

*General*

# Fish Creek Mountains Tuff And Volcanic Center, Lander County, Nevada

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*Description of a new formation (a composite ash-flow sheet), and a discussion of its source in the Fish Creek Mountains of central Nevada*



## CONTENTS

	Page		Page
Abstract .....	1	Fish Creek Mountains Tuff—Continued	
Introduction .....	1	Upper cooling unit—Continued	
Acknowledgments .....	1	Chemistry .....	10
Physiography and general geology .....	1	Remanent magnetization .....	12
Geologic relations of the Fish Creek Mountains Tuff .....	3	Age .....	13
Rocks older than Fish Creek Mountains Tuff .....	4	Tertiary structure in the Fish Creek Mountains .....	13
Rocks younger than Fish Creek Mountains Tuff .....	4	Pre-Basin and Range structure .....	13
Fish Creek Mountains Tuff .....	7	Basin and Range faults .....	14
Distribution and dimensions of the ash-flow sheet .....	7	Miocene to Holocene geologic history .....	14
Type locality and alternate localities .....	8	Sequence of events .....	14
Nature of the ash-flow sheet .....	8	Interpretation of the Fish Creek Mountains	
Lower cooling unit .....	9	volcanic center .....	15
Upper cooling unit .....	10	Summary .....	15
Lithology .....	10	Selected references .....	17

## ILLUSTRATIONS

	Page
FIGURE 1. Map showing the general location of the Fish Creek Mountains and other topographic and cultural features in the region, with index map .....	2
2. Shaded relief map of the Fish Creek Mountains showing the saucerlike shape of the range .....	3
3. Aerial view of the Fish Creek Mountains showing the saucerlike shape of the range .....	3
4. Mosaicked aerial photograph of the southern part of the Fish Creek Mountains .....	5
5. Geologic map of the Fish Creek Mountains .....	6
6-9. Photographs of:	
6. Fish Creek Mountains Tuff, lithic unit at the mouth of Dacies Canyon .....	9
7. Fish Creek Mountains Tuff, lithic unit viewed west from the mouth of Dacies Canyon .....	10
8. Fish Creek Mountains Tuff at the east margin of the range .....	11
9. Two hand specimens of Fish Creek Mountains Tuff .....	12
10. Trilinear plot of normative molecular Ab, An, and Or .....	13
11. Schematic possible history of the Fish Creek Mountains volcanic center .....	16

## TABLES

	Page
TABLE 1. Description and estimate of amount of matrix and of crystal, lithic, and pumice fragments at five horizons through the lithic-bearing ash-flow cooling unit of the Fish Creek Mountains Tuff at the mouth of Dacies Canyon, west side of Fish Creek Mountains .....	8
2. Modes of four samples of Fish Creek Mountains Tuff .....	11
3. Chemical analyses of two samples of Fish Creek Mountains Tuff and the "average calc-alkali, rhyolite and rhyolite-obsidian" from Nockolds (1954, table 1) .....	11
4. Analyses of Rb, Sr, and K from sanidine separates of Fish Creek Mountains Tuff .....	12
5. Mean remanent magnetization directions, Fish Creek Mountains Tuff .....	13
6. Radiometric dates of Fish Creek Mountains Tuff .....	13

# FISH CREEK MOUNTAINS TUFF AND VOLCANIC CENTER, LANDER COUNTY, NEVADA

By EDWIN H. MCKEE

## ABSTRACT

The Fish Creek Mountains in central Nevada are the site of an early Miocene volcano (about 24 million years old on the basis of potassium-argon and fission-track ages) from which was erupted about 75 cubic miles of crystal-rich rhyolitic ash-flow tuff, here named the Fish Creek Mountains Tuff. The formation appears to be a composite sheet, although most of it was erupted during a short period of time and cooled as a large, nearly homogeneous body. Two cooling units that make up the sheet are separated by a cooling break and can be distinguished in most places by the presence of a large amount of lithic debris in the lower unit. The ashflow spread outward uniformly in all directions from a vent area in the south-central part of the range. Collapse of this vent area probably accompanied eruption, and the depression so formed acted as a trap for continued eruption of similar tuff. Evidence of resurgence of the vent area is unclear, although tectonic activity probably related to the final phase of volcanism is evident. Several long, arcuate faults that circumscribe about half of a "core" area of leached and tectonically chaotic tuff may be remnants of a caldera structure.

## INTRODUCTION

Numerous ash-flow sheets have been recognized in central Nevada, and the distribution of many of them has been delineated fairly accurately. The source area of most of these units, however, has not been found, although a definite effort has been made to locate volcanic centers, especially those with collapse caldera structures.

The south-central part of the Fish Creek Mountains in Lander County, Nev., is the source of a thick, but areally restricted composite sheet of ash-flow tuff that is not found in any adjacent region of central Nevada, except a short distance to the west in the Tobine Range. The restricted occurrence of this tuff in the Fish Creek Mountains is evidence that its source was within the boundary of the present range; its thickness and distribution pattern within these mountains support this conclusion. Inconclusive evidence suggests that there was some

subsidence of the vent area during eruption and perhaps some resurgence at a later time.

Although about 75 cubic miles of ash-flow material was erupted, it did not spread more than 10 miles from its source; this suggests that it was low-energy eruption. This ash-flow sheet formed a lens-shaped body about 3,000 feet thick at its center and 15-20 miles in diameter.

## ACKNOWLEDGMENTS

John H. Stewart, of the U.S. Geological Survey, visited the Fish Creek Mountains with the author a number of times and offered many valuable suggestions on interpretation of the geology. Charles W. Naeser, of the U.S. Geological Survey, collected samples of welded tuff and determined their age by the fission-track method. A summary of his data is included. C. Sherman Grommé, also of the U. S. Geological Survey, visited the area and collected drill samples for studies of remanent magnetization. The result of this work is also included. Donald C. Noble, of Harvard University, offered stimulating discussion, and he and Ted G. Theodore of the U.S. Geological Survey critically reviewed the manuscript. Fieldwork was done in cooperation with the Nevada Bureau of Mines as part of the Lander County map project.

## PHYSIOGRAPHY AND GENERAL GEOLOGY

The Fish Creek Mountains, approximately 40 miles southwest of the town of Battle Mountain, Nev. (fig. 1), form a circular-shaped range that covers an area of about 200 square miles and has an average relief of about 1,500 feet. The range is surrounded by broad alluvial valleys except on the southwest near the north end of the Augusta Mountains; here some low hills and a canyon separate the two ranges. The circular shape of the Fish Creek Mountains, in particular its broad arcuate southern

the two ash-flow units bears out this conclusion. The fact that the Fish Creek Mountains Tuff spread over a surface of some relief is shown by local thick accumulations of weakly welded to nonwelded tuff at the base of the formation; the thickness indicates this material must have filled shallow depressions in the old topographic surface. The lithic-bearing portion of the tuff, the lowest unit in the vicinity of the mouth of Dacies Canyon (fig. 5), has an especially thick basal zone of nonwelded tuff and probably filled a small basin at this site.

#### ROCKS OLDER THAN FISH CREEK MOUNTAIN TUFF

The oldest rocks in the Fish Creek Mountains are strata of Pennsylvanian and Permian age that make up a series of hills along the western edges of the range; they are separated from the Fish Creek Mountains Tuff by an angular unconformity. It seems likely that Paleozoic rocks underlie that tuff in most of the southern part of the range also, although the basal contact is not exposed in this part of the mountains. South of the Fish Creek Mountains, at the north end of the Augusta Mountains, the Fish Creek Mountains Tuff locally lies on the Triassic Augusta Mountain Formation.

Coarse-grained granite rock of presumed Middle Jurassic age underlies the Fish Creek Mountains Tuff at one place in the north-central part of the range. On the northeastern edge of the Fish Creek Mountains, a series of dark lava flows and lenticular tuffaceous sedimentary rocks of Oligocene(?) age crop out beneath the Fish Creek Mountains Tuff; the tuff lies unconformably on both of these older Tertiary rock types and in places overlaps the contact between these units. Stratigraphic relations between similar units in the Shoshone Range about 5 miles east of the Fish Creek Mountains and K-Ar dates on rocks associated with them suggest that the older lava flows and sedimentary rocks probably are about 10 million years older than the Fish Creek Mountains Tuff.

The Caetano Tuff (Gilluly and Masursky, 1965), a widespread ash-flow unit in areas east of the Fish Creek Mountains, locally underlies the Fish Creek Mountains Tuff in the northern part of the range. Both units here are flat or nearly flatlying so that the contact appears conformable. Mapping on a regional scale, however, shows that the units have a different geographic distribution, the Fish Creek Mountains Tuff lapping onto the Caetano Tuff only in a small area in the northern part of the Fish Creek Mountains. Potassium-argon ages of the two units (32.3 m.y. for Caetano Tuff in the Fish Creek

Mountains, McKee and Silberman, 1970; 24.3 m.y. by K-Ar and fission-track dating for Fish Creek Mountains Tuff) support a hiatus of nearly 10 m.y.

#### ROCKS YOUNGER THAN FISH CREEK MOUNTAINS TUFF

In the area where the Fish Creek Mountains Tuff is thickest, and throughout most of the region where it is found, it is the youngest unit. Only in the north, north-central, and western parts of the range are there younger rocks. The oldest of these younger units is an ash-flow cooling unit questionably identified as Bates Mountain Tuff, a formation widespread southeast of the Fish Creek Mountains (Sargent and McKee, 1969; McKee and Stewart, 1970). The Bates Mountain (?) Tuff is the same age (24.0 m.y. in the Fish Creek Mountains by fission-track dating (McKee and Naeser, 1970)) as the underlying Fish Creek Mountains Tuff (24.3 m.y. by K-Ar and fission-track dating; see section on "Age") within the resolution of the radiometric dates. This unit forms a thin (about 50 ft thick) veneer on the Fish Creek Mountains Tuff at several localities in the northern part of the range and probably was once more extensive. There is no evidence, however, that it ever spread across what is now the central and southern Fish Creek Mountains. The overlapping of Bates Mountain(?) Tuff on Fish Creek Mountains Tuff in the northern part of the range and its absence in the central and southern parts, where the Fish Creek Mountains Tuff is thickest, suggests that this thin tuff spread unconformably around and on the edge of a wedge-shaped body of Fish Creek Mountains Tuff.

Sedimentary rocks, mostly tuffaceous sandstone and mudstone, crop out in a shallow basin in the central part of the Fish Creek Mountains (figs. 3 and 5). These strata dip gently away from the margins of the basin, reaching a maximum thickness of several hundred feet near the center of the basin. No fossils have been found in these rocks, but their general similarity to vertebrae-bearing beds in nearby regions (including Jersey Valley to the west, the Shoshone Range to the east, and Reese River Valley localities to the southeast) suggests that they are late Miocene or early Pliocene (Gilluly and Gates, 1965, p. 88). On the basis of petrographic evidence, Deffeyes (1959, p. 35) speculated that they are older than late Miocene and early Pliocene but was unable to establish a definite age for them. They lie unconformably on the Fish Creek Mountains Tuff (earliest Miocene). It seems likely that a hiatus of several million years, perhaps as much as 10 m.y., separates the tuffaceous sedimentary rocks from the Fish Creek Mountains Tuff.



FIGURE 4.—Mosaicked aerial photograph of the southern part of the Fish Creek Mountains. The arcuate lines (unretouched) in the bottom half of the photograph are probably faults ringing the vent area of the volcanic center.

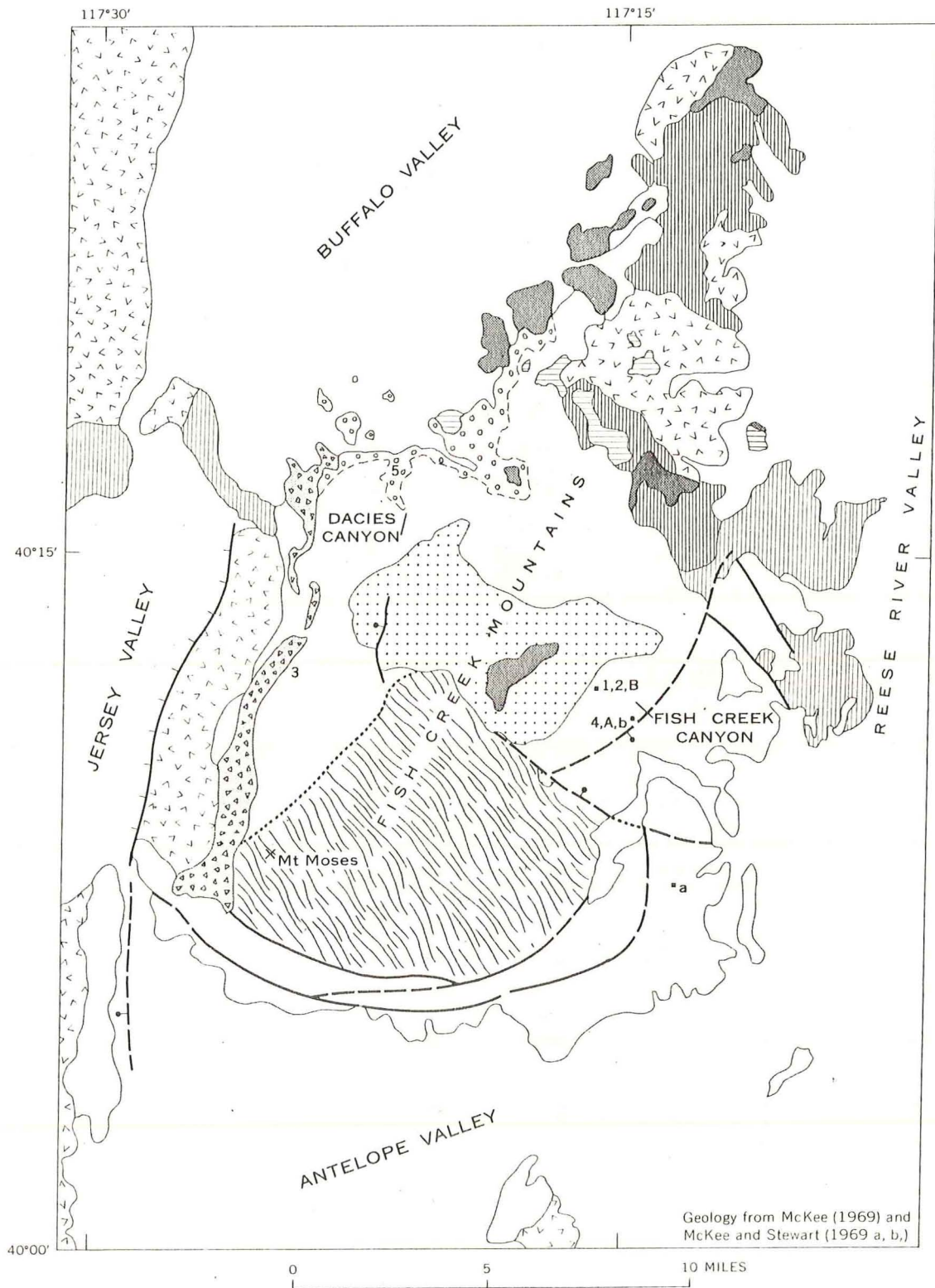
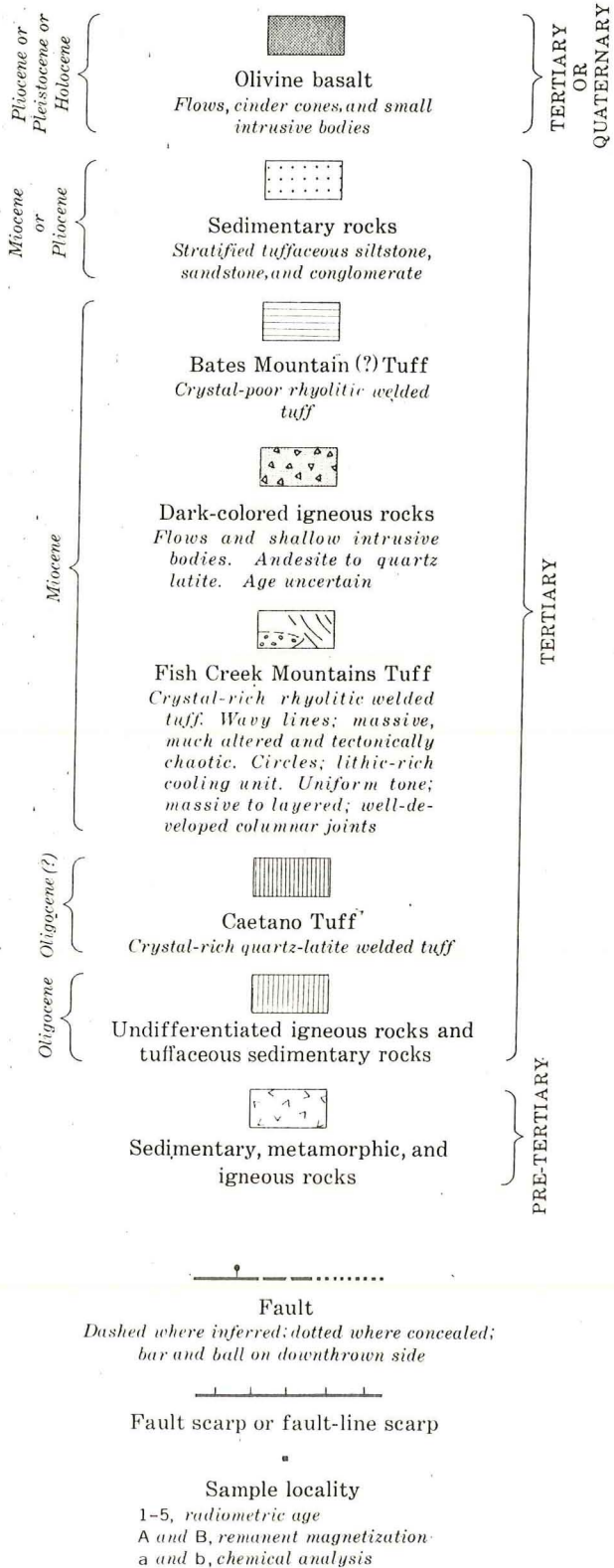


FIGURE 5.—Geologic map of the Fish Creek Mountains.

EXPLANATION



These tuffaceous sedimentary rocks are overlain in the center of the basin by an olivine basalt flow that covers about 1.5 square miles and is about 50 feet thick. Other small olivine basalt flows, cinder cones, and dikes crop out in a northeast-trending belt along the northern edge of the range. These basalts intrude or lie on all older rock types and are the youngest rocks in the region. The cinder cones are only slightly eroded, retaining their original profile, and samples of the basalt are fresh and show little signs of weathering. The age of the olivine basalts is unknown but probably is late Tertiary or Quaternary.

A belt of dark intrusive and extrusive rock of andesitic to quartz latitic composition of unknown age crops out along most of the western side of the Fish Creek Mountains. These rocks lie along the inferred northern projection of several long arcuate faults which ring the southern part of the range. The time of emplacement of the dark-colored igneous rocks may be related to the time of eruption of the Fish Creek Mountains Tuff or to subsequent tectonic activity, or these rocks may be younger and related to later Basin and Range faulting. The fact that they lie about 2 miles from the range front and may be associated with the pre-Basin and Range arcuate faults suggests that the andesites and quartz latites are related to the development of the Fish Creek Mountains volcanic center and are possibly early Miocene in age.

**FISH CREEK MOUNTAINS TUFF  
DISTRIBUTION AND DIMENSIONS OF  
THE ASH-FLOW SHEET**

Fish Creek Mountains Tuff is here named for a composite ash-flow sheet that makes up the entire southern part of the Fish Creek Mountains. The tuff crops out within the range in a circular area about 16 miles in diameter. This tuff is also found in three other localities, all less than 5 miles from the southern edge of the Fish Creek Mountains and it occurs in the Tobin Range at localities as far as 10 miles from the Fish Creek Mountains. Fish Creek Mountains Tuff is exposed over an area of about 200 square miles. It seems unlikely that the tuff ever spread much beyond the area in which it is now found, as no outcrops of the tuff are known outside this area, although rocks of the same age are widespread in nearby regions.

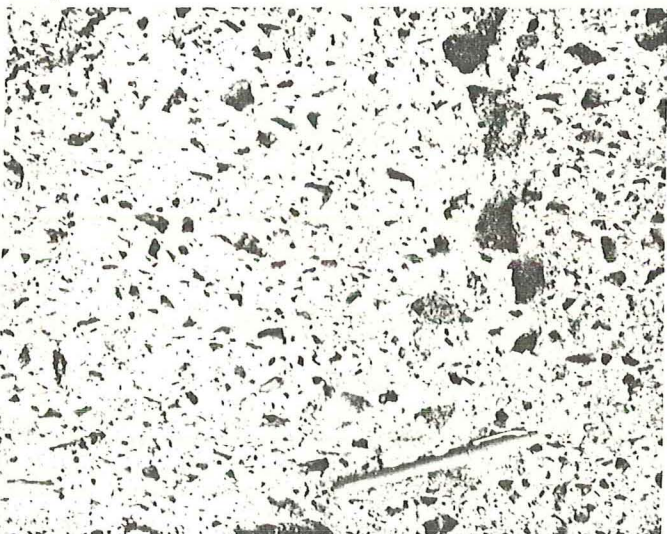
The thickness of the formation ranges from a maximum of about 3,000 feet in the south-central part of the Fish Creek Mountains to about 100 feet at the margins of the range. This change in thickness occurs across a distance of about 8 miles.



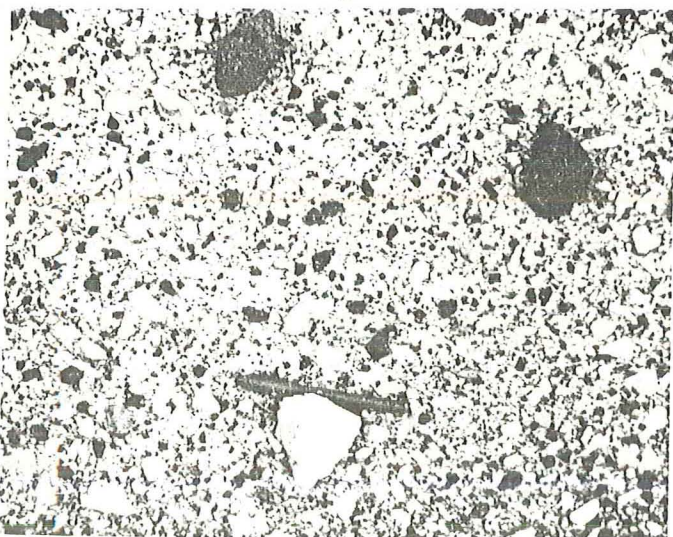




A



B



C

FIGURE 6.—Fish Creek Mountains Tuff, lithic unit at the mouth of Dacies Canyon, in stratigraphic sequence (downward A-C) through about the lower two-thirds of the unit. The pen is 6 inches long. *A*, Moderately to densely welded. Eutaxitic texture with relatively few small lithic fragments. *B*, Slightly welded to nonwelded. Pumice orientated and slightly flattened. Moderate number of lithic fragments, most less than 2 inches in diameter. *C*, Completely nonwelded. Large blocks of pumice and numerous lithic fragments up to 4 inches in diameter.

observed in these soft rocks suggests that in this place the lower unit was completely cool before the overlying ash flow was deposited. This cooling break can be mapped for about a mile in the vicinity of Dacies Canyon, but it becomes less discernible and ultimately cannot be found in the southern part of the range, where the main body of the ash flow was deposited.

#### LOWER COOLING UNIT

The lower cooling unit is a lenticular body of nonwelded to densely welded tuff characterized by numerous large blocks of pumice and relatively large xenoliths, as much as 4 inches in diameter, of volcanic rock of intermediate composition. The volcanic fragments are concentrated near the base of this unit and are largest and most numerous in the lower nonwelded part of the tuff. The unit becomes progressively more densely welded upward, and near the top, where it is most densely welded, it contains only a scattering of small lithic fragments. The difference in lithology between the top of the unit and its base is so great that were it not for the gradational middle part, one would not suspect that the two rock types are from the same ash-flow cooling unit. Detailed studies were made at five horizons in vertical alinement on a section of the lithic-bearing unit at the mouth of Dacies Canyon. At each point a 2-foot square was measured, and the percentage of lithic, pumice, and crystal fragments estimated. The degree of welding was also observed, and in the more densely welded parts of the tuff, the crystal content was ascertained. No correction is made in the relative percentage of lithic fragments and matrix with regard to the amount of compaction. Had this correction been made on the assumption of several-fold compaction indicated by the flattening of pumice, the relative amount of lithic debris in the nonwelded to weakly welded lower part of the tuff would be increased proportionally. The relative percentages at the five horizons through the cooling unit are given in table 1, and three horizons typical of intermediate parts of the tuff are shown in figure 6. The lower two-thirds of the unit is nonwelded to moderately

welded tuff (fig. 7). The concentration of the lithic fragments and their lateral and vertical gradation in this unit indicate that they probably represent a local concentration related either to preeruption topography or to contamination of one of the initial flows on eruption.



FIGURE 7.—Fish Creek Mountains Tuff, lithic unit viewed west from the mouth of Dacies Canyon. About two-thirds of the cooling unit shown. The upper, densely welded part has been eroded from the top. Approximately 500 feet of non-welded to weakly welded tuff exposed.

#### UPPER COOLING UNIT

The general appearance of the upper cooling unit of the Fish Creek Mountains Tuff in the south-central part of the range, where it is thickest, differs in gross aspect from that at the margins of the range, where it is thinner. This difference is due to the development of persistent subhorizontal to horizontal layering, as well as to well-formed columnar joints normal to this stratification (fig. 8A, B) in the unit at the margin. The thick, massive central part of the tuff, structureless and otherwise devoid of any feature that would influence the erosion pattern, has eroded into deeply incised badland topography. Within the central region there are also large areas of less resistant, highly leached and altered Fish Creek Mountains Tuff. However, rocks representative of the thick central tuff and the thinner margin tuff usually cannot be distinguished from each another in hand specimen or thin section.

#### LITHOLOGY

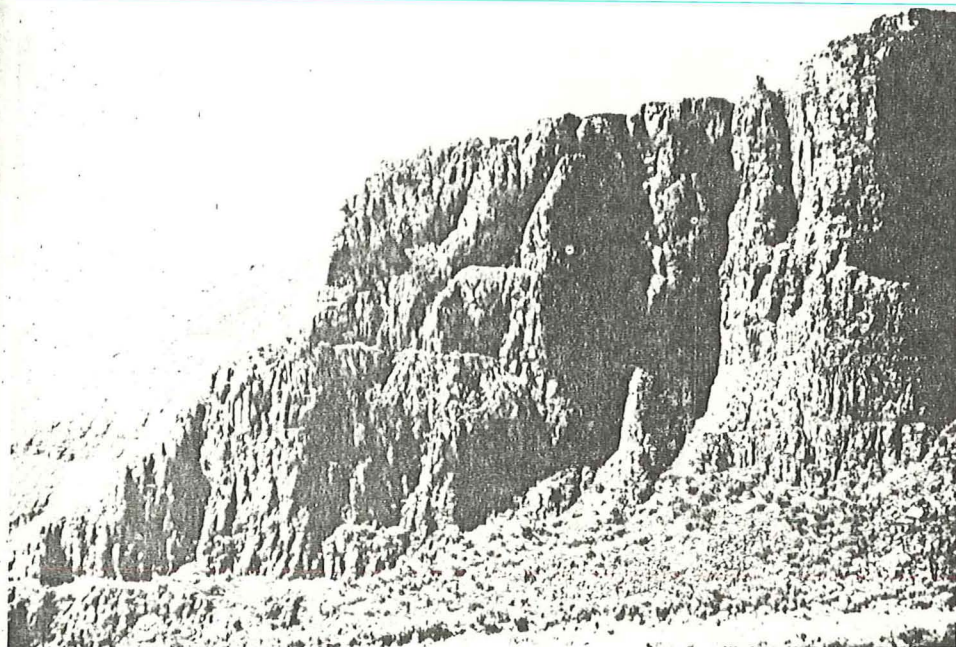
The Fish Creek Mountains Tuff is a light-gray to pink crystal-rich (greater than 30 percent crystals) rock that is usually structureless (fig. 9A) and rarely shows eutaxitic structure except in thin section or on wetted polished surfaces. At a few local-

ities, however, eutaxitic texture is obvious in the outcrop (fig. 9B). Most of the tuff is hard, dense rock containing about equal amounts of smoky quartz and sanidine as crystals and crystal fragments as much as 1 mm in diameter. A very few completely altered mafic phenocrysts are present in the rock, and in some places a few lithic fragments can be seen on an outcrop of several square feet. Zones of vitrophyre and vapor-phase alteration are rare or nonexistent and weakly welded parts of the tuff are also uncommon and not obvious in the field. Point counts on thin sections, however, reveal variations in the degree of welding. The most densely welded rock is about half matrix (devitrified glass) and half crystal phenocrysts; the least welded of the samples studied contains about 25 percent crystals and 75 percent matrix and voids per unit area. A typical piece of Fish Creek Mountains Tuff is made up of about 65 percent matrix and 35 percent phenocrysts. Modes based on 1,000 points counted on thin sections of four samples are shown in table 2. Two samples are "typical" or average Fish Creek Mountains Tuff; the other two represent more or less welded varieties. Heavy minerals separated from three samples are zircon and apatite. They make up appreciably less than 1 percent of the rock.

The quartz phenocrysts in most rocks are smoky to black, but in some places are colorless. Localities with smoky or clear quartz show no obvious correlation with position in the volcanic pile or with degree of welding. The development of smoky quartz may be related to the heating or radiation history of the rock, but this is uncertain.

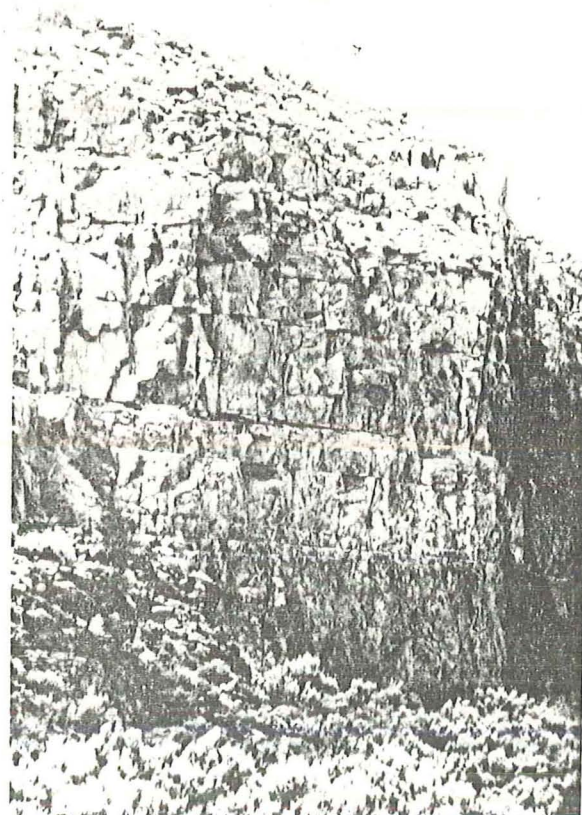
#### CHEMISTRY

The Fish Creek Mountains Tuff is of rhyolitic composition. Two whole-rock analyses of densely welded devitrified tuff are given in table 3, and normative Ab, An, and Or in molecular proportions are plotted on a ternary diagram (fig. 10). The analyses are similar to the "average calc-alkali rhyolite and rhyolite-obsidian" of Nockolds (1954), shown in table 3 and figure 10 for comparison, although they are richer in silica and poorer in total iron oxides, magnesia, lime and titania. The triangular plot of normative Ab, An, and Or shows that the samples of Fish Creek Mountains Tuff are within the rhyolite portion of the diagram as defined by O'Conner (1965, fig. 3) for volcanic rocks from southern Nevada. Within the rhyolite field, a subfield delineated by normative feldspar values from eight analyses of two rhyolite welded tuffs given by O'Conner is shown. The Fish Creek Mountains Tuff lies within this subfield.



A

FIGURE 8.—Fish Creek Mountains Tuff at the east margin of the range. The columnar joints cut the layering and are pervasive through the entire sequence. *B* is a closer view of tuff shown in *A*.



B

TABLE 2.—Modes of four samples of Fish Creek Mountains Tuff

[Based on 1,000 points counted per thin section]

	Composition, in percent			
	Densely welded "typical" sample	Densely welded "typical" sample	Densely welded	Moderately welded
Matrix and voids:				
Devitrified pumice and glass shards....	64	68	50	74
Crystal phenocrysts:				
Sanidine .....	20	17	29	15
Quartz .....	15	14	19	10
Plagioclase .....	1	1	2	<1
Total .....	36	32	50	26

TABLE 3.—Chemical analyses of two samples of Fish Creek Mountains Tuff and the "average calc-alkali rhyolite and rhyolite-obsidian" from Nockolds (1954, table 1).

[Samples analyzed by methods described in U.S. Geol. Survey Bull. 1144-A, supplemented by atomic-absorption method; analyzed under the direction of Leonard Shapiro]

	Fish Creek Mountains Tuff: fig. 5, a	Fish Creek Mountains Tuff, fig. 5, b	"Average calc-alkali rhyolite and rhyolite-obsidian" of Nockolds (1954)
SiO <sub>2</sub> .....	75.3	74.0	73.66
Al <sub>2</sub> O <sub>3</sub> .....	12.3	13.6	13.45
Fe <sub>2</sub> O <sub>3</sub> .....	1.1	.84	1.25
FeO .....	.20	.24	.75
MgO .....	.12	.15	.32
CaO .....	.61	.84	1.13
Na <sub>2</sub> O .....	4.2	3.3	2.99
K <sub>2</sub> O .....	4.9	5.4	5.35
H <sub>2</sub> O+ .....	.68	.38	.78
H <sub>2</sub> O- .....	.30	.82	.....
TiO <sub>2</sub> .....	.14	.17	.22
P <sub>2</sub> O <sub>5</sub> .....	.....	.04	.07
MnO .....	.....	.02	.03
CO <sub>2</sub> .....	<.05	<.05	.....

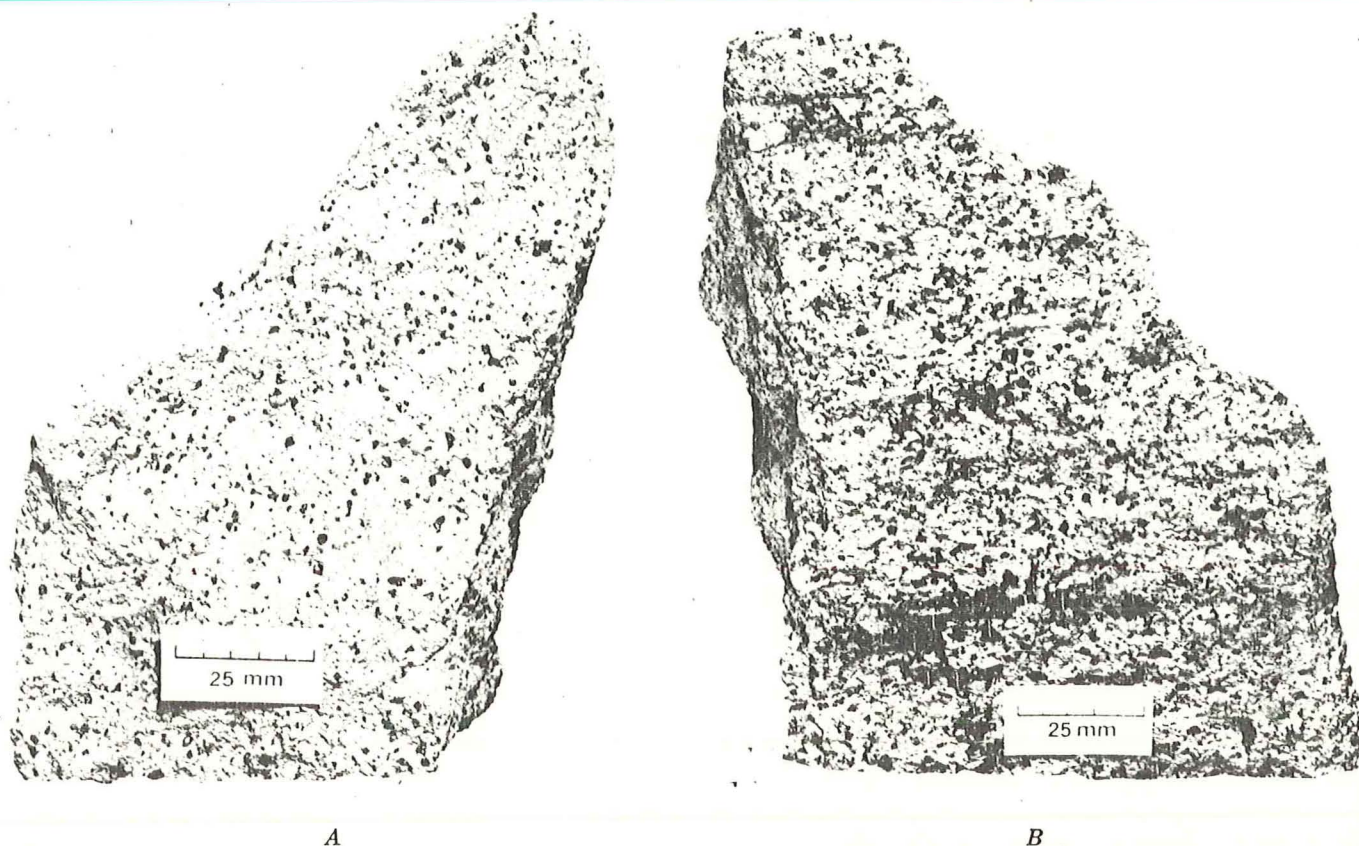


FIGURE 9.—Two hand specimens of Fish Creek Mountains Tuff. Dark phenocrysts are smoky quartz. Both specimens contain about 35 percent crystals of quartz, sanidine, and a little plagioclase. A, Eutaxitic structure not developed. B, Strong eutaxitic structure parallel to the base of the specimen.

Sr, Rb, and K values for phenocrystic sanidine from three samples of Fish Creek Mountains Tuff are given in table 4. From these values, approximate Rb and Sr contents for the whole rock can be estimated if the weight percent of sanidine phenocrysts and groundmass material is known (see table 2) and the amount of Sr and Rb in the groundmass of the rock can be inferred. The estimated whole-rock values are 65 ppm Sr and 265 ppm Rb, values based on an average of the three Rb, Sr, and K determinations shown in table 4, an average modal content of 26 percent sanidine and 53 percent groundmass with a  $K_2O$  content of 4.7 percent (table 3) and 20 ppm Sr, and the assumption that the K:Rb ratio of glass divided by that of coexisting sanidine is about 0.24 (D.C. Noble and C. E. Hedge, unpub. data).

The calculated Sr value (65 ppm) is relatively low compared with that for many quartz latitic volcanic rocks in the Great Basin and is comparable with subalkaline rhyolites from southern Nevada (Noble and Hedge, 1969). The Rb value (265 ppm) is relatively high for silicic rocks (Heier and Adams, 1965, Ewart and others, 1968).

Although both the Rb and Sr values suggest appreciable differentiation by fractional crystallization, the rocks do not appear to be as fractionated as many of the Sr-poor peralkaline and subalkaline rocks found at the margins of the Great Basin (Noble, Haffty, and Hedge, 1969).

TABLE 4.—Analyses of Rb, Sr, and K from sanidine separates of Fish Creek Mountains Tuff

[Rb and Sr determined by Donald C. Noble using X-ray fluorescence methods.  $K_2O$  analyzed by Lois B. Schlocker using flame-photometer methods]

Sample (fig. 5)	Rb (ppm)	Sr (ppm)	K (percent)
1	154	200	7.85
3	170	219	7.63
4	215	182	7.43

#### REMANENT MAGNETIZATION

Thirteen drill samples from the upper cooling unit of the Fish Creek Mountains Tuff from two localities in the range were collected by Sherman Grommé, and remanent magnetization of the samples was determined in the U.S. Geological Survey's remanent

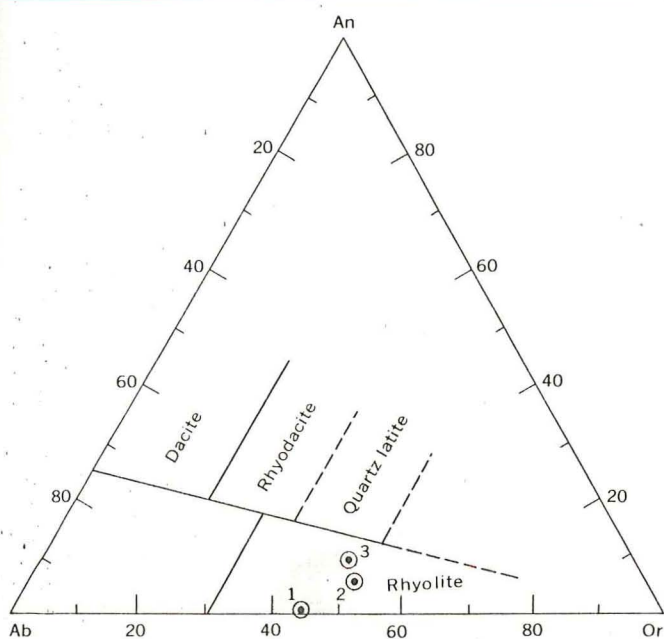


FIGURE 10.—Normative molecular Ab, An, and Or. Normative classification after O'Connor 1965 (fig. 3). Nos. 1 and 2, Fish Creek Mountains Tuff; No. 3, the "average calcalkali rhyolite and obsidian" of Nockolds (1954, table 1). Shaded area is the approximate field defined by eight samples of two rhyolite ash-flow tuffs from southern Nevada shown in O'Connor (1965, fig. 3).

magnetization laboratory. The results of the determinations are shown in table 5.

The fields of the two directions (D and I) overlap and the remanent magnetization is the same at both localities. These data strongly suggest that the two

TABLE 5.—Mean remanent magnetization directions, Fish Creek Mountains Tuff

Sample (fig. 5)	N	D	I	$\alpha_{95}$	H
A	10	344.3°	36.7°	2.5°	200.00
B	3	344.0°	39.1°	3.3°	100.00

N = number of specimens.

D = declination, east of north.

I = inclination, downward.

$\alpha_{95}$  = radius of 95-percent confidence cone around mean directions.

H = peak alternating field, in oersteds, used to remove unstable magnetization.

parts of Fish Creek Mountains Tuff were contemporaneous in cooling, and it seems most likely that they were also erupted at nearly the same time.

#### AGE

The age of the Fish Creek Mountains Tuff is considered to be early Miocene on the basis of radiomet-

ric dates. Three K-Ar age determinations were made on sanidine in samples from different places in the mountains, and two samples were dated on zircon using the fission-track method. Samples 1-4 are from the upper cooling unit; sample 5 is from the lower unit. The average age of the five samples date, as shown in table 6, is 24.3 m.y., which is early Miocene (Harland and others, 1964).

TABLE 6.—Radiometric dates of Fish Creek Mountains Tuff [Average of dates is 24.3 m.y.]

Sample (fig. 5)	Method of dating	Age (m.y.)	Mineral used	Reference
1	K-Ar	23.6	Sanidine	McKee and Silberman, 1970.
2	Fission-track	23.9	Zircon	McKee and Naeser, 1970.
3	K-Ar	24.4	Sanidine	McKee and Silberman, 1970.
4	do	24.5	do	Do.
5	Fission-track	25.0	Zircon	McKee and Naeser, 1970.
Average		24.3		

The standard deviation of this group of dates is 0.6. The range of the mean age at the 95-percent confidence level is 0.7 m.y., as determined by a standard table of cumulative *t* distribution. From these age determinations, the samples of Fish Creek Mountains Tuff can be considered to be  $24.3 \pm 0.7$  m.y.

#### TERTIARY STRUCTURE IN THE FISH CREEK MOUNTAINS

The generally massive nature of the Fish Creek Mountains Tuff makes it difficult to recognize structure within the range. At various places along the edges of these mountains, where the tuff is thin and where its contact with older rocks serves as a datum, faults can be observed, but in most places within the tuff, few features exist that can be used to demonstrate faulting or folding. Probable faults have been mapped locally in the eastern part of the range, where the horizontal layering or jointing offers some control; however, in most of the range, where the layering is not developed, faults have not been mapped. Aerial photographs, however, offering an overall view of the body of tuff, show several persistent linear features, not obvious on the ground, that probably are faults (fig. 4).

#### PRE-BASIN AND RANGE STRUCTURE

Two or more linear arcuate faults parallel the curved southern edge of the Fish Creek Mountains for at least 10 miles. Inspection of these faults in the field shows that they are zones about 100 feet wide of crushed and leached Fish Creek Mountains Tuff bounded on either side by relatively fresh tuff. Because they are bounded by identical material, it is impossible to determine the amount of displacement or even the relative movement along these faults.

The trace of these faults across topography indicates that they are steeply dipping and their arcuate shape suggests that movement, if any, was approximately vertical, with the central part of the range moving relatively up or down, or perhaps both ways at different times.

The two most prominent of these faults lie half a mile or more from the topographic edge of the range and are cut at places by drainage flowing outward from the center of the range. They are not related to the present physiography of the Fish Creek Mountains. Younger, generally north-trending Basin and Range faults are responsible for the present topography of the Fish Creek Mountains and surrounding ranges of central Nevada. The arcuate faults in the southern part of the Fish Creek Mountains trend at right angles to this regional northerly grain.

The projection of one of the arcuate faults as it curves around the southwestern part of the Fish Creek Mountains is defined by a belt of andesitic to quartz latitic igneous rocks about 1.5 miles from the western edge of the range (fig. 5). It is possible that these rocks were emplaced along the zone of weakness caused by the arcuate fault and that the fault is now obscured by the intrusions and small extrusions.

The central and south-central part of the Fish Creek Mountains (the "core" of the range) is a deeply dissected region underlain by tuff characterized by irregular zones of leaching, minor alteration, brecciation, and variable welding. No definite faults can be mapped, but the overall chaotic aspect of the rocks suggests that this area has been subjected to intense tectonism.

#### BASIN AND RANGE FAULTS

The Fish Creek Mountains are uplifted along their western edge by well-defined Basin and Range faults. Scarps can be seen in the field and a well-marked north-northeast-trending line at the base of the range, clearly visible on air photographs, probably is the trace of the most recent fault. Uplift on this western Basin and Range fault is about 1,000 feet or more and has elevated the Fish Creek Mountains Tuff as well as about 1,000 feet of the underlying Paleozoic basement. The tuff-basement contact exposed here because of Basin and Range faulting is not seen anywhere else in the southern half of the Fish Creek Mountains, although it is seen in the northern part of the range and at the north end of the Augusta Mountains. (See section on "Rocks older than Fish Creek Mountains Tuff.")

Basin and Range faulting at other places in the range is less obvious, or the faults have much less dis-

placement. Short faults with vertical displacement of several hundred feet or less displace other units in the northern part of the range, north of the northernmost outcrops of Fish Creek Mountains Tuff. The line of Pleistocene or Holocene basalt cones and flows along the northwest edge of the range probably represents eruption along the western Basin and Range fault zone; this line of eruptions is about 10 miles long and generally lines up (although it trends more north-easterly) with the fault scarp along the southwestern part of the range (see preceding section). The eastern edge of the range is not defined by Basin and Range faults, although several linear north-northeast-trending canyons in this part of the range may follow the trace of, or have been caused by, block faulting. About 5-7 miles east of the Fish Creek Mountains, the western scarp of the Shoshone Range is a very prominent north-northeast-trending fault; and in the low hills between the Fish Creek Mountains and the Shoshone Range in the Reese River Valley, there are well-defined parallel faults of smaller displacement.

#### MIOCENE TO HOLOCENE GEOLOGIC HISTORY SEQUENCE OF EVENTS

Eruption of Fish Creek Mountains Tuff began in early Miocene time ( $24.3 \pm 0.7$  m.y. by radiometric dating). (See section on "Age.") The first of the ash-flows probably spread over an area of slight relief, but local thick and lenticular accumulations of nonwelded to weakly welded lithic-rich tuff of the basal units suggest that some of the tuff ponded in shallow depressions. Eruption continued for an undetermined period of time, but radiometric ages on both high and low units in the series (maximum radiometric age 25.0, minimum 23.6 m.y.) suggest that the eruptive phase probably lasted for about 1 m.y. Remanent magnetization of two samples from different levels in the pile suggests that much of the tuff erupted and cooled at the same time. The Fish Creek Mountains Tuff spread outward from its source in the area that is now the south-central part of the Fish Creek Mountains more or less uniformly for about 10 miles in all directions. Tectonic adjustment, probably of collapse type, must have taken place during eruption, and the thick, massive tuff in the south-central part of the mountains represents tuff trapped in this caldera-type depression.

The dark andesitic to quartz latitic rocks were probably emplaced along the western part of the caldera fault zone shortly after subsidence, although these rocks may not be related to the Fish Creek Mountains Tuff volcanism at all.

Fish Creek Mountains Tuff accumulated to a thickness of more than 3,000 feet near its source in the

south-central part of the range, but less than 100 feet of tuff was deposited within a distance of about 10 miles from the source. This pile of tuff remained as a topographic high for at least a million years; during this time a thin ash-flow sheet of Bates Mountain (?) Tuff (radiometric age in the Fish Creek Mountains about 24 m.y.) spread around the southern, eastern, and northern part of the Fish Creek Mountains volcanic center. There is no evidence that this tuff sheet ever completely overlapped the region that is now the Fish Creek Mountains.

Following deposition of the Bates Mountain ash-flow sheet in early Miocene time, there is no record of geologic events in the Fish Creek Mountains until the deposition of tuffaceous sedimentary rocks of late Miocene(?) or early Pliocene(?) age. These strata accumulated in a shallow basin within the range and in nearby areas to the east, south, and west. Local units of conglomerate in some of these sedimentary sequences and the fact that basins in which they could accumulate developed suggest that the first stage of tectonism related to Basin and Range structure began at this time. Basin and Range faulting responsible for the present physiography of central Nevada subsequently "blocked out" the Fish Creek Mountains as they are today. The main faulting of this type in the Fish Creek Mountains is along their western edge. Olivine basalt flows and cones, many of which were erupted along the major western Basin and Range fault, are the last volcanic rocks deposited in the Fish Creek Mountains.

Recent erosion has deeply incised the south-central part of the range in the vicinity of the source of the Fish Creek Mountains Tuff. This area is particularly susceptible to erosion because of pervasive alteration as well as the presence of a large amount of soft, partially to moderately welded tuff.

#### INTERPRETATION OF THE FISH CREEK MOUNTAINS VOLCANIC CENTER

The thickness and distribution patterns of the Fish Creek Mountain Tuff strongly suggest that the source of this ash-flow sheet was from the south-central part of the Fish Creek Mountains. Lithologic variations and zones of alteration within the tuff, as well as large tectonic features, support this conclusion and offer clues to the nature of the volcanic center. No single line of evidence is conclusive, and some of the obvious features seen today, such as the basin in the center of the range, the sedimentary beds within this basin, and the capping basalt flow, are not related to the Fish Creek Mountains volcanic center. These features postdate the Fish Creek Mountains Tuff by as

much as 10 m.y. and belong to a later chapter in the geologic history of the range.

A series of schematic diagrams showing what the author considers to be the most likely history of the Fish Creek Mountains volcanic center are shown in figure 11. The major elements in this model of the evolution of the volcano are: (1) Accumulation of a thick pile of tuff erupted as a low-energy ash-flow sheet (Noble, 1969) from a central vent area. The margins of the pile are thin and show horizontal joints which probably are partings between ash flow pulses. (2) Probable subsidence of the central part of the tuff pile during eruption and subsequent filling and possible overflowing of the collapsed area by tuff. Tuff in this area is nonstratified, and the collapse area is characterized by chaotic structure, alteration of the tuff, and irregular zones of welding. The long arcuate faults that circumscribe the southern part of this central core are probably traces of the original collapse zone. (3) Possible resurgence of the central core of the tuff pile along the same zones of weakness developed on collapse. Resurgence might account for elevation of the core area and the beginning of the deep erosion of this part of the range. Later Basin and Range faulting, however, has elevated the mountains to their present height, and most erosion is related to this uplift. The belt of andesitic to quartz latitic rocks in the western part of the range may have been emplaced along the fracture formed by collapse of the source area of the Fish Creek Mountains Tuff. If it was so emplaced, the time of emplacement was probably not long after the eruption and subsequent collapse of the volcano.

#### SUMMARY

The Fish Creek Mountains in central Nevada are composed almost entirely of a single probably composite ash-flow sheet, the Fish Creek Mountains Tuff, considered to be of early Miocene age. This sheet is found only in this range or within a few miles of its edge. In the south-central part of the range, the formation is more than 3,000 feet thick, is devoid of structure except for some columnar jointing, and appears to be pervasively faulted. Irregular zones of alteration and differential welding also characterize the thick central part of the tuff body. Around the margins of the range a strong layering is present; many layers of tuff can be seen, all of which are cut by well-formed columnar joints which pass from one layer to the next without change.

In the southern part of the range, several long arcuate faults, trending approximately at right angles to the regional north-south topographic grain of central

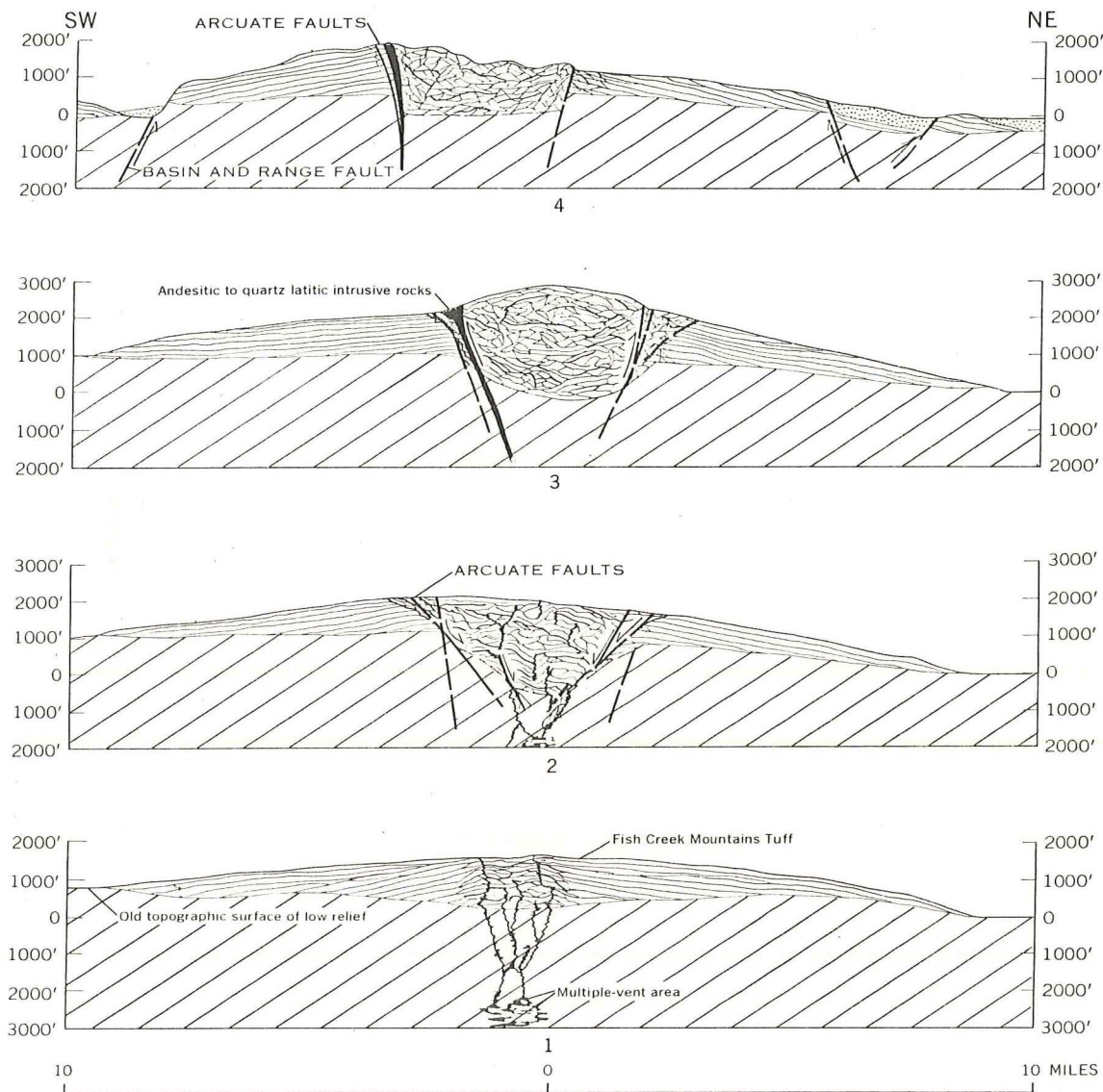


FIGURE 11.—Schematic possible history of the Fish Creek Mountains volcanic center. Horizontal and vertical scale approximate. 1, Initial eruption—a large volume (approximately 75 cu mi) of tuff erupted nearly simultaneously. Layering more pronounced at the margins. Approximately 24 m.y. ago. 2, Collapse during eruption—the collapse structure filled with tuff from continued eruption. Central collapse are structurally chaotic and highly altered. Approximately 24 m.y. ago. 3, Possible resurgence following eruption—elevation of the core area and beginning of deep erosion. Possible intrusion of andesitic to quartz latitic rocks along the faults on the western edge of the core area. Slightly less than 24 m.y. ago. 4, Present-day topography—the Fish Creek Mountains are elevated along north-northeast-trending Basin and Range faults. Such faults are especially obvious on the west side of the range.



Nevada, separate the central massive and tectonically chaotic and altered core area of tuff from the marginal layered tuff. These faults, which are not related to more recent Basin and Range faulting, are considered remnants of collapse or resurgent structures formed at the time of eruption (about 24 m.y. ago). The ash-flow sheet probably was erupted from vents within the south-central part of the Fish Creek Mountains.

The geologic history of the Fish Creek Mountains volcanic center started with the eruption of a voluminous (about 75 cu mi) ash-flow sheet. The eruption was probably of a low-energy type, for the ash flow spread only a short distance from its source and formed a relatively thick pile of tuff. Subsidence of the source area probably accompanied eruption and served to further localize the ash flow near its source. The total duration of ash-flow eruption probably was less than several thousand years, and there was no later ash-flow activity from the volcanic center.

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