Cenozoic Volcanic Rocks of the Devils Postpile Quadrangle, Eastern Sierra Nevada California

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CENOZOIC VOLCANIC ROCKS OF THE DEVILS POSTPILE QUADRANGLE, EASTERN SIERRA NEVADA, CALIFORNIA

By N. KING HUBER and C. DEAN RINEHART

ABSTRACT

Cenozoic volcanic rocks of the Devils Postpile quadrangle are of late Pliocene to Recent age and are divided into 11 map units. The suite is alkalic-calcic and ranges in composition from basalt to rhyolite. It includes a rhyolitic welded ash-flow tuff which is probably correlative with the Bishop Tuff, although the two units are geographically isolated by the Sierra Nevada drainage divide. The Devils Postpile itself is a classic example of columnar jointing in the lower part of a lava flow.

INTRODUCTION

The Devils Postpile quadrangle straddles the crest of the Sierra Nevada southeast of Yosemite National Park and contains the Devils Postpile National Monument (fig. 1). The pre-Cenozoic rocks of the quadrangle include Paleozoic and Mesozoic metasedimentary and metavolcanic rocks. The metamorphic rocks have been intruded by various granitoid igneous rocks, which form a part of the composite Sierra Nevada batholith (Bateman and others, 1963; Huber and Rinehart, 1965a). By late Tertiary time the Sierra Nevada had attained approximately its present overall configuration, except for later modifications caused by faulting, uplift, and increased dissection. Regional volcanism began during the late Tertiary and has continued spasmodically to the present.

The Cenozoic volcanic rocks of the Devils Postpile quadrangle resulted from several types of eruption throughout late Tertiary and Quaternary time; the forms of eruption include domes, lava flows, ash flows, and extensive pumice falls. The volcanic rocks range in composition from basalt to rhyolite, the oldest being basaltic to andesitic and the youngest, rhyolitic; however, most mafic and felsic rocks alternate haphazardly without regard to stratigraphic position. For this reason and because many of the volcanic units remain only as scattered erosional remnants, correlations are difficult. Interpretation of the volcanic history has been greatly assisted by potassium-argon age dating.

Mapping in the Devils Postpile quadrangle (Huber and Rinehart, 1965a) and in the Mount Morrison quadrangle to the east (Rinehart and Ross, 1964) allows the division of the Cenozoic volcanic rocks of the Devils Postpile quadrangle into 11 mappable units. Scattered erosional remnants of uncertain stratigraphic position have tentatively been assigned to these units, although some of the remnants may represent additional episodes of volcanic activity not otherwise recognized. Table 1 lists the 11 units and their radiometric ages where available, and plate 1 shows their distribution.

TABLE 1.—*Ages of Cenozoic volcanic rocks of the Devils Postpile quadrangle*

[See text for source and other data regarding individual age determinations]

Age and unit	Potassium-argon age determination [1] (million years)
Recent:	
Rhyolite	
Basalt of the Red Cones	
Pleistocene or Recent:	
Olivine-bearing quartz latite	
Pleistocene:	
Andesite of Pumice Butte	
Andesite from Dry Creek area	
Quartz latite of Mammoth Mountain	0.37±0.04; 0.18±0.09
Andesite of the Devils Postpile	0.94±0.15; 0.63±0.35
Tuff of Reds Meadow	0.66±0.04; (1.1); (1.4)
Pliocene or Pleistocene:	
Andesite from Deadman-Glass Creeks area	
Pliocene:	
Quartz latite of Two Teats	3.0±0.1
Andesite of Deadman Pass	3.1±0.1; 3.3±0.1; 3.5±0.1

[1] The plus-or-minus figure that accompanies these age determinations is not an estimate of accuracy but rather an estimate of analytical precision at the 68-percent confidence interval. Figures in parentheses are two older ages from samples contaminated with granite; youngest age is accepted as most reliable.

In order to provide a background for description of the individual volcanic units, a general summary of petrologic and chemical data is presented for the entire volcanic suite. Following this, field relationships and general characteristics of each volcanic unit are described in order of decreasing age, rather than by petrologic type, to provide a clearer picture of the sequence of events.

We wish to thank G. B. Dalrymple for making his potassium-argon age determinations available to us in advance of their being published and Gerhard Schumacher for the use of some of his excellent photographs of the Mammoth Lakes region. We also express our

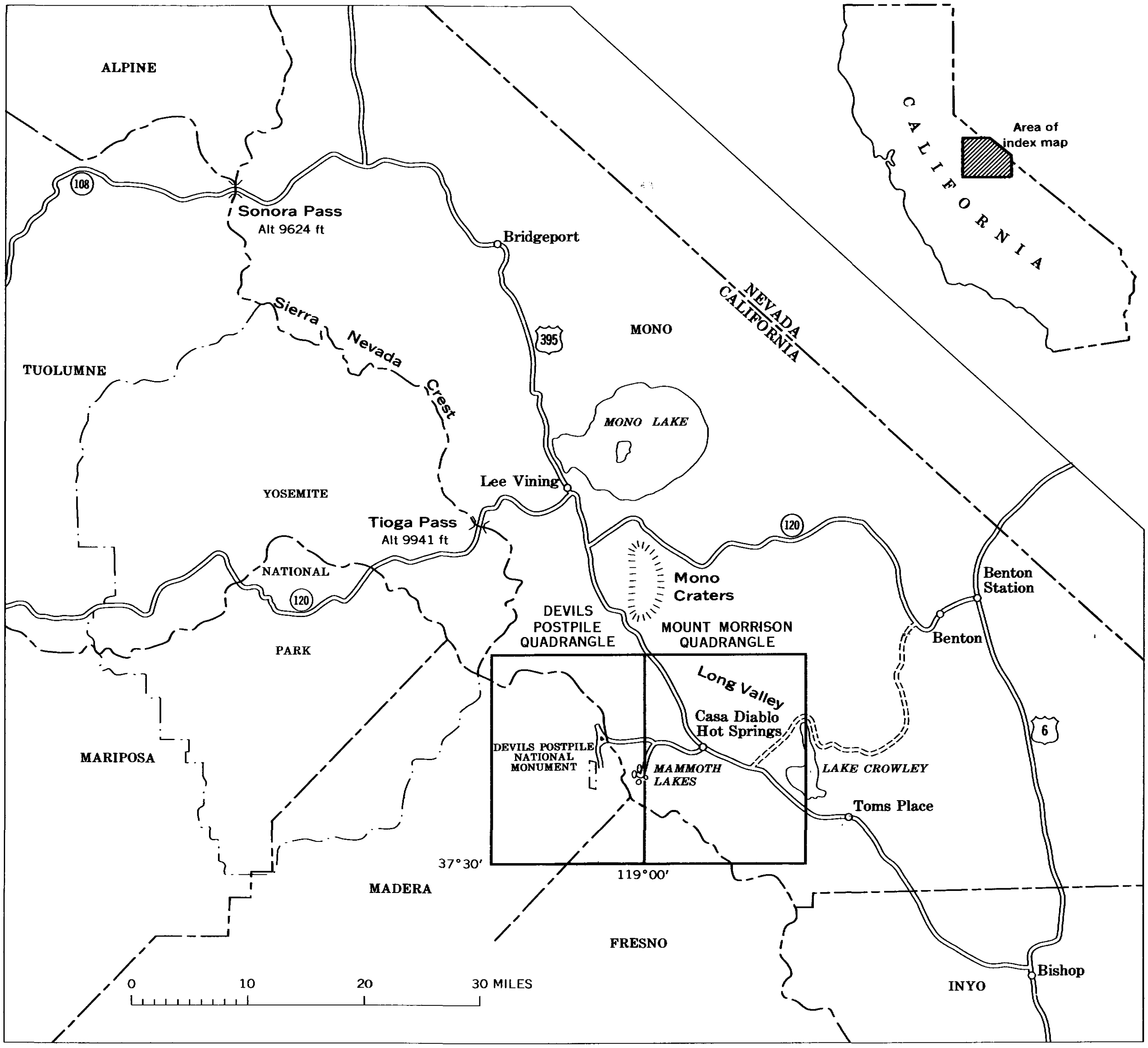

FIGURE 1.—Location of the Devils Postpile quadrangle and the adjacent Mount Morrison quadrangle.

appreciation to R. J. Janda for many stimulating discussions of the interrelations of volcanic and glacial events.

PETROLOGIC AND CHEMICAL DATA

MICROSCOPIC PETROGRAPHY

Data obtained from the petrographic study of the volcanic rocks are recorded in table 2. Percentages of constituents are based upon visual estimates obtained from thin-section study and are little more than rough approximations. The percentages, however, can be effectively used to distinguish major and minor constituents and to reveal the large proportion of indeterminate material occult in the groundmass of most of the rocks. Minerals listed in groups of two or more are given in order of decreasing abundance. In most specimens range in anorthite content of the plagioclase was determined from twinning relationships. Olivine is typically magnesium rich.

CHEMICAL DATA

Table 3 presents chemical analyses and norms for seven samples of volcanic rock from the Devils Postpile quadrangle and one from the Mount Morrison quadrangle.

TABLE 2.—*Petrographic summary of the volcanic rocks*

[An, anorthite; *n*, refractive index; Fa, fayalite]

Volcanic unit	Color (Goddard, 1948)	Texture	Phenocrysts: Mineral	Phenocrysts: Average range in size (mm)	Phenocrysts: Percent	Matrix: Material	Matrix: Percent	Remarks
Rhyolite.	Light gray to black.	Holohyaline to vitrophyric.	Plagioclase ($An_{\approx 10}$). Sanidine. Quartz. Biotite. Oxyhornblende. Granular opaque minerals.	1–5 2–10 0.5–2 <0.5 <0.5 <0.5	See remarks.	Glass and impalpable dust, minor feldspar, microlites.	See remarks.	Material is dominantly obsidian and pumice. Where phenocrysts are locally abundant (as at Deer Mountain), they occur in approximately the following ratio—plagioclase:sanidine:quartz:mafic minerals: 6:2:1:1. The *n* of fused obsidian from small dome north of Deadman Creek is 1.490.
Quartz latite of Mammoth Mountain.	Light gray to nearly black.	Vitrophyric to pilotaxitic, dominantly hyalopilitic.	Plagioclase (An_{30-50}). Biotite, oxyhornblende, clinopyroxene, granular opaque minerals, minor apatite.	1–5 0.1–2	5–15 1–5	Plagioclase and potassium feldspar. Glass and impalpable dust.	0–75 5–90	Plagioclase phenocrysts are commonly zoned and contain irregular patches of glass; potassium feldspar in matrix is indicated by stain tests; *n* of natural glass is 1.493–1.500, rock commonly shows flow banding.
Quartz latite of Two Teats.	Light gray to dark or purplish gray.	Hyalopilitic.	Plagioclase (An_{25-45}). Biotite, oxyhornblende, granular opaque minerals, minor apatite and zircon.	1–5 0.1–1	15–30 <5–10	Plagioclase. Glass and opaque dust.	15–70 15–70	Most plagioclase phenocrysts are embayed, riddled with glass, and zoned; mafic phenocrysts are generally strongly oxidized and otherwise altered.
Olivine-bearing quartz latite.	Dark gray.	Hyalopilitic to intergranular.	Plagioclase (An_{25-50}). Sanidine. Biotite, oxyhornblende, clinopyroxene, orthopyroxene, olivine.	2–5 2–5 0.1–0.5	20–30 5–10 5	Plagioclase, glass, and minor opaque dust.	60–70	Plagioclase phenocrysts are commonly riddled with glass disposed in somewhat vermicular pattern and have some reverse zoning of plagioclase. Olivine has a composition about Fa_{20} according to optical data.
Tuff of Reds Meadow.	Variable with position within flow; light to dark gray to reddish brown.	Vitroclastic.	Sanidine. Quartz. Plagioclase (An_{15-25}). Biotite, granular opaque minerals.	0.2–2 0.2–2 0.2–1 0.1–0.5	5–10 ≈5 ≈5 <1	Glass and impalpable dust; minor devitrification locally.	70–90	Many phenocrysts are commonly fragmented, showing some preserved crystal faces; exotic rock fragments are common; degree of welding and formation of eutaxitic structure is variable; *n* of pumice from base is 1.497; phenocrysts make up 10–30 percent of the rock with average of 20 percent. Potassium-sodium ratio in sanidine is about 2:1, as estimated from partial chemical and X-ray diffraction data.
Andesite from Dry Creek area.	Medium light gray to medium dark gray.	Trachytic to intergranular.	Plagioclase (An_{45-70}). Olivine. Clinopyroxene.	0.1–3 0.1–1 <0.1–0.5	<5–20 5–10 <5	Plagioclase. Olivine and clinopyroxene. Magnetite and other opaque minerals, glass(?).	50–75 10–20 10–20	Olivine and pyroxene are moderately to strongly altered to black opaque material; olivine is composed of about Fa_{10-20} according to optical data and also altered to iddingsite(?) or bowlingite(?).
Andesite from Deadman–Glass Creeks area.	Medium light gray to medium dark gray.	Pilotaxitic.	Olivine. Clinopyroxene.	0.15–2 <0.01–0.13	3–5 5–10	Plagioclase An($_{35-55}$). Olivine and clinopyroxene. Magnetite and minor opaque minerals.	50–75 10–25 5–10	Only about half a dozen highly altered plagioclase phenocrysts occur in thin section; otherwise, alteration in rock is restricted to rims of iddingsite(?) or bowlingite(?) around olivine. Sufficient magnetite is present to affect hand magnet. Olivine is composed of about Fa_{20} according to optical data.

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TABLE 2.—*Petrographic summary of the volcanic rocks*—Continued

[An, anorthite; *n*, refractive index; Fa, fayalite]

Volcanic unit	Color (Goddard, 1948)	Texture	Phenocrysts			Matrix		Remarks
			Mineral	Average range in size (mm)	Percent	Material	Percent	
Andesite of Pumice Butte	Medium light gray to dark gray.	Merocrystalline to trachytic.	Plagioclase (An_{60-70}). Clinopyroxene, olivine.	0.1-3 0.05-0.3	10-20 2-5	Plagioclase. Olivine, pyroxene, impalpable dust, opaque minerals, and glass.	20-50 30-70	In specimens with appreciable glass, plagioclase phenocrysts are typically embayed and riddled with matrix material; olivine is composed of about Fa_{10-20} according to optical data. Specimens from small knobs at north edge of outcrop area appear to be more latitic than average, a conclusion based upon data from fused glass beads; they also contain up to 5 percent euhedral plates and wedges of opaque material apparently altered from hornblende.
Andesite of the Devils Postpile.	Medium light gray to m' dium dark gray.	Trachytic to intergranular.	Plagioclase (An_{50-70}). Clinopyroxene, olivine.	0.2-5 0.1-2	1-5 <5-25	Plagioclase. Olivine, pyroxene, opaque minerals, and impalpable dust.	40-75 20-50	Rock in unit as mapped ranges from basalt to latite (48-66 percent SiO_2) with andesite predominant; plagioclase phenocrysts in andesitic composition range are An_{55} to An_{65}; plagioclase and pyroxene phenocrysts are commonly zoned. Olivine, being composed of about Fa_{10-20} according to optical data, is locally altered to iddingsite(?) or bowlingite(?).
Andesite of Deadman Pass.	Medium light gray to medium dark gray.	Pilotaxitic to trachytic.	Olivine. Clinopyroxene.	0.1-2 0.1-1.5	10-25	Plagioclase. Olivine, pyroxene, and granular opaque minerals.	50-75 20-25	Rock is predominantly andesitic but includes some basalt. Percentage of olivine and clinopyroxene decreases with increasing silica. One specimen, with the highest silica content as estimated from fused beads, contains both ortho- and clinopyroxene. Olivine, being composed of about Fa_{20} according to optical data, is locally altered to iddingsite(?) or bowlingite(?).
Basalt of the Red Cones.	Medium gray to medium dark gray.	Merocrystalline.	Plagioclase (An_{65-70}). Olivine. Clinopyroxene.	0.5-3 0.2-2 0.2-2	20-25 <5 <5	Plagioclase, olivine, pyroxene, granular opaque minerals, and glass.	70	Clinopyroxene and olivine are generally unaltered, with the composition of olivine being about Fa_{20} according to optical data.

While only the Cenozoic volcanic rocks of the Devils Postpile quadrangle are described in this report, the volcanic rocks of both the Devils Postpile and Mount Morrison quadrangles (an area we call the Mammoth Lakes area) overlap in time and space and are here considered part of a consanguineous suite which has alkalic affinities, at least in the mafic rocks of the suite. The nature of this suite is illustrated by a Peacock (1931) variation diagram (fig. 2). The alkali-lime index, approximately 54, places the suite in the alkalic-calcic type. Alkalic affinities also are well shown at the mafic end of the series, where the Rittmann p values are less than 55 (alkaline <55 <calc-alkaline; Rittmann, 1953), and the rocks are trachybasalt and trachyandesite (table 3) according to Rittmann's classification. Figure 3 further illustrates the alkalic tendencies of the suite at its mafic end, as alkalic rocks typically fall within the undersaturated field of silica-differentiation-index plots (Thornton and Tuttle, 1960).

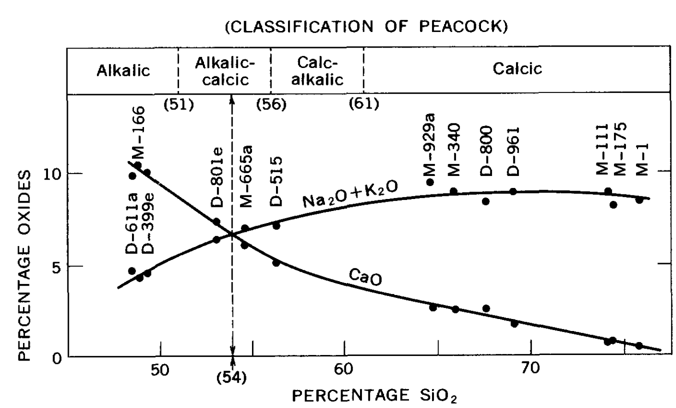

FIGURE 2.—Variation diagram of the Mammoth Lakes volcanic suite showing classification according to the "alkali-lime index" (percentage of SiO_2 at which $Na_2O+K_2O=CaO$) of Peacock (1931). D samples are from table 3; M-1 is a rhyolite from the nearby Mono Craters (R. A. Loney, written commun., 1965); the other M samples are from Rinehart and Ross (1964, table 9).

TABLE 3.—*Chemical analyses and norms of the volcanic rocks*

[Analyses by the rapid method of Shapiro and Brannock (1956)]

Volcanic Unit	Andesite of the Devils Postpile			Andesite of Deadman Pass	Quartz latite of Two Teats	Quartz latite of Mammoth Mountain		Olivine-bearing quartz latite
Rittmann classification	Trachybasalt	Trachybasalt	Trachyandesite	Trachyandesite	Quartz latite	Quartz latite	Quartz latite	Quartz latite
Field No. (See explanation below)	D-399e	D-611a	D-515	D-801e	D-800	D-961	[3] M-340	[3] M-929a
Laboratory No.	[1] 154228	[1] 154230	[1] 154229	[1] 154232	[1] 154231	[2] 63M-12	144089	148741
Sp gr (powder)	2.95	2.85	2.64	2.73	2.58	n.d.	2.62	2.56
Rittmann *p* value (alkaline <55< calc-alkaline)	52.5	51.7	54.5	50.4	58.0	57.2	55.3	53.7
Differentiation index	35.0	35.8	59.8	53.0	82.0	86.3	80.1	79.2
Average refractive index of fused glass beads	1.594	1.583	1.545	1.560	1.505	1.505	1.510	1.515
Chemical analyses (percent)								
SiO_2	49.2	48.4	56.2	53.0	67.5	68.9	65.8	64.7
Al_2O_3	14.9	15.2	17.5	15.7	16.4	16.4	16.8	17.0
Fe_2O_3	2.3	3.0	3.2	2.6	2.2	1.1	2.7	1.8
FeO	5.6	4.6	3.7	3.8	.32	1.3	1.0	2.2
MgO	10.0	8.5	2.5	5.0	.76	[4] .27	1.0	1.1
CaO	10.1	9.9	5.2	7.4	2.7	1.8	2.7	2.7
Na_2O	2.9	3.0	4.7	3.8	4.4	4.9	5.0	4.5
K_2O	1.8	1.8	2.5	2.7	4.1	4.1	3.9	4.8
H_2O	.30	1.1	1.1	.92	.77	.19	.18	.60
TiO_2	1.3	1.0	1.5	.94	.34	.51	.70	.64
P_2O_5	.80	.62	.79	.50	.24	.20	.22	.16
MnO	.06	.18	.16	.14	.09	.08	.08	.06
CO_2	.08	2.0	.09	2.8	.08	<.05	.05	.07
Total	99.3	99.3	99.1	99.3	99.9	99.8	100.1	100.3
Norms (weight percent)								
Quartz	—	—	6.2	4.7	20.2	20.7	14.9	12.5
Orthoclase	10.6	10.6	14.7	16.0	24.2	24.2	22.8	28.4
Albite	24.1	25.4	39.7	32.1	37.2	41.4	42.4	38.3
Anorthite	22.3 (An_{48})	22.7 (An_{47})	19.3 (An_{33})	15.7 (An_{33})	11.3 (An_{23})	7.6 (An_{16})	12.0 (An_{22})	12.0 (An_{24})
Nepheline	0.3	—	—	—	—	—	—	—
Diopside	17.6	7.7	0.6	—	—	—	1.1	0.9
Hypersthene	—	13.1	7.9	16.0	1.9	1.5	2.0	3.9
Apatite	1.9	1.5	1.9	1.2	0.6	0.5	—	—
Corundum	—	—	—	0.8	0.6	1.1	—	—
Magnetite	3.3	4.4	4.6	3.8	0.3	1.6	1.2	2.6
Ilmenite	2.5	1.9	2.8	1.8	0.6	1.0	1.4	1.2
Hematite	—	—	—	—	2.0	—	1.9	—
Calcite	0.2	4.5	0.2	6.4	0.2	—	—	—
Olivine	16.4	6.5	—	—	—	—	—	—
Total	99.2	98.3	97.9	98.5	99.1	99.6	99.7	99.8

D-399e. At outlet of Lake Mamie, Mammoth Lakes basin.
D-611a. On small ridge half a mile northeast of bench mark 7607 in Snow Canyon, King Creek.
D-515. On Boundary Creek just below John Muir trail southeast of Reds Meadow.
D-801e. On slope one-quarter of a mile northeast of bench mark 8425 along road southeast of Agnew Meadows.
D-800. Summit of Two Teats.
D-961. On northwesternmost spur of Mammoth Mountain at 10,000-ft elevation.
M-340. One-quarter of a mile north of Mammoth Rock (in Mount Morrison quadrangle, half a mile east of Devils Postpile quadrangle boundary).
M-929a. One-quarter of a mile west of quadrangle boundary along Deadman Creek.

[1] Analysts: P. L. D. Elmore, S. D. Botts, and I. H. Barlow.
[2] Analysts: L. B. Beatty and A. C. Bettiga.
[3] Analysts: K. E. White, P. L. D. Elmore, P. W. Scott, and S. D. Botts (from Rinehart and Ross, 1964, table 9).
[4] Quantitative spectrographic analysis (63MS-60).

In order to extrapolate from data of the few chemical analyses, the rapid-fusion technique described in Rinehart and Ross (1964) was used to obtain estimates of percent silica from a large number of specimens. Available chemical analyses cover a range in silica content sufficient to establish a reasonably definitive silica-refractive-index curve for the Mammoth Lakes suite (Huber and Rinehart, 1966). This curve, shown in figure 4, is a slight modification, based upon additional data, of an earlier version (Rinehart and Ross, 1964). The rapid-fusion techniques used were the same as described in these two earlier reports.

The data obtained from refractive-index determinations are in figure 5, which gives an indication of the average percent silica as well as the general range in percent silica for the map units indicated. (See pl. 1 for geographic plot of silica distribution.) The variation within some of the map units is extreme but may be in part explained by the probability that the units represent more than one eruptive cycle. The significance of this variation is considered later in discussions of the individual map units.

CLASSIFICATION

The volcanic rock classification used in this report is based upon chemical composition rather than mineralogy, and therefore many of the rock names used are different from those used by previous workers in the area (chiefly Erwin, 1934). The chemically analyzed samples represent the entire compositional range of the suite (table 3) fairly well and are classified according to the Rittmann system (Rittmann, 1952). Fused-bead data provide a good estimate of the silica percentage of the remaining samples; hence, silica percentage pro-

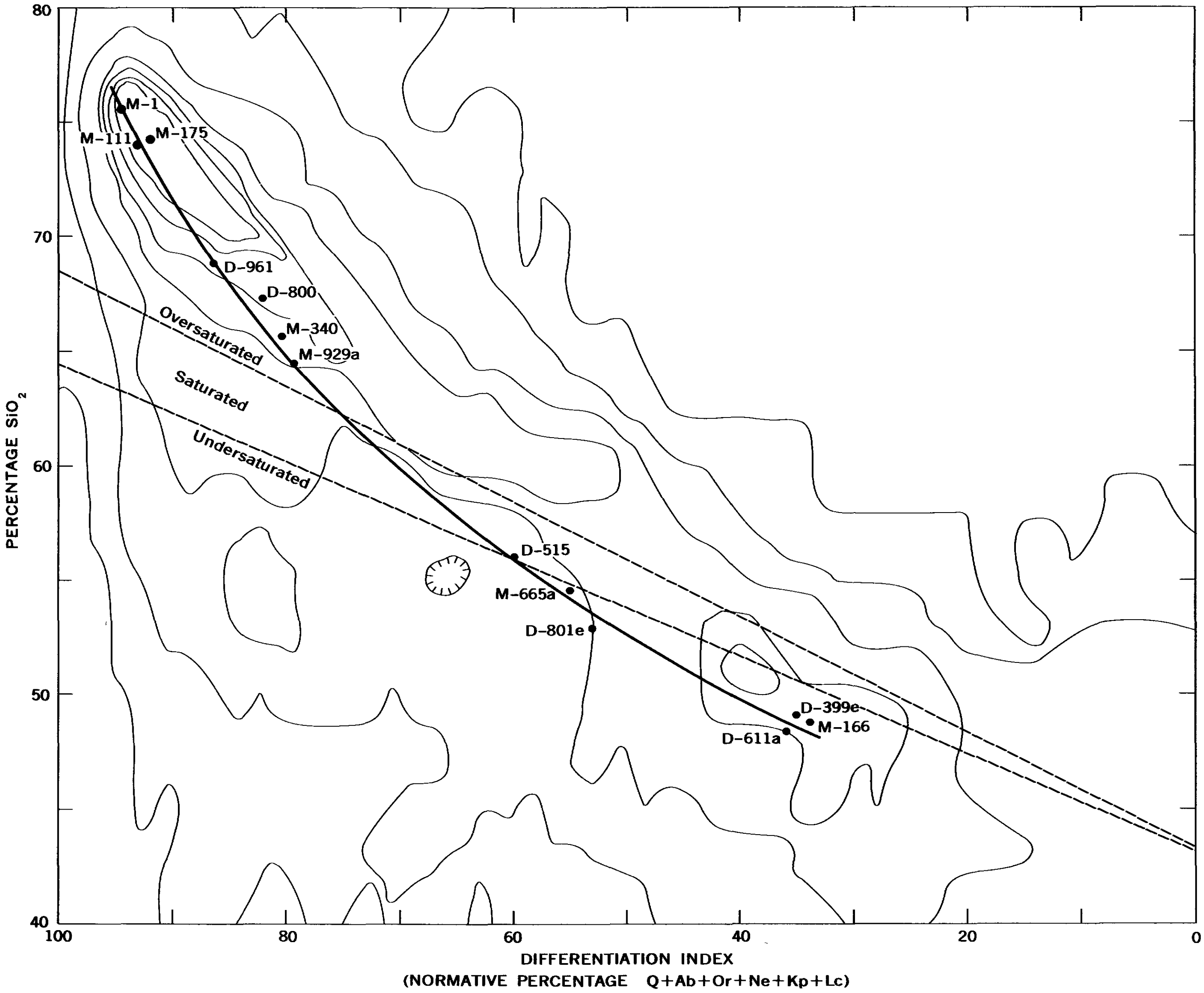

FIGURE 3.—"Differentiation trend" for the Mammoth Lakes volcanic suite as determined by utilization of the "differentiation index" of Thorton and Tuttle (1960). Background contours indicate frequency distribution of the silica-differentiation-index values for 5,000 analyses in H. S. Washington's tables (from Thornton and Tuttle, 1960). Sample sources listed in figure 2.

provides an auxiliary basis for classifying these rocks. From a study of the classifications of Rittmann and of Nockolds (1954), which are similar, we have arrived at the classification shown on figure 5, which is based solely upon percent silica. For convenience, the prefix "trachy" is generally omitted in the ensuing discussion, although most, and perhaps all, of the andesites and basalts in the quadrangle are trachyandesites and trachybasalts.

ANDESITE OF DEADMAN PASS

The oldest known Cenozoic volcanic unit exposed in the quadrangle consists of andesite and basalt flows of late Pliocene age. They are well exposed on the flanks of the ridge that extends northwestward from Minaret Summit to the north edge of the quadrangle. The flows are exceptionally well exposed in the vicinity of Deadman Pass, and this locality is informally used to designate the unit. Although the unit here has generally been considered to be of Miocene (Erwin, 1934) or early Pliocene age (Gilbert, 1941), Axelrod and Ting (1960) postulated a late Pliocene age from a spore-pollen flora in underlying and intercalated sediments in the basal part of the section. A late Pliocene age is supported by a potassium-argon age determination of 3.1 ± 0.1 million years for a sample obtained just north of Minaret Summit (Dalrymple, 1964a, table 1).

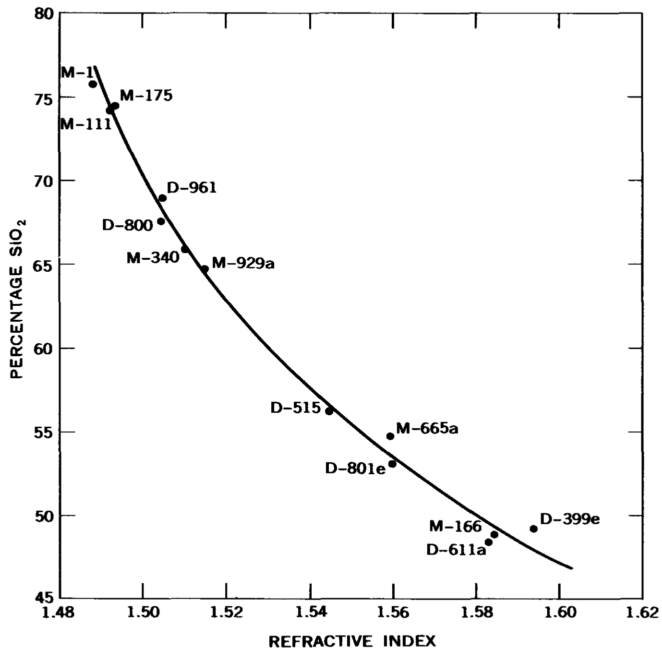

FIGURE 4.—Silica-refractive-index diagram showing curve established for volcanic rocks of the Mammoth Lakes area. Same sources as listed in figure 2. The positions of M–111 and M–175 were transposed in Rinehart and Ross (1964).

The single chemically analyzed sample from this unit is an olivine trachyandesite (table 3). Data from additional fused samples (fig. 5), however, indicate a wide range in composition, with an average silica content of approximately 51 percent, occurring principally at the basalt-andesite boundary used in this report. In two earlier reports (Huber and Rinehart, 1965a, b) based upon data then available, this map unit was classified as andesite. This designation is retained here, although basalt is more abundant than previously suspected and is the dominant rock type locally, as in the Agnew Pass area.

In the Deadman Pass area the andesite occurs as a series of nearly horizontal flows and intercalated andesitic cinders and rubble. The flows range in thickness from a few feet to 25 feet, and most intervening rubble zones are less than 5 feet thick. Exposures south and northwest of Deadman Pass indicate that locally the unit had an original thickness of at least 1,600 feet; the imposing cliffs indicate that the flows also must have once extended over a much larger area than they now occupy. The andesite flows originally probably covered much of the area of the present val-

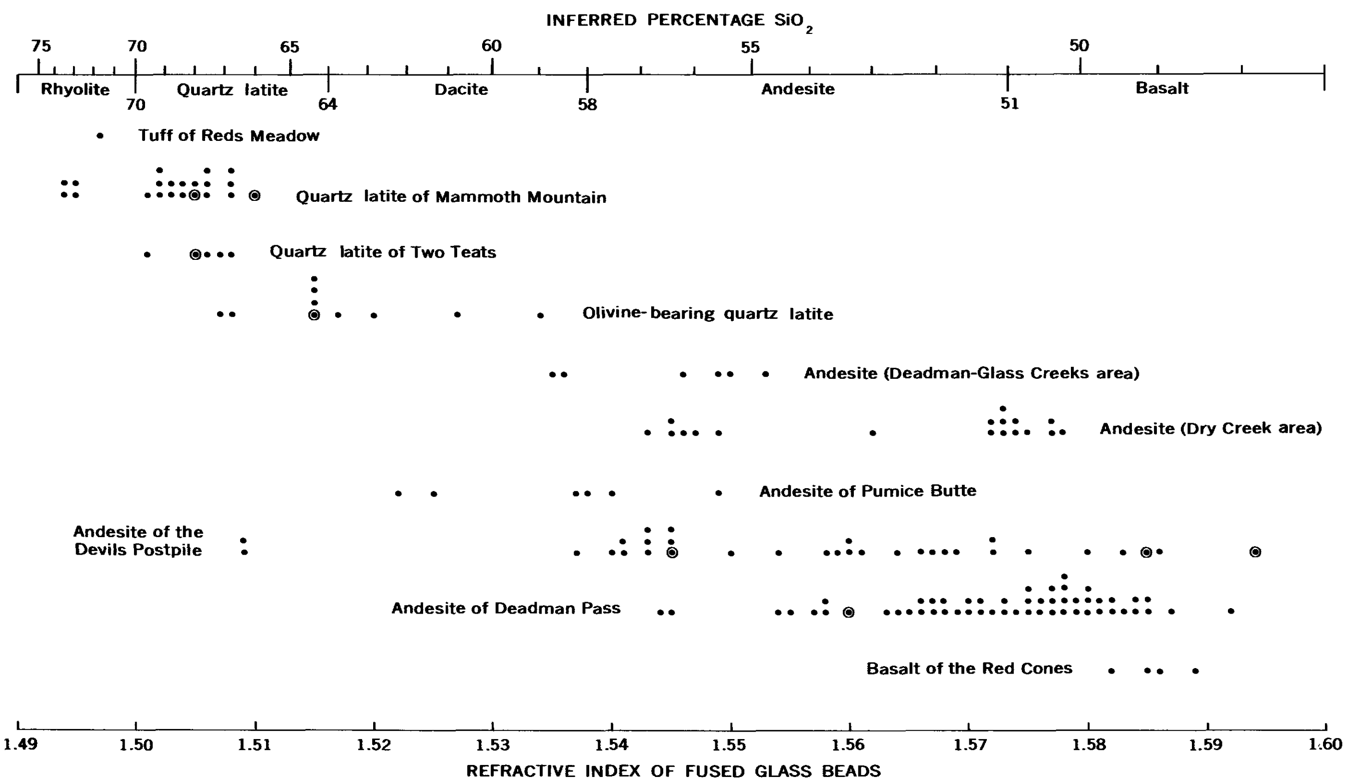

FIGURE 5.—Range in percentage of silica of some of the mapped volcanic units as inferred from refractive indices of fused samples. Percentage of silica is projected from figure 4. Each dot represents one sample; some samples were collected a short distance into the Mount Morrison quadrangle. Circled dots indicate chemically analyzed samples. The rock classification used in this report is also shown.

ley of the Middle Fork of the San Joaquin River south and west of Deadman Pass and extended at least 3 miles eastward in the northeast corner of the quadrangle into the Mammoth Embayment, a large reentrant in the eastern front of the Sierra Nevada (Mayo, 1934, p. 79; Rinehart and Ross, 1964, p. 52). In fact, inasmuch as the San Joaquin Mountain ridge has been uplifted relative to the Mammoth Embayment, an appreciable thickness of the andesite of Deadman Pass may lie concealed beneath the extensive pumice cover of the Embayment. Small exposures of andesite of uncertain age occur at scattered localities in the Mammoth Embayment.

In the south half of the quadrangle, erosional flow remnants, similar in composition and age to the andesite of Deadman Pass, are preserved on benches above the Middle and North Forks of the San Joaquin River and in several places extend part way down into the canyons. Potassium-argon ages of 3.3±0.1 million years for a remnant south of Snake Meadow and 3.5±0.1 million years for a remnant east of Pine Flat have been obtained (Dalrymple, 1964a, table 1).

Andesites exposed in erosional remnants on Mammoth Crest are similar to the andesite of Deadman Pass and are tentatively correlated with it. Support for this correlation is lent by a remnant of andesite in a similar physiographic position on the ridge above the old Mammoth Mine in the Mount Morrison quadrangle 2 miles east of Mammoth Crest. This andesite has been dated by the potassium-argon method at 3.1±0.1 million years (Dalrymple, 1964a, table 1).

The scattered erosional remnants in the southwestern part of the quadrangle rest in places upon an erosion surface which Matthes (1960, p. 41–44) correlated with his "Broad Valley stage" of erosion that he considered to be of late Miocene age. The Broad Valley surface had not only been established prior to the eruption of the late Pliocene andesitic rocks, but had also been dissected to a depth of approximately 2,000 feet in the Middle Fork canyon, as indicated by andesitic remnants within the canyon. This dissection probably represents erosion during Matthes' (1960, p. 40) "Mountain Valley stage," which Matthes considered to be of Pliocene age, perhaps continuing into the early part of his subsequent "Canyon stage" (Dalrymple, 1964a, p. 28). Whatever the absolute age of the Broad Valley and Mountain Valley erosion stages, it is clear that both antedate late Pliocene and cannot be of Pleistocene age as postulated by Hudson (1960, p. 1556) and Axelrod (1962, p. 185–186).

The relationship of the andesite near Deadman Pass to the Broad Valley surface is critical to the interpretation of the local geomorphic history, inasmuch as we correlate andesites which rest upon the already partly dissected Broad Valley surface in the southern and western parts of the quadrangle with those near Deadman Pass. Matthes (1930, 1960) concluded that during the late Tertiary a major fork (perhaps the main channel) of the San Joaquin River probably had its source east of the present drainage divide and was beheaded by the formation of the fault escarpment on the east side of that ridge. Erwin (1934) apparently accepted the concept of a throughgoing drainage at this locality and suggested that the lavas exposed on the San Joaquin Mountain ridge may have in places flowed down this ancient drainage and were later uplifted along the fault-bounded range front. If this drainage reconstruction is true, and we consider it a reasonable interpretation, then the Broad Valley surface, with an inner channel perhaps representing the Mountain Valley stage, presumably extended eastward from the present Middle Fork valley beneath the andesite of Deadman Pass. A possible location for such an old channel is just south of Deadman Pass, where the base of the andesite is at its lowest elevation.

Axelrod and Ting (1960, p. 8, 25) also considered the Broad Valley surface to extend from the Middle Fork basin eastward beneath the andesite near Deadman Pass, although Axelrod (1962, p. 186) later revised his views and stated that the andesite near Deadman Pass "lies on the older Boreal surface which has been downdropped on a north-trending fault that traverses the west side of San Joaquin Mountain to give the illusion that it is on the Broad Valley surface which is well exposed across the valley." We were unable to find any evidence in the field for such a fault and therefore support the view that the Broad Valley surface, probably modified by Mountain Valley stage erosion, continues eastward beneath the andesite near Deadman Pass.

We do not intend to imply that all the andesites and basalts in this map unit were necessarily part of a single sheet of uniform age. Rather, the evidence merely suggests that slightly over 3 million years ago widespread andesitic flows were deposited over extensive areas. As mentioned previously, Erwin (1934, p. 47, 58) suggested that the source of the andesites was east of the present drainage divide (San Joaquin Mountain ridge), and that the andesites flowed southwestward and southward down an ancient fork of the San Joaquin River. Gilbert (1941, p. 793) also considered the andesites and basalts in this part of the Sierra crestal area to be similar to rocks exposed over extensive areas north and east of Long Valley, 10 miles and more east of Deadman Pass. Although an eastern source for much of the andesite appears reasonable, there is evidence for local sources in various parts of the Devils Postpile quadrangle. For example, two andesitic necks, planed by glaciation and presumably of Pliocene age, were noted near Emerald and Cabin Lakes in the metamorphic belt west of Middle Fork. In addition, the joint pattern and rock textures of some of the andesitic outcrops north of Agnew Pass and south of Iron Creek suggest scattered local volcanic sources. Differences in average composition of andesitic outliers also are compatible with scattered local sources.

QUARTZ LATITE OF TWO TEATS

Quartz latite caps the andesite of Deadman Pass over much of the ridge that extends northwestward from Minaret Summit and is especially well exposed on the double prominence of Two Teats, where its thickness is more than 1,000 feet. Additional erosional remnants east of Two Teats, such as ridges north and south of Glass Creek Meadow, attest to a much greater original extent. This unit is the "Miocene andesite" of Erwin (1934, p. 47–48), but its age has been determined as late Pliocene by the potassium-argon method (3.0 ± 0.1 million years, Dalrymple, 1964a, table 1). The rock is extremely varied in both color and texture, but it is generally porphyritic with phenocrysts of plagioclase, hornblende, and biotite in a microcrystalline groundmass. Flow structures are common. Classification of this rock as quartz latite is based on chemical analysis (table 3) and fused-bead data (fig. 5).

The base of the quartz latite of Two Teats is nearly everywhere concealed by slope wash and pumice. Although in most places it appears to be underlain by andesite of Deadman Pass, the quartz latite rests unconformably upon metasedimentary rocks about 1 mile southeast of Two Teats. There the lowermost rock of the unit is pyroclastic and contains numerous fragments of the underlying metasedimentary and granitic rocks, as well as the andesite. On the east slope of San Joaquin Mountain, the basal part of the unit is a coarse breccia that consists of fragments of quartz latite, ranging in size from cobbles to blocks more than 15 feet across that are enclosed in a tuffaceous matrix (fig. 6). The breccia is rudely stratified and dips about 20° to the west (into San Joaquin Mountain). The coarse breccia blocks suggest an explosive initial phase from an apparently nearby vent. Further indications of a neighboring source are: (1) a narrow hypabyssal dike that cuts pre-Tertiary granitic rocks a mile northeast of Glass Creek Meadow is, except for a holocrystalline groundmass, petrographically similar to the quartz latite and may be a feeder and (2) a small intrusive body, petrographically identical with the quartz latite, that cuts the andesite of Deadman Pass about a mile southeast of Deadman Pass and may also be a feeder.

Examination of the map shows that the surface on which the quartz latite was deposited had considerable local relief; for example, the surface varies as much as 1,500 feet in elevation within half a mile, southeast of Two Teats. The westward inclination of the breccia beds may reflect initial slope from an eastern source or perhaps only the slope of underlying topography.

ANDESITE FROM DEADMAN-GLASS CREEKS AREA

Andesite underlies a small area in the extreme northeast corner of the quadrangle and is nearly contiguous with with a large mass that extends for several miles northeast of the quadrangle, where it forms part of the northern escarpment of the Long Valley basin. The typical rock is medium gray and locally somewhat vesicular and contains abundant brownish-olive equant crystals of olivine and clinopyroxene. Scattered tiny pyrite crystals are fairly common. Fused samples of several specimens indicate a fairly wide range in the percentage of silica but suggest that the average chemical composition is andesitic.

Because exposures of this andesite in both the Devils Postpile and the Mount Morrison quadrangles occupy less than half a square mile, the rock was not studied in

FIGURE 6.—Basal part of quartz latite of Two Teats on east side of San Joaquin Mountain showing blocks of quartz latite in a tuffaceous matrix.

sufficient detail to determine its relation to the local volcanic sequence. Near Crestview, a little more than a mile northeast of the quadrangle, similar andesite is overlain by the Bishop Tuff, a relation indicating an age no younger than middle Pleistocene. Furthermore, the position of the andesite exposed in the escarpment of the Long Valley basin—an eroded fault scarp possibly as old as late Tertiary—suggests that the andesite may be as old as Tertiary and is shown as Tertiary by Gilbert (1941, p. 785 and 787, figs. 2 and 3).

TUFF OF REDS MEADOW

A rhyolitic ash-flow tuff, in part welded, is exposed in the vicinity of Reds Meadow and in other erosional remnants on the valley sides of the Middle Fork of the San Joaquin River. This tuff near Reds Meadow was briefly noted by Erwin (1934, p. 50), but its rather large original area and volume have not previously been appreciated because of the scattered and remote nature of other outcrops. The rhyolitic tuff is very similar to the Bishop Tuff, first described by Gilbert (1938), the nearest exposure of which is along Deadman Creek in the Mount Morrison quadrangle 10 miles northeast of Reds Meadow. The tuff of Reds Meadow is a crystal-vitric tuff composed of 15 to 30 percent crystals, 15 to 25 percent pumice fragments, and 45 to 70 percent fine ash and shards. The crystals consist of quartz and sanidine in nearly equal amounts, minor oligoclase, and very minor biotite; similar crystals also occur sparsely in the pumice fragments. The sanidine has a potassium-sodium ratio of about 2 (estimated from a potassium analysis made in connection with a potassium-argon age determination) and is generally in euhedral crystals with an average size of 1 millimeter. The quartz occurs both as euhedral crystals and as rounded embayed grains, also about 1 millimeter in average size. Except for minor variation in relative percentages of the constituents, the tuff appears to be quite uniform in composition throughout the stratigraphic section examined in detail near Reds Meadow. An estimate of 72 percent silica was obtained from a refractive-index determination on a fused sample of pumice from the base of the tuff.

ZONATION IN THE TUFF

Exposures of ash-flow tuff in a small stream gully on the slope east of the Reds Meadow Ranger Station, together with an exposure of the approximate base of the tuff near Sotcher Lake half a mile to the north, permit the division of the tuff into nearly horizontal zones similar to those described by Smith (1960) as characterizing welded ash flows. In the 600+foot exposed section of tuff, two distinct zones of dense welding, indicating two flow units, can be distinguished.

These localities are the only ones where two zones were recognized, and even there, the zones are not sharply defined. Hence, they are not separately delineated on the geologic map.

LOWER FLOW UNIT

Lower zone of no welding (*about 100 ft thick*).—A zone of no welding consists of unconsolidated ash containing millimeter-size crystals of quartz and sanidine, pumice fragments, numerous pebbles of granitic and metamorphic rock, and andesite of probable Pliocene age. The pumice fragments and exotic pebbles are commonly grouped in layers which define a rude bedding that dips 5° to 10° W. toward the center of the Middle Fork valley. Crossbedding is also evident at one exposure. Bedding appears to be limited to this zone and is not found higher in the section. Tuff in the lower half of this zone is unconsolidated, whereas that in the upper half becomes progressively more indurated upward. The color also grades upward from a very light gray to a reddish orange.

Lower zone of partial welding (*about 50 ft thick*).—Although outcrops are not continuous, the transition between the zone of no welding and the zone of partial welding appears gradational over a few tens of feet. The rock in the zone of partial welding is highly indurated and pale red. The pumice fragments, collapsed and flattened in a nearly horizontal plane, are black and obsidianlike; but on a fresh surface many have a brownish tinge and exhibit a fibrous structure indicating incomplete welding. In thin section the pumice fragments and shards can be seen to be locally molded around quartz and sanidine crystals and other fragments but are otherwise not strongly deformed (fig. 7*A*).

Zone of intense welding (*about 100 ft thick*).—The transition between the lower zone of partial welding and the zone of intense welding is not exposed; but across a span of about 25 feet of stratigraphic section, the change in appearance of the tuff is striking. The dull-red matrix of the partially welded zone gives way to a vitreous brownish- or purplish-black matrix; the pumice fragments are jet black and obsidianlike and commonly fracture concoidally. Complete welding, as defined by Smith (1960, p. 155), was not achieved, however, for the pumice fragments and glass shards are not completely homogenized. The pumice fragments and shards are more strongly flattened than in the zone of partial welding and are tightly molded around the crystal fragments (fig. 7*B*). Incipient devitrification has not progressed far enough for the

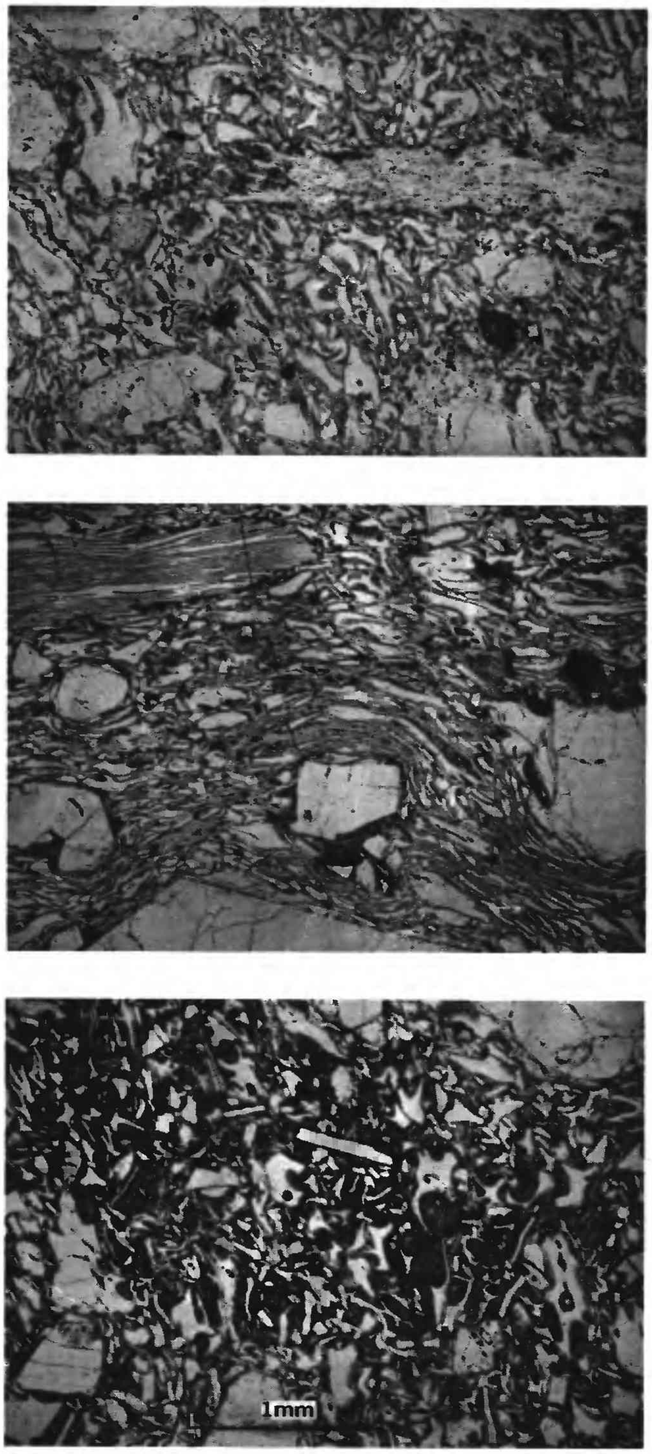

FIGURE 7.—Photomicrographs of tuff of Red Meadow, lower flow unit. *A* (upper), Lower zone of partial welding showing shards and flattened pumice fragment. *B* (middle), Zone of intense welding showing flattened shards bent around crystals and flattened pumice fragment. *C* (lower), Upper zone of partial welding showing undeformed shard structures.

formation of spherulitic or axiolitic structures, except adjacent to quartz crystals. Columnar jointing is locally present.

Upper zone of partial welding (*about 200 ft thick*).—The lower 50 feet of the upper zone of partial welding is similar to the lower zone of partial welding, and hand specimens are identical. Higher, however, a gradation begins which continues to the top of the zone. The color of the matrix changes upward from a pale red to a very light gray. The pumice fragments become lighter in color and less strongly welded and flattened until their fibrous structure is readily apparent in hand specimen. In the upper part the glass shards are largely undeformed (fig. 7*C*). Incipient devitrification is noticeable but not extensive. There is no completely nonwelded tuff preserved above this zone.

UPPER FLOW UNIT

Division of the upper flow unit into distinct zones is more difficult than with the lower flow unit; in fact, the placement of the contact between the two flow units is somewhat arbitrary. A continuous and fairly homogeneous zone of partially welded tuff extends from the densely welded zone of the lower flow unit to the densely welded zone of the upper flow unit. No obvious textural or mineralogic change is apparent in this interval. The base of the upper flow unit is about 50 feet below the zone of dense welding, where the number of exotic rock fragments increases and the pumice fragments become somewhat darker and more strongly welded.

Lower zone of partial welding (*about 50 ft thick*).—In the lower part of this zone, pumice fragments are largely collapsed, but these fragments and the shards are otherwise little deformed. The degree of welding and compaction increases upward, but the rock does not assume the reddish hues typical of comparable zones in the lower flow unit. Some pumice fragments are partly devitrified.

Zone of intense welding (*about 130 ft thick*).—The change in the rock at the base of the zone of intense welding is gradational. The two most important changes used to define the boundary are darkening of the grayish matrix and welding of the pumice fragments into dense obsidianlike pellets that fracture concoidally. The most striking microscopic change is the nearly pervasive but incomplete devitrification—the only extensive devitrification within the entire section of tuff. This is evidenced by the formation of spherulitic and axiolitic structures, which here and there selectively envelop the pumice fragments, and by the obliteration of shard structures (fig. 8). The top of this zone and higher zones, which presumably were present following eruption and cooling of the tuff, have been removed by erosion; and the tuff is unconformably overlain by the andesite of the Devils Postpile.

THICKNESS AND LATERAL EXTENT

A complete section of the ash-flow tuff is nowhere preserved, and therefore only an estimate of its original thickness can be obtained. Approximately 600 feet of tuff is preserved in the thickest section on the valley wall east of Reds Meadow Ranger Station. If the upper flow unit had originally been a virtual duplicate of the lower, the total original thickness of the tuff at this locality would have been about 900 feet. Reconstruction of the postulated nearly flat flow surface across the Middle Fork of the San Joaquin River on the basis of outcrops of tuff on the west side of the valley suggests a minimum thickness of 1,000 feet before erosion (fig. 9). Further extrapolation of this surface upvalley and downvalley suggests a minimum areal extent of 22 square miles and a volume of 4 cubic miles for the tuff east of Lion Point. In arriving at the area and volume, allowance was made for posttuff deepening of the canyon; the figures are believed to represent reasonable minimums. Because at least 500 feet of tuff are preserved nearly 2,000 feet above the present stream level near Lion Point, the ash flow must have originally extended down the Middle Fork Canyon well beyond the limit of present outcrop, a condition adding considerably to the estimates of areal extent and volume noted above.

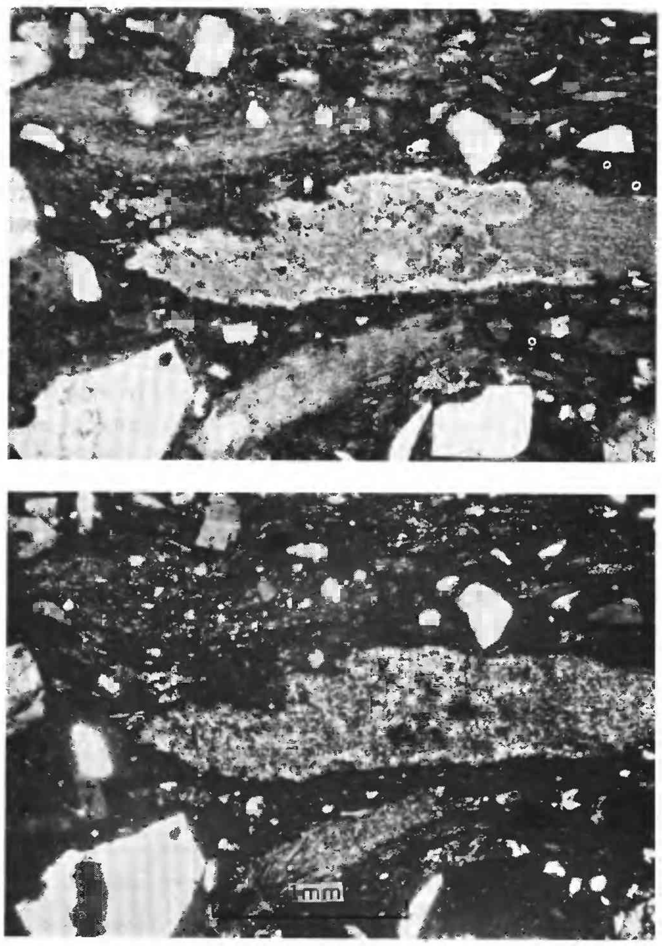

FIGURE 8.—Photomicrographs of tuff of Reds Meadow, upper flow unit. *A* (upper), Zone of intense welding showing flattened pumice fragments and opaque materials in groundmass, with obliteration of shard structure. *B* (lower), Same, cross nicols. Note devitrification.

AGE, SOURCE, AND CORRELATIONS

Similarities between the lithology and welding characteristics of the tuff of Reds Meadow and the Bishop Tuff lead us to speculate on possible correlations between the two tuffs. A potassium-argon age of approximately 0.7 million years has been reasonably well established for the Bishop Tuff (Dalrymple, Cox, and Doell, 1965). Three age determinations—0.66±0.02 million years,[1] 1.4 million years, and 1.1 million years—have been made on sanidine from the tuff of Reds Meadow. The two older ages were determined on sanidine separated from samples of the lower zone of partial welding in the lower flow unit. This material was contaminated with exotic fragments of granitic rock (approximately 80 million years old) including fragments of feldspar in the same size range as the sanidine. Every precaution was taken to get a pure sanidine separate, but we believe that some exotic material was included which biased the age determinations toward an older age. The third potassium-argon determination, 0.66 million years, was made on sanidine concentrated from uncontaminated pumice fragments collected from the unconsolidated basal portion of the tuff. This type of material is the most satisfactory for potassium-argon dating of ash-flow deposits (Dalrymple, Cox, and Doell, 1965), and 0.66 million years is accepted as the most reliable age determination for the tuff of Reds Meadow.

The remanent paleomagnetic polarity (normal) and orientation of the tuff of Reds Meadow is identical with that of the Bishop Tuff (A. V. Cox, oral commun., 1963). The Brunhes normal-polarity epoch, which extends from approximately 0.7 million years ago to the

[1] The analytical data for this determination are as follows (G. B. Dalrymple, written commun., 1966): K_2O, 10.72 percent (average of two analyses); radiogenic Ar_{40}, 1.043×10^{-11} mole per g (average of two analyses); radiogenic Ar_{40}, 56 and 62 percent for the two argon extractions.

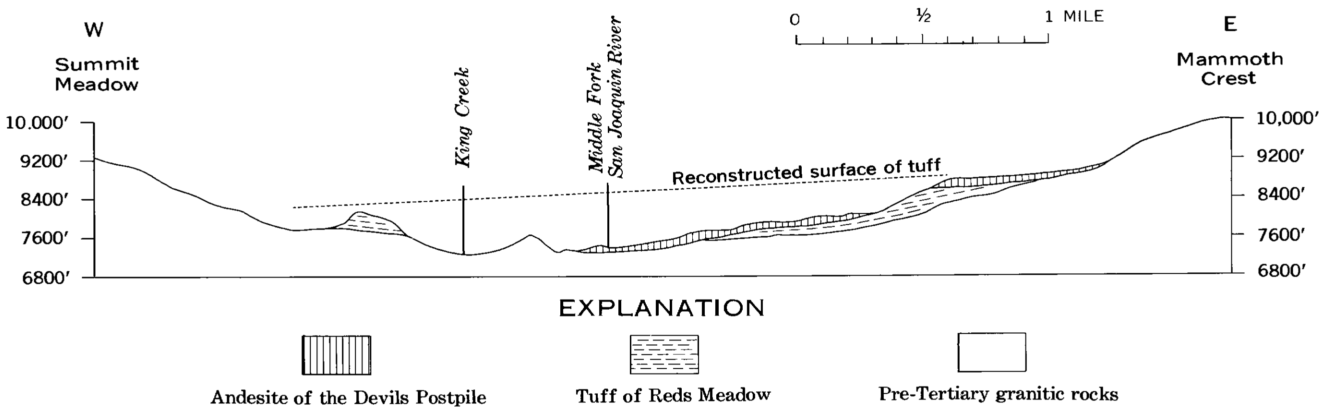

FIGURE 9.—West-east section in vicinity of Rainbow Falls showing reconstructed surface of the tuff of Reds Meadow.

present, was preceded by the Matuyama reversed-polarity epoch from approximately 2.5 to 0.7 million years ago (Dalrymple, Doell, and Cox, 1965). This suggests that the tuff of Reds Meadow is not appreciably older than 0.7 million years and could well be the same age as the Bishop Tuff.

Cobbles of gray ash-flow tuff and pumice pebbles are common in alluvial deposits at Friant, where the San Joaquin River emerges from the foothills of the Sierra Nevada and flows onto the alluvial plain of the San Joaquin Valley. The tuff pebbles are similar to material from the tuff of Reds Meadow, although some petrographic and chemical differences do exist; no other source of similar tuff is known in the San Joaquin drainage basin. A potassium-argon age determination on sanidine phenocrysts from pumice pebbles associated with the tuff pebbles gave and age of 0.60±0.02 million years (Janda, 1965), which is compatible with the age determined for the tuff of Reds Meadow.

No source for the tuff of Reds Meadow was found within the present drainage basin of the Middle Fork of the San Joaquin River. Possible vents could be hidden beneath the younger rocks in the Mammoth Mountain area or farther northeast. Past areal contiguity with the Bishop Tuff is a possibility, but one for which direct evidence is lacking.

Glacial deposits lie beneath the Bishop Tuff (Putnam, 1960, 1962; Wahrhaftig, 1965; Sharp, 1965); hence if the tuff of Reds Meadow is equivalent to the Bishop Tuff, it also should overlie glacial debris. Because the base of the tuff of Reds Meadow is nowhere exposed, we do not know whether or not the surface on which it rests was glaciated.

Indirect evidence suggests pretuff glaciation, however. Numerous pebbles and cobbles of older andesite and granitic and metamorphic rocks from the headwaters of the Middle Fork (Huber and Rinehart, 1965a) occur in the unconsolidated ash deposit at the base of the tuff near Sotcher Lake. The pebbles are rounded and must have been present as gravels in the Middle Fork valley at the time of eruption of the tuff. R. J. Janda (oral commun., 1965), in his study of the stream regimen of the upper San Joaquin basin, has concluded that these pebbles are too heterogeneous and too large to have been transported to this site by modern stream processes; hence the pebbles may represent incorporated glacial materials.

Prior to the eruption of the andesite of the Devils Postpile, a minimum volume of 4 cubic miles of the tuff had probably been removed from the Middle Fork valley during an interval of a few hundred thousand years at most. This feat would seem to require some process, presumably glaciation, in addition to normal stream erosion. Owens River, about 15 miles east of the quadrangle, receives drainage from a 25-mile segment of the eastern part of the Sierra Nevada, yet in a much longer time has only been able to cut a narrow, steep-walled gorge into the Bishop Tuff. Thus we favor glacial erosion as the agent of removal of the tuff of Reds Meadow prior to the eruption of the andesite of the Devils Postpile; the eruption probably occurred about half a million years ago.

ANDESITE OF THE DEVILS POSTPILE

Andesite and basalt are exposed on Mammoth Pass, in the Mammoth Lakes basin, and in the valley of the Middle Fork of the San Joaquin River. This unit is here referred to as the andesite of the Devils Postpile. Two of the three analyzed samples (table 3) are trachybasalt, and the third is trachyandesite; but inasmuch as data from fused glass beads (fig. 5) give an average composition of approximately 53 percent silica, the map unit is called andesite.

Basalt predominates in the bottom of the Middle Fork valley and in the Mammoth Lakes basin; andesite is predominant elsewhere, except in the southern part of the outcrop area where more siliceous quartz latite occurs.

A potassium-argon age determination of 0.94±0.16 million years was reported by Dalrymple (1964b) for the andesite of the Devils Postpile. A redetermination on a second split of the same sample yielded an age of 0.63±0.35 million years.[2] Because the amount of potassium in the sample and the percentage of radiogenic argon relative to total argon are so low in both of these determinations, they indicate little more than that the age of the andesite probably is between a quarter of a million and a million years. It is thus possible to reconcile these data with an age of approximately 0.7 million years for the tuff of Reds Meadow, which the andesite unconformably overlies.

The andesite was erupted in large part in the Mammoth Pass-Mammoth Mountain area, as noted by Matthes (1930) and Erwin (1934), from whence it flowed eastward into the Mammoth Lakes basin and westward into the valley of the Middle Fork. There is some evidence for an additional local source in the northern part of Pumice Flat, where an apparent andesitic dike cuts a deposit of ash and volcanic rubble. The pattern of silica distribution (pl. 1) also suggests the possibility of separate source areas within the Middle Fork valley and in the Mammoth Lakes basin. Perhaps the samples anomalously high in silica from south of the Lower Falls also came from local vents. Three small outliers south of Lost Dog Lake are also derived from a local source; their correlation with the andesite of the Devils Postpile is uncertain. The Red Cones, considered to be an additional source by Erwin (1934, p. 49), have not been glaciated and are of Recent age rather than Pleistocene.

Prior to the eruption of the andesite of the Devils Postpile, the tuff of Reds Meadow had been almost completely removed from the central part of the Middle Fork valley (see above), and there the andesite rests directly upon granitic rocks. The andesite was subsequently largely removed by glaciation, leaving behind remnants on the valley bottom and slopes. Reconstruction from these remnants suggests an original thickness of at least 600 feet for the andesite in the vicinity of the Devils Postpile. The original extent of the andesite is unknown.

The andesite displays conspicuous jointing nearly everywhere, with three distinct types represented. Locally near the base of the flows, particularly along the Middle Fork in the vicinity of Rainbow Falls, nearly horizontal platy jointing has formed. Most commonly the jointing is of the orthogonal contraction-crack polygon type, giving outcrops a blocky appearance. Least common, but in places very well developed, are joints of the nonorthogonal contraction-crack polygon type, as for example, in the Devils Postpile itself (frontispiece and fig. 10). The origin of both orthogonal and nonorthogonal polygonal jointing has recently been studied by Lachenbruch (1962) and by Spry (1962), and we have discussed it briefly with reference to the Devils Postpile (Huber and Rinehart, 1965b). The columns of the Devils Postpile, some of which are as much as 60 feet long, are polygonal, with hexagonal columns slightly more abundant than pentagonal ones, and with other forms making up 10–20 percent of the total (Hartesveldt, 1952; Beard, 1959). The jointing which defines the columns formed near the base of the flow, and the curved and tilted forms of some of the columns are probably due to irregularities in the isotherms during cooling, which may have been caused, at least in part, by topographic irregularities on the bedrock surface over which the lava flowed.

[2] The analytical data for this determination are as follows (G. B. Dalrymple, written commun., 1965): weight, 10.02 grams; K_2O, 0.268 percent; radiogenic Ar_{40}, 1.1 percent; radiogenic Ar_{40}, 2.50×10^{-13} mole per g.

QUARTZ LATITE OF MAMMOTH MOUNTAIN

Mammoth Mountain has been described by Mayo (1941, p. 1068) as "the most impressive volcanic edifice in the region," an apt description, because it rises abruptly over 2,000 feet above the surrounding countryside. The eruptive history of Mammoth Mountain includes intrusion of a massive dome or domes, explosive

FIGURE 10.—Polygonal joint pattern displayed by tops of columns in the Devils Postpile. Note glacial striations and remnants of glacial polish. Photograph by Gerhard Schumacher.

activity, and the outpouring of extensive glassy flows, especially on the northeast side of the mountain.

Like the quartz latite of Two Teats, the rock which makes up this unit is extremely variable in color and texture. It ranges from shades of brown and pink through gray to nearly black in the glassiest flows. The rock is typically flow banded and porphyritic; plagioclase and biotite dominate and vary widely in crystal size and relative amounts. Despite the wide petrographic variation, the silica in 17 of 21 samples shows a range of only 4 percent and averages 68 percent, as inferred from the index of refraction of fused samples (fig. 5). The other four, with 73–74 percent silica, represent rhyolitic obsidian flows that are locally interlayered with lithoidal quartz latite flows. Sampling of this unit and analytical work are inadequate to determine whether these obsidian flows are chemically distinct from the quartz latite, although the data available indicate such a possibility.

The quartz latite of Mammoth Mountain was considered by Erwin (1934, p. 45) to be of Miocene age and by Matthes (1930, 1960) to be "preglacial" in age. Rinehart and Ross (1964, p. 64) also considered the quartz latite of Mammoth Mountain to be of late Tertiary (Pliocene) age, because of its degree of dissection and its earlier correlation with the very similar quartz latite on Two Teats and San Joaquin Mountain, for which a late Tertiary age appears correct. Unlike Two Teats and San Joaquin Mountain, however, Mammoth Mountain does retain appreciable constructional form, and its degree of dissection is not incompatible with a Pleistocene—even a relatively late Pleistocene—age. Although he did not study the quartz latite of Mammoth Mountain in any detail, Gilbert (1941, p. 799 and fig. 2) implied that it is of Pleistocene age. Field relations between the quartz latite of Mammoth Mountain and the andesite of the Devils Postpile are equivocal as to their relative ages. However, two potassium-argon age determinations on the quartz latite yielded ages of 0.37 ± 0.04 million years (Dalrymple, 1964a, table 1) and 0.18 ± 0.09 million years.[3] Mammoth Mountain is therefore considered to be of late Pleistocene age and younger than the andesite of the Devils Postpile.

The construction of Mammoth Mountain appears to have been complex, involving extrusion of viscous flows of highly varied petrographic character that range from crystal-rich lithoidal types to crystal-poor obsidian. Some of the flows were sufficiently fluid to advance at least 2 miles beyond the north base of the mountain, but most appear to have moved only down the slopes over earlier flows, thus piling up around the vent to form a rather typical cumulodome. The high degree of dissection of the north side of the mountain is probably due to the removal of much material by violent explosive activity and to the subsequent modification by glaciation. In addition to the construction of Mammoth Mountain, this episode of volcanism produced a satellite dome 1 mile in diameter and 1,000 feet in height, about 1 mile northeast of the base of Mammoth Mountain. Glassy flows are discontinuously exposed over an extensive area north of Mammoth Mountain. Minor late-stage activity is manifested by small postglacial phreatic explosion pits at the north base of Mammoth Mountain and by present-day fumarolic activity at the south base and at the crest.

Mammoth Mountain lies on or immediately adjacent to the western perimeter fault that defines the Long Valley volcano-tectonic depression (Pakiser and others, 1964, p. 17 and pl. 1). Inasmuch as the location of a volcanic pile the size of Mammoth Mountain would probably be dictated by a major zone of crustal weakness, it is likely that this fault provided structural control for the vents from which the quartz latite erupted. In this respect Mammoth Mountain would lie in a structural position similar to the "late rhyolite domes" peripheral to the Valles caldera, New Mexico (Smith and others, 1961). When the structural depression began to form cannot be stated with any degree of certainty because not enough is yet known about the detailed relationships of the volcanic rocks in the Long Valley basin and adjacent areas, especially their relative and absolute ages. However, the vertical displacement along the western part of the fault, which resulted in the Sierran escarpment east of Deadman Pass, must have occurred later than approximately 3 million years ago, the age of the quartz latite of Two Teats. If this fault controlled the location of Mammoth Mountain, then it must have been active prior to approximately a quarter of a million years ago, and thus movement must have begun between approximately a quarter of a million and 3 million years ago.

ANDESITE FROM DRY CREEK AREA

In the Dry Creek drainage area, north of Mammoth Mountain, a number of scattered outcrops of andesite and basalt are exposed through the mantle of pumice and alluvium, chiefly along recent faults or in explosion pits or cinder cones. Because of the generally poor exposures of this unit, it is difficult to determine its stratigraphic position relative to the other volcanic rocks in the area and, indeed, whether all of the scattered outcrops are correlative.

[3] The analytical data for this determination are as follows (R. W. Kistler, written commun., 1961): biotite, 9.25 g; K, 6.8 percent; radiogenic Ar_{40}, 3.8 percent; radiogenic Ar_{40}, 2.21×10^{-12} moles per g.

Analysis of fused-bead data (fig. 5) indicates a distinct bimodal composition distribution with maximums at basalt (51 percent SiO_2) and andesite (56 percent SiO_2). The more silicic rocks are concentrated near the Inyo Craters and along the eastern edge of the quadrangle (pl. 1).

At three localities the andesite and basalt can be demonstrated to be younger than the quartz latite of Mammoth Mountain. These three exposures are (1) along a recent fault scarp about 1 mile north of Mammoth Mountain, (2) on the north flank of the quartz latite dome northeast of Mammoth Mountain, and (3) on the northeast flank of Mammoth Mountain just west of a recent fracture known locally as the "Earthquake Fault." The rock in exposures 1 and 3 has been glaciated, and therefore the unit is considered to be of late Pleistocene age rather than Recent. Although exact correlations are questionable, all the andesite and basalt in Dry Creek area appear to be approximately the same age and are arbitrarily assigned to the same map unit. In addition, some glaciated andesitic cinder cones near the base of the San Joaquin Mountain ridge are also assigned to this unit.

ANDESITE OF PUMICE BUTTE

Pumice Butte is one of the two andesitic cinder cones in the southeast quadrant of the quadrangle. These cones, together with a vesicular andesite that appears to have originated as a flow from the base of Pumice Butte, were not overridden by glacial ice. They are above the elevation limit of the main valley glaciers of Wisconsin age, but a small tributary glacier of presumed Wisconsin age overrode a low shoulder on the northwesternmost of the two cones, and the margins of the flow were glaciated during latest Wisconsin (R. J. Janda, oral commun., 1965). This andesite is therefore thought to have been erupted during a pre-Wisconsin or intra-Wisconsin interglaciation. The rock is typically scoriaceous and appears fresh—quite unlike most of the andesitic flows and rubble south of Deer Creek and east of Pond Lily Lake, which are correlated with the andesite of Deadman Pass. Contacts shown between these units on the map are only approximate, however, and have been distinguished in part by aerial photointerpretation. Included with the andesite of Pumice Butte is a domelike mass of dacite (at the north edge of the map unit), which appears to be more highly dissected and is probably older than the main mass of the andesite.

OLIVINE-BEARING QUARTZ LATITE

In the extreme northeast corner of the quadrangle, olivine-bearing quartz latite covers an area of about half a square mile. It is exposed somewhat more extensively in the Mount Morrison quadrangle, where it has been described by Rinehart and Ross (1964, p. 57). The three following lines of evidence suggest that the quartz latite is of late Pleistocene to Recent age: (1) There is no evidence that the quartz latite has been glaciated, although late Pleistocene glaciations probably did not extend this far from the range front, (2) only slight dissection is shown in the major area of outcrop, which consists of a relatively flat topped stubby steepfaced flow that can be traced westward into steep-sided domes that retain much of their original form, (3) a north-trending fault scarp in the Mount Morrision quadrangle, along which old glacial till has been displaced, terminates abruptly at the edge of the flow and is probably buried by it.

The rock contains abundant white feldspar phenocrysts 2–5 millimeters long in a dark-gray aphanitic or glassy groundmass. Flow banding is visible locally, and in general appearance the rock is not unlike some of the darker varieties of the older quartz latites.

BASALT OF THE RED CONES

At the point where Crater Creek tumbles from a bench above the Middle Fork of the San Joaquin River—a bench which Matthes (1960, p. 43) considered part of the Broad Valley Surface—two basalt cinder cones lie on either side of the creek, and associated basalt flows cascade down the slope into the Middle Fork valley. The Red Cones were previously considered contemporaneous with, and a source of, part of the andesite of the Devils Postpile in the Middle Fork valley. Unlike the andesite of the Devils Postpile, however, the basalt of the Red Cones is typically vesicular with prominent phenocrysts of plagioclase and olivine. Moreover, the Red Cones have obviously not been glaciated, as has the andesite of the Devils Postpile; Matthes (1960, pl. 1) and Erwin (1934, p. 49) attributed this to the elevation of the cones above the Wisconsin glaciers in the Middle Fork valley. However, the associated flows extending into the Middle Fork valley also escaped glaciation—not only is there a complete absence of glacial erratics, striations, or polish, but the flows also exhibit scoriaceous and rubbly surfaces of a type nowhere present on the glaciated andesite of the Devils Postpile. The basalt of the Red Cones is therefore considered to be of postglacial, or Recent, age. The Red Cones still exhibit summit craters (fig. 11), and a detailed examination of aerial photographs suggests that most of the flow material was erupted from the western base of the southernmost of the two craters. The flow has been only slightly modified by subsequent erosion.

FIGURE 11.—The northernmost of the two Red Cones as viewed from the southern cone. Note breached summit crater.

RHYOLITE

In the northeast corner of the quadrangle is a series of rhyolite domes that have been considered to be a southern extension of the Mono Craters and have been described in some detail by Mayo, Conant, and Chelikowsky (1936). This series consists of six rhyolite domes, alined in a north-south direction over a distance of 6 miles, beginning about 2 miles south of the main mass of the Mono Craters. They tend to be nearly equidimensional and range in size from less than half a mile to nearly a mile in diameter. The four southernmost domes are in the Devils Potpile quadrangle.

There is little doubt that these domes are of very recent origin; for erosional modification of their forms is negligible and several of them support no vegetation. Each has a multiphase origin, which is best understood by comparison with Panum Crater at the northern end of the Mono Craters, where evidence of the evolution of a dome has been excellently preserved (Williams, 1932; Putnam, 1938). At Panum Crater the initial phase involved the excavation of an explosion pit with the expulsion of vast quantities of pumice and the construction of a pumice-lapilli rim around the perimeter of the pit. This explosive phase was succeeded by the protrusion of a nearly solid column of pumiceous obsidian and partly crystalline material in the form of a dome on the floor of the explosion pit. As the dome rose, it tended to fracture and spread laterally, with blocks of pumiceous obsidian spalling off and accumulating in steep talus slopes at its margins.

The two larger domes in the Devils Postpile quadrangle—the one just south of Deadman Creek and the other just south of Dry Creek—had a similar mode of origin. However, these two domes spread laterally during their protrusion so that they almost completely overwhelmed their original lapilli cones and thus nearly erased all evidence of the earlier explosive phase of their eruption. The dome just south of Deadman Creek (fig. 12) has only a small remnant of its lapilli rim on its southwest side, and the dome south of Glass Creek has none. The top surfaces of each of these domes are very irregular with numerous spires and loosely piled, angular blocks of pumiceous obsidian (fig. 13). They have a generally concentric structure which is obscure on the surface but readily apparent on aerial photographs (fig. 14). The small tree-covered dome north of Deadman Creek is probably of the same origin, having similar spires and an irregular blocky surface. This

FIGURE 12.—Rhyolite dome south of Deadman Creek as seen from Deer Mountain. Dome is about three-quarters of a mile in diameter. A second rhyolite dome, just south of Glass Creek, can be seen in the right middle distance. Photograph by Gerhard Schumacher.

FIGURE 13.—Upper surface of rhyolite dome south of Glass Creek showing typical irregular blocky surface. Taken from top of dome in right middle distance of figure 12.

FIGURE 14.—Vertical aerial photographs of Deer Mountain area, mounted as a stereopair. Main features from south to north are the Inyo Craters, Deer Mountain, and several rhyolite domes. Note remnant of lapilli rim on southern side of rhyolite dome south of Deadman Creek.

dome, however, is slightly older than the two larger domes, for it is mantled with debris from later explosions and its surface structure consequently obscured.

Deer Mountain, the southernmost of the rhyolite domes, has a somewhat more complex history. It may have had an initial origin similar to that of the other domes, but this has been obscured by a late explosive phase, which blasted a summit crater and expelled large quantities of material, including the fine ash that mantles the mountain and gives it the appearance of a volcanic cone and not a dome. Several explosion pits near the base of the mountain, the largest two of which are known as the Inyo Craters (fig. 15), further attest to the late explosive phase.

A radiocarbon age determination on a log buried within the ejecta that form the parapet of the southernmost of the Inyo Craters yielded an age of 650±200 years (lab. No. W–1431). However, a minimum age of 500 years for the craters, slightly older than the minimum radiocarbon age, is required by the fact that 400-year-old pines and firs, whose age is based on ring counts of recently cut specimens, are growing within the craters (fig. 15). Allowing 100 years for trees to become established after eruption fixes the minimum age of the craters at 500 years. The craters, therefore, must have formed between 500 and 850 years ago (Rinehart and Huber, 1965).

PUMICE

Pumice of varying thickness is ubiquitous in most of the Devils Postpile quadrangle east of the Ritter Range, and has obscured many stratigraphic relations between the various Cenozoic units.

The pumice cover is most extensive on the east flank of the San Joaquin Mountain ridge and in the lowlands to the east. Much of this pumice was undoubtedly derived from explosive eruptions associated with the rhyolite domes just described and the Mono Craters farther to the north. It is also probable, however, that large quantities of pumice were ejected during one or more phases in the formation of Mammoth Mountain; much of the pumice in the valley of the Middle Fork of the San Joaquin River and in the vicinity of Pumice Butte, southwest of Mammoth Crest, may have come from this source. Despite its name, Pumice Butte, as has been noted, is an andesitic cinder cone and therefore an unlikely source of pumice in that area, although Birman (1964, p. 7) suggested this possibility. No other likely source of pumice within the San Joaquin drainage basin was noted.

FIGURE 15.—View of Inyo Craters from Deer Mountain. Ash-covered rim of summit crater on Deer Mountain can be seen in foreground.

A study of the surficial pumice in and around the Mammoth Embayment and Mono Basin should contribute much to the understanding of volcanism in this region over the past few million years, particularly in the light of the recent success of similar studies (Powers and Wilcox, 1964; Czamanske and Porter, 1965). Our knowledge of the volcanic history of the region will not be complete until such a study has been made.

THERMAL ACTIVITY

Extensive thermal activity in the general Mammoth Lakes area also attests to the recency of volcanic activity. Although hot springs and areas of thermal alteration are more numerous in the Mount Morrison quadrangle to the east (Rinehart and Ross, 1964; McNitt, 1963), Mammoth Mountain itself is a thermal area, and hot springs exist at two other localities in the Devils Postpile quadrangle.

Until at least the late 1950's, there were a number of active fumaroles near the summit of Mammoth Mountain, and indications of thermal alteration are visible over an extensive area. On the south flank of Mammoth Mountain, within a less extensive area of thermal alteration, just north of Mammoth Pass, a few small steam vents are still active.

The hot spring at Reds Meadow emerges from a grassy slope underlain by the tuff of Reds Meadow. It appears to issue from near the base of the lower zone of intensely welded tuff, which exhibits conspicuous jointing in nearby outcrops. As the tuff is an ash flow whose source we believe to be outside of the Reds Meadow area, it is unlikely that the hot spring is genetically related to the tuff. In fact, it cannot be related to any episode of local volcanic eruptive activity. Nor can Fish Creek Hot Springs be related to known volcanism; for they issue from a grassy slope underlain by granitic rocks, 3 miles from the nearest exposure of Cenozoic volcanic rocks. In addition, several cold springs rich in carbon dioxide are in the quadrangle, but their relation to volcanism, if any, is unknown.

SUMMARY

By late Pliocene time, the rolling upland surface of Matthes' Broad Valley erosion stage had been considerably incised during the Mountain Valley and possibly the Canyon erosion stages. The Middle Fork of the San Joaquin River appears to have had a principal tributary whose source was east of the present Sierran divide; the ancestral channel crossed what is now the drainage divide, probably in the area between Deadman Pass and Two Teats. Upon this surface, somewhat less than 4 million years ago, large quantities of andesite and basalt were erupted from scattered vents to cover an extensive part of the quadrangle. Shortly thereafter, the quartz latite of Two Teats buried a large area in the northeastern part of the quadrangle.

It is possible that some of this volcanic activity was related to an early stage in the formation of the Long Valley volcano-tectonic depression, although at least some of the movement along the western perimeter fault occurred later. If the relationships are analogous to those at the Valles Caldera, N. Mex., this faulting probably was associated with the eruption of the Bishop and Reds Meadow ash-flow tuffs, the next major volcanic episode.

About 0.7 million years ago the tuff of Reds Meadow was erupted into the valley of the Middle Fork of the San Joaquin River, which probably had been previously glaciated. In a relatively brief period of time, several cubic miles of the tuff was almost completely removed from the valley, possibly during a glacial advance, and subsequent eruption of the andesite of the Devils Postpile followed about half a million years ago.

By this time it is probable that the Long Valley volcano-tectonic depression had formed, and quartz latite was erupted to form Mammoth Mountain on the periphery of the depression. Subsequently, other minor andesites and quartz latites were erupted and were overridden by glaciers.

Two Recent, or postglacial, events were the eruption of the basalt of the Red Cones in the Middle Fork valley and the extrusion of the rhyolite domes in the northeast corner of the quadrangle. Minor phreatic explosions in and near the domes, resulting in craters up to 600 feet in diameter, occurred as recently as 500 to 850 years ago, and thermal activity continues to the present.

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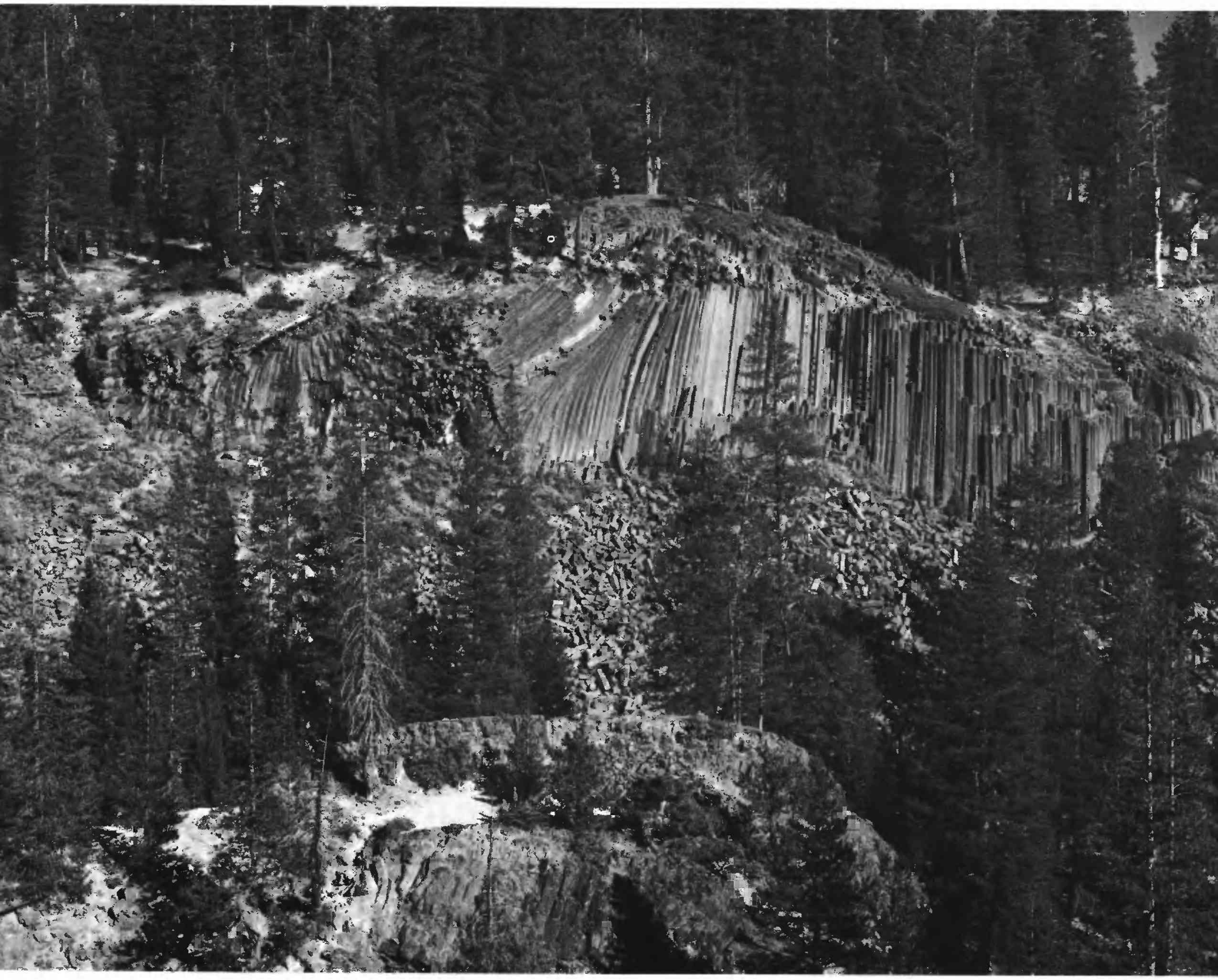
CENOZOIC VOLCANIC ROCKS OF THE DEVILS POSTPILE QUADRANGLE, EASTERN SIERRA NEVADA CALIFORNIA



Well-developed columnar jointing in andesite at the Devils Postpile. Photograph by Gerhard Schumacher.