CENOZOIC CHRONOLOGY OF THE SIERRA NEVADA, CALIFORNIA

BY

G. BRENT DALRYMPLE

UNIVERSITY OF CALIFORNIA PRESS
BERKELEY AND LOS ANGELES
1964

CONTENTS

CENOZOIC CHRONOLOGY OF THE SIERRA NEVADA, CALIFORNIA

BY

G. BRENT DALRYMPLE

ABSTRACT

Middle to late Tertiary volcanism began in the Sierra Nevada with the eruption of rhyoltic material. Potassium-argon dates of 19.9 to 33.2 million years on 18 early rhyolitic tuffs show that the major period of rhyolitic volcanism began in the late Oligocene and continued through early Miocene time; however, dates of 4.7 and 4.8 million years on the Nobel Canyon rhyolite near Ebbetts Pass, and of 16.1 million years on a rhyolite tuff near Sattley in the northern Sierra show that some rhyolite was erupted after the early Miocene. Dates of 19.9 to 23.1 million years on welded tuffs from the upper and middle parts of the rhyolitic Valley Springs Formation in the central Sierra foothills, and dates of 20.5 to 26.1 million years on rhyolites from the Delleker Formation near Blairsden show that these formations are approximately correlative. Basalts of the Lovejoy Formation, previously thought to be Eocene, are overlain by 22.2-million-year-old rhyolite at the Lovejoy Formation type locality near Blairsden and are underlain by 23.8-million-year-old dacite tuff at Oroville Table Mountain; they are therefore early Miocene and are included within the history of deposition of the Delleker and Valley Springs formations.

Andesite pebbles from the Wheatland Formation, which contains Eocene marine mollusks, give a "composite" date of 53.5 million years and thus record andesite eruptions which predate the earliest known Sierran rhyolites by at least 20 million years.

Deposition of the Mehrten Formation—which in the Stanislaus drainage includes the Table Mountain latite and associated latites dated as 8.8 to 9.3 million years old—and similar andesitic deposits throughout the Sierra had apparently begun by the middle Miocene and continued until late Pliocene time. In the northern Sierra the andesitic Ingalls Formation—which overlies Lovejoy basalt and underlies 22.2-million-year-old rhyolite of the Delleker Formation near Blairsden—and andesitic material beneath Lovejoy basalt at Oroville Table Mountain are early Miocene and show that andesitic volcanism there began before eruption of Delleker and Valley Springs rhyolites had ceased. The andesitic Penman and Bonta formations in the Blairsden area are probably correlative with at least part of the Mehrten Formation. Hypersthene basalt (7.4 million years old) and basalt breccia that overlie andesitic mudflow breccia and tuff near Donner Pass are Pliocene and therefore correlative with part of the Mehrten Formation.

A date of 28.5 million years on a rhyolite boulder from auriferous gravels in the Tuolumne drainage near Groveland, and the presence of late to middle Oligocene mammal fossils in auriferous gravels in Calaveras County (Wood, 1960) indicate that at least some of the prevolcanic auriferous gravels are as young as late Oligocene.

Dates of 2.9 to 3.5 million years on basalts that spill over the lip of the inner gorges of the North, Middle, and South forks of the San Joaquin River and were deposited at elevations below Matthes' profile of the Pliocene (Mountain Valley) San Joaquin River, show that the Canyon stage of erosion was initiated by late Pliocene time.

Dates on volcanic rocks truncated by basin-range faulting on the eastern escarpment of the Sierra Nevada near Mammoth, and in the Benton Range to the east, show that the last major faulting which produced the present scarps began after 2.6 to 3.2 million years ago; consequently these movements did not initiate the Canyon stage of erosion as defined by Matthes. Similar movements responsible for the Tahoe–Truckee depression near Lake Tahoe began long after 7.4 million years ago and shortly before 2.2 to 2.3 million years ago.

INTRODUCTION

THE PURPOSE of this paper is to report potassium-argon dating research pertinent to some problems of the Cenozoic history of the Sierra Nevada.

In the northern and central Sierra, middle Tertiary rhyolitic volcanism was followed by voluminous eruptions of tuffs, breccias, and flows, largely andesitic, that flooded valleys, rearranged preëxisting drainage, and buried the range under thousands of feet of volcanic material. Rivers and streams, rejuvenated by this constructional volcanism and by intervening periods of uplift of the Sierran block, carried volcanic detritus to the western foothills where it was deposited as fluvial sediments that are now intercalated with the occasional flows of volcanic material that reached the lower altitudes. Tertiary river gravels, some richly auriferous, are preserved in segments of ancient river channels that now lie buried beneath rhyolitic and andesitic debris. The major uplift of the Sierra Nevada apparently occurred in one or more episodes during the later Tertiary. The present rivers flow in gorges as much as several thousand feet below the base of the earlier volcanic material and river gravels, and steep fault scarps outline the eastern front of the range.

In the southern Sierra these intermittent periods of uplift and erosion left several giant treadlike erosion surfaces, each with relatively low relief and separated from the others by abrupt rises; here only sparse flows of basalt were erupted, mostly toward the end of the Tertiary.

These volcanic and sedimentary rocks, in which much of the Tertiary history of the Sierra Nevada is recorded, contain only rare deposits of fossil plants and land mammals, mostly in the western foothills of the northern and central parts of the range; consequently the geochronology of the Tertiary history of the Sierra is imperfectly known. The application of potassium-argon dating techniques to these volcanic rocks affords a means whereby some of this history can be viewed in proper temporal perspective.

This work is intended to be a geochronologic reconnaissance wherein the ages of certain rocks in a few selected areas throughout the Sierra have been investigated, on the assumption that this approach may be of more immediate value to the history of the range in general than a more detailed investigation of limited geographic extent. The results of such an investigation could be reported either by jumping from area to area and back again, taking the geologic events in their proper time-sequence, or by discussing all the results from each area before going on to the next. Because it necessitates less "geographic saltation," I have chosen the last.

Because of the nature of this research, I have relied heavily on the detailed field work of others. Wherever possible, the findings of recent workers have been used, but invaluable to any student of Sierran geology are the classic works of Waldemar Lindgren (1911), H. W. Turner (1894, 1896), and F. L. Ransome (1898), and the U. S. Geological Survey Folios of the Sierra Nevada, also done largely by these three men; they deserve especial tribute.

Figure 1 (in pocket) is an index map showing the localities of dated samples. The analytical data for potassium-argon age determinations are presented in table 1. Sample locations and descriptions are given on pages 34–38.

METHODS

Argon determinations were made in the Berkeley laboratory using the techniques described by Evernden and Curtis (in press); isotope dilution and a Reynolds-type mass spectrometer were employed. Potassium values were determined with a Perkin-Elmer flame photometer using a lithium internal standard and propane fuel.

Rocks from which minerals were separated were inspected in thin section and the mineral concentrates were examined in an attempt to evaluate and eliminate contamination from older included material; many separates were hand-picked in the final stages of concentration. All whole-rock basalt samples were carefully examined with a petrographic microscope to make sure that they contained no mineral phases which were alteration products or which might be nonretentive of radiogenic argon, e.g., devitrified glass, fresh glass in large quantities, or extremely fine-grained feldspar; alteration of olivine to iddingsite does not affect the age determination of basalts high in potassium. Any sample about which there was the slightest doubt was rejected as unsatisfactory, except for the Lovejoy basalt samples for which a minimum age was considered useful.

Decay constants used in the calculation of ages are $\lambda_\epsilon = 0.585 \times 10^{-10}$ yr^{-1} and $\lambda_\beta = 4.72 \times 10^{-10}$ yr^{-1}.

ACKNOWLEDGMENTS

I wish to thank Professors G. H. Curtis, Clyde Wahrhaftig, D. E. Savage, and J. F. Evernden for their encouragement and help. Much was gained by innumerable discussions with these men and with C. S. Grommé, who accompanied the author in the field on many occasions. Clyde Wahrhaftig, G. H. Curtis, D. E. Savage, and C. S. Grommé read the manuscript and contributed many helpful suggestions. Robert Fleck assisted in the field during the summer of 1961; potassium values were determined by Joachim Hampel; to both I express thanks.

The support of the National Science Foundation, of the Geological Society of America Penrose Bequest Fund, and of the Department of Geology and Geophysics of the University of California at Berkeley is gratefully acknowledged.

CENTRAL SIERRA NEVADA

The Tertiary rocks of the western foothills of the central Sierra Nevada have been divided broadly into three units: from oldest to youngest, (1) the interfingering Eocene Ione Formation and the auriferous gravels, (2) the Valley Springs Formation, and (3) the Mehrten Formation.

The Valley Springs Formation (Piper and others, 1939, pp. 71–80) comprises rhyolitic tuffs, clays, sandstones, and conglomerates that are the product of the early period of rhyolitic volcanism in the Sierra Nevada. The formation is unconformable upon the Ione Formation, auriferous gravels, or pre-Tertiary basement rock, and has produced only a small fossil flora assigned by Axelrod (1944, p. 217) to the "late upper Miocene."

The Valley Springs Formation is overlain by the Mehrten Formation (Piper and others, 1939, pp. 61–71) and most of the contact between these two units is unconformable, although in places they interfinger. The Mehrten Formation is formed from andesitic sediments, tuffs, and mudflow breccias that originated in the Sierra Nevada, and its top and bottom are distinguished by the occurrence of andesitic material (pp. 65–66). The age of the Mehrten Formation has recently been discussed by Dalrymple (1963), who concluded that it ranges in age from

TABLE 1

Analytical Data for Potassium-Argon Age Determinations

Sample		Material	Weight (gms.)	K (pct.)	Ar^{at}_{40} (pct.)	Ar^{r}_{40}/K_{40}	Age (m.y.)
KA 969	Dardanelle facies basalt	whole-rock	14.58	1.43	79	5.46×10^{-4}	9.3 ± .4
KA 975A	Lower Eagle Meadow rhyolite tuff	biotite	0.96	5.68	13	15.38	26.1 ± .5
KA 994	Lovejoy Fm. basalt, type section, lowest flow	whole-rock	16.79	1.53	67	6.74	11.5 ± .4
KA 999	Rhyolite boulder from Tuolumne auriferous gravels	sanidine	3.47	9.13	1	16.79	28.5 ± .6
KA 1011	Leavitt Creek rhyolite tuff	sanidine	2.43	8.88	4	17.35	29.5 ± .6
KA 1070	Benton Range basalt	whole-rock	13.19	2.15	20	1.88	3.2 ± .1
KA 1071	Benton Range basalt	whole-rock	13.04	2.14	64	1.89	3.2 ± .1
KA 1072	Valley Springs Fm., upper tuff, top of type section	biotite	1.86	6.54	26	12.89	21.9 ± .4
KA 1073	Lovejoy Fm. basalt, Stoney Ridge	whole-rock	7.38	1.50	78	5.90	10.1 ± .5
KA 1075	Lovejoy Fm. basalt, type section, second flow from bottom	whole-rock	9.58	1.59	74	6.82	11.6 ± .6
KA 1076	Lovejoy Fm. basalt, type section, 4th flow from bottom	whole-rock	9.97	1.53	66	7.95	13.6 ± .4
KA 1077	Lovejoy Fm. basalt, type section, 7th flow from bottom	whole-rock	11.58	1.52	92	2.06	3.5 ± .7
KA 1078	Bald Mtn. olivine latite	whole-rock	9.89	1.61	51	0.73	1.2 ± .1
KA 1092	Mammoth mine basalt	whole-rock	11.03	2.12	15	1.80	3.1 ± .1
KA 1093	Four Forks Creek basalt[a]	whole-rock	10.15	1.82	41	1.67	2.9 ± .1
KA 1094	Hirschdale olivine latite	whole-rock	8.80	2.53	29	0.73+	1.3 ± .1
KA 1096	Watsons Creek basalt	whole-rock	10.69	1.69	14	1.27	2.2 ± .1
KA 1097	Tahoe City olivine latite	whole-rock	9.68	1.88	14	1.10	1.9 ± .1
KA 1098	Sattley rhyolite tuff	sanidine	1.43	9.00	1	9.44	16.1 ± .3
KA 1101	Valley Springs Fm., upper tuff, Ponderosa Way	sanidine	1.42	8.54	1	12.39	21.1 ± .4
KA 1102	Alder Hill basalt	whole-rock	9.26	2.11	25	1.34	2.3 ± .1
KA 1103	San Joaquin Mtn. basalt	whole-rock	9.81	2.62	5	1.84	3.1 ± .1
KA 1109	Boreal Ridge basalt	plagioclase	11.23	0.63	22	4.31	7.4 ± .2
KA 1110	Table Mtn. latite	plagioclase	9.62	0.87	15	5.25	9.0 ± .2
KA 1119	Nobel Canyon rhyolite	biotite	1.14	6.55	38	2.81	4.8 ± .1
KA 1120	Nobel Canyon rhyolite	plagioclase	6.44	0.69	54	2.75	4.7 ± .1
KA 1121	Upper Kinney Lake rhyolite tuff	sanidine	1.97	9.36	1	12.17	20.7 ± .4
KA 1122	Rattlesnake Hill welded tuff	plagioclase	3.18	0.66	34	19.58	33.2 ± .7
KA 1123	Valley Springs Fm., lower tuff, Ponderosa Way	sanidine	1.52	9.19	1	13.58	23.1 ± .5

TABLE 1—(*continued*)

Sample		Material	Weight (gms.)	K (pct.)	Ar^{at}_{40} (pct.)	Ar^{r}_{40}/K_{40}	Age (m.y.)
KA 1124	McKay biotite-augite latite	biotite	1.57	6.52	25	5.37×10^{-4}	9.2 ± .2
KA 1126	Delleker rhyolite tuff, sec. 32	sanidine	1.48	8.71	8	12.07	20.5 ± .4
KA 1127	Delleker rhyolite tuff, Feather River highway	sanidine	1.53	8.43	1	15.33	26.1 ± .5
KA 1128	Plum Creek rhyolite tuff	sanidine	1.53	8.60	1	13.76	23.4 ± .5
KA 1129	Skillman Flat rhyolite tuff	sanidine	1.51	8.58	1	13.37	22.8 ± .5
KA 1130	Lake Alta rhyolite tuff	sanidine	1.27	8.43	1	13.28	22.6 ± .5
KA 1131	Beacon Peak rhyolite, lower welded tuff	sanidine	1.19	6.67	4	19.59	33.2 ± .7
KA 1132	Valley Springs Fm., lower tuff, type section	sanidine	2.25	8.67	1	13.42	22.8 ± .5
KA 1133	La Porte Tuff[a]	plagioclase	3.08	0.40	31	16.92	28.7 ± .6
KA 1135	Two Teats quartz latite	plagioclase	7.08	0.77	69	1.76	3.0 ± .1
KA 1163	Lower Eagle Meadow rhyolite tuff	sanidine	1.43	8.98	1	13.67	23.3 ± .5
KA 1167	Mammoth Mtn. quartz latite	plagioclase	8.33	0.55	92.5	0.22	0.37 ± .04
KA 1186	Pine Flat basalt	whole-rock	9.67	1.72	70	2.05	3.5 ± .1
KA 1187	Snake Meadow basalt	whole-rock	12.27	2.22	15	1.91	3.3 ± .1
KA 1190	Delleker rhyolite tuff, sec. 32	biotite	0.40	5.96	19	17.60	29.9 ± .6
KA 1191	Oroville Table Mtn. tuff	plagioclase	2.11	0.35	53	12.70	23.8 ± .6
KA 1200	Lake Alta rhyolite tuff	plagioclase	3.22	1.04	27	16.54	28.1 ± .6
KA 1202	Sattley rhyolite tuff	plagioclase	3.53	0.95	18	16.56	28.1 ± .6
KA 1234	Delleker rhyolite tuff, Lovejoy Fm., type section	sanidine	1.19	8.64	1	13.02	22.2 ± .4
KA 1235	Beacon Peak rhyolite, upper welded tuff	sanidine	1.09	6.09	8	15.27	26.0 ± .5
KA 1253	Andesite pebbles from Wheatland Fm.	plagioclase	3.85	0.44	40	31.73	53.5 ± 1.1

[a] This determination is now considered low. See addendum on page 33.

late Pliocene to middle or late Miocene. He also states that the Table Mountain latite and the associated augite latites of the Sonora Pass area are members of the Mehrten Formation.

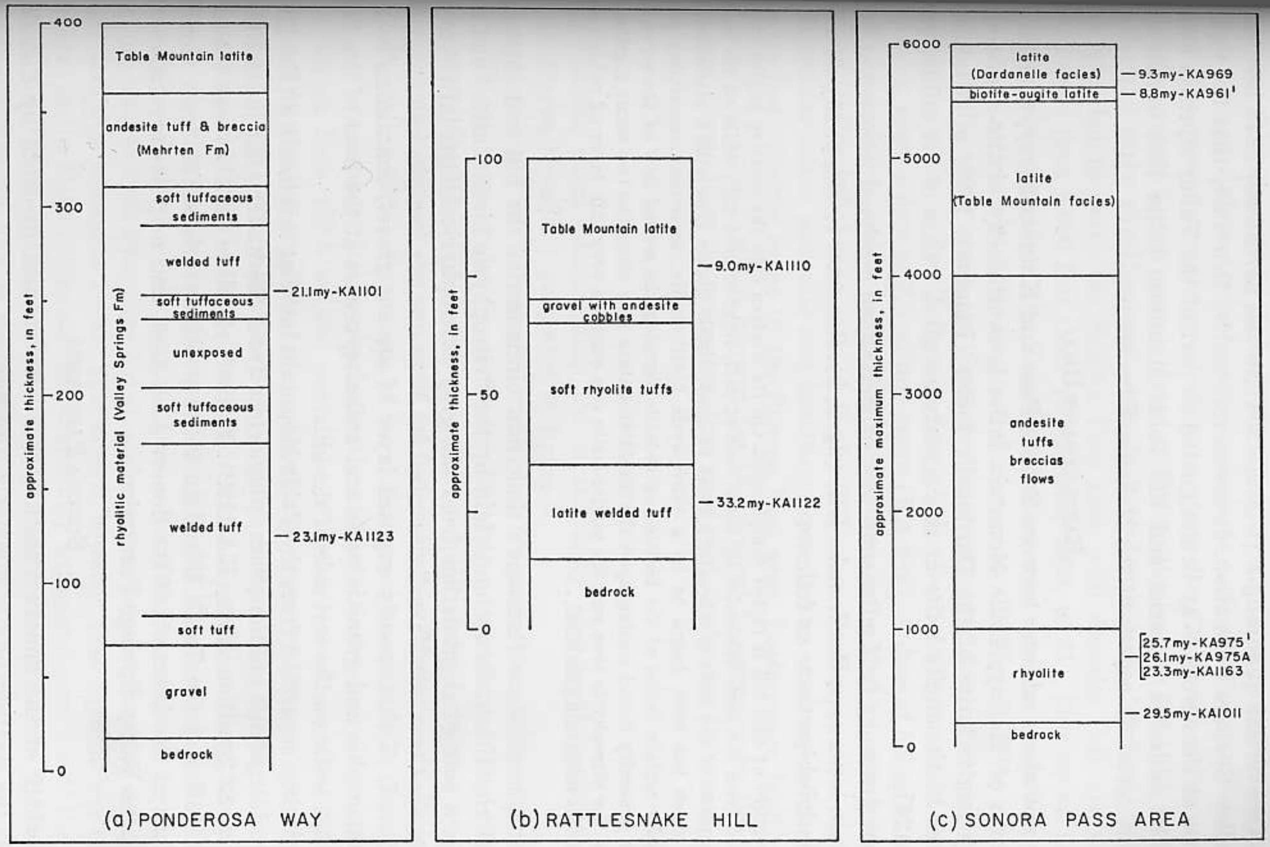
The Table Mountain latite fills a channel (the Cataract Channel of Lindgren, 1911, pp. 36, 201) cut into andesitic deposits of the lower part of the Mehrten Formation from Sonora Pass to the western foothills, and caps Table Mountain near Knights Ferry. This latite, first studied in detail by Ransome (1898), is part of a larger sequence of augite latites that can be traced along the Stanislaus drainage to the crest of the Sierra Nevada near Sonora Pass. These latites were divided by Ransome into three units: from oldest to youngest, (1) the Table Mountain facies, (2) a distinctive biotite-augite latite, and (3) the Dardanelle facies. At several localities described by Ransome (1898, pp. 21–22) and by Dalrymple (1963), andesite breccia overlies these latites. In the Sonora Pass area, the latites are underlain by thick deposits of andesitic material and rhyolite tuff that seem to be counterparts of the Mehrten and Valley Springs formations in the foothills. The name "Mehrten Formation" has been extended (Curtis, 1954, p. 457) to include the thick sequence of andesitic tuffs, breccias, flows, and mudflows that overlie older rhyolitic deposits in the northern and central Sierra.

VALLEY SPRINGS

The type section of the Valley Springs Formation on Valley Springs Peak near the town of Valley Springs contains two welded rhyolite tuffs (Piper and others, 1939, pp. 72–73). The upper tuff, which forms the top of the section, is 70 feet thick. Biotite (KA 1072) from this upper tuff gives 21.9 million years; a date of 19.9 million years on sanidine from this same rock was reported by Dalrymple (1963). The top of the lower welded tuff is 110 feet below the base of the upper tuff; the exposed part of the intervening 110 feet consists of rhyolitic conglomerate. Sanidine from the lower tuff gives a date of 22.8 million years (KA 1132). This lower tuff is about 70 feet thick and is underlain by approximately 160 feet of rhyolitic sediments, which are in turn, underlain by the Ione Formation.

PONDEROSA WAY

About 25 miles northwest of Knights Ferry, near the towns of Murphys and Vallecito, a sequence of rhyolite tuffs and tuffaceous rhyolitic sediments more than 200 feet thick is underlain by auriferous gravel and overlain by andesite tuff and breccia and by Table Mountain latite (fig. 2, *a*). The section, about 25 miles east and 5 miles south of the Valley Springs Formation type section, is exposed along a dirt road (Ponderosa Way) southeast of Murphys in sections 11 and 14, T. 3 N., R. 14 E. The area is shown on geologic maps by Turner and Ransome (1898), Ransome (1898, p. 18 and pl. II), and Lindgren (1911, pl. XXVI). Dates on sanidine from each of the two welded tuffs in this section are as follows: KA 1101 from the upper tuff gives 21.1 million years and KA 1123 from the lower tuff gives 23.1 million years. The lithologic and geochronologic similarities between this rhyolitic sequence and that of the type section of the Valley Springs Formation are striking. Furthermore, similar rhyolites in the Sonora and Angels Camp quadrangles to the south and west, respectively (Eric and others, 1955), and



(a) PONDEROSA WAY

(b) RATTLESNAKE HILL

(c) SONORA PASS AREA

Fig. 2. Columnar sections of Tertiary rocks at: (*a*) Ponderosa Way; (*b*) Rattlesnake Hill, and (*c*) Sonora Pass.

[1] Reference: Dalrymple (1963).

in the Calaveritas quadrangle (Clark, 1954) to the northwest, have been called the Valley Springs Formation. It seems reasonable, therefore, that the rhyolite sequence at Ponderosa Way be designated as part of the Valley Springs Formation. The andesitic material and the Table Mountain latite that overlie these rhyolites certainly represent the Mehrten Formation.

RATTLESNAKE HILL

At a point about midway between Sonora Pass and Knights Ferry, near the old mill town of McKay, Table Mountain latite is overlain by biotite-augite latite and by augite latite of the Dardanelle facies (Ransome, 1898, p. 20). Biotite from the biotite-augite latite at this occurrence gives a date of 9.2 million years (KA 1124).

About five and a half miles southwest of McKay, an erosional remnant of Table Mountain latite caps Rattlesnake Hill (fig. 2, *b*). Ransome (1898, p. 19) described the relationships there as follows:

> The structure of this hill is rather complicated. On its western side the massive augite-latite is separated from the Bed-rock series by three beds of soft, light-colored tuff, while on the eastern side the place of the tuffs is taken by a sheet of gray, highly glassy lava with a pitchstone-like luster, which has been found to be a vitrophyric biotite-latite, somewhat resembling petrographically certain facies of the biotite-augite-latite forming the second flow of the series, and which is generally found resting *upon* the Table Mountain flow when the two occur together... Between the vitrophyric lava and the augite-latite cap occurs a very thin layer of reddish lava, of somewhat uncertain affinities...

Roadcuts, made since Ransome's time, now circumscribe the hill and show that the soft rhyolitic tuffs are underlain by the "vitrophyric biotite-latite" and that there is a continual gradation from the gray "vitrophyric biotite-latite" to the "red lava"; these two "lavas" described by Ransome are two phases of the same welded tuff. A thin, poorly exposed layer of stream gravel, containing cobbles of metamorphic and granitic rocks and andesite, occurs at the base of the Table Mountain latite on the east side of the hill.

Plagioclase separated from the Table Mountain latite at this locality (KA 1110) gives a date of 9.0 million years; plagioclase from the underlying latite welded tuff gives 33.2 million years (KA 1122). The soft rhyolitic tuffs between the latite welded tuff and the Table Mountain latite probably originated from rhyolitic eruptions in the direction of the Sonora Pass area, and may be correlative with part of the Valley Springs Formation.

SONORA PASS AREA

The geology of the Sonora Pass area has been studied in detail by Slemmons (1953); the stratigraphy is summarized in figure 2, *c*. The oldest Tertiary rocks in this area are rhyolite tuffs that filled channels cut into the early Tertiary surface to depths of as much as 800 feet. Rhyolites from two localities where such channel fillings occur have been dated. KA 975A (biotite) is from a sample collected from the lower part of the rhyolite sequence in Lower Eagle Meadow; the indicated age is 26.1 million years. This is an argon redetermination on a sample previously reported by Dalrymple (1963) as 25.7 million years old. Saniine from this same rock (KA 1163) gives 23.3 million years (discrepancies between ages on different minerals from the same rock are discussed later in this paper). The second occurrence of rhyolite, along Leavitt Creek about two miles east of the present Sierra crest, is dated as 29.5 million years (KA 1011, sanidine).

After the early rhyolites were deposited, andesitic tuffs, breccias, and flows were extruded to cover the Sonora Pass area with deposits that are now, in places, more than 3,000 feet thick (Slemmons, 1953, p. 41). During an interval in the andesitic eruptions, the Cataract Channel was cut into andesitic deposits to depths of as much as 1,500 feet near Sonora Pass (Lindgren, 1911; Slemmons, 1953, p. 189), after which the thick sequence of latitic flows was extruded. A whole-rock sample of basalt from a flow of the Dardanelle facies, collected at Bald Peak, gives a date of 9.3 million years (KA 969). A date of 8.8 million years on the underlying biotite-augite latite from the same locality was previously reported (Dalrymple, 1963).

Except for minor andesitic and basaltic eruptions, the extrusion of the latites was the last volcanic event in the Sonora Pass area. Basin-range faulting and the period of erosion which account for the present topography in the Sonora Pass area began after the volcanism that produced the latites (Slemmons, 1953, p. 146).

SUMMARY

A correlation chart summarizing the stratigraphy and geochronology of the central Sierra Nevada is presented in figure 3.

Volcanism began in the central Sierra by late Oligocene time (33.2 million years ago) with the eruption of the latite welded tuff at Rattlesnake Hill. Rhyolitic volcanism in the High Sierra was preceded by uplift and by a period of erosion during which V-shaped canyons were cut into the early Tertiary surface (Curtis, 1951; Slemmons, 1953). Deposition of the tuffaceous sediments of the lower Valley Springs Formation probably began shortly after the earliest rhyolitic eruptions near Sonora Pass (29.5 million years ago or before), and rhyolitic volcanism continued in the Sonora Pass area at least into the early Miocene (23.3 to 26.1 million years ago). The middle and upper parts of the Valley Springs Formation are dated as 22.8 to 23.1 million years and 19.9 to 21.9 million years, respectively. Whether rhyolite tuff was still accumulating in the Sonora Pass area while the upper Valley Springs was being deposited is not definitely known, for only two localities near Sonora Pass were dated, and erosion removed much of the rhyolite before andesitic volcanism began. It is known, however, that rhyolite was erupted elsewhere in the High Sierra contemporaneously with the deposition of the upper parts of the Valley Springs Formation, because rhyolite tuff near Ebbetts Pass has been dated as 20.7 million years (see pp. 20–21 and table 2).

The andesitic volcanism which caused the deposition of the extensive pre-latite breccias, tuffs, and flows in the central Sierra Nevada took place throughout all or part of the middle and late Miocene and early Pliocene. Sometime toward the end of this period of volcanism and before the extrusion of the Table Mountain latite, an ancient channel of the Stanislaus River (the Cataract Channel) extending from Sonora Pass to near Knights Ferry was cut into these deposits

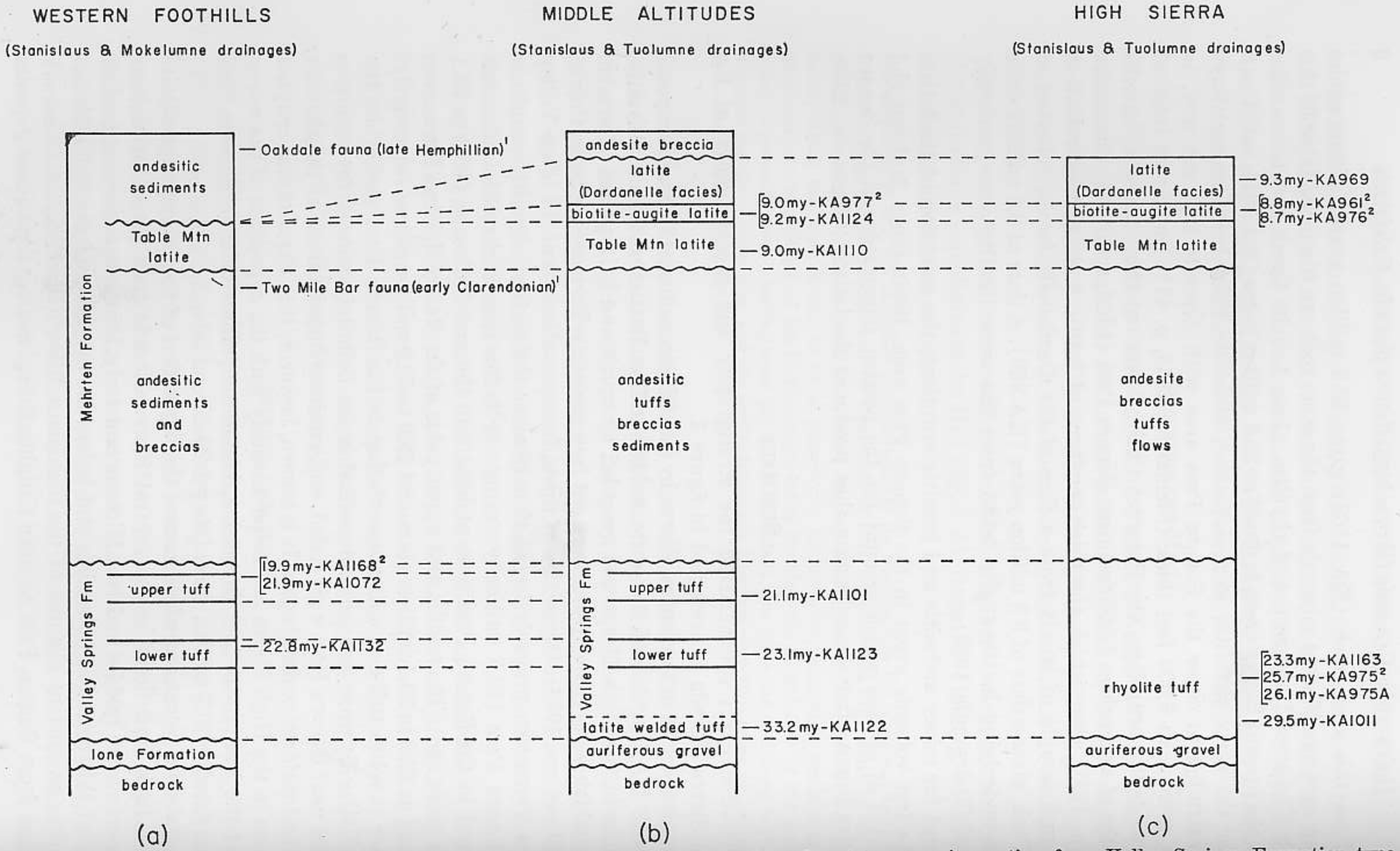


Fig. 3. Correlation and summary diagram of Tertiary rocks of the central Sierra Nevada; (*a*) composite section from Valley Springs Formation type section (Piper and others, 1939) and Knights Ferry area (Taliaferro and Solari, 1949; Stirton and Goeriz, 1942); (*b*) composite section from Ponderosa Way, Rattlesnake Hill, McKay (Ransome, 1898), and Jawbone Ridge (Dalrymple, 1963); (*c*) composite section from Sonora Pass area (Slemmons, 1953) and Rancheria Mountain (Dalrymple, 1963).

[1] Reference: Stirton and Goeriz (1942). [2] Reference: Dalrymple (1963).

depths of as much as 1,500 feet near Sonora Pass. Segments of this channel re preserved beneath the Table Mountain latite, which filled most of its length. date of 9.3 million years on basalt of the Dardanelle facies, dates of 8.8 to 9.2 illion years on biotite-augite latite, and a date of 9.0 million years on the Table ountain latite show that these deposits in the Stanislaus drainage are early liocene and that this thick sequence of latites was deposited in a relatively short ime.

Contemporaneous with andesitic volcanism in the Sonora Pass area, the Mehrten ormation was being formed in the foothills from andesitic material swept westard as fluvial sediment and as mudflows. Some andesite breccia was deposited est of Sonora Pass after the deposition of the latites. The Mehrten Formation ntinued to accumulate in the foothills at least until late Hemphillian (late liocene) time.

BLAIRSDEN AREA

he Tertiary rocks of the Blairsden area comprise a thick sequence of andesitic yroclastic material, rhyolite tuffs, basalt flows, and fluvial and lacustrine deposits. hese rocks have been studied and described by Durrell (1959*a*, 1959*b*), who ivided them into eight formations, summarized in figure 4. Durrell (1959*a*, p. 2) states that "with the exception of the Auriferous gravels and the Lovejoy rmation, which were evidently confined to valleys, the Tertiary units were eposited as sheets of wide extent, and . . . each formation is separated from the ext by faulting and erosion."

The ages assigned by Durrell (1959*a*, 1959*b*) to the formations of the Blairsden rea, if correct, would necessitate a considerably different history of Tertiary lcanism for the northern Sierra than for the central part of the range. His signment of the Ingalls and Lovejoy formations to the Oligocene and Eocene, spectively, would indicate that volcanism began in the Blairsden area much rlier than to the south and that the first eruptions were basaltic and andesitic ther than rhyolitic. It therefore seemed desirable to date some of these rocks that events and units in this part of the Sierra Nevada could be correlated ith those in other parts of the range.

The middle and late Tertiary history of the Blairsden area is not so grossly ifferent from that of the central Sierra as was previously supposed, but, with inor exceptions, fits very well with the sequence of events established for the ntral Sierra.

AGE OF THE DELLEKER FORMATION

urrell (1959*a*, pp. 171–172) has correlated the Delleker Formation with rhyolitic ffs in the Virginia Range of Nevada that are overlain by volcanic rocks dated s middle Miocene on the basis of fossil leaves. Three samples, collected from ree different occurrences of the Delleker Formation, have been dated. KA 1126 anidine) was concentrated from tuff from the section described by Durrell (p. 70) as the most representative and gives a date of 20.5 million years; a biotite ncentrate from this same rock gives 29.9 million years (KA 1190). The paricular sample from which these concentrates come contains small inclusions of diorite that is composed entirely of fresh biotite and plagioclase. The biotite concentrate (KA 1190) apparently contains flakes of biotite from this older granitic material that were not sufficiently heated to release all the previously accumulated radiogenic argon, whereas KA 1126, because of the paucity of potassium feldspar in the diorite inclusions, is uncontaminated. The date of 20.5 million years is therefore considered the most nearly correct age for the Delleker Formation at this locality.

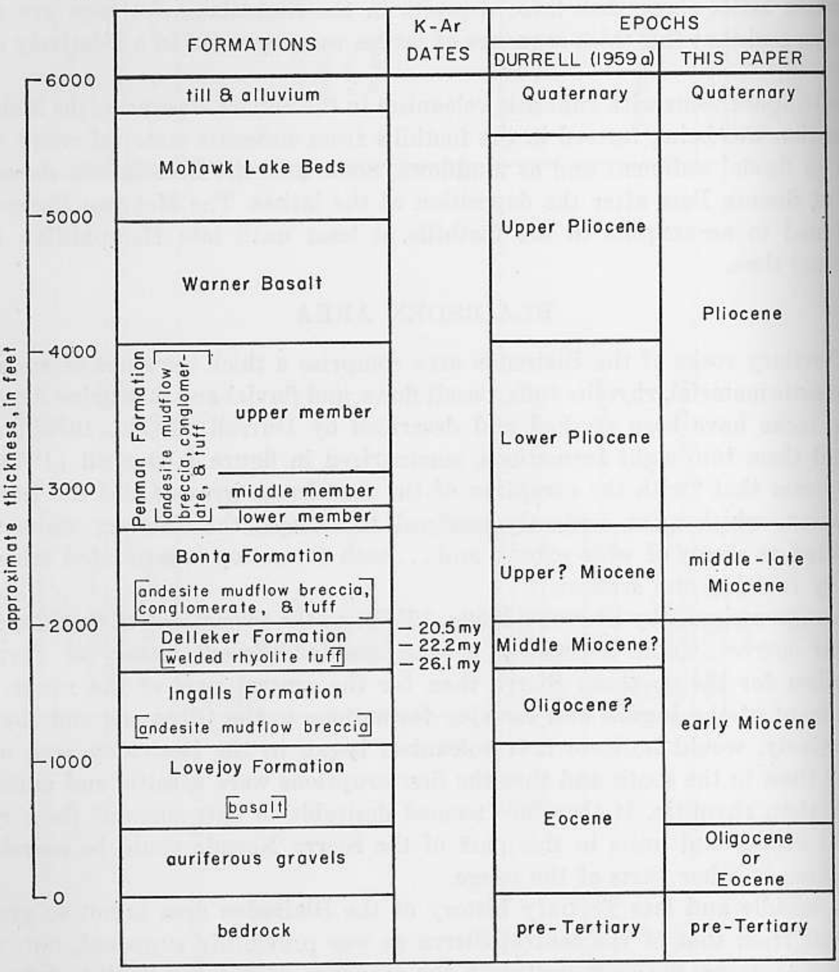


Fig. 4. Stratigraphy of the Blairsden area. After Durrell (1959*a*).

KA 1234 is sanidine from an outcrop of the Delleker Formation at the type section of the Lovejoy Formation along Red Clover Creek. At this locality there is a continuous section in which the Lovejoy, Ingalls, Delleker, and Bonta formations are all exposed (Durrell, 1959*a*, p. 168, map 4; 1959*b*, p. 203, map 3). This sample gives a date of 22.2 million years; the Lovejoy and Ingalls formations at this locality must, therefore, be older than this.

The third sample, KA 1127 (sanidine), was collected from an outcrop of Delleker rhyolite tuff on the Feather River highway between Delleker and Portola; the indicated age is 26.1 million years. Unfortunately, neither Lovejoy nor Ingalls occurs at this locality and therefore the relation of these units to the rhyolite cannot be determined in the field.

It appears that the Delleker Formation comprises at least three distinct rhyolite tuffs whose eruptions were separated in time by some 5 to 6 million years. The Delleker is early Miocene and is approximately correlative with the Valley Springs Formation in the foothills of the central Sierra Nevada.

AGE OF THE LOVEJOY FORMATION

Durrell has correlated the Lovejoy Formation with occurrences of lithologically similar basalts at Oroville Table Mountain in the foothills near Oroville, in the subsurface of the Sacramento Valley, at Putnam Peak near Vacaville, and at Orland Buttes. These correlations are based on a peculiarly distinctive lithology, both megascopic and microscopic (see Durrell, 1959*b*, pp. 198–202, 211–213). In agreement with the correlation of the basalt at Oroville with that of the Lovejoy Formation, paleomagnetic studies have shown that the directions of remnant magnetization at both the type section and at Oroville Table Mountain are approximately antiparallel to the present axial dipole field (C. S. Grommé, personal communication, 1963).

The age of the Lovejoy Formation is considered by Durrell to be "Upper Eocene or Lower Oligocene" (1959*b*, pp. 193, 216). He places the lower limit of age at "Middle Eocene" because "in the Blairsden quadrangle, at Oroville Table Mountain, and at numerous places in between, the basalt rests on the Auriferous gravels that are Middle Eocene (MacGinitie, 1941). In the Sacramento Valley the basalt rests on the Middle Eocene Capay formation . . ." (1959*b*, p. 215). His evidence for the upper limit of "Lower Oligocene" is the occurrence of two large boulders and "numerous" smaller blocks of Lovejoy basalt in the Upper Dutch Diggings placer pit near the town of La Porte; this is the pit in which the La Porte leaf-bearing tuff crops out (Potbury, 1935; MacGinitie, 1941). The La Porte flora has been called "Upper Eocene or Lower Oligocene" by Potbury (1935, p. 59) and by H. D. MacGinitie and D. I. Axelrod (quoted in Durrell, 1959*a*, p. 167). This hypersthene dacite vitric tuff is unconformably overlain by andesite mudflow breccia and conglomerate and appears to fill a small channel cut into carbonaceous lacustrine clay and arkose which overlie auriferous gravels. Durrell states that fragments of Lovejoy basalt can be found in place in the lacustrine clays and that the Lovejoy must therefore predate the La Porte flora—i.e., must be older than "Upper Eocene or Lower Oligocene" (1959*b*, p. 216).

I collected fourteen samples of Lovejoy basalt from the Blairsden area. These and numerous others, collected by C. S. Grommé for paleomagnetic study, were examined and adjudged unsatisfactory for potassium-argon dating; i.e., they would probably give dates later than the time of deposition of the basalt. However, potassium and argon determinations were made on five samples in the hope that a minimum age might be obtained that would prove useful. The results are:

KA 994	Type section, lowest flow	11.5 million years
KA 1073	Stoney Ridge	10.1 million years
KA 1075	Type section, second flow from bottom	11.6 million years
KA 1076	Type section, fourth flow from bottom	13.6 million years
KA 1077	Type section, seventh flow from bottom	3.5 million years

The only conclusion that can be drawn from these results is that the Lovejoy basalt must be older than 13.6 million years. A more meaningful minimum age, however, is provided by the date of 22.2 million years (KA 1234) on the Delleker rhyolite that overlies Ingalls and Lovejoy formations at the Lovejoy type section.

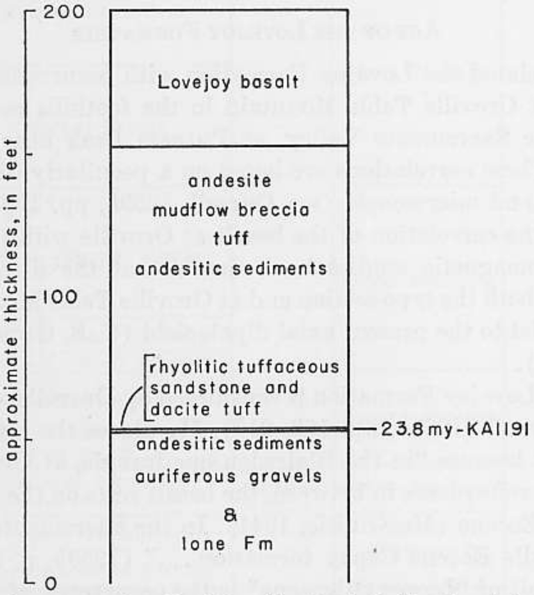


Fig. 5. Columnar section at north end of Oroville South Table Mountain. Location: Oroville quadrangle (U. S. Geol. Survey, 1942 ed.), 3,000 feet S. 27 E. from northeast corner of sec. 29, T. 20 N., R. 4 E., on north side of saddle.

At Oroville South Table Mountain C. S. Grommé and I found a fine-grained vitric dacite tuff about 3 inches thick, approximately 100 feet below the base of the basalt flows (fig. 5). Plagioclase from this tuff (KA 1191) gives a date of 23.8 million years, which places the maximum age of the Lovejoy basalt in the early Miocene. The tuff is immediately overlain by andesite mudflow breccia that is indistinguishable from the andesite mudflow breccias of the Mehrten Formation. That andesite mudflow breccia occurred below the basalt at Oroville Table Mountain was recognized by Dickerson (1916, p. 390), Allen (1929, pp. 372–373), and Creely (1954, pp. 164–174). Creely described this andesitic material in detail and tentatively referred it to the Mehrten Formation. Durrell, however, states that "the basalt at Oroville Table Mountain rests on the Ione formation and on Auriferous gravels, and there is no intervening andesite tuff, breccia, or mudflow breccia that can be correlated with any such unit elsewhere in the Sierra Nevada" (1959*b*, p. 209); this statement is incorrect.

Plagioclase from the La Porte leaf-bearing tuff gives dates of 32.3 million years and 32.5 million years (Evernden and James, in press).[1] Furthermore, neither C. S. Grommé nor I could find Lovejoy basalt in place in the sediments that underlie the La Porte Tuff; the small blocks mentioned by Durrell are embedded in slopewash from the steep cliff face.

SUMMARY

The ages of the rocks in the Blairsden area, based on the evidence presented here, are summarized in figure 4. Auriferous gravels in the Blairsden area contain pebbles of rhyolite which Durrell (1959*a*, p. 165) attributes to sources northeast of the present Sierra Nevada. It is worth considering the possibility that these rhyolite pebbles came from the Sierra Nevada and that some of the auriferous gravels in this area might be as young as late Oligocene or early Miocene. The Lovejoy and Ingalls formations can be no older than 23.8 million years and no younger than 22.2 million years; hence their age must be early Miocene. Also, the age of the La Porte Tuff (and the La Porte flora) is 32 million years; therefore Lovejoy basalt could not, and in my experience does not, occur in sediments underlying the La Porte Tuff. Because the rhyolites of the Delleker Formation range in age from 26.1 to 20.5 million years, the eruptions of the Lovejoy basalts and the andesite breccias of the Ingalls Formation are included within the history of deposition of the Delleker Formation (as described by Durrell, 1959*a*), which is approximately correlative with the Valley Springs Formation and associated rhyolite tuffs in the central Sierra Nevada. The facts that the Ingalls Formation is overlain by 22.2-million-year-old rhyolite tuff and that andesite breccia and tuff occur between Lovejoy Formation basalt and 23.8-million-year-old dacite tuff at Oroville Table Mountain indicate that Mehrten-type andesitic volcanism began in the northern Sierra Nevada before rhyolitic volcanism ended in the northern and central Sierra. The Bonta and Penman formations are probably approximately correlative with the Mehrten Formation. The age of the Warner Basalt was not determined because the samples that were collected were deemed unsatisfactory for whole-rock analysis, but Durrell (1959*a*, p. 179) states that "the Warner may be approximately the same age as the Tuscan, which is Upper Pliocene (Anderson, 1933, p. 236)." Durrell (*loc. cit.*) also notes that the Warner Basalt "was erupted before the period of faulting that produced the present scarps." That the Warner may be approximately correlative with the early Pliocene latite sequence in the central Sierra is not precluded.

DONNER PASS–TRUCKEE AREA

The Cenozoic rocks of the Donner Pass–Truckee area comprise, from oldest to youngest: auriferous gravels; rhyolite; andesite tuffs, breccias, and flows; basalt breccias and flows. Lindgren (1897, 1911) believed that the essential topographic features of this area were established prior to "Neocene" time and that the Cenozoic

---

[1] The first determination on plagioclase from the La Porte Tuff (KA 1133) gave a date of 28.7 million years (table 1; Dalrymple, 1963*b*, p. 34). Two subsequent determinations by J. F. Evernden, on splits from the same mineral concentrate that was used for the first determination, gave dates of 32.3 and 32.5 million years. Although the reason for this discrepancy is unknown, it is probably due to a technical error in the first determination. Because of the good agreement between the two determinations made by Evernden, they probably most nearly represent the age of the La Porte Tuff.

volcanic rocks were deposited on a topography similar to that of today. Lindgren also thought that the basalts of this area were Pleistocene.

Hudson studied an area west of Donner Lake, near Donner Pass, and concluded (1951, p. 941) that "the basalt of the Truckee quadrangle was deposited in a continuous sheet on a surface of low relief which was in no way the ancestor of the present rugged terraine. It was then severely deformed and dissected prior to glaciation." He believed these basalts to be Pliocene.

The Pleistocene geology of the Truckee area, east of Donner Pass, has been studied by Birkeland (1961, 1962, 1963), who concluded that the basalts there are early Pleistocene, that the deformation which formed much of the present topography is Plio-Pleisticene, and that the basalts spread out from numerous vents over a surface similar to the present one (1961, 1963).

AGE OF VOLCANIC ROCKS NEAR DONNER PASS

The geology of the area near Donner Pass has been studied by Hudson (1948, 1951). The stratigraphy of the area is summarized in figure 6 along with the ages assigned to these rocks by Hudson (1951) and in this paper. Two dates on sandine from the welded rhyolite tuffs at Beacon Peak (fig. 7, *a*) show that these rhyolites are late Oligocene and earliest Miocene, not "Middle Eocene" (Hudson, 1951, p. 945). Hudson (p. 937) mentions that about 1000 feet of rhyolite occur in the area, two miles southwest of Mount Lincoln; it is probable that the thin occurrence at Beacon Peak represents the older deposits of rhyolite in the Donner Pass area. KA 1235 (26.0 million years) is from a dense, gray welded tuff that occurs at the top of the rhyolite sequence at Beacon Peak. This upper tuff is distinctly different from the underlying pink welded tuff (KA 1131, 33.2 million years) and was not described by Hudson (1951, pp. 936–937). The rhyolites are overlain by andesite tuff to which Hudson (pp. 944–945) assigns an age of "Lower Oligocene or Upper Eocene" because of correlation with the La Porte Tuff. The andesite tuff is overlain by andesite mudflow breccia, which Hudson calls "lower Pliocene or upper Miocene" (p. 944).

The andesites on Beacon Peak are overlain by mudflow breccias composed of basalt which has hypersthene as an essential constituent (Hudson, 1951, p. 943). This breccia seems to be correlative with similar deposits which cap Castle Peak, about three miles north of Beacon Peak, and are underlain by massive hypersthene basalt flows (fig. 7, *b*). Two flows of hypersthene basalt cap Boreal Ridge, one mile northwest of Beacon Peak, overlying andesite mudflow breccia (fig. 7, *c*); plagioclase from the lower flow gives a date of 7.4 million years (KA 1109). This is in agreement with the Pliocene age assigned by Hudson to the hypersthene basalt flows and agglomerates.

AGE OF BASALTS IN THE TAHOE–TRUCKEE DEPRESSION

Basalts in the immediate vicinity of Truckee and the northwest shore of Lake Tahoe have been studied in detail by Birkeland (1961, 1962, 1963), who included them in the Lousetown Formation. He has given informal member names to these flows and placed some of them in their approximate relative order, as shown in figure 8. The flows are all underlain by andesitic deposits and, according to Birke-

STRATIGRAPHY		K-Ar DATES	EPOCH	
			HUDSON (1951)	THIS PAPER
hypersthene basalt (0-700')	mudflow breccia		Pliocene	middle and/or late Pliocene
	flows	-7.4my		
andesite (0-1350')	mudflow breccia tuffs flows		Pliocene Upper Miocene	early Pliocene and/or late-middle Miocene
	tuff		Lower Oligocene or Upper Eocene	
rhyolite tuff (0-1000')		-26.0my -33.2my	Middle Eocene	early Miocene - late Oligocene
auriferous gravel (0-13')				Oligocene or Eocene
bedrock			pre-Tertiary	pre-Tertiary

Fig. 6. Summary of stratigraphy and age of Tertiary rocks near Donner Pass. After Hudson (1951).

land (1961, 1963), postdate the inception of the faulting which produced the present topography.

The oldest of these flows, the Alder Hill basalt, has suffered considerably more dissection and faulting than the younger flows (Birkeland, 1961, p. 27 and pl. I; 1963). A whole-rock sample of this basalt gives a date of 2.3 million years

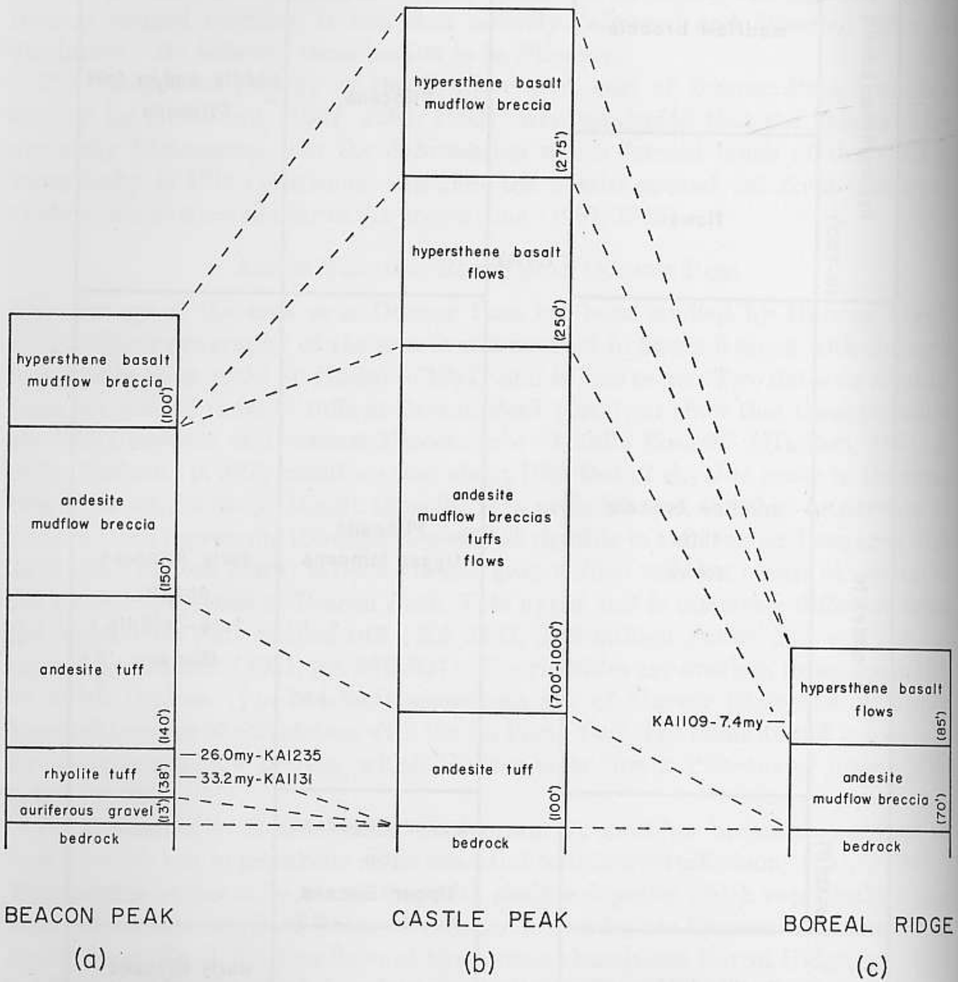


Fig. 7. Correlation of Tertiary rocks near Donner Pass. Sections from Beacon Peak and Castle Peak after Hudson (1951). Numbers in parentheses indicate approximate thicknesses.

(KA 1102). A geomorphically similar basalt northeast of Tahoe City near Watsons Creek gives a date of 2.2 million years (KA 1096). [This latter basalt is just southeast of the area studied by Birkeland, but is shown on Lindgren's geologic map of the Truckee quadrangle (1897).] The other flows shown in figure 8 are notably dissected only where incised by the Truckee River, and the effects of faulting are slight or absent. The Hirschdale (KA 1094), Bald Mountain (KA 1078), and Tahoe City (KA 1097) olivine latites give dates of 1.3 million years, 1.2 million years, and 1.9 million years, respectively. The difference of 0.1 million years between the Hirschdale and the Bald Mountain olivine latites may not be significant. Birkeland's (1961) evidence for the relative ages of these two units is that alluvium deposited when the Hirschdale flow blocked the Truckee River overlies the Bald Mountain member.

Fig. 8. Sequence of some of the Pleistocene lava flows of the Lousetown Formation near Truckee, according to Birkeland (1961).

SUMMARY

The disagreement between Lindgren (1897) and Hudson (1951) concerning the age of the basalts in the Donner Pass and Truckee areas and their relation to the faulting that produced the present topography is a direct consequence of not recognizing that there are two distinct generations of basalt. The hypersthene basalt and basalt agglomerate west of the Tahoe–Truckee depression (near Donner Pass) has been deeply eroded. It occurs only on ridge crests and was deposited well before the present topography was formed; its age is middle to late Pliocene. The lava flows in the Tahoe–Truckee depression (Lousetown Formation), in contrast, are early and middle Pleistocene and were deposited on a topography similar to that of today. The faulting that produced the Tahoe–Truckee depression must have been initiated long after the deposition of the 7.4-million-year-old basalt on Boreal Ridge, but before extrusion of the Lousetown Formation basalts began 2.3 million years ago. Accordingly, the age of the inception of the faulting is late Pliocene or early Pleistocene. This is in accord with the views of Louderback (1924, p. 5), who states that "... it seems reasonable to conclude that the [scarp producing] faulting was begun in late Pliocene or early Pleistocene time," and of Birkeland (1961, 1962, 1963).

The rhyolite tuff near Donner Pass is late Oligocene and early Miocene and therefore approximately correlative with the Valley Springs Formation and associated rhyolites in the central and northern Sierra. Andesitic and older basaltic deposits (hypersthene basalt) near Donner Pass are approximately correlative with part of the Mehrten Formation.

DATES FROM SIERRAN RHYOLITIC TUFFS

Additional Dates

Several other rhyolite tuffs were dated in an attempt to help establish the limits of rhyolitic volcanism in the Sierra Nevada. Table 2 presents all the potassium-argon dates on rhyolites and similar rocks from the Sierra Nevada. The oldest dates on

TABLE 2

Potassium-Argon Dates on Rhyolitic Volcanic Rocks of the Sierra Nevada

Sample	Number	Material	Age (m.y.)
Valley Springs Fm.			
Type section			
Upper tuff	KA 1168	sanidine	19.9[a]
	KA 1072	biotite	21.9
Lower tuff	KA 1132	sanidine	22.8
Ponderosa Way			
Upper tuff	KA 1101	sanidine	21.1
Lower tuff	KA 1123	sanidine	23.1
Rattlesnake Hill tuff	KA 1122	plagioclase	33.2
Lower Eagle Meadow tuff	KA 1163	sanidine	23.3
	KA 975	biotite	25.7[a]
	KA 975A	biotite	26.1
Leavitt Cree tuff	KA 1011	sanidine	29.5
Delleker Fm.			
In sec. 32	KA 1126	sanidine	20.5
	KA 1190	biotite	29.9
Lovejoy Fm. type section	KA 1234	sanidine	22.2
Feather River highway	KA 1127	sanidine	26.1
La Porte Tuff	KA 1133	plagioclase	28.7
			32.3[b]
			32.5[b]
Oroville Table Mtn. tuff	KA 1191	plagioclase	23.8
Beacon Peak			
Gray upper tuff	KA 1235	sanidine	26.0
Pink lower tuff	KA 1131	sanidine	33.2
Upper Kinney Lake tuff	KA 1121	sanidine	20.7
Plum Creek tuff	KA 1128	sanidine	23.4
Skillman Flat tuff	KA 1129	sanidine	22.8
Lake Alta tuff	KA 1130	sanidine	22.6
	KA 1200	plagioclase	28.1
Sattley tuff	KA 1098	sanidine	16.1
	KA 1202	plagioclase	28.1
Nobel Canyon rhyolite	KA 1119	biotite	4.8
	KA 1120	plagioclase	4.7

[a] Reference: Dalrymple (1963).

[b] Reference: Evernden and James (in press).

hyolitic material were obtained on the welded tuffs at Rattlesnake Hill and Beacon Peak (both 33.2 million years old, late Oligocene). Although the extreme range in ge of the dates is from late Oligocene to late Pliocene, by far the majority are early Miocene. It seems conclusive that the major period of rhyolitic volcanism in the Sierra Nevada occurred in early Miocene time; included in this period are the depositions of the Valley Springs and Delleker formations.

The Upper Kinney Lake tuff (KA 1121, 20.7 million years) was collected near Ebbetts Pass and is shown on Wilshire's (1956) geologic map of that area. This tuff rests on granitic basement rock and is overlain by andesite mudflow breccia. According to Curtis (1951, 1954), these early rhyolites of the Ebbetts Pass area filled stream channels carved on the prevolcanic bedrock surface.

The Nobel Canyon rhyolite (KA 1119, 4.8 million years; KA 1120, 4.7 million years), also from the Ebbetts Pass area, is 800 to 1,000 feet thick, and is overlain and underlain by andesite mudflow breccia. Curtis (1951, pp. 161–162) interpreted the Nobel Canyon rhyolite as a welded tuff. If this interpretation is correct, the thick deposits of andesite mudflow breccia that overlie the tuff are no older than late Pliocene and, accordingly, represent some of the youngest andesitic deposits in the Sierra Nevada. Wilshire (1956, pp. 71–73), in contrast, concluded that the Nobel Canyon rhyolite may be an intrusive body; if so, the overlying andesites would be Miocene or Pliocene. The question of the genesis of the Nobel Canyon rhyolite is still to be resolved, but the significance for the purpose of this study is that not all Sierran rhyolites are Miocene. Other young rhyolites in the Ebbetts Pass area are mentioned by Curtis (1951) and by Wilshire (1956).

The Plum Creek (KA 1128, 23.4 million years), Skillman Flat (KA 1129, 22.8 million years), Lake Alta (KA 1130, 22.6 million years; KA 1200, 28.1 million years), and Sattley (KA 1098, 16.1 million years; KA 1202, 28.1 million years) rhyolite tuffs all rest on basement rock and are overlain by andesite mudflow breccia. They were all undoubtedly deposited during the early rhyolitic volcanism and the indicated ages are Miocene.

DISCORDANT MINERAL PAIRS AND EVALUATION OF RHYOLITE DATES

Of the six rhyolite tuffs from which two minerals have been dated (table 2), all but one (the Nobel Canyon rhyolite) have given internally discordant ages. There are two possible explanations for this: (1) argon diffusion from the mineral that gives the younger age, or (2) contamination by older material of the mineral concentrate that gives the older age. It is interesting to note that in each of the five discordant mineral pairs, the sanidine always gives the younger age. Sanidine is a highly retentive mineral (Evernden and others, 1960; Evernden and Richards, 1962, pp. 5–7) and diffusion of radiogenic argon from the sanidine would not take place unless the rock was affected by considerable postdepositional heating. Such heating of these Sierran rhyolites is unlikely—had it occurred it would be apparent in these rocks because it would have caused similar argon losses from the biotites and plagioclases—and therefore discordance due to diffusion of radiogenic argon from the sandine is considered improbable. The most probable explanation is that the plagioclase and biotite concentrates are contaminated by older granitic material. Contamination of plagioclase and biotite separates is more likely than contamination of sanidine concentrates because the probable source of contamination, the Sierran batholithic complex, is low in potassium feldspar (mostly quartz diorite and granodiorite). Small inclusions of granitic material can be found in hand specimens and thin sections of many of the Sierran rhyolites, and are generally composed of biotite, hornblende, and plagioclase. Although contamination by older biotite and plagioclase is the more likely, contamination of sandine concentrates by older potassium-feldspar cannot be precluded and dates on Sierran rhyolites must therefore be treated conservatively. It is important that all dates in table 2 be evaluated in context with their geologic setting and with other dates that are closely related. My evaluation of the dates listed in table 2 is as follows:

Valley Springs Formation.—The discordance between sanidine and biotite from the upper tuff in the type section is not serious and, considering the agreement between all the dates on Valley Springs Formation tuffs, the age of the upper and middle parts of the Valley Springs Formation is well established.

Rattlesnake Hill Tuff.—Considering its position in the geologic section, this date can be trusted to indicate the proper order of magnitude. i.e., this tuff is late Oligocene or early Miocene.

Lower Eagle Meadow Tuff.—For the purpose of this investigation the discrepancy is not serious, but I would place slightly greater confidence in the sanidine date. The age of rhyolites from this section is, however, well established as early Miocene.

Leavitt Creek Tuff.—Probably correct, at least in order of magnitude: i.e., this tuff is late Oligocene or early Miocene.

Delleker Formation.—KA 1190 is contaminated and has been discussed in the section with the Delleker Formation. KA 1126, KA 1127, and KA 1234 are geologically reasonable and I consider these dates reliable. The age of the Delleker Formation is well established as early Miocene.

La Porte and Oroville Table Mountain Tuffs.—The hand specimens and the plagioclase concentrates were examined carefully for signs of contaminating material and none were found. The discrepancy in the La Porte dates was discussed in the section dealing with the Lovejoy Formation. The dates are considered reliable.

Beacon Peak Tuffs.—Probably correct, at least in order of magnitude; i.e., these tuffs are late Oligocene or early Miocene.

Upper Kinney Lake, Plum Creek, and Skillman Flat Tuffs.—These fit well with the geochronology of Tertiary rhyolites from other parts of the range and are probably nearly correct.

Lake Alta and Sattley Tuffs.—The plagioclase dates are most certainly affected by contamination and the sanidine dates are considered the more reliable.

Nobel Canyon Rhyolite.—These dates are considered reliable because of their close agreement.

A DATE ON ANDESITE PEBBLES FROM THE WHEATLAND FORMATION

The Wheatland Formation comprises tuffaceous sandstone and shale which overlie a basal conglomerate that contains andesite pebbles and "Upper Eocene or

Lower Oligocene" marine mollusks (Clark and Anderson, 1938). The formation crops out about five miles northeast of Wheatland and is of only local extent. It was decided to date some of the andesite pebbles to see whether these andesites were erupted prior to the late Oligocene–early Miocene rhyolitic volcanism or whether the source of these pebbles might be deposits of approximately Mehrten age, with the fossils being reworked from older beds.

Plagioclase was separated from about 35 to 40 andesite pebbles collected from the basal conglomerate and was analyzed for potassium and argon; the resulting age is 53.5 million years (KA 1253). It should be emphasized that this indicated age was obtained from a composite sample, and is therefore a "composite age"; it does not necessarily represent either the age of the Wheatland Formation or the age of the source(s) of the pebbles. It indicates only that (1) the Wheatland Formation is younger than 53.5 million years (late Paleocene to early Eocene), and (2) at least one of the sources of the andesite pebbles (if there was more than one source) is older than 53.5 million years and thus predates the late Oligocene–early Miocene rhyolitic volcanism. The location and nature of the source(s) are unknown.

AGE OF THE AURIFEROUS GRAVELS

Some recent workers have inferred that the prevolcanic gravels of the Sierra Nevada are categorically of Eocene age. The following comments are offered to emphasize that this is not necessarily so.

Lindgren subdivided the auriferous gravels into four principal "epochs"—from older to younger, deep gravels, bench gravels, interrhyolitic gravels, and interandesitic gravels (1911, p. 29)—about which he made the following statement: "According to present evidence, then, nearly the whole of the auriferous gravel series, from the top of the deep gravels to the latest andesitic flows, were deposited during the Miocene epoch. The deep gravels are recognized as probably Eocene" (p. 57). (It must be remembered that during Lindgren's time, "Oligocene" was not generally used and therefore never appears in Lindgren's age assignments.) A middle Eocene age for some of the Sierran auriferous gravels in or near the foothills seems to be well established (Dickerson, 1916; Allen, 1929; Creely, 1954); however, the following evidence indicates that many of the seemingly prevolcanic auriferous gravels are Oligocene and perhaps some are as young as early Miocene.

Wood (1960, p. 107), restudied several fossil mammals from the auriferous gravels of the Sierra Nevada and concluded: "The fossil mammals of the Whitney collection from the California 'auriferous gravels' are all of mid-Tertiary age, with the probable spread only from Orellan to Whitneyan (middle to upper Oligocene). The extreme possible spread would be from Chadronian to Arikareean" [early Oligocene to early Miocene]. One of the specimens studied by Wood is described as having come from the "deep 'auriferous gravels' " at Douglass Flat, Calaveras County (p. 88).

KA 999 is sanidine from a rhyolite boulder found in place in the quartz gravels of the Tertiary Tuolumne River. These gravels are the oldest Tertiary deposits in the Tuolumne drainage; the Tertiary channel of the Tuolumne River is described by Turner (1901, pp. 540–541) and by Lindgren (1911, pp. 218–219). The gravels are about 30 to 40 feet thick at the locality from which the sample was collected, and the boulder was found about 15 feet above the base of the channel. The indicated age of the boulder is 28.5 million years. Thus the Tertiary Tuolumne River was active until after the eruption of the tuff from which the boulder came, i.e., in the late Oligocene to early Miocene.

The auriferous gravels beneath the La Porte Tuff are often cited as an example of a gravel deposit whose age is older than late Eocene. It has been shown in a previous section of this paper, however, that the La Porte Tuff is Oligocene; the underlying gravels therefore need not be any older than Oligocene.

There is thus evidence that Tertiary gravels of widely diverse ages exist in the Sierra Nevada. Because rhyolitic volcanism apparently did not begin in the Sierra until the late Oligocene, it is reasonable to conclude that many of the Tertiary rivers, although they may have begun their courses in the Eocene, were probably active until late Oligocene or even early Miocene time—i.e., until such time as their channels were filled, their gravels were buried by volcanic debris, and the rivers were forced to seek new courses. Therefore, unless there is good evidence for assigning a definite age to prevolcanic gravels of a particular locality, it is wise to refer them to the broad period of the middle Eocene and the Oligocene rather than to a narrower interval.

AGE OF THE CANYON STAGE OF EROSION IN THE UPPER SAN JOAQUIN BASIN

Sierran Erosion Surfaces

A classic area for Sierran erosion surfaces is the upper Kern River basin, where broad uplands of relatively low relief are separated by abrupt rises. The geomorphology of this area was first studied by A. C. Lawson and G. K. Gilbert in 1903. Their observations were recorded by Lawson (1904), who named these surfaces the Summit Upland, the Subsummit Plateau, the High Valley, and the Canyon. Matthes (1937, 1950) later studied these surfaces and renamed them the Mount Whitney, Boreal Plateau, Chagoopa, and Canyon erosion surfaces, respectively, adding another, the Cirque Peak erosion surface, between the Mount Whitney and the Boreal. Matthes' names will be used in this paper (fig. 9, *a*).

In studies of the Yosemite Valley and of the San Joaquin River basin (1930, 1960), Matthes recognized four stages of erosion, which he called the Canyon stage, the Mountain Valley stage, the Broad Valley stage, and an older stage he referred to as "an Eocene surface" (fig. 9, *b*).

Estimates of the ages of these Sierran erosion surfaces have varied widely. Lawson believed that the uplift that initiated the High Valley surface (Chagoopa surface of Matthes) was "a part of the very much wider disturbance of the Cordilleran region which inaugurated the Quaternary" (1904, p. 364), and that the development of the high valleys "occupied the greater part of the Quaternary" (p. 365). Matthes, appraising the durations of the successive erosion cycles in the Kern River basin, estimated approximately one million years for the Canyon, 10 to 15 million years for the Chagoopa, and perhaps as long as 20 million years—at least 5 to 10 million years—for the Boreal (1937). In the Yosemite and San Joaquin areas, Matthes (1930, 1960) considered the Canyon stage to have been carved entirely during the Pleistocene, the Mountain Valley stage to have embraced most of the Pliocene, and the Broad Valley stage to have been initiated sometime in the Miocene. Matthes did not attempt to correlate the surfaces in the Yosemite and San Joaquin areas with those in the Kern River basin because he felt that the Kern River basin was atypical for the range as a whole and that a precise correlation presented difficulties (1960, pp. 20–21).

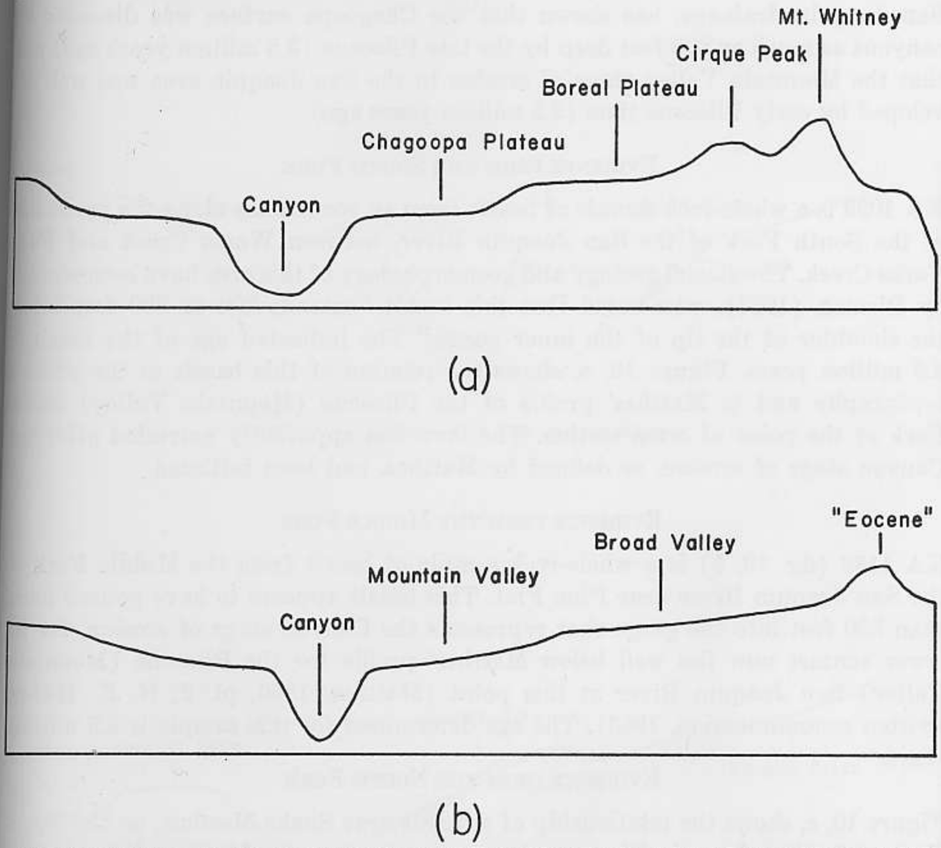


Fig. 9. Diagrams of: (*a*) erosion surfaces of Kern River basin. Adapted after Knopf (1918) and Matthes (1937). (*b*) Erosion stages of Yosemite and San Joaquin areas. Adapted after Matthes (1933).

Axelrod and Ting have studied fossil pollen from the Chagoopa and Boreal surfaces and have correlated the "Eocene" surface in the Yosemite–San Joaquin areas with the Boreal surface in the Kern River basin, assigning to them a late Pliocene age (Axelrod and Ting, 1961, pp. 120, 145; Axelrod, 1962, pp. 185–186). They correlate the Broad Valley stage with the Chagoopa Plateau, which they date as Pleistocene [Kansan] (Axelrod and Ting, 1961, p. 145; Axelrod, 1962, pp. 185–186), and state that the Mountain Valley stage was no more than an early cycle in the development of the Canyon stage, both appearing to be middle Pleistocene (1961, p. 146).

Hudson (1960, pp. 1555–1556) concluded that the Broad Valley surface was carved on the andesitic deposits of the Mehrten Formation, is therefore no older than later Pliocene, and that the "date of the final broad-valley channels is ... between lower and middle Pleistocene." He also believed that "the end of the mountain-valley stage was in late middle Pleistocene time" (p. 1556).

Recently Dalrymple (1963), applying the potassium-argon method to a basalt which fills a canyon cut into the Chagoopa surface in the Kern River drainage and to one that was deposited on the Mountain Valley surface in Jose Basin in the San Joaquin drainage, has shown that the Chagoopa surface was dissected by canyons as much as 800 feet deep by the late Pliocene (3.5 million years ago) and that the Mountain Valley stage of erosion in the San Joaquin area was well developed by early Pliocene time (9.5 million years ago).

EVIDENCE FROM THE SOUTH FORK

KA 1093 is a whole-rock sample of basalt from an occurrence along the north side of the South Fork of the San Joaquin River, between Warm Creek and Four Forks Creek. The glacial geology and geomorphology of this area have been studied by Birman (1957), who noted that this basalt "extends 200 to 300 feet below the shoulder of the lip of the inner gorge." The indicated age of the basalt is 2.9 million years. Figure 10, *a,* shows the relation of this basalt to the present topography and to Matthes' profile of the Pliocene (Mountain Valley) South Fork at the point of cross section. The lava was apparently extruded after the Canyon stage of erosion, as defined by Matthes, had been initiated.

EVIDENCE FROM THE MIDDLE FORK

KA 1186 (fig. 10, *b*) is a whole-rock sample of basalt from the Middle Fork of the San Joaquin River near Pine Flat. This basalt appears to have poured more than 500 feet into the gorge that represents the Canyon stage of erosion, for its lower contact now lies well below Matthes' profile for the Pliocene (Mountain Valley) San Joaquin River at this point (Matthes, 1960, pl. 2; N. K. Huber, written communication, 1963). The age determined for this sample is 3.5 million years.

EVIDENCE FROM THE NORTH FORK

Figure 10, *c,* shows the relationship of a basalt near Snake Meadow, on the North Fork of the San Joaquin River, to the present topography. Matthes did not draw profiles of the ancient North Fork, but the lower contact of the Snake Meadow basalt is approximately 400 to 500 feet below his profile of the Pliocene Middle Fork at the present confluence of the Middle and North forks (N. K. Huber, written communication, 1963). The Pliocene North Fork clearly must have been higher than this at the point of the cross section in figure 10, *c.* This basalt, then, was also extruded after the initiation of the Canyon stage of erosion; its indicated age is 3.3 million years.

MINIMUM RELIEF DURING THE LATE PLIOCENE

The relationships of these basalts to the present high peaks in the area can be used to estimate the minimum relief, and consequently the minimum altitude, of the Sierra Nevada in the San Joaquin drainage at the time of eruption of

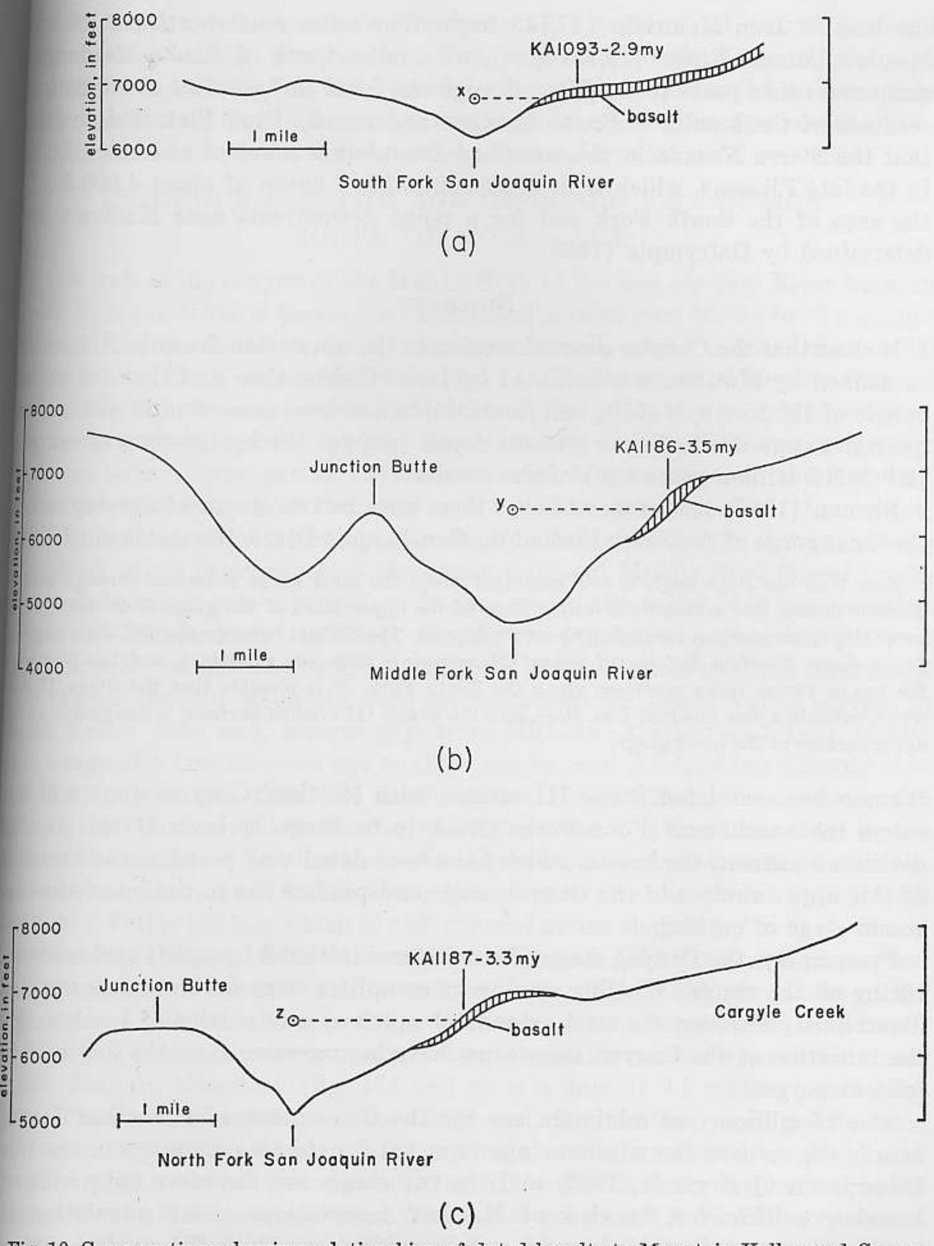


Fig. 10. Cross sections showing relationships of dated basalts to Mountain Valley and Canyon stages of erosion in South Fork (*a*), Middle Fork (*b*), and North Fork (*c*) of San Joaquin River. x = elevation of Pliocene (Mountain Valley) San Joaquin South Fork at point of cross section; y = elevation of Pliocene (Mountain Valley) San Joaquin Middle Fork at point of cross section; z = elevation of Pliocene (Mountain Valley) San Joaquin Middle Fork at confluence of Middle and North forks. References: Matthes (1960, pl. 2); Birman (1957); N. K. Huber (written communication, 1963). Locations of sections (U. S. Geol. Survey, 1953 ed.): (*a*) Kaiser Peak quadrangle, intersects river 4,200 feet N. 20 E. from northwest corner of sec. 1, T. 7 S., R. 26 E., trends N. 12 E.; (*b*) Devils Postpile quadrangle, intersects river 2,000 feet N. 66 W. from southeast corner of sec. 1, T. 5 S., R. 25 E., trends N. 66 W.; (*c*) Devils Postpile quadrangle (U. S. Geol. Survey, 1953 ed.), intersects river 800 feet N. 58 E. from northwest corner of sec. 1, T. 5 S., R. 25 E., trends N. 11 E.

the basalts. Iron Mountain (11,149 feet), four miles north-northwest of Snake Meadow, Mount Ritter (13,157 feet), nine miles north of Snake Meadow, and numerous other peaks in the Ritter Range rise 5,000 to 7,000 feet above the lower contacts of the basalts at Snake Meadow and nearby Pine Flat. This indicates that the Sierra Nevada in this area had a minimum relief of at least 5,000 feet in the late Pliocene, which is in agreement with a figure of about 4,000 feet for the area of the South Fork and for a point downstream near Mammoth Pool determined by Dalrymple (1963).

SUMMARY

It is clear that the Canyon stage of erosion in the upper San Joaquin River basin, as defined by Matthes, was initiated by late Pliocene time and that the present gorges of the North, Middle, and South forks had been excavated to at least one-quarter to one-third of their present depth (see fig. 10) by the time of eruption (2.9 to 3.5 million years ago) of the basalts.

Birman (1957) has suggested that there may be two stages of development in the inner gorge of the South Fork of the San Joaquin River. His statement follows:

> More than one slope angle is well exhibited where the inner gorge is incised through massive granitic domes. The average side-valley slope of the upper third of the gorge is 45 degrees; the lower slopes are steeper, averaging about 60 degrees. The contact between the two slope angles is fairly sharp. Twofold division of Stage III cutting is therefore suggested, and this is evident for ten or twelve miles upstream along the South Fork. It is possible that the Stage II lava, which extends a few hundred feet down into the Stage III erosion surface, is assignable to this upper surface of the inner gorge.

Birman has correlated Stage III erosion with Matthes' Canyon stage and considers the basalt near Four Forks Creek to be Stage II lava. If this twofold division is correct, the basalts which have been dated may postdate the inception of this upper surface of the Canyon stage and predate the initiation of the most recent stage of cutting.

Presumably, the Canyon stage of erosion was initiated by uplift and westward tilting of the range. Whether one or more uplifts were involved has not been determined; however, the total amount of uplift at any particular locality since the initiation of the Canyon stage must have been greater than the depth of the present gorges.

The 3.5-million-year minimum age for the Canyon stage in the San Joaquin area is the same as the minimum age reported for the Canyon stage in the Kern River basin (Dalrymple, 1963) and the two stages are therefore approximately correlative. However, in view of Matthes' reservations about correlating the erosion stages of the San Joaquin and Yosemite areas with the erosion surfaces of the Kern River basin, and because a satisfactory maximum age has not been established for the Canyon stage in either of these two areas, I feel that a precise correlation is inappropriate until further data are available. These two Canyon stages of erosion may prove to be approximately correlative to the cycle of erosion that has cut, and is today cutting, the deep canyons of the present rivers of the northern and central Sierra Nevada. About 25 miles north of Oroville, Tuscan Formation breccia and tuff (Anderson, 1933) fills a recent channel (Magalia

Channel) cut into basement rock (Lindgren, 1911, p. 91; G. H. Curtis, personal communication, 1963). The Nomlaki Tuff, a member of the Tuscan Formation occurring near its base, has been dated by potassium-argon as 3.3 million years old (Evernden and Curtis, in press); this provides a minimum age for the initiation of the recent canyons of the northern Sierra Nevada.

EVIDENCE FOR THE AGE OF SCARP PRODUCTION SOUTH OF MONO LAKE

The east wall of the canyon of the Middle Fork of the San Joaquin River between Agnew Pass and Minaret Summit is constructed in large part from a thick sequence of basalt and quartz latite flows, nearly horizontal, which is more than 2,500 feet thick near San Joaquin Mountain (fig. 11). To the south of Minaret Summit is Mammoth Mountain, described by Matthes (1960, p. 18) as a preglacial volcano. The volcanic rocks at San Joaquin Mountain and Mammoth Mountain occupy what was once a large gap in the Sierran crest. Matthes believed that this gap was an ancient feature of the crest and could be interpreted in three ways: "The sag in the crest of the range may simply mark a low divide; it may indicate an ancient valley through which the upper course of Middle Fork flowed northeastward, before it was captured; or it may record the valley of a former tributary to the Middle Fork" (1960, p. 45). Erwin (1934), who described the area in detail, believed that the basalts and quartz latites (Erwin used the term andesite) at San Joaquin Mountain were extruded onto the Broad Valley surface in Broad Valley time and, accordingly, were Miocene. Axelrod and Ting (1960) have assigned a late Pliocene age to these basalts, and Axelrod has recently concluded (1962, p. 186) that "the basalt at San Joaquin Mountain is not on the Broad Valley surface as both Matthes and Erwin report. It lies on the older Boreal ("Eocene") surface which has been down-dropped 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."

A whole-rock sample of basalt near Minaret Summit (KA 1103) and plagioclase from a sample of quartz latite from Two Teats (KA 1135) give dates of 3.1 million years and 3.0 million years, respectively. An erosional remnant of basalt near the Old Mammoth mine appears to be geologically correlative with the basalt at San Joaquin Mountain (fig. 11) and gives a date of 3.1 million years (KA 1092). These volcanic rocks were thus deposited after the Canyon stage of erosion had begun, and their westward extension has since been removed by glacial and fluvial erosion. Detailed geologic mapping in the Devils Postpile quadrangle has shown that the fault proposed by Axelrod does not exist (N. K. Huber, personal communication, 1963). If the basalts at San Joaquin Mountain were deposited on either the Broad Valley or the "Eocene" surfaces, they must rest on erosional remnants of these surfaces. Furthermore, the gap in the crest discussed by Matthes and by Erwin need not be an ancient feature of the range but could be as young as late Pliocene.

Plagioclase from a sample of quartz latite from the north shoulder of Mammoth Mountain gives a date of 370,000 years (KA 1167), which indicates that Mammoth Mountain was active at least until then.

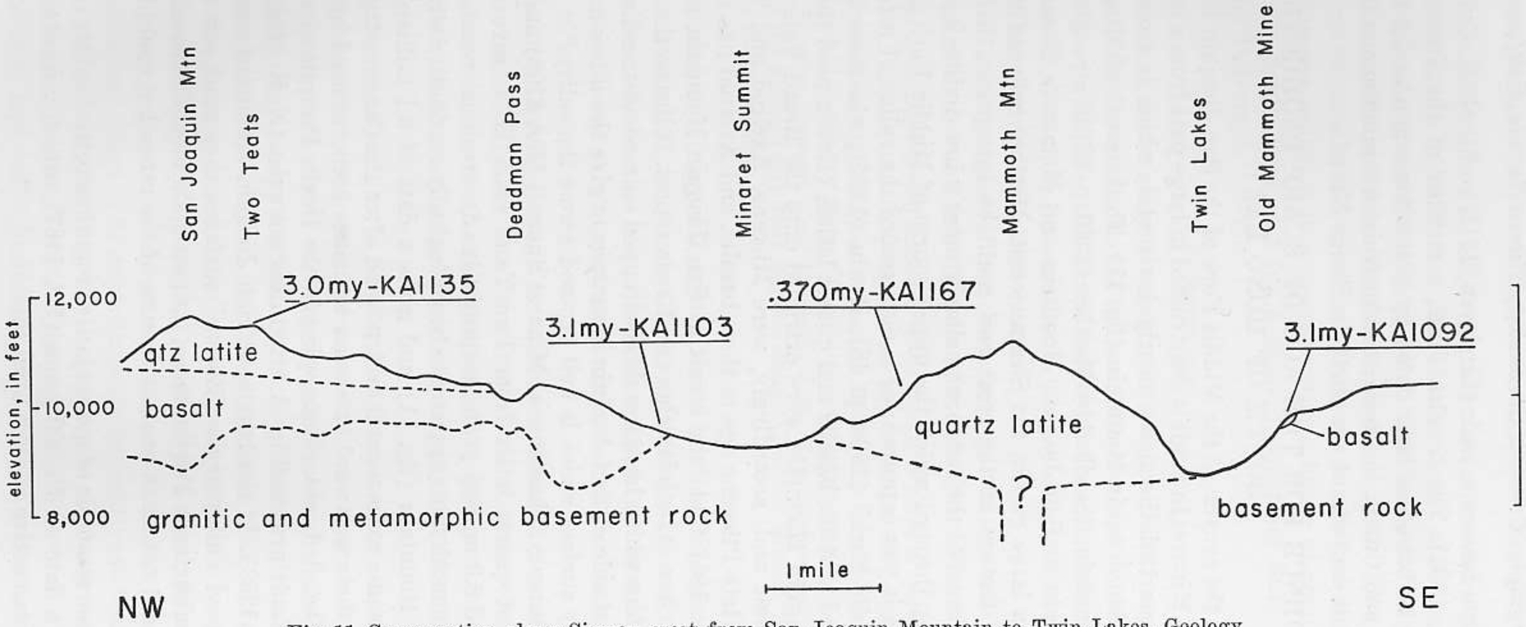


Fig. 11. Cross section along Sierran crest from San Joaquin Mountain to Twin Lakes. Geology after Erwin (1934) and N. K. Huber (written communication, 1963).

The thick sequence of basalt and quartz latite flows at San Joaquin Mountain is truncated on its eastern side by the major fault scarp that defines the eastern front of the Sierra in this area (N. K. Huber, personal communication, 1963). The age of these flows therefore provides a maximum age for the beginning of the faulting that produced the scarp.

In the area east of Mammoth, the relationship of Tertiary basalt flows to basin-range faulting has been described by Gilbert (1941, pp. 793–794), who places the beginning of this faulting in the latest Pliocene (p. 802):

> The olivine basalt was erupted before fault displacements formed the present ranges, for the flows, as gently tilted lava fields elevated by faulting, cap many of the ranges. This sequence may be observed at Granite Mountain, in the Benton Range, south of Black Lake, in Owens Gorge, and on the plateaulike summits between Bald and Glass Mountains . . . Apparently a deeply weathered old-age erosion surface was flooded, chiefly in the broad valleys, by basaltic flows which issued from scattered vents. An unbroken basalt field across the entire area never existed for the higher parts of the old surface rose above the lava. Basaltic remnants are distributed on the lower parts of the crest of the Sierra Nevada lying in ancient broad valleys now uplifted. Indeed a small basalt exposure on McGee Mountain lies in an old valley, later the path of an early glacier which left its moraine on the basalt (McGee Stage of Blackwelder, 1931, p. 902–906).

Putnam (1962, p. 202) agrees that the McGee Mountain basalt predates the scarp production.

Two whole-rock samples of displaced basalts from the Benton Range (KA 1070 and KA 1071) give dates of 3.2 million years; basalts from Owens Gorge and McGee Mountain give dates of 3.2 million years and 2.6 million years, respectively (Dalrymple, 1963).

In summary, evidence from San Joaquin Mountain, McGee Mountain, and the Benton Range indicates that the faulting which produced the present prominent scarps in the area south of Mono Lake began sometime after 2.6 to 3.2 million years ago. Consequently, these movements could not have been the same as the uplift that initiated the Canyon stage of erosion, as defined by Matthes, in either the San Joaquin or the Kern River basins. It is possible, however, that these movements might be correlative with the beginning of the more recent period of Birman's (1957) suggested twofold division of the cutting of the Canyon stage. It is also possible that the initiation of recent scarp production in this area may correlate with the similar event that has led to the development of the present topography in the area of the Tahoe–Truckee depression, but the evidence does not warrant precise correlation at this time.

SUMMARY AND CONCLUSIONS

A correlation chart (fig. 12, in pocket), based on the evidence presented in the text, summarizes the temporal relations of some of the Sierran Cenozoic rocks and events.

The earliest record of Tertiary volcanism in the Sierra Nevada may be the andesite pebbles in the Wheatland Formation which give a "composite" date of 53.5 million years (late Paleocene to early Eocene). This andesitic material predates the earliest rhyolitic eruptions by at least 20 million years.

There is good evidence to show that some of the auriferous gravels, commonly referred to the Eocene, are as young as late Oligocene. If the age of prevolcanic gravels at a particular locality is not known, they should be referred to the broad period consisting of the middle Eocene and the Oligocene.

Later Tertiary volcanism in the northern and central Sierra Nevada was preceded by a period of uplift and erosion during which canyons were cut into the early Tertiary bedrock surface. Segments of these channels now lie preserved beneath rhyolite tuffs at Sonora and Ebbetts passes. The exact time of the inception of these channels is not known.

Extensive dating of rhyolitic deposits in the northern and central Sierra Nevada has shown that the total time spanned by the eruption of rhyolitic material is from late Oligocene (33.2 million years) to late Pliocene (4.7 to 4.8 million years), but also that the major period of rhyolitic volcanism is early Miocene. Deposition of the rhyolitic Valley Springs Formation of the central Sierra foothills probably began shortly after the first eruptions of rhyolite tuff near Sonora Pass (29.5 million years ago, late Oligocene), and the Valley Springs was deposited by about 20 million years ago (early Miocene). Coetaneously with the deposition of the Valley Springs Formation, rhyolite tuff was erupting periodically throughout the northern and central Sierra. Included in this period of rhyolitic volcanism is the Delleker Formation near Blairsden, comprising at least three distinct rhyolite tuffs that range in age from 20.5 million years to 26.1 million years, and rhyolite tuffs near Donner Pass that have a minimum range in age of 26.0 million years to 33.2 million years. Basalts of the Lovejoy Formation, previously thought to be Eocene, are overlain by 22.2-million-year-old Delleker rhyolite tuff at the Lovejoy Formation type locality, and are underlain by 23.8-million-year-old dacite tuff and by andesite tuff and mudflow breccia at Oroville Table Mountain. The Lovejoy Formation is therefore included within the history of deposition of the rhyolitic Delleker and Valley Springs formations.

Mehrten-type andesitic volcanism began in the northern Sierra Nevada in the early Miocene, before the deposition of Valley Springs and Delleker rhyolites had ceased; however, the bulk of the andesitic tuffs, mudflow breccias, and flows were extruded after the deposition of the Valley Springs Formation. The Mehrten Formation ranges in age from approximately middle Miocene to late Pliocene and includes, as members, the Table Mountain latite and associated latites near Sonora Pass. The andesitic Bonta and Penman formations, and possibly the Warner Basalt in the Blairsden area, are approximately correlative with part of the Mehrten Formation, as are the andesitic tuffs and breccias and basalt breccias and flows near Donner Pass. The Nobel Canyon rhyolite near Ebbetts Pass was deposited about the time of deposition of the upper part of the Mehrten Formation in the central Sierra foothills.

While Mehrten andesitic volcanism was occurring in the northern and central Sierra Nevada, the Mountain Valley surface in the Yosemite and San Joaquin areas and the Chagoopa surface in the Kern River basin were being developed in the southern part of the range, which was largely free of the middle and late Tertiary volcanism that covered the northern and central parts of the Sierra with thick volcanic deposits. The inception of these two approximately correlative erosion stages has not been dated, but the Mountain Valley stage had formed a well-developed surface in the San Joaquin drainage by early Pliocene time. The

Canyon stages of erosion, as defined by Matthes, in the Yosemite–San Joaquin and in the Kern River areas are approximately correlative and had been initiated by 3.5 million years ago (late Pliocene). These stages are still in progress and might be approximately correlative with the erosion stage which caused the present deep canyons in the northern and central Sierra.

The basin-range faulting which produced the present youthful scarps along the eastern Sierra just south of Mono Lake began less than 2.6 to 3.2 million years ago and consequently does not account for the initiation of the Canyon stages of erosion as defined by Matthes. The faulting which produced the Tahoe–Truckee depression and is responsible for the present landforms in that area began long after 7.4 million years ago and shortly before 2.2 to 2.3 million years ago (early Pleistocene), the time of deposition of the earliest volcanic flows of the Lousetown Formation near Truckee.

Addendum: Recent preliminary data indicate that the age reported (pp. 26–27, table 1) for the Four Forks Creek basalt is too low, and that the age of this unit is more nearly 3.8 million years (based on two recent determinations). This does not significantly affect the conclusions of this paper.

Also, two additional determinations on the Mammoth Mine basalt have confirmed the age of 3.1 million years (pp. 29–30, table 1).

SAMPLE LOCATIONS AND DESCRIPTIONS

Following are detailed sample locations; petrographic notes are included where appropriate. The references include the principal workers in the area from which the sample comes.

KA 969. Dardanelle facies basalt.

Dardanelles Cone quadrangle (U. S. Geol. Survey, 1956 ed.), on ridge 1,000 feet south of Bald Peak at 9,230 feet elevation. Avg. plagioclase 0.04 mm × 0.2 mm with extremes of 0.01 mm × 0.03 mm and 0.1 mm × 0.4 mm; small shale inclusion almost completely clouded with magnetite observed in one thin section; probable max. contribution of inclusions to age = 0.3–0.5 million years. *Refs.:* Slemmons (1953); Ransome (1898).

KA 975A. Lower Eagle Meadow rhyolite tuff.

Dardenelles Cone quadrangle (U. S. Geol. Survey, 1956 ed.), 7,300 feet elevation, 300 feet east and 2,000 feet north of southwest corner of sec. 1, T. 5 N., R. 19 E. This is an argon rerun of KA 975 reported by Dalrymple (1963). *Ref.:* Slemmons (1953).

KA 994. Lovejoy Formation basalt, type section, lowest flow.

Blairsden quadrangle (U. S. Geol. Survey, 1956 ed.), 1,000 feet S. 35 W. from northeast corner of sec. 31, T. 25 N., R. 13 E., near Creek bottom on south side of creek. Collected by C. S. Grommé, summer of 1960. Plagioclase laths avg. 0.01 mm × 0.06 mm with min. of 0.005 mm × 0.02 mm; 85% have short dimensions >0.01 mm; 20 per cent brown glass with R. I. <1.54 and clouded with magnetite; 5 per cent altered glass; not reliable for K-Ar dating. *Ref.:* Durrell (1959*a*, 1959*b*).

KA 999. Rhyolite boulder from Tuolumne auriferous gravels.

Tuolumne quadrangle (U.S. Geol. Survey, 1948 ed.), from gravel pit in northern half of northwest quarter of sec. 28, T. 1 S., R. 17 E., 750 feet N. 11 E. from BM 3042. *Refs.:* Turner and Ransome (1897); Lindgren (1911).

KA 1011. Leavitt Creek rhyolite tuff.

Sonora Pass quadrangle (U. S. Geol. Survey, 1956 ed.), southeast corner of northwest quarter of sec. 7, T. 5 N., R. 22 E., 200 feet southwest of road at 8,580 feet elevation. *Ref.:* Slemmons (1953).

KA 1070. Benton Range basalt.

Mount Morrison 30′ quadrangle (U. S. Geol. Survey, 1914 ed.), 2,000 feet N. 47 E. from southwest corner of sec. 20, T. 2 S., R. 31 E., at 7,500 feet elevation. Avg. groundmass plagioclase 0.01 mm × 0.05 mm, min. 0.005 mm × 0.02 mm; 40 per cent have short dimensions <0.01 mm; 3–5 per cent K-feldspar in subophitic patches; 3 per cent brown biotite, avg. 0.03 mm associated with minor brown glass lining vesicles; date should be reliable. *Ref.:* Gilbert (1941).

KA 1071. Benton Range basalt.

Forty feet above and 200 feet south of KA 1070 and from same flow. Avg. groundmass plagioclase 0.015 mm × 0.05 mm and min. of 0.007 mm × 0.02 mm; 10 per cent have short dimensions <0.01 mm; 1 per cent brown biotite avg. 0.005 mm; date should be reliable. *Ref.:* Gilbert (1941).

KA 1072. Valley Springs Formation, upper tuff, top of type section.

Valley Springs quadrangle (U. S. Geol. Survey, 1956 ed.), top of Valley Springs Peak in sec. 11, T. 4 N., R. 10 E. *Ref.:* Piper and others (1939).

KA 1073. Lovejoy Formation basalt, Stoney Ridge.

Milford quadrangle (U. S. Geol. Survey, 1950 ed.), 1,500 feet S. 49 E. from VABM 6998 in sec. 14, T. 27 N., R. 13 E. Avg. plagioclase 0.02 mm × 0.1 mm; 30 per cent brown glass clouded with magnetite dust; 2 per cent altered glass; not reliable for K-Ar dating. *Ref.:* Durrell (1959*b*).

KA 1075. Lovejoy Formation basalt, type section, second flow from bottom.

Blairsden quadrangle (U. S. Geol. Survey, 1956 ed.), on south-southwest-trending ridge in sec. 30, T. 25 N., R. 13 E. Avg. plagioclase 0.05 mm × 0.2 mm with rare min. of 0.005 mm × 0.02 mm; 35 per cent brown glass with R. I. <1.54 and nearly opaque with included magnetite dust; 10 per cent of glass altered; not reliable for K-Ar dating. *Ref.:* Durrell (1959*a*, 1959*b*).

KA 1076. Lovejoy Formation basalt, type section, fourth flow from bottom.

Overlies KA 1075. Avg. plagioclase 0.015 mm × 0.065 mm, min. 0.005 mm × 0.02 mm; 15 per cent brown glass with R. I. <1.54 and clouded with magnetite dust; 5 per cent altered glass; not reliable for K-Ar dating. *Ref.:* Durrell (1959*a*, 1959*b*).

KA 1077. Lovejoy Formation basalt, type section, seventh flow from bottom.

Overlies KA 1076. Avg. plagioclase 0.015 mm × 0.07 mm, min. 0.003 mm × 0.02 mm rare; 25 per cent dark brown glass with R. I. <1.54 and clouded with magnetite dust; 5 per cent altered glass; not reliable for K-Ar dating. *Ref.:* Durrell (1959*a*, 1959*b*).

KA 1078. Bald Mountain olivine latite.

Truckee quadrangle (U. S. Geol. Survey, 1955 ed.), 4,000 feet S. 50 W. from northeast corner of sec. 28, T. 17 N., R. 16 E., on west side of Highway 89 at 6,250 feet elevation. Avg. plagioclase 0.015 mm × 0.08 mm, max. 0.025 mm × 0.1 mm, min. 0.005 mm × 0.025 mm; 95 per cent of laths have short dimensions >0.01 mm; <1 per cent pink glass with R. I. <1.54; date should be reliable. *Refs.:* Birkeland (1961, 1963); Lindgren (1897).

KA 1092. Mammoth mine basalt.

Mount Morrison quadrangle (U. S. Geol. Survey, 1953 ed.), center of southeast quarter of sec. 9, T. 4 S., R. 27 E., 500 feet south of Old Mammoth mine at 9,360 feet elevation. Avg. plagioclase 0.02 mm × 0.1 mm with min. of 0.01 mm × 0.05 mm rare; 2 per cent biotite avg. 0.02 mm; 3–5 per cent alkali feldspar (sanidine?) in subophitic patches; date should be reliable.

KA 1093. Four Forks Creek basalt.

Kaiser Peak quadrangle (U. S. Geol. Survey, 1953 ed.), 4,500 feet S. 42 E. from BM 7069 at 7,000 feet elevation. Avg. plagioclase 0.01 mm × 0.05 mm with the min. of 0.005 mm × 0.02 mm composing 20 per cent of all plagioclase; 1 per cent biotite avg. 0.02 mm; <1 per cent pink glass; 1 per cent granitic inclusions that have been over 75 per cent resorbed, composed mostly of quartz and plagioclase with minor potassium feldspar; max. contribution of inclusions to age = 0.1 million years; age should be reliable. *Ref.:* Birman (1957).

KA 1094. Hirschdale olivine latite.

Truckee quadrangle (U. S. Geol. Survey, 1955 ed.), 2,500 feet S. 52 W. from northeast corner of sec. 32, T. 18 N., R. 17 E., on east side of Highway 40. Avg. plagioclase 0.04 mm × 0.03 mm with rare min. of 0.01 mm × 0.05 mm, subophitically enclosed in patches of "potassic-oligoclase" (Birkeland, 1961); rare biotite avg. 0.05 mm; should give reliable date. *Refs.:* Birkeland (1961, 1963); Lindgren (1897).

KA 1096. Watsons Creek basalt.

Tahoe quadrangle (U. S. Geol. Survey, 1955 ed.), one-eighth mile south of Watsons Creek on west side of Highway 28, north end of Lake Tahoe. Avg. plagioclase 0.015 mm × 0.1 mm, min. 0.01 mm × 0.05 mm rare; plates of more sodic plagioclase enclose laths and compose 20–30 per cent of all feldspar; 1–2 per cent biotite avg. 0.03 mm; date should be reliable. *Ref.:* Lindgren (1897).

KA 1097. Tahoe City olivine latite.

Tahoe quadrangle (U. S. Geol. Survey, 1955 ed.), northwest quarter of sec. 12, T. 15 N., R. 16 E., on Highway 89 and 600 feet from western section boundary. Avg. plagioclase 0.05 mm × 0.2 mm with min. of 0.005 mm × 0.03 mm very rare; over 95 per cent of all plagioclase have short dimensions >0.01 mm; should give reliable date. *Refs.:* Birkeland (1961); Lindgren (1897).

KA 1098. Sattley rhyolite tuff.

Sierraville quadrangle (U. S. Geol. Survey, 1955 ed.), one-fourth mile west of Sattley on Highway 49.

KA 1101. Valley Springs Formation, upper tuff, Ponderosa Way.

Columbia quadrangle (U. S. Geol. Survey, 1948 ed.), 2,300 feet N. 71 W. from southeast corner of sec. 11, T. 3 N., R. 14 E., on road at 2,480 feet elevation. *Refs.:* Ransome (1898); Turner and Ransome (1898).

KA 1102. Alder Hill basalt.

Truckee quadrangle (U. S. Geol. Survey, 1955 ed.), northeast corner of sec. 5, T. 17 N., R. 16 E. Collected by P. W. Birkland, 1960. Avg. plagioclase 0.01 mm × 0.07 mm, min. 0.005 mm × 0.02 mm; over 70 per cent of laths have short dimensions >0.01 mm; plates of more sodic feldspar subophitically enclose laths of plagioclase and compose 20–30 per cent of rock; should give reliable date. *Refs.:* Birkeland (1961, 1963); Lindgren (1897).

KA 1103. San Joaquin Mountain basalt.

Devils Postpile quadrangle (U. S. Geol. Survey, 1953 ed.), 3,000 feet due west of southwest corner of sec. 18, T. 3 S., R 27 E., at 9,680 feet elevation. Avg. plagioclase 0.015 mm × 0.08 mm, min. 0.005 mm × 0.02 mm very rare; 80 per cent of laths have short dimensions >0.01 mm; plates of more sodic feldspar compose 15 per cent of rock and subophitically enclose laths; 1 per cent biotite avg. 0.02 mm; date should be reliable. *Ref.:* Erwin (1934).

KA 1109. Boreal Ridge basalt.

Donner Pass quadrangle (U. S. Geol. Survey, 1955 ed.), 3,500 feet S. 56 W. from northeast corner of sec. 24, T. 17 N., R. 14 E., at 7,590 feet elevation. *Refs.:* Hudson (1951); Lindgren (1897).

KA 1110. Table Mountain latite.

Columbia quadrangle (U. S. Geol. Survey, 1948 ed.), 1,000 feet N. 64 E. from southeast corner of sec. 19, T. 4 N., R. 15 E., 20 feet above canal. *Refs.:* Ransome (1898); Turner and Ransome (1898).

KA 1119. Nobel Canyon rhyolite.

Markleeville quadrangle (U. S. Geol. Survey, 1956 ed.), 6,000 feet S. 59 W. from Silver Peak at 8,300 feet elevation. *Refs.:* Curtis (1951); Wilshire (1956).

KA 1120. Nobel Canyon rhyolite.

Same as KA 1119.

KA 1121. Upper Kinney Lake rhyolite tuff.

Markleeville quadrangle (U. S. Geol. Survey, 1956 ed.), one-fourth mile west of Upper Kinney Lake. *Refs.:* Curtis (1951); Wilshire (1956).

KA 1122. Rattlesnake Hill welded tuff.

Columbia quadrangle (U. S. Geol. Survey, 1948 ed.), southeast corner of sec. 19, T. 4 N., R. 15 E., 10 feet above canal. *Refs.:* Ransome (1898); Turner and Ransome (1898).

KA 1123. Valley Springs Formation, lower tuff, Ponderosa Way.

Columbia quadrangle (U. S. Geol. Survey, 1948 ed.), 2,000 feet S. 79 W. from northeast corner of sec. 14, T. 3 N., R. 14 E., on road at 2,320 feet elevation. *Refs.:* Ransome (1898); Turner and Ransome (1898).

KA 1124. McKay biotite-augite latite.

Blue Mountain quadrangle (U. S. Geol. Survey, 1956 ed.), 1,500 feet due west of southeast corner of sec. 27, T. 5 N., R. 15 E. *Refs.:* Ransome (1898); Turner and Ransome (1898).

KA 1126. Delleker rhyolite tuff, sec. 32.
Blairsden quadrangle (U. S. Geol. Survey, 1956 ed.), center of sec. 32, T. 23 N., R. 13 E., to east of road in gully. *Ref.:* Durrell (1959*a*).

KA 1127. Delleker rhyolite tuff, Feather River highway.
Portola quadrangle (U. S. Geol. Survey, 1950 ed.), 1,700 feet N. 53 E. from southwest corner of sec. 35, T. 23 N., R. 13 E., on Feather River highway (California Highway 24). *Ref.:* Durrell (1959*a*).

KA 1128. Plum Creek rhyolite tuff.
Leek Spring Hill quadrangle (U. S. Geol. Survey, 1951 ed.), 1,000 feet N. 34 E. from southwest corner of sec. 3, T. 10 N., R. 14 E., at Plum Creek Mill site. *Refs.:* Lindgren and Hoover (1896).

KA 1129. Skillman Flat rhyolite tuff.
Alleganey quadrangle (U. S. Geol. Survey, 1950 ed.), southeast corner of sec. 24, T. 17 N., R. 10 E., on Highway 20 on north side of road.

KA 1130. Lake Alta rhyolite tuff.
Colfax quadrangle (U. S. Geol. Survey, 1950 ed.), southeast quarter of sec. 35, T. 16 N., R. 10 E. *Ref.:* Lindgren (1900).

KA 1131. Beacon Peak rhyolite, lower welded tuff.
Donner Pass quadrangle (U. S. Geol. Survey, 1955 ed.), 1,500 feet N. 66 W. from southeast corner of sec. 17, T. 17 N., R. 15 E., at 7,200 feet elevation. *Refs.:* Hudson (1951); Lindgren (1897).

KA 1132. Valley Springs Formation, lower tuff, type section.
Valley Springs quadrangle (U. S. Geol. Survey, 1956 ed.), 1,200 feet S. 40 W. from top of Valley Springs Peak at 975 feet elevation. *Ref.:* Piper and others (1939).

KA 1133. La Porte Tuff.
Downieville quadrangle (U. S. Geol. Survey, 1951 ed.), in Upper Dutch Diggings, 2,000 feet S. 16 W. from northeast corner of sec. 8, T. 21 N., R. 9 E., tuff contains La Porte flora. *Refs.:* Potbury (1937); MacGinitie (1941); Durrell (1959*b*).

KA 1135. Two Teats quartz latite.
Devils Postpile quadrangle (U. S. Geol. Survey, 1953 ed.), 500 feet northwest from Two Teats on northeast facing cirque wall. Collected by Allan Cox, 1962. *Ref.:* Erwin (1934).

KA 1163. Lower Eagle Meadow rhyolite tuff.
Dardanelles Cone quadrangle (U. S. Geol. Survey, 1956 ed.), 7,300 feet elevation, 300 feet east and 2,000 feet north of southwest corner of sec. 1, T. 5 N., R. 19 E. *Ref.:* Slemmons (1953).

KA 1167. Mammoth Mountain quartz latite.
Devils Postpile quadrangle (U. S. Geol. Survey, 1953 ed.), 4,400 feet S. 8 W. from southwest corner of sec. 30, T. 3 N., R. 27 E., on ridge trending northwest from Mammoth Mountain at 10,000 feet elevation. Collected by N. K. Huber, 1962.

KA 1186. Pine Flat basalt.
Devils Postpile quadrangle (U. S. Geol. Survey, 1953 ed.), 4,000 feet N. 11 E. from southeast corner of sec. 12, T. 5 S., R. 25 E., at 6,370 feet elevation. Collected by N. K. Huber, 1961. Avg. plagioclase 0.015 mm × 0.06 mm, min. 0.005 mm × 0.02 mm. over 70 per cent of laths have short dimensions > 0.01 mm; 1 per cent fresh pink glass with R. I. < 1.54; should give reliable date.

KA 1187. Snake Meadow basalt.
Devils Postpile quadrangle (U. S. Geol. Survey, 1953 ed.), 7,700 feet N. 7 E. from northwest corner of sec. 1, T. 5 S., R. 25 E., at 6,970 feet elevation. Collected by N. K. Huber, 1961.

Avg. plagioclase 0.02 mm × 0.2 mm; over 95 per cent of laths have short dimensions > 0.01 mm; 1 per cent brown biotite avg. 0.1 mm; date should be reliable.

KA 1190. Delleker rhyolite tuff, sec. 32.
Same as KA 1126.

KA 1191. Oroville Table Mountain tuff.
Oroville quadrangle (U. S. Geol. Survey, 1942 ed.), 3,000 feet S. 27 E. from northeast corner of sec. 29, T. 20 N., R. 4 E., on north side of saddle at 870 feet elevation. *Refs.:* Creely (1954); Dickerson (1916); Allen (1929).

KA 1200. Lake Alta rhyolite tuff.
Same as KA 1130.

KA 1202. Sattley rhyolite tuff.
Same as KA 1098.

KA 1234. Delleker rhyolite tuff, Lovejoy Formation type section.
Blairsden quadrangle (U. S. Geol. Survey, 1956 ed.), 2,000 feet S. 10 E. from northwest corner of sec. 33, T. 25 N., R. 13 E., at 5,780 feet elevation. *Ref.:* Durrell (1959*a*).

KA 1235. Beacon Peak rhyolite, upper welded tuff.
Immediately overlies KA 1131.

KA 1253. Andesite pebbles from Wheatland Formation.
Wheatland quadrangle (U. S. Geol. Survey, 1949 ed.), 2 miles S. 68 W. from northwest corner of sec. 8, T. 14 N., R. 6 E., and 3,700 feet N. 72 W. from BM 199, in bed of Dry Creek. *Ref.:* Clark and Anderson (1938).

LITERATURE CITED

Allen, V. T.

1929. The Ione Formation of California. Univ. Calif. Dept. Geol. Sci. Bull., 18:347–448.

Anderson, C. A.

1933. The Tuscan Formation of northern California with a discussion concerning the origin of volcanic breccias. Univ. Calif. Dept. Geol. Sci. Bull., 23:215–276.

Axelrod, D. I.

1944. The Pliocene sequence in central California. *In* R. W. Chaney, ed., Pliocene floras of California and Oregon, Carnegie Inst. Wash. Publ. 553, pp. 207–224.

1962. Post-Pliocene uplift of the Sierra Nevada, California. Geol. Soc. Amer. Bull., 73: 183–198.

Axelrod, D. I., and W. S. Ting

1960. Late Pliocene floras east of the Sierra Nevada. Univ. Calif. Publ. Geol. Sci., 39:1–118.

1961. Early Pleistocene floras from the Chagoopa surface, southern Sierra Nevada. *Ibid.*, 39: 119–194.

Birkland, P. W.

1961. Pleistocene history of the Truckee area, north of Lake Tahoe, California. Unpublished Ph.D. thesis, Stanford Univ. 126 pp.

1962. Pleistocene volcanism and deformation of the Truckee area, California. Guidebook Ann. Field Trip Geol. Soc. Sacramento, 1962, pp. 59–63.

1963. Pleistocene volcanism and deformation of the Truckee area, north of Lake Tahoe, California. Geol. Soc. Amer. Bull.

Birman, J. H.

1957. Glacial geology of the upper San Joaquin drainage, Sierra Nevada, California. Unpublished Ph.D. thesis, Univ. of Calif., Los Angeles. 237 pp.

Clark, B. L., and C. A. Anderson

1938. Wheatland Formation and its relation to early Tertiary andesites in the Sierra Nevada. Geol. Soc. Amer. Bull., 49:931–956.

Clark, L. D.

1954. Geology and mineral deposits of the Calaveritas quadrangle, Calaveras County, California. Calif. Div. Mines Spec. Rept. 40. 23 pp.

Creely, R. S.

1954. Geology of the Oroville quadrangle. Unpublished Ph.D. thesis, Univ. of Calif., Berkeley. 269 pp.

Curtis, G. H.

1951. Geology of the Topaz Lake quadrangle and eastern half of the Ebbetts Pass quadrangle. Unpublished Ph.D. thesis, Univ. of Calif., Berkeley. 310 pp.

1954. Mode of origin of pyroclastic debris in the Mehrten Formation of the Sierra Nevada. Univ. Calif. Publ. Geol. Sci., 29:453–502.

Curtis, G. H., D. E. Savage, and J. F. Evernden

1961. Critical points in the Cenozoic. Ann. New York Acad. Sci., vol. 91, art. 2, pp. 342–351.

Dalrymple, G. B.

1963*a*. Potassium-argon dates of some Cenozoic volcanic rocks of the Sierra Nevada, California. Geol. Soc. Amer. Bull., 74:379–390.

1963*b*. Potassium-argon dates and the Cenozoic chronology of the Sierra Nevada, California. Unpublished Ph.D. thesis, Univ. of Calif., Berkeley. 107 pp.

Dickerson, R. E.

1916. Stratigraphy and fauna of the Tejon Eocene of California. Univ. Calif. Dept. Geol. Sci. Bull., 9:363–524.

Durrell, Cordell

1959*a*. Tertiary stratigraphy of the Blairsden quadrangle, Plumas County, California. Univ. Calif. Publ. Geol. Sci., 34:161–192.

1959*b*. The Lovejoy Formation of northern California. *Ibid.*, 34:193–220.

Eric, J. H., A. A. Stromquist, and C. M. Swinney

1955. Geology and mineral deposits of the Angels Camp and Sonora quadrangles, Calaveras and Tuolumne counties, California. Calif. Div. Mines Spec. Rept. 41. 55 pp.

Erwin, H. D.

1934. Geology and mineral resources of northeastern Madera County, California. Calif. Jour. Mines and Geol., Rept. 30 of State Min., pp. 7–78.

Evernden, J. F., and G. H. Curtis

In press. The present status of potassium-argon dating of Tertiary and Quaternary rocks. Proc. INQUA Congr., Warsaw, 1961.

In press. The potassium-argon dating of late Cenozoic rocks in East Africa and Italy.

Evernden, J. F., G. H. Curtis, R. W. Kistler, and J. D. Obradovich

1960. Argon diffusion in glauconite, microcline, sanidine, leucite, and phlogopite. Amer. Jour. Sci., 258:583–604.

Evernden, J. F., and G. T. James

In press. Potassium-argon dates and the Tertiary floral chronology of North America.

Evernden, J. F., and J. R. Richards

1962. Potassium-argon ages in eastern Australia. Jour. Geol. Soc. Australia, vol. 9, part 1, pp. 1–50.

Evernden, J. F., D. E. Savage, G. H. Curtis, and G. T. James

1964. Potassium-argon dates and the Cenozoic mammalian chronology of North America. Amer. Jour. Sci., 262:145–198.

Gilbert, C. M.

1941. Late Tertiary geology southeast of Mono Lake, California. Geol. Soc. Amer. Bull., 52: 781–816.

Hudson, F. S.

1948. Donner Pass zone of deformation, Sierra Nevada, California. Geol. Soc. Amer. Bull., 59:795–800.

1951. Mount Lincoln—Castle Peak area, Sierra Nevada, California. *Ibid.*, 62:931–952.

1960. Post-Pliocene uplift of the Sierra Nevada, California. *Ibid.*, 71:1547–1574.

Knopf, Adolph

1918. A geologic reconnaissance of the Inyo Range and the eastern slope of the southern Sierra Nevada, California. U. S. Geol. Survey Prof. Paper 110. 130 pp.

Lawson, A. C.

1904. The geomorphogeny of the upper Kern basin. Univ. Calif. Dept. Geol. Sci. Bull., 3: 291–376.

Lindgren, Waldemar

1897. Truckee folio, California. U. S. Geol. Survey Geol. Atlas, Folio 39.

1900. Colfax folio, California. *Ibid.*, Folio 66.

1911. The Tertiary gravels of the Sierra Nevada of California. U. S. Geol. Survey Prof. Paper 73. 226 pp.

Lindgren, Waldemar, and H. C. Hoover

1896. Pyramid Peak folio, California. U. S. Geol. Survey Geol. Atlas, Folio 31.

Louderback, G. D.

1924. Period of scarp production in the Great Basin. Univ. Calif. Dept. Geol. Sci. Bull., 15: 1–44.

MacGinitie, H. D.

1941. A Middle Eocene flora from the central Sierra Nevada. Carnegie Inst. Wash. Publ. 534, pp. 1–178.

Matthes, F. E.

1930. Geologic history of the Yosemite Valley. U. S. Geol. Survey Prof. Paper 160. 137 pp.

1933. Geography and geology of the Sierra Nevada. 16th Int. Geol. Congr. Guidebook 16, pp. 26–40.

1937. The geologic history of Mt. Whitney. Sierra Club Bull., 22:1–18.

1950. Sequoia National Park: A geological album [F. Fryxell, ed.]. Berkeley and Los Angeles: Univ. Calif. Press. 136 pp.

1960. Reconnaissance of the geomorphology and glacial geology of the San Joaquin basin, Sierra Nevada, California. U. S. Geol. Survey Prof. Paper 329. 62 pp.

Piper, A. M., H. S. Gale, H. E. Thomas, and T. W. Robinson

1939. Geology and ground-water hydrology of the Mokelumne area, California. U. S. Geol. Survey Water-Supply Paper 780. 230 pp.

Potbury, S. S.

1935. The La Porte flora of Plumas County, California. Carnegie Inst. Wash. Publ. 465, pp. 29–81.

Putnam, W. C.

1962. Late Cenozoic geology of McGee Mountain, Mono County, California. Univ. Calif. Publ. Geol. Sci., 40:181–218.

Ransome, F. L.

1898. Some lava flows of the western slope of the Sierra Nevada, California. U. S. Geol. Survey Bull., 89:1–74.

Slemmons, D. B.

1953. Geology of the Sonora Pass region. Unpublished Ph.D. thesis, Univ. of Calif., Berkeley. 201 pp.

Stirton, R. A., and H. F. Goeriz

1942. Fossil vetebrates from the superjacent deposits near Knights Ferry, California. Univ. Calif. Dept. Geol. Sci. Bull., 26:447–472.

Taliaferro, N. L., and A. J. Solari

1949. Geology of the Copperopolis quadrangle, California. Calif. Div. Mines Bull. 145 (map only).

Turner, H. W.

1894. The rocks of the Sierra Nevada. U. S. Geol. Survey, 14th Ann. Rept., pp. 435–495.

1896. Further contributions to the geology of the Sierra Nevada. *Ibid.*, 17th Ann. Rept., part 1, pp. 521–1076.

1901. Post-Tertiary elevation of the Sierra Nevada. Geol. Soc. Amer. Bull., 13:540–541.

Turner, H. W., and F. L. Ransome

1897. Sonora folio, California. U. S. Geol. Survey Geol. Atlas, Folio 41.

1898. Big Trees folio, California. *Ibid.*, Folio 51.

Wilshire, H. G.

1956. The history of Tertiary volcanism near Ebbetts Pass, Alpine County, California. Unpublished Ph.D. thesis, Univ. of Calif., Berkeley. 123 pp.

Wood, H. E.

1941. Nomenclature and correlation of the North American continental Tertiary. Geol. Soc. Amer. Bull., 52:1–48.

1960. Eight historic fossil mammal specimens in the Museum of Comparative Zoology. Bull. Mus. Compar. Zool., Harvard Coll., 123:87–110.