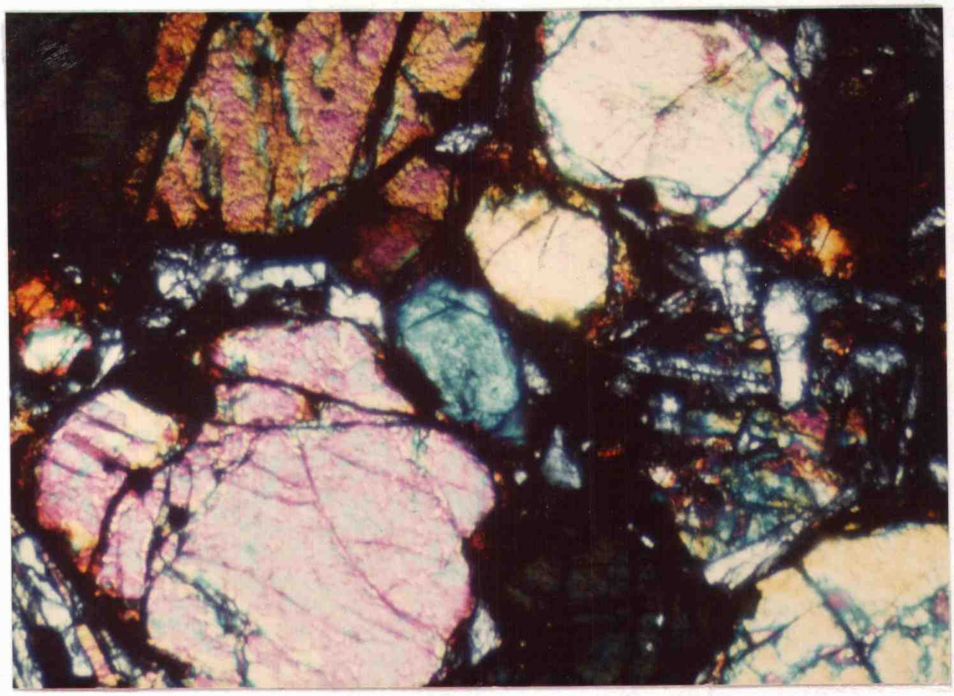


Figure 13. Olivine phenocrysts in Steens Basalt flow (X20, cross-polarized light).

often seen in clots with other phenocrysts, or as inclusions in large feldspar phenocrysts.

The groundmass normally contains plagioclase, olivine, clinopyroxene, and magnetite. It also contains minor devitrified and altered glass and minor secondary minerals, including zeolites, calcite, and clays. Most samples show a felted texture. Plagioclase is nearly always the dominant phase, occurring as microlites and small laths of labradorite (An50 to An55). Clinopyroxene occurs both as discrete microlites and in larger ophitic grains. Magnetite is very common and forms small euhederal to subhederal grains. Clays are common throughout the groundmass, particularly in slightly weathered samples. These occur as greenish to brownish alteration products of groundmass material.

Secondary minerals are seen as fillings in void spaces. These include zeolites, calcite, and chalcedony. They are found in greatest abundance in the Mickey Hot Springs area, and are thought to have been deposited by thermal waters in a long-lived geothermal system still active today.

Vertical Petrologic Variations

A vertical traverse of the Steens Basalt was made along the eastern scarp of Steens Mountain to provide a descriptive stratigraphic section for correlation with Steens Basalt in the Mickey Hot Springs area. One result of this work was the identification of a possible cyclicity in the basalts. The vertical traverse was made along the north branch of Willow Creek, in the south half of Section 7, Township 33 South, Range 34 East. between 7,300 and 9,400 feet in elevation (See sample location map). Each cooling unit that could be identified was described with the aid of a hand lens. Color, phenocryst mineralogy, with visual estimation of percentages, vesicularity, and flow characteristics such as brecciation, jointing and thickness were noted. The net result of this work is that no radical variations in mineralogy were observed, but a cyclicity in plagioclase and olivine content was seen.

Figure 14 is a plot of the visually estimated percentages of plagioclase and olivine observed in the Steens Basalt section. Four complete episodes are depicted. These can be typified as follows: The

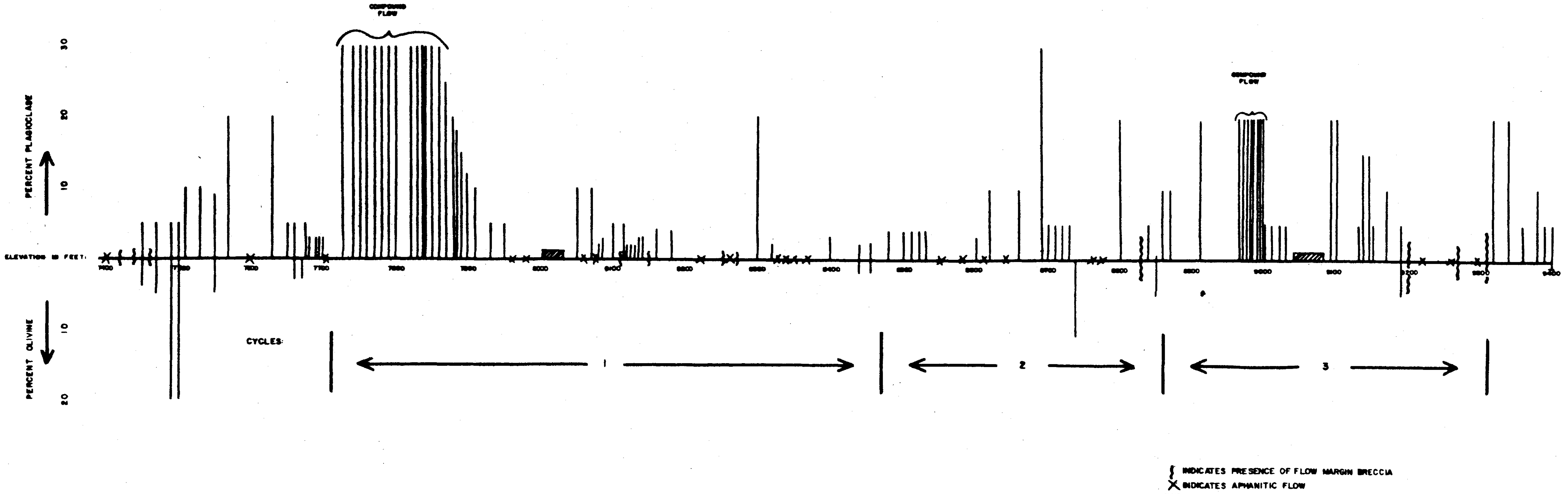


Figure 14: Estimated Phenocryst Content In Steens Basalt.

beginning of each cycle is represented by abundant feldspar phenocrysts, at the expense of olivine. As the cycle progresses, feldspar phenocryst content begins to decrease and toward the end of each cycle the flows become more olivine-rich, at the expense of plagioclase. A brief period of predominately aphanitic flows may follow, then the cycle is repeated.

Gunn and Watkins (1970) published a paper dealing with regular chemical variations between 70 "consecutive flows" that Watkins had sampled somewhere in the upper part of the Alvord Creek Canyon. They felt they could identify a primary fractionation trend due to crystallization of plagioclase in an intermediate-level magma chamber and a secondary trend due to the crystallization of olivine. These trends were periodically interrupted as the magma was erupted and the chamber refilled. On the basis of major oxide and trace element analysis, Gunn and Watkins delineated eight "groups" of lavas. The data they presented contain a lot of scatter and the division of their "groups" appears somewhat arbitrary, but the idea of an intermediate-level magma chamber in which discrete batches of magma temporarily resided and began to differentiate via the crystallization of plagioclase and olivine is enthusiastically supported.

Each cycle is thought to result from the concentration of plagioclase phenocrysts near the top of the intermediate-level magma chamber with olivine concentrating toward the bottom. Plagioclase phenocrysts which are less dense than their surrounding basaltic melt, might tend to float, becoming concentrated near the top of the chamber. Gravity settling of olivine is well documented in layered igneous intrusions

(Wager and Brown, 1968) and could account for its concentration near the bottom of the chamber.

As the contents of the chamber were replaced by new batches, an early phase, rich in volatiles and plagioclase, was extruded. This resulted in very fluid flows which were rich in plagioclase phenocrysts. Diktytaxitic texture is also suggestive of this type of lava. As the eruptions tapped progressively deeper levels in the chamber, the plagioclase became less abundant and the percentage of olivine increased. Between some cycles, the presence of aphanitic flows may indicate that some of the new magma filling the chamber was erupted without long intervals of storage and hence little crystallization took place.

These conclusions are tentative and based on insufficient data. Before any firm conclusion can be drawn about the significance of cycles in the phenocryst content of the basalt, more work such as careful sampling and examination of all flows in thin section will have to be done. Such detailed work was not the purpose of the present study, but presents an attractive problem for future work.

Horizontal Petrologic Variations

Due to the inaccessibility of many outcrops along the eastern scarp of Steens Mountain, individual flows cannot be followed for great distances laterally. When viewed from aircraft, single flows appear continuous for miles along the scarp. Lateral variations appear minor and local in nature over the relatively short distances which flows can be followed.

The correlation between the Steens Basalt of Steens Mountain and the basalts in the Mickey Hot Springs area is strongly supported by the petrology of the flows. Many flows in the Mickey Hot Springs area are virtually identical to those on Steens Mountain. However, on careful examination of the entire sequence exposed on Mickey Mountain some differences are noted. On Mickey Mountain, the average flow is thicker, and accompanied by more flow margin breccia than is present on Steens Mountain. The presence of dikes in the Mickey Hot Springs area, which are very similar to Steens Basalt in appearance and composition, suggests that some of the basalt in the Mickey Hot Springs area was erupted there and did not flow from the area of the present-day Steens scarp. The basalt in the Mickey Hot Springs area is very similar in both age and composition to the basalts erupted on Steens Mountain. They should therefore be considered part of the same system and use of the name Steens Basalt in the Mickey Hot Springs area is valid.

Geochemistry

The geochemistry of Steens Basalt has been discussed at length by Gunn and Watkins (1970). The thesis of their work was to identify interflow variations vertically through the basalt section. For their study 70 "successive flows" were sampled and analyzed for paleomagnetic orentation and major, minor and trace element analysis. Thin sections were also prepared and the petrography described. The focus of the present study is to correlate the exposures on Steens with similar basalts to the east in the Alvord Desert area. Although vertical variations are discussed from a descriptive standpoint in this text, the reader is referred to their paper for a more complete discussion.

In this study major oxide analyses were made on 23 basalt samples. The results of the analyses are shown in Table 2. A map showing sample locations is included in the pocket.

When plotted on an AFM diagram (Figure 15) the Steens Basalt is seen to be transitional between olivine tholeiite, such as the Columbia River Basalts, and a calc-alkaline high-alumina basalt, similar to those found in the Cascade Range of Oregon. The name high-alumina olivine basalt is applied on the basis of Al_2O_3 averaging in excess of 17% (Kuno, 1960) and because of the presence of olivine.

The chemical analyses show that the samples from Steens Mountain are generally very similar to those from the Mickey Hot Springs Area. The minor differences between the basalts of the two areas are discussed below. A second type of basalt, informally called Mickey basalt in this study, was found overlying the Steens Basalt in the Mickey Hot Springs area. It is characterized by lower alumina and higher silica contents than the Steens Basalt. Most dikes analyzed also are similar in composition to Steens Basalt and with the exception of MM-1, a dike near Mickey Hot Springs, are thought to have fed Steens flows.

Horizontal Geochemical Variations

Flows were sampled in an effort to establish a general correlation between the outcrops on Steens Mountain and those of the Mickey Hot Springs area. No attempt was made to detect minor intraflow variations. In one case, a single flow was sampled at three remote locations (MM-10, MP-53 and EC-3). This flow directly underlies a distinctive ignimbrite and was therefore easily traced throughout the eastern part of the study area. Analyses for the samples are listed in Table 2, and show only minor variations.

Table 2. Oxide Analyses of Basalts in Percent

Steens Mountain Steens Basalt

	HS-2	HS-3	HS-8	HS-9	HS-11	HS-14	HS-19	HS-22	HS-24
SiO_2	47.1	47.8	47.7	51.4	47.7	47.1	48.8	47.3	48.9
Al_2O_3	16.3	17.0	16.7	16.3	16.5	16.5	15.8	16.7	17.9
FeO	13.4	13.4	12.8	11.8	12.5	13.4	11.3	13.2	12.1
CaO	8.1	8.6	8.6	6.4	9.6	8.7	10.3	8.3	9.1
MgO	6.5	6.2	6.9	4.1	7.4	6.1	9.3	6.7	6.9
K_2O	1.00	1.00	0.95	2.30	0.75	1.00	0.40	1.05	0.65
Na_2O	3.1	3.4	3.4	4.6	3.3	3.6	3.0	3.5	3.4
TiO_2	2.70	2.70	2.35	2.35	2.25	2.60	1.75	2.60	1.80
Total	98.20	100.10	99.40	99.25	100.00	99.00	100.65	99.35	100.75

Mickey Hot Springs Area Steens Basalt

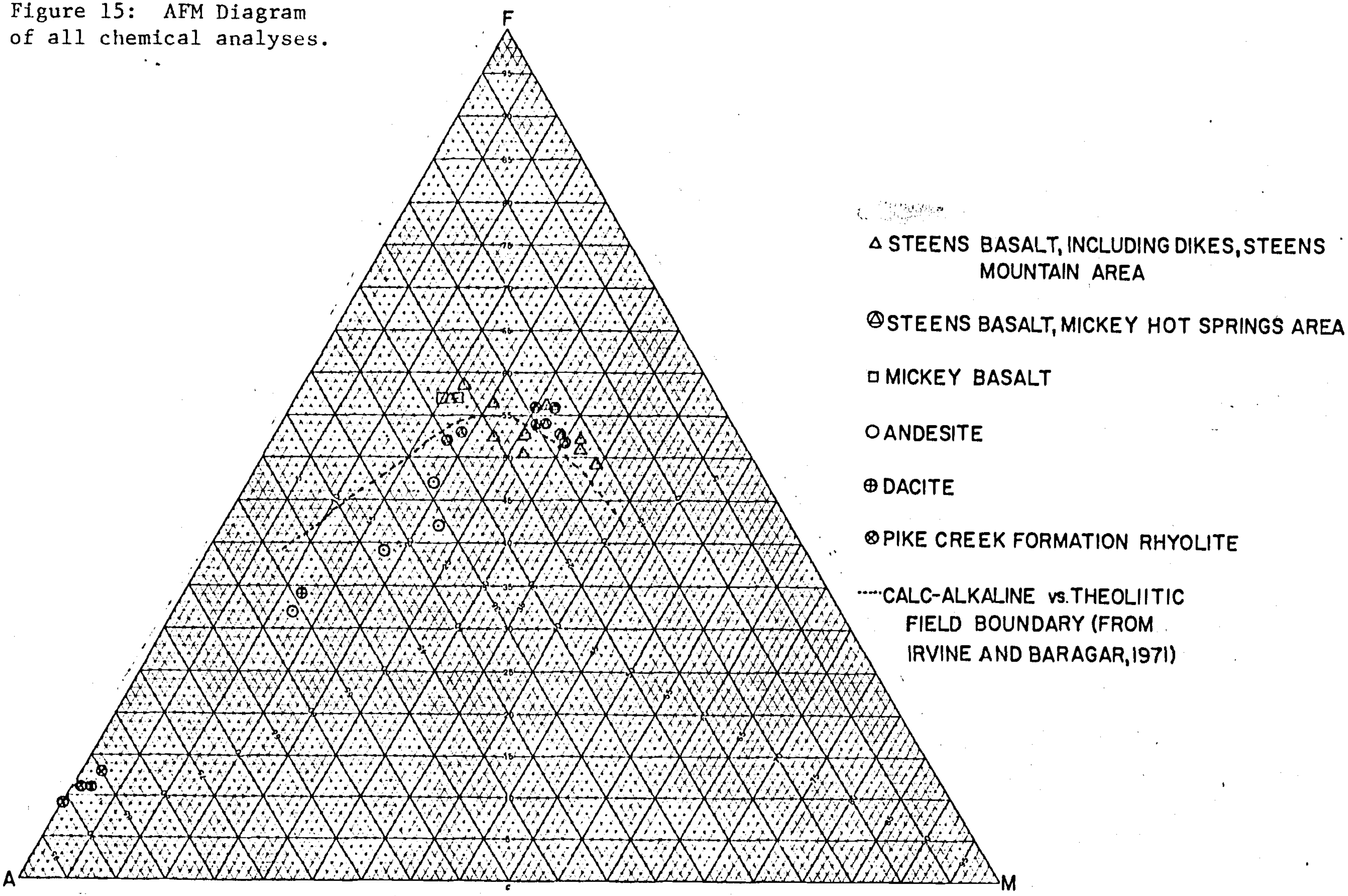
	MM-3	MM-9	SM-11	SM-12	SM-19	SM-21	MM-10	MP-53	EC-3
SiO_2	48.3	52.3	48.0	48.3	52.0	50.8	49.1	49.6	50.0
Al_2O_3	16.2	17.2	16.9	17.1	16.2	18.5	18.7	18.2	18.1
FeO	11.6	11.0	11.4	12.3	12.0	10.8	11.9	11.6	11.0
CaO	9.2	7.8	9.5	8.6	7.4	8.4	8.8	8.4	8.3
MgO	7.1	5.7	7.7	7.1	5.5	4.1	5.6	4.1	3.2
K_2O	0.75	1.55	0.65	1.05	1.60	1.25	1.00	1.30	1.25
Na_2O	3.0	3.5	3.0	2.7	3.4	3.4	3.1	3.3	4.0
TiO_2	2.15	1.85	1.95	2.35	2.15	2.65	2.60	2.85	2.70
Total	98.30	100.90	99.10	99.50	100.25	99.90	100.80	99.35	98.55

Table 2 - Continued

	Steens Mountain Dikes		Mickey Hot Springs Area Dikes			
	HS-21	HS-5	SM-9	MM-2	MM-1	MM-12
SiO_2	50.6	49.0	49.4	50.8	48.7	48.5
Al_2O_3	16.7	17.9	17.7	17.3	21.7	16.9
FeO	12.4	11.7	12.1	12.1	9.1	12.9
CaO	6.5	9.1	8.1	8.1	9.7	8.9
MgO	4.5	5.6	5.5	3.3	3.8	5.9
K_2O	2.05	1.05	1.50	1.50	0.90	1.00
Na_2O	4.4	3.4	3.6	3.6	3.4	3.1
TiO_2	2.40	1.95	2.30	2.45	1.65	2.65
Total	99.55	99.70	100.20	99.15	98.95	99.85

	Mickey Basalt		Steens Mountain Dacite Ignimbrite	Average Steens Basalt, Mickey Hot Springs Area	Average Mickey Basalt
	EL-10	ER-2	HS-0		
SiO_2	52.0	52.0	63.3	49.7	52.0
Al_2O_3	14.2	14.05	17.00	17.7	14.1
FeO	12.2	12.2	4.8	11.6	12.2
CaO	7.1	7.1	4.3	8.5	7.1
MaO	3.3	3.3	1.7	5.3	3.3
K_2O	1.75	1.90	4.30	1.15	1.80
Na_2O	4.0	4.0	3.4	3.3	4.0
TiO_2	3.20	3.20	0.80	2.50	3.2
Total	97.75	97.75	99.60	99.75	97.70

Figure 15: AFM Diagram of all chemical analyses.



As with the petrographic results, the geochemical data support the correlation between the lavas of the Mickey Hot Springs area, and the Steens Basalt. Although the samples from the Mickey Hot Springs area average very slightly higher in Al_2O_3, and SiO_2, the differences are not considered significant.

Paleomagnetism

Samples from 5 vertical traverses within the study area were analyzed for paleomagnetic orientation. The results of this work are shown in Figure 16. Watkins et al. (1967), reported a transition from reversed to normal polarity somewhere in the Steens Basalt section of Steens Mountain. Based on extensive potassium-argon dating, they placed an age of 15.1 .3 million years on the reversal. Such a transition was also found during the present study of the Steens Mountain section in samples collected along a traverse up Willow Creek between the elevations of 8,765 and 8,940 feet. Reverse-to-normal transitions were also found in the Mickey Hot Springs area; on Mickey Mountain between 4,855 and 5,050 feet, and on South Mickey Mountain between 4,350 feet and 4,600 feet. It is suggested that the reversal in the Mickey Hot Springs area is the same as that on Steens Mountain and that it can be used as a time line in stratigraphic correlation.

It can be seen from Figure 16 that paleomagnetic data, combined with the position of the post-Steens Basalt Mickey ignimbrite, allows confident correlation within the Steens Basalt throughout the study area. Using the paleomagnetic reversal and the Mickey ignimbrite as equal-time lines, it can be shown that even after allowing for minor

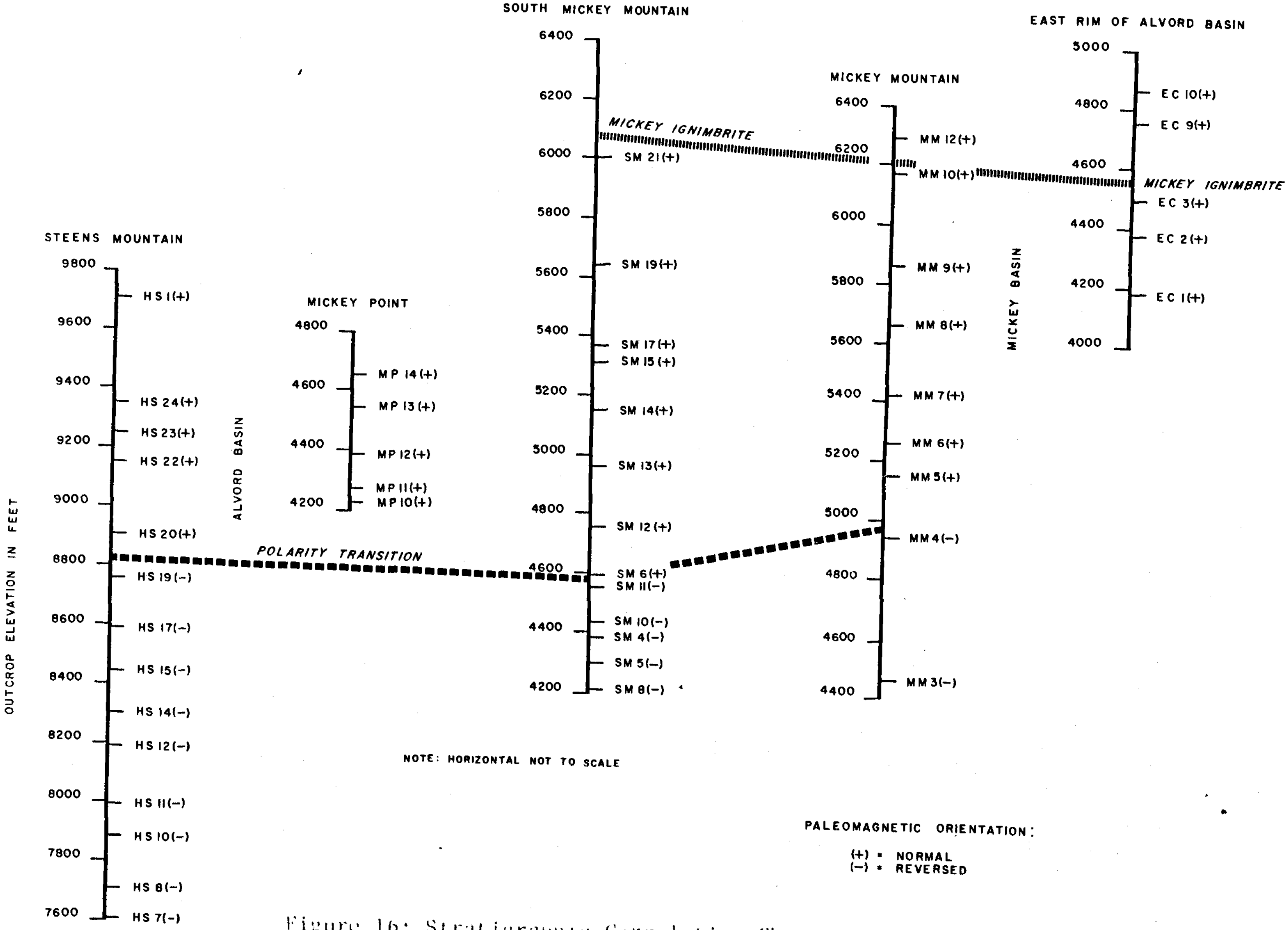


Figure 16: Stratigraphic Correlation Chart.

erosion on the summit of Steens, a greater thickness of Steens Basalt was deposited in the Mickey Hot Springs area. A rhyolite ignimbrite, very similar to the Mickey ignimbrite is reported to overlie the Steens Basalt in the Smith Flats area, about eight miles southwest of the study area, but is not present on the summit of High Steens. Further work is needed before these units might be correlated.

Dacite Ignimbrite

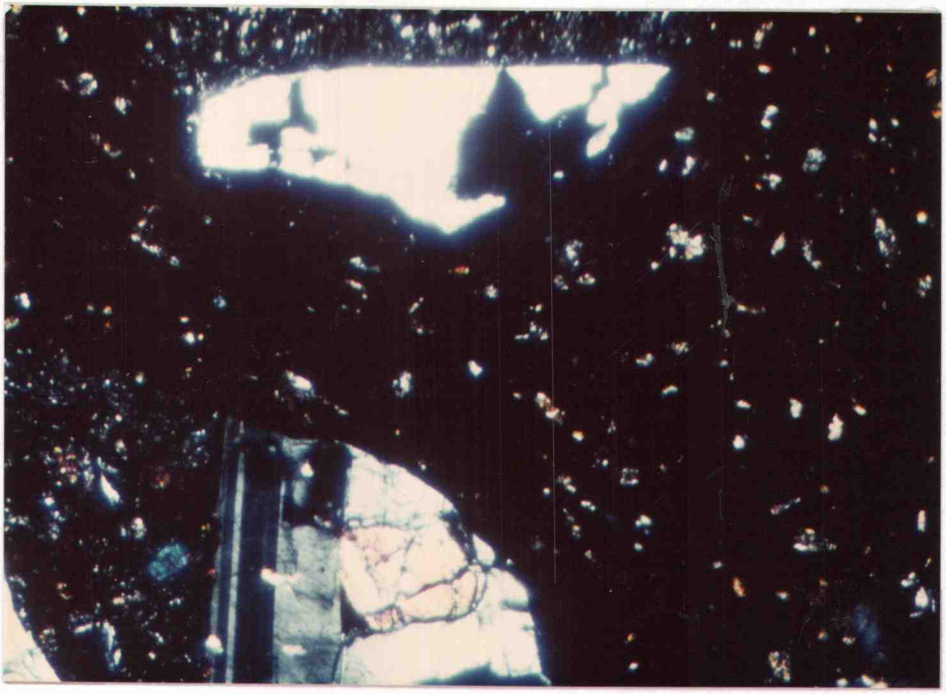


Figure 17. Labradorite phenocrysts in Dacite ignimbrite.

The Steens Basalt section observed within the study area is composed entirely of basalt with one exception. A thin dacite ignimbrite was found in the upper part of the Mosquito Creek Canyon at an elevation of 8,000 feet. This ignimbrite is about 10 inches thick and can be followed laterally for about 200 yards. Although lack of exposure limits the distance this unit can be traced, it was not observed in the neighboring canyons, and therefore may not be widespread. It contains labradorite, olivine, clinopyroxene, and basaltic rock fragments in a glassy groundmass (Figure 17). The plagioclase and olivine are strongly resorbed. A chemical analysis of this rock is shown in Table 2. When observed in hand specimen this unusual rock has the appearance of a highly porphyritic obsidian. It is interpreted to have formed during a violent eruption of volatile-rich magma. The phenocrysts are all typical of the surrounding basalts and were entrained as the ignimbrite flowed across a surface of porphyritic basalt.

Mickey Ignimbrite

As noted in the previous chapter, the Steens Basalt crops out on the summit of Steens Mountain within the study area, but in the Mickey Hot Springs area the basalt is overlain by a rhyolite ignimbrite, here informally named the Mickey ignimbrite. This ignimbrite rests conformably upon the Steens Basalt, but its age is unknown. It averages about 30 feet in thickness and includes a densely welded vitric central portion about 15 feet thick, with poorly welded margins above and below. The vitric portion is light grey, the unwelded base is reddish brown with local baked soil zones. The upper part is usually weathered to a light yellow. With dark-colored basalts both above and below, the Mickey ignimbrite is highly visible at a distance (Figure 18).

Because this unit is of uncertain age, it has not been correlated with any of the other similar ignimbrites in southeastern Oregon. Several thin ignimbrites are described in the Catlow and Harney Basins to the north and west of the study area, and in the Trout Creek Valley south of the area (Greene, 1973). All of these units are Pliocene in age. The conformable relationship between the Mickey ignimbrite and the Steens Basalt may suggest that it is Miocene in age. The Mickey basalt, which conformably overlies the ignimbrite, has the same paleomagnetic orientation as the Steens Basalt. These factors suggest that the minimum age for the ignimbrite is about 14.5 million years, based on a normal-to-reverse paleomagnetic transition of that age reported for the Columbia River Basalt (Hooper, et al., 1979).

The vitric central part of this ignimbrite was examined in thin section from several outcrops in the eastern part of the study area. Glass shards and devitrified glass display eutaxitic texture. The shards are dusty brown. Collapsed pumice is common, with the degree of flattening variable. Phenocrysts of sanidine constitute about 5 percent of the rock. Minor amounts of quartz, clinopyroxene, biotite, and basaltic rock fragments are noted in some samples. The clinopyroxene is often rimmed by magnetite. When glass and pumice shards have devitrified, a distinct spherulitic texture is seen. Although no chemical analyses were made of this unit, it is inferred on the basis of petrography to be rhyolitic in composition.

Figure 18. Mickey ignimbrite near Mickey Hot Springs.

Mickey Basalt

Conformably above the Mickey ignimbrite is a series of dark-colored, aphanitic basalt flows. These flows differ from Steens Basalt, in that they do not contain the plagioclase phenocrysts commonly seen in Steens flows. This unit, informally named Mickey basalt, makes up most of the highlands in the Mickey Hot Springs area, with a maximum thickness in outcrop of about 400 feet along the eastern rim of the Alvord Desert east of Mickey Hot Springs. Drill cuttings from an Anadarko Production Company temperature gradient well (ANA-5) in the north end of the Mickey Basin suggest that the thickness in the graben is about 600 feet. Individual flows average about 30 feet thick and are bounded by minor flow-margin breccias.

In hand specimen, the fine-grained basalt appears almost glassy. It is extremely hard. Most flows are dense throughout and diktytaxitic texture is not developed.

In thin section the Mickey Basalt is seen to be much finer-grained than any Steens Basalt examined. It is aphyric, with an aphanitic groundmass. Diabasic and intergranular textures are noted. Mineralogically the rock consists of plagioclase (labradorite), clinopyroxene, minor orthopyroxene, olivine, magnetite, and a dusty brown alteration product presumed to have been glass. Secondary quartz, calcite, opaline silica and zeolites are seen in fractures and open spaces.

Geochemically the rock is significantly different from Steens Basalt. Table 2 compares an average composition for all Steens Basalt samples analyzed from the Mickey Hot Springs area, with the average of the two samples of Mickey basalt. The two samples of Mickey basalt show much higher SiO_2 and much lower Al_2O_3. Samples of Steens Basalt that were analyzed do not show a similar composition.

As mentioned in the Mickey ignimbrite section, the paleomagnetic orientation of this unit is normal, as is the upper part of the Steens Basalt. It is believed that this unit was erupted soon after the Steens Basalt, prior to the polarity transition reported in the Columbia River Basalts at 14.5 million years (Hooper, et.al., 1979).

Dikes of an appearance or composition similar to Mickey basalt were not identified within the study area, nor were any vents noted. Further work needs to be done to determine the area from which these flows were erupted and a date would be useful in correlating both this unit and the underlying rhyolite with similar units in the area.

STRUCTURE

The dominant structural style within the study area is Basin and Range type of normal faulting. These faults have a predominant orientation of roughly north-south, with a subordinate orientation of northeast-southwest. Northeast-trending faults are seen to the north of the area, along the Brothers Fault Zone and to the south, along the Eugene-Denio Lineament (Lawrence, 1976), but are not prevalent within the study area. Most of the major faults are range-front bounding faults, and as a result are quickly covered by slump, landslide and alluvial material. For this reason, it is difficult to determine their precise location. The presence of stair-step displacement is suspected along the major faults in the area but is masked by the alluvial material.

The youthful appearance of the major fault scarps, combined with the rapidly infilling basins, suggests that most of the range-front faults have been recently active. It is not clear how long they have been active but based on the correlation of the Steens and Mickey Basalts, it appears that most displacement is younger than 14.5 million years. The angular unconformities seen in the lower part of the Steens Mountin scarp suggest that particular block had undergone 4 to 6 degrees of tilting prior to the eruption of the basalt, and about 5 degrees afterword.

Throughout the study area, most of the fault blocks show relatively little dip. A maximum dip of approximately 11 degrees is noted at the base of Steens Mountain. Various small blocks in the Mickey Hot Springs are tilted up to 7 degrees, dipping generally to the north and west.

The major range-front fault to Steens Mountain runs north-south through the study area. The exact location of this fault, its dip, or its complexity, cannot be determined because of Pleistocene and Recent alluvium. At no place along the base of the scarp is the surface of the range-front fault seen in outcrop. It is inferred that normal displacement occurs over a three-quarter-mile-wide zone which parallels the base of the scarp. Dip is steeply to the east. Due to a lack of subsurface control the displacement on this fault can only be estimated. Cleary (1976) reports that based on gravity data, dense rock is about 5,000 feet beneath the central part of the Alvord Desert, south of the study area. This would suggest a displacement of around 11,000 feet on the Steens Mountain range-front fault in that area. Figure 3 shows the area of maximum displacement on this fault occurs in the area east of the Alvord Hot Springs. There the range-front fault is thought to bifurcate, one arm continuing north through the study area with about 8,000 feet of displacement. The other arm turns northeast and becomes the east-bounding fault to Mickey and South Mickey Mountains. This northeast arm may carry about 3,000 feet of displacement. In the north end of the Mickey Basin correlation on the Mickey ignimbrite between Mickey Mountain and the Anadarko well, ANA-5, indicates 2,500 feet displacement across this fault. Along this fault in the Mickey Basin, recent displacement has created a mini-scarp about six feet high, cutting the alluvial material. Such evidence of recent displacement confirms the area as being structurally active today. The proximity of this active fault to the Mickey Hot Springs shows the probable relationship between active fault zones with open fractures, and rising geothermal fluids.

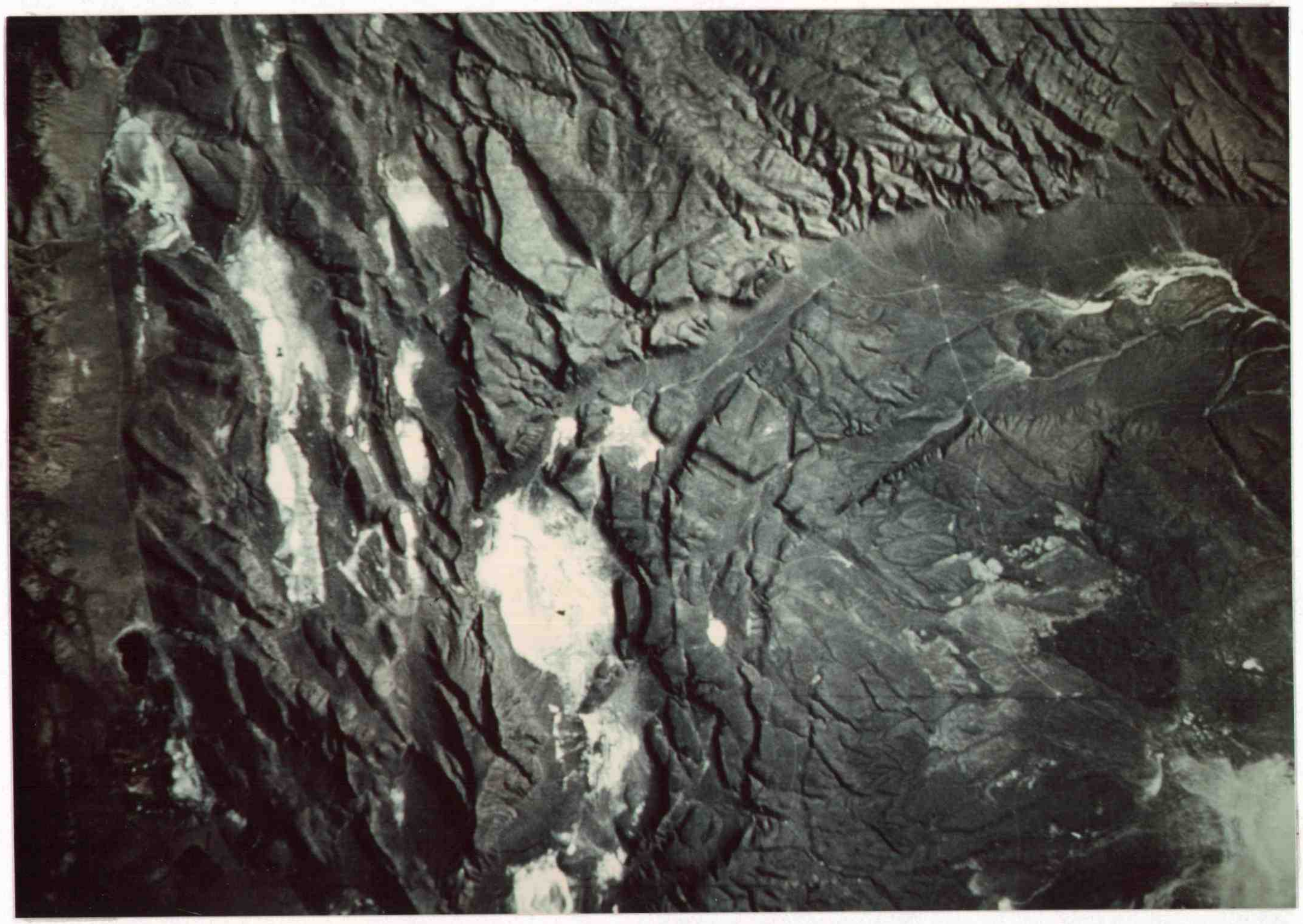


Figure 19. ERTS image of the Mickey Hot Springs area. North is to the top. The large circular feature near the center of the photo is suspected to be the remnant of a collapsed caldera structure.

Throughout the study area, the major blocks tend to dip generally west. For this reason, the faults showing the most displacement are the east-bounding range-front faults. In the extreme east end of the study area the normal faults have less displacement, but they are well-exposed and can be mapped with greater precision than the major faults to the west. The Alvord Desert occupies a large linear graben east of Steens Mountain. The Desert is bounded on the east by a low north-trending scarp. Toward the north end of the Alvord Desert this north-trending grain is lost and the faults become arcuate, curving to the east (see Figure 19). This zone of arcuate trending faults appears to be part of a large circular fault basin. It does not fit into the structural grain seen elsewhere in the region. Possibly it is part of a large ring fault system which was part of a caldera complex. The caldera may have subsequently been covered by the younger Miocene volcanics, but a portion of the fault system remained active, making the structure still visible today.

GEOLOGIC HISTORY

The known geologic history of the rocks exposed in the study area begins in the Tertiary, and can be summarized as follows: The welded tuffs of the Pike Creek Formation were erupted during the early Miocene, 24 million years ago. This unit, or a related lithic unit probably rests with great unconformity on a Paleozoic surface consisting of metamorphic and intrusive rocks in a manner similar to that seen in the Pueblo Mountains, 30 miles to the south. The eruption of this thick section must have been very large and violent possibly causing a caldera collapse. The presence of the circular fault basin north of the study area suggests that a caldera may have existed there and deposited these tuffs.

A period of erosion followed, with a large lake existing in the area of the present day Big Alvord Creek. This lake was filled with fine grained tuffaceous sediment from nearby acidic volcanic activity forming the Alvord Creek Beds. The source for this sediment was the assemblage of rhyolite and dacite flows and pyroclastics seen south of the Pike Creek Formation.

The date of 21.3 million years (Evernden and James, 1967) on the upper part of the Alvord Creek Beds may be considered about the time that volcanic activity began to shift to more mafic compositions. The "Basic" Andesites were erupted and filled the basin in which the Alvord Creek Beds had been deposited. A chain of small andesite, dacite, and basaltic cinder cones developed in the position of present day scarp. These deposited the "Upper" Andesite within the study area, and the more variable Steens Mountain Volcanic series to the south.

Throughout Pliocene and Pleistocene time the basins developed into pluvial lakes which were slowly filled by the detrital material from the neighboring ranges. Glaciers active during Pleistocene time carved the "U" shaped valleys and the cirques seen near the top of Steens Mountain (Figure 19).

On Steens Mountain, which receives more rainfall than the rest of the area, due to its elevation, streams have rapidly incised deep canyons. Large amounts of detrital material have been carried down these canyons and deposited as vast alluvial fans at the canyon mouths. The streams themselves disappear into the porous gravels of the alluvial fans before they reach the floor of the basins.

Glaciation and headward erosion on the streams flowing both east and west from the summit of High Steens, has resulted in making the once broad and relatively flat summit of the mountain a narrow ridge. Just north of the study area, Mann Creek and Keiger Creek have merged through headward erosion forming a hogback between them. Cirques were carved in the upper parts of the valleys draining High Steens during the Pleistocene. The glaciation was most extensive on the western side of the mountain due to increased snowfall there. The gorges of Big Indian, Little Donner and Blitzen, and Kiger Creeks are "U" shaped as a result of that glaciation (Figure 20). Below the cirques, the east-flowing drainages show evidence of stream-erosion.

In the eastern part of the study area, the factors of lower relief and less rainfall have combined to make the erosional rate slower, and drainage patterns are not well developed. There are no major streams in this area. Deposits of terrace-gravels on many hillslides are evidence of the once extensive system of pluvial lakes which filled the basins during the Pleistocene. Small gullies now carry storm run-off onto the basin floors, which are undrained. Alluvial fans are seen at the mouths of some of these gullies.

The basins are flat, and for the most part are large playas. During periods of exceptional rainfall they still partially fill with water, and some deposition of finer alluvial material takes place. The effects of wind can be seen in the basins where dunes and desert pavement have developed locally.

Figure 20. Kiger Gorge near the summit of Steens Mountain showing the effects of Pleistocene glaciation.

ECONOMIC GEOLOGY

The tremendous exposures along eastern scarp of Steens Mountain have been extensively prospected for minerals in the last 50 years. Mercury has been found and commercially developed in the Pike Creek Formation south of the study area. This activity began in the 1930's, and reached a peak during World War II. Sporadic activity has continued in small weekend-type operations since. Production figures for the mercury are scarce because of the spotty records of these small-scale operations. No large deposits were found and there appears little chance that a deposit large enough to sustain full-time mining operation will be found.

The mercury occurs as cinnabar in veins hosted by the fractured Pike Creek rhyolite and dacite. Quartz is the most common gangue. Presumably the cinnabar was deposited as part of a low-temperature hydrothermal system which was active along the normal faults in the area.

Uranium has also been found in small quantities in the Pike Creek Formation south of the study area. There are no records of production. Assessment work is being done on some currently active uranimum claims but no commercial deposits have ever been found.

The most recent economically-motivated interest in the area has been in its geothermal potential. Activity on this front began in the 1960's when the first geothermal leases on private lands were granted. In the early 1970's the Geothermal Steam Act created the Alvord KGRA, (Known Geothermal Resource Area) which includes most of the study area, along with the rest of the Alvord Basin. The Act also opened the public lands in the area to geothermal entry, and leasing activity has continued since.

A U.S. Geologic Survey spring sampling study was conducted in the Alvord Basin, with the results published in 1975. This study spurred interest in the area by estimating the reservoir temperature of Mickey Hot Springs as 210°C on the basis of silica and alkali geothermometers (U.S. Geologic Survey, 1975). Private companies have conducted extensive exploration programs throughout the area including gravity, magnetic, magnetotelluric and resistivity surveys, as well as shallow temperature-gradient drilling.

To fully evaluate the geothermal potential of the study area, deep production-type wells will have to be drilled. Because of the remote location and other complications, such as the possible inclusion of the study area into a Wilderness Area, no such deep tests have been drilled to date. The combination of a high temperature gradient and the possibility of fractured Pike Creek rhyolite at depth make the area around Mickey Hot Springs a good prospect, although the high cost of a production test likely cannot now be justified economically.

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