The Bishop Ash Bed (Middle Pleistocene) and Some Older (Pliocene and Pleistocene) Chemically and Mineralogically Similar Ash Beds in California, Nevada, and Utah

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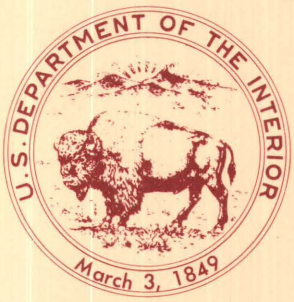

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By GLEN A. IZETT, JOHN D. OBRADOVICH, and HARALD H. MEHNERT

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By Glen A. Izett, John D. Obradovich, *and* Harald H. Mehnert

Abstract

The Long Valley–Glass Mountain volcanic field of eastern California has been the site of repeated eruptions of high-silica rhyolite tephra in the late Cenozoic. In and adjacent to the volcanic field, stratigraphic information and potassium-argon (K-Ar) ages clearly indicate that there are a minimum of 11 tephra units older than the middle Pleistocene Bishop Tuff. The 7 oldest of these 11 formed during pyroclastic eruptions about 2.8 to 2.1 million years ago. In ascending order, these informally named tephra beds are the Black Canyon-4, Black Canyon-5, Waucoba Road-1, Waucoba Road-2, Taylor Canyon-P, Taylor Canyon-C, and Taylor Canyon-U. The Taylor Canyon-C was dated by the K-Ar method at about 2.10 million years. The youngest 4 of the 11 are tephra units interlayered in middle Pleistocene sedimentary rocks that lie 15–20 m below the Bishop Tuff along the Owens River, 7 km north of Bishop, Calif. Listed in ascending stratigraphic position, the four tephra beds are the Glass Mountain-G, Glass Mountain-T, Glass Mountain-D, and Glass Mountain-U. They are chemically and mineralogically allied and record closely spaced episodes of pyroclastic volcanism about 1.0 million years ago in the Long Valley–Glass Mountain area.

In California, Nevada, and Utah, stratigraphic information, chemical and mineralogical data, and isotopic ages of six different upper Pliocene and lower Pleistocene ash beds indicate that they had their origin during pyroclastic volcanic activity in the Long Valley–Glass Mountain volcanic field from about 2.5 to 1.2 million years ago. In ascending order these six informally named ash beds are the Frenchman Flat, Manix-2, Manix-3, Last Chance Bench, South Mountain, and Bailey.

The pyroclastic materials formed during the many different pyroclastic eruptions in the volcanic field are united by a common set of physical and chemical properties. These properties are considerably different from those of tephra generated at other uppermost Cenozoic volcanic centers of the Western United States such as in Yellowstone National Park, Wyo.; the Jemez Mountains, N. Mex.; and the Coso volcanic field, eastern California. Mineralogically, the many different tephra units generated in the Long Valley–Glass Mountain volcanic field are similar: they contain quartz, sanidine, oligoclase, biotite, allanite, zircon, titanomagnetite, and ilmenite microphenocrysts. Allanite ocurs in all units of the Bishop Tuff. Although the tephra units generated in the volcanic field are united by overall chemical similarity, small but consistent differences in the amounts of some elements such as cesium, rubidium, uranium, lanthanum, hafnium, tantalum, manganese, and iron allow their recognition and separation.

The catastrophic eruption of the Bishop Tuff 0.74 million years ago was the largest of all the pyroclastic eruptions generated in the volcanic field. About 500 km^3 of tephra that now forms ash flows of the Bishop Tuff was expelled in a very brief time from vents in Long Valley. A large volume of volcanic ash, also produced during the Bishop eruptive cycle, was carried away from the vents by high-altitude winds and deposited as a thin blanketlike deposit that must have covered more than a million square kilometers of the Western United States. Remnants of this ash blanket are found as far east as central Nebraska, as far south as southern New Mexico, and as far north as southern Idaho.

An air-fall pumice layer at the base of the Bishop Tuff is uniformly about 4 m thick in the volcanic field. The thickness of layers of ash equivalent to the Bishop Tuff decreases away from the volcanic field, but not in a systematic way. Lack of a systematic pattern of thinning away from the vents results from the fact that most ash beds are not composed of a uniformly thick, primary, air-fall ash layer. Rather, they consist of lenses of ash thickened by secondary depositional processes. Only at a few sites can the thicknesses of the primary ash fall be identified and measured. In western Utah, 500 km east of the vent area, the primary air-fall ash is at least 10 cm thick. In eastern Utah, 800 km east of the vent area, the primary air-fall ash is 6 cm thick. The total volume of ash carried away from the vents by high-altitude winds is difficult to determine, but it must have been enormous, perhaps as much as several hundred cubic kilometers.

Mineralogical evidence gained from study of the Bishop Tuff and distal ash beds supports the idea that a considerable amount of the pyroclastic material that comprises the ash beds was generated early in the Bishop Tuff eruptive cycle. The evidence includes (1) similarity in the composition of titanomagnetite microphenocrysts in the lower part of the Bishop Tuff and in distal ash beds and (2) the lack in Bishop ash beds of significant amounts of orthopyroxene and clinopyroxene that characterize the upper unit of the Bishop. Similarity in the amounts of trace elements in the earliest airfall pumice at the

base of the Bishop Tuff and ash beds herein correlated with the Bishop also supports the idea that a considerable amount of the pyroclastic material that forms distal ash beds was generated early in the Bishop Tuff eruptive cycle.

Because considerable progress has been made in the techniques and equipment used for K-Ar dating since Dalrymple and his coworkers dated the Bishop Tuff in the middle 1960's, 17 new K-Ar age determinations of the Bishop Tuff were made. The weighted mean of sanidine, plagioclase, and biotite ages from the lower nonpyroxene-bearing part of the Bishop is 0.738 ± 0.003 m.y. The weighted mean of sanidine, plagioclase, biotite, and glass ages from the upper pyroxene-bearing part of the Bishop is 0.736 ± 0.005 m. y., statistically indistinguishable from the age of the lower unit. These ages are not significantly different from the recalculated mean age (0.727 m.y.) of the Bishop reported by Mankinen and Dalrymple in 1979. We believe that the best K-Ar age for the Bishop Tuff, as determined on sanidine, is 0.738 ± 0.003 m.y.

Inasmuch as the Bishop Tuff has normal magnetic polarity and a K-Ar age of 0.74 million years, the Brunhes Normal Polarity Chronozone must have begun before that time. The beginning of the Brunhes is further constrained by K-Ar ages of reversely magnetized rhyolite domes in the Jemez Mountains, N. Mex., reported by Doell and his colleagues in 1968. These K-Ar ages combined with two new K-Ar ages herein reported suggest that the Matuyama Reversed Polarity Chronozone ended and the Brunhes began about 0.75 million years ago.

INTRODUCTION

The chief purpose of this report is to tabulate previously unpublished mineralogical and chemical data for a comagmatic group of over 40 middle Pleistocene volcanic ash beds that occur at widely scattered localities in the Western United States. These ash beds have properties nearly identical to those of tephra[1] of the Bishop Tuff of eastern California, and this similarity permits their correlation. A second purpose of the report is to provide a map showing the distribution of the ash beds and a summary of stratigraphic and other information pertinent to the ash localities. Similar information is given for a few localities of Bishop Tuff in its source area north of Bishop, Calif. A third purpose of the report is to summarize previously published K-Ar ages and to present 17 newly determined K-Ar ages of the Bishop Tuff. The final purpose of the report is to present chemical data and other information for a group of older ash beds that are chemically and mineralogically allied with the Bishop. These ash beds, which are widely scattered in California, Nevada, and Utah, probably formed in late Pliocene to early Pleistocene time during early volcanic stages of the evolutionary magmatic process that culminated in the eruption of the Bishop Tuff.

Before an ash bed can be identified with a high degree of certainty as a remnant of the Bishop ash fall, its mineralogical, chemical, petrographical, and other physical properties must match closely those of the Bishop tephra of the source area. It should be emphasized that a combined approach for the identification and correlation of volcanic ash beds such as the Bishop must be used. Many different analytical techniques must be used (Wilcox, 1965, p. 813–814; Izett and others, 1972, p. 555; Izett, 1981; Westgate and Gorton, 1981) to fully document the range of chemical and physical properties for a particular ash fall. Moreover, the chemical and physical properties of other ash falls in the same general region and geologic age also must be explored to insure that no other ash beds match the properties of the ash fall under study. Because it is important to fully explore the properties of other ash beds of similar age before correlations are made, trace-element data for older silicic ash beds in California and adjacent States are presented to document their range of variation and their degree of similarity with Bishop ashes.

A question that often arises when dealing with a large array of tephrochronologic data is how closely must the chemical and physical properties of ash beds agree before their correlation can be considered firm. Of course, an exact numerical match for the amounts of the seven major and several minor rock-forming elements of silicic ash beds is highly unlikely. Even more unlikely is an exact numerical match in chemical composition for a score or more of trace elements commonly analyzed for in tephrochronological studies. In particular, small differences in chemical analytical data inherently can arise from several sources, including (1) spurious analytical variations, (2) systematic analytical variations resulting from using different analytical techniques, (3) natural chemical variations of pyroclastic materials, (4) induced chemical variations arising from sorting by size and density of particles of varying composition during transportation and deposition, (5) post-depositional changes of glass shards including hydration and associated chemical changes, and (6) post-depositional changes in the composition of the mineral assemblage such as dissolution of the less stable minerals by intrastratal solutions.

An exact match in measured physical properties of geographically scattered ash beds of the same ash fall is also unlikely. Although the properties of different samples of a tephra fall in its source area may be identical, distal ash beds related to the tephra fall may have somewhat different properties owing to the possibility that ash carried away from the vent undergoes different

[1]In this report the term "tephra" is used to describe pyroclastic material as defined by Thorarinsson (1974, p. xvii), but with a further connotation to the term. Herein the term "tephra" is used to describe pyroclastic material only in volcanic source regions. The term "volcanic ash" is used in this report for informal names of pyroclastic beds and the unconsolidated, fine-grained, pyroclastic material far downwind from volcanic vent areas.

transportational, depositional, and post-depositional processes. These processes can induce differences in observed and measured physical properties of ashes found in different geologic and geographic settings. Variations can arise from (1) sorting by size, density, and shape of inhomogeneous pyroclastic materials during transportation; (2) sorting by wind and water into different size, density, and shape fractions during deposition; (3) the introduction of detrital minerals during deposition that results in the masking of the primary microphenocryst assemblage; (4) varying degrees of hydration of glass shards that result in slight variations in the index of refraction of the shards; and (5) selective dissolution of microphenocrysts by intrastratal fluids resulting in a different mineral assemblage as compared to the erupted material.

Statistical methods, such as the similarity coefficient of Borchardt and others (1972), can aid in the evaluation of large arrays of chemical data for volcanic ash beds. However, in some instances, only small differences occur in the similarity coefficient for ash beds generated at the same volcanic center but at significantly different times. Similarity coefficients were calculated using results of instrumental neutron activation analyses of the glass phases of samples of suspected Bishop ash beds and air-fall Bishop Tuff analyzed by the same analytical method. They were calculated using a modified form of the coefficient used by Borchardt and others (1972). The amount of cesium, rubidium, thorium, uranium, lanthanum, ytterbium, tantalum, hafnium, manganese, and iron in ash beds was compared with the average amount of these elements in air-fall Bishop Tuff from the source area.

Just as important as statistical analysis is a full understanding of the efficacy of other analytical techniques and an appreciation of the sources of variation other than analytical. In this report statistical analysis of the chemical data alone was not used to estimate the probability of correlation among samples of ash beds and tephra. Instead, the amount of each trace element in samples of ash beds was carefully inspected, evaluated, and compared with the mean values of similar data for samples of the Bishop Tuff. In addition, the stratigraphic, paleomagnetic, geochronologic, petrographic, mineralogic, and other physical properties of each ash bed were compared with those of samples of Bishop Tuff tephra to further test the possibility of correlation.

Caution must be exercised in the use of similarity coefficients to reject or confirm correlations. For example, samples collected from two different stratigraphic horizons in the same ash bed may have slightly different chemical signatures. The difference in chemical signature may reflect the sequential eruption of pyroclastic material from slightly different levels of a chemically zoned magma chamber. The material may be so different that the similarity coefficient might be well below 0.90, which normally would suggest a lack of correlation in tephrochronologic studies.

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BISHOP ASH BED

An enormous volume of rhyolite tephra was catastrophically erupted about 0.74 million years ago in the Long Valley area of eastern California, resulting in the formation of the middle Pleistocene Bishop Tuff (Gilbert, 1938; Bateman, 1953, 1965; Dalrymple and others, 1965; Sheridan, 1965, 1968; Bailey and others, 1976; Hildreth, 1977, 1979). The eruption that produced the Bishop lasted only a brief time, perhaps only a few days, and consisted of two clearly discernible stages. During the initial Plinian stage of the eruption cycle, a large volume of tephra was generated that now forms a pervasive, air-fall pumice unit at the base of the Bishop. Following the Plinian stage, an enormous volume of tephra was produced that now forms sequential, thick ash flows that are radially distributed around the source area, at Long Valley. A large volume of fine-grained pyroclastic material also was produced during the eruptions, and it was carried far downwind by high-level, atmospheric winds and deposited as a thin, blanketlike deposit that must have covered more than a million square kilometers of the Western United States (fig. 1). In favorable sedimentary environments, this blanketlike deposit, called the Bishop ash fall, was covered by younger sedimentary deposits and thus was preserved. The favorable sedimentary environments for the preservation of the Bishop ash fall included lakes, ponds, oxbow lakes, and swales on alluvial

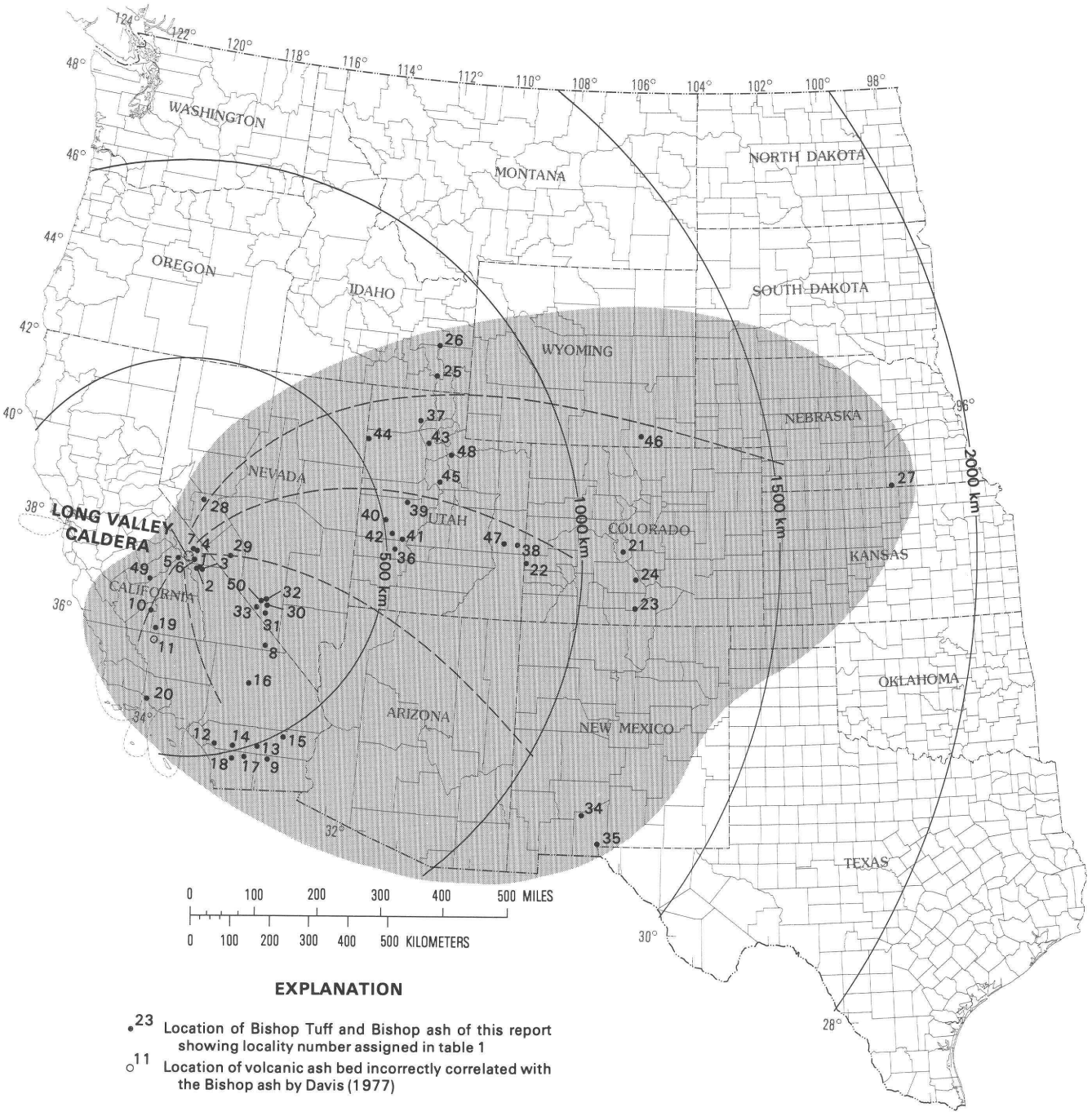


Figure 1. Distribution of Bishop ash beds in the Western United States. Shaded area indicates inferred extent of original ash fall.

terraces and pediments. Widely separated remnants of this formerly widespread, blanketlike deposit have been found in middle Pleistocene deposits and identified on the basis of their chemical and physical properties as equivalents of the Bishop Tuff (Izett and others, 1970; Borchardt and others, 1972; Merriam and Bischoff, 1975; Izett, 1982; Sarna-Wojcicki and others, 1980, 1984).

Historical review.—In the early 1960's, H. A. Powers and R. E. Wilcox of the U.S. Geological Survey suspected that a few volcanic ash beds that they had studied in Utah might be downwind correlatives of the Pleistocene Bishop Tuff. In 1970, Izett and others confirmed their suspicion by conclusively matching the chemical and physical properties of these ashes with the basal air-fall pumice unit of the Bishop Tuff. In addition, Izett and others (1970) identified other volcanic ash beds in California, Colorado, Nebraska, and Nevada that also have mineralogical and chemical properties nearly identical to air-fall pumice at the base of the Bishop Tuff. Because the Bishop had been dated accurately by the

K-Ar method by Dalrymple and others in 1965, the identification of ash beds as Bishop equivalents was particularly important for it provided a dated marker horizon in sediments that enclose the ash beds in areas far removed from the source area. Moreover, correct identification of the ashes as Bishop Tuff correlatives provided important information that allowed refinement of Quaternary paleontologic and paleomagnetic chronologies on a regional scale.

Borchardt and others (1972) applied the instrumental neutron activation method to the analysis of the same samples studied by Izett and his colleagues and supported their correlation of the volcanic ashes with the Bishop Tuff. In 1975, Merriam and Bischoff reported chemical data for some ash beds in southern California, and they suggested that these ashes also might be Bishop ash-bed equivalents. Izett and Naeser (1976) determined fission-track ages of zircon crystals of Bishop Tuff tephra that are compatible with the K-Ar ages obtained by Dalrymple and his coworkers in 1965. Sarna-Wojcicki and others (1980, 1984) correlated ash beds in the Pliocene and Pleistocene Pico Formation near Ventura, Calif., and ash in middle Pleistocene deposits from elsewhere in southern California with the Bishop Tuff.

Distribution

More than 40 localities of Bishop ash are plotted on figure 1 and listed in table 1. Of these, only 8 were known in 1970 (Izett and others, 1970). This increase of over 30 localities is a testimony to the interest and stratigraphic usefulness of this radiometrically dated marker bed. Also shown on figure 1 are the locations of several important localities of source-area tephra of the Bishop Tuff. Geologic and geographic information relative to the localities of Bishop Tuff is also given in table 1. Closely spaced localities on figure 1 were given the same locality number. Occurrences of the Bishop ash are scattered as far east as central Nebraska, as far south as southern New Mexico, and as far north as southern Idaho (fig. 1). The shaded area on figure 1 shows the general area where Bishop ash beds have been identified and the inferred extent of the original Bishop ash fall. Dashed lines on figure 1 show inferred trajectories of plumes of ash that were carried away from the vent area in the Long Valley–Glass Mountain volcanic field by upper atmospheric winds. The exact configuration of such plumes of ash and their trajectories are highly speculative, and their inferred positions are shown on figure 1 only to stimulate future research and stress the idea that the ash distributional process away from Long Valley during the brief eruption must have been very complex. Almost certainly, additional localities of Bishop ash will be found in the future within and outside the shaded area of figure 1.

Mineralogy of Bishop Tuff and Bishop Ash Beds

One of the basic assumptions made in tephrochronologic studies is that all geographically separated remnants of an ash fall should contain the same assemblage of primary microphenocrysts as their suspected source tephra. Furthermore, the chemical composition of each type of microphenocryst in downwind ash beds should match very closely the chemical composition of the same kind of microphenocryst in the source-area tephra. This simple matching test can be complicated by several processes that may occur at the time of or following deposition of an ash bed. For instance, the microphenocryst assemblage of a volcanic ash bed, as it is erupted, can be masked by the addition of detrital minerals to the primary assemblage during deposition. Furthermore, under some geologic conditions, the primary microphenocryst assemblage (as well as detrital minerals) of an ash can be selectively modified by complete dissolution of the unstable minerals by intrastratal solutions. Not only can the primary microphenocryst assemblage be modified by contamination or dissolution, but the abundance of certain microphenocrysts in a distal ash may differ considerably from the abundance in the source-area tephra owing to a process named "eolian differentiation" by Murray and Renard (1884, p. 486) and Larsson (1937). This process acts in the following way. During transportation through the atmosphere, the most dense or largest crystals have a tendency to be deposited nearest the source area. The less dense or smallest crystals have a tendency to be deposited farthest from the source area. Processes acting at the deposition site can further alter the primary microphenocrysts assemblage. Ash particles may be sorted by wind or water into discrete layers enriched in light, small, heavy, or large particles.

Mineralogic descriptions of the Bishop Tuff and Bishop ash beds have been reported by Gilbert (1938), Sheridan (1965), and Izett and others (1970). More recently, Hildreth (1977, 1979) made a detailed study of the vertical and lateral chemical changes in the composition of primary minerals in samples of the Bishop Tuff using the electron microprobe. These studies demonstrated that the primary mineral assemblage of the Bishop consists of crystals of high temperature beta-quartz, sanidine, oligoclase, biotite, orthopyroxene, clinopyroxene, pale-pink zircon, allanite, titanomagnetite, and ilmenite. Pyrrhotite and apatite have been found only as inclusions in some of the above-named microphenocrysts. Zircon, titanomagnetite, and ilmenite are invariably small, nearly complete euhedral crystals. Quartz, sanidine, oligoclase, and allanite from samples of the Bishop Tuff

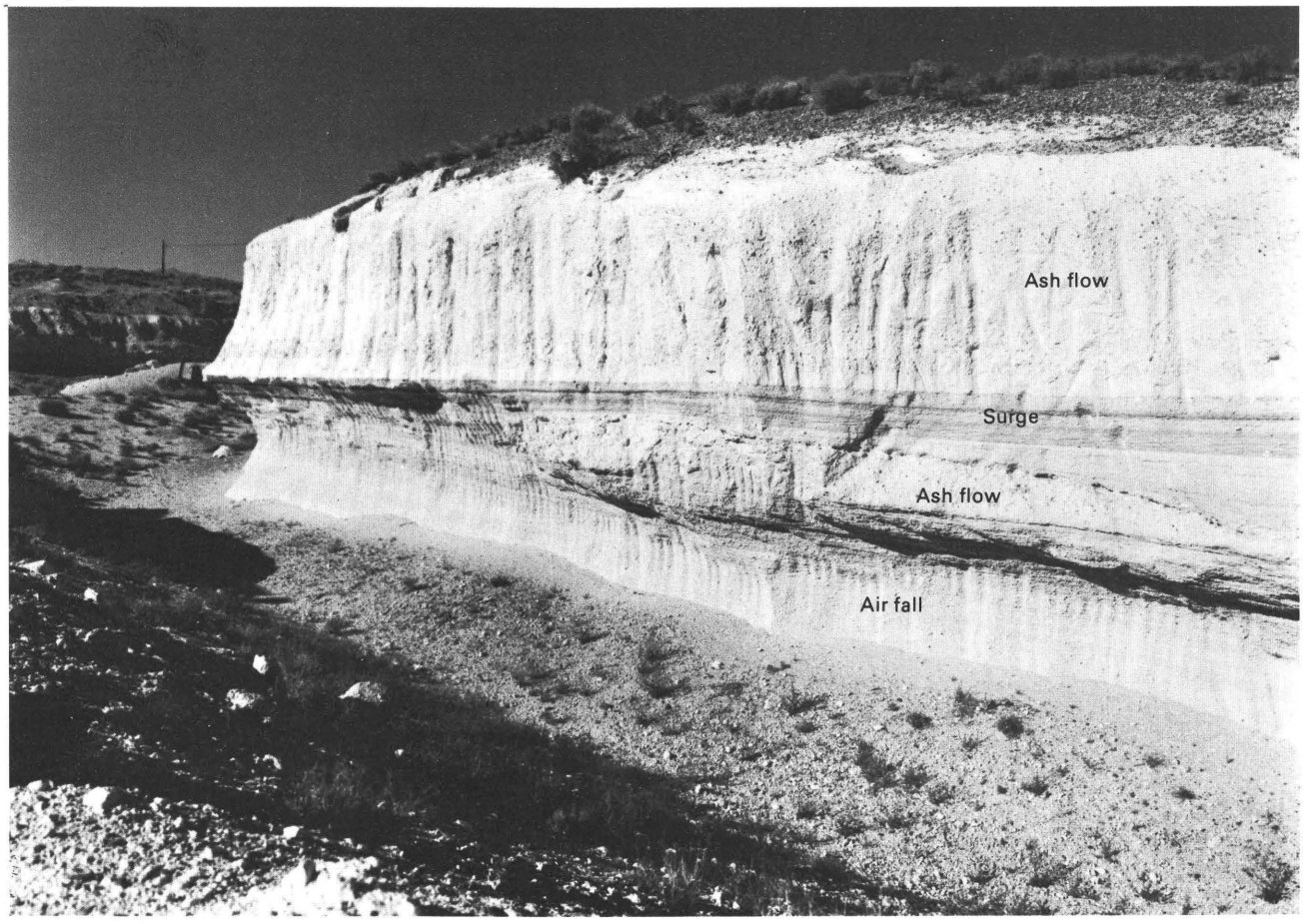


Figure 2. Lower part of the Bishop Tuff at the Insulating Aggregates Co. quarry about 10 km north of Bishop, Calif. A basal air-fall pumice unit is overlain by a thin, lenticular ash flow, which in turn is overlain by a thin, pumice-rich surge deposit followed by a thick ash flow. Pyroxene microphenocrysts were found in a few pumice lumps in the surge deposit. Air-fall unit is about 4 m thick (base not exposed); surge deposit is about 1 m thick.

ash flows are generally, but not always, broken crystals or cleavage fragments. In pumice lumps collected from the Bishop, these minerals are generally euhedral.

Most of the ash beds herein correlated with the Bishop Tuff are pervasively contaminated with detrital minerals incorporated in the ash at the time of its deposition. However, in all instances, the ash samples herein correlated with the Bishop, including the most pervasively contaminated ones, contain a few glass-coated microphenocrysts characteristic of the primary pumice lumps of the Bishop Tuff including glass-coated crystals of quartz, sanidine, oligoclase, biotite, allanite, zircon, titanomagnetite, and ilmenite. Glass-coated primary crystals could be identified only by microscopic study of mineral concentrates of the ashes mounted in immersion oil having an index of refraction near that of the glass shards of the host ash (n=1.496). Recognition of those crystals that had glass coatings among the multitude of detrital heavy minerals that had no glass coatings was facilitated by using a petrographic microscope equipped so that the focal masking technique (Wilcox, 1962) could be used.

The Bishop Tuff seemingly can be divided into two stratigraphic parts on the basis of mineralogical differences observed by Hildreth (1977, 1979). The lower part of the Bishop contains quartz, sanidine, oligoclase, biotite, zircon, allanite, titanomagnetite, and ilmenite. The upper part contains the above listed minerals, but in addition contains orthopyroxene, clinopyroxene, and pyrrhotite. The presence of orthopyroxene and clinopyroxene in the youngest, uppermost ash flows of the Bishop is, according to Hildreth (1977, p. 89), "* * * a useful stratigraphic indicator." He further stated that the presence of orthopyroxene and clinopyroxene "* * * distinguishes the upper cooling unit in both the San Joaquin and Volcanic Tableland sections." Whether the mineralogical difference used in this report to divide the Bishop Tuff into two parts coincides with a mappable lithologic break in the ash-flow sequence has not been determined. Hildreth (1977, p. 1–2) suggested that the appearance of orthopyroxene and clinopyroxene in the youngest ash flows of the Bishop reflects the tapping of a mineralogically, chemically, and thermally zoned

magma chamber. According to his model, the upper, cooler part of the Bishop magma chamber was erupted first and now forms the lower, older part of the Bishop Tuff, which lacks orthopyroxene and clinopyroxene. A deeper, hotter part of the magma chamber was erupted last and now forms the youngest, stratigraphically highest, orthopyroxene- and clinopyroxene-bearing ash flows of the Bishop.

A rare exception to Hildreth's mineralogical observations concerning the distribution of orthopyroxene and clinopyroxene in the Bishop was found by us. At the Insulating Aggregates Co. quarry about 10 km north of Bishop, Calif. (table 1, loc. 1), a surgelike deposit overlies the basal air-fall pumice unit of the Bishop. Pumice lapilli in the deposit (fig. 2) contain both glass-mantled orthopyroxene and clinopyroxene, and they are compositionally identical to those in the uppermost ash flows of the Bishop. Perhaps a deep part of the Bishop magma chamber that contained orthopyroxene and clinopyroxene was tapped early in the Bishop eruptive activity. An alternative explanation is that a chemically and mineralogically different (pyroxene-bearing) but closely related magma was tapped early as well as late during the eruptive cycle that formed the Bishop. Presumably this magma occupied a deeper but adjacent position to the main Bishop magma chamber.

Another significant mineralogical difference can be used to distinguish the lower from the upper part of the Bishop Tuff. The lower part contains titanomagnetite that has a chemical composition consistently different than that of the upper part. The amount of magnesium in titanomagnetite of the lower unit is consistently and significantly less than that of the upper unit. Furthermore, the titanomagnetite of the lower unit contains more manganese than that of the upper unit. These differences in chemical composition of titanomagnetite microphenocrysts are shown by a compilation (table 2) of the electron-microprobe data of Hildreth (1977, p. 31–37). The analytical data of table 2 are arranged in approximate ascending stratigraphic order and broadly grouped by their stratigraphic position in either the lower or upper unit of the Bishop. Informal names for the various ash-flow lobes designated by Hildreth are also given in table 2.

A second type of compilation of the electron-microprobe data of Hildreth (1977) for titanomagnetite is shown in table 3, which lists analyses of only those samples that occur in definite stratigraphic succession.

Table 2. Compilation of electron-microprobe analyses made by Hildreth (1977) of titanomagnetite microphenocrysts from samples of the lower and upper units of the Bishop Tuff of eastern California grouped in approximate ascending stratigraphic order

[Analyses in weight percent; compiled from electron microprobe data of Hildreth (1977); ± is one standard deviation of the mean; Usp, molecular percent ulvospinel]

Bishop Tuff ash-flow lobe of Hildreth (1977)	No. of samples	Al_2O_3	MnO	MgO	FeO	TiO_2	[1]Fe_2O_3	[2]FeO	[3]Usp
Upper unit of the Bishop Tuff (clinopyroxene-bearing and orthopyroxene-bearing pumice)									
Mono----------	6	1.3±0.04	0.47±0.03	0.7±0.06	84.1±0.68	9.2±0.10	25.9	50.6	38.6
Adobe Valley----	10	1.2± .07	.55± .07	.6± .06	82.9± .80	9.3± .14	26.5	49.7	38.2
San Joaquin-2	2	1.1± .06	.75± .06	.5± .06	82.6±1.0	9.4± .04	26.8	49.4	38.2
Tableland-------	7	1.2± .09	.74± .10	.5± .08	84.0± .68	9.3± .26	26.4	50.4	38.6
Mean-----		1.2	0.63	0.6	83.4	9.3	26.4	50.0	38.4
Lower unit of the Bishop Tuff (nonpyroxene-bearing pumice)									
Little Round Valley	4	1.0±0.03	0.97±0.14	0.3± .06	84.4±1.04	9.2±0.14	26.0	50.9	38.6
San Joaquin-1	4	0.9± .06	.87± .03	.3± .01	84.3± .68	9.0± .10	25.6	51.0	38.5
Upper Owens Gorge	4	.9± .01	1.03± .06	.3± .01	83.7± .65	9.2± .24	26.1	50.4	38.3
Gorges----------	5	.9± .07	.97± .10	.2± .01	84.1± .65	9.2± .04	26.1	50.6	38.5
Chidago---------	8	1.0± .06	.83± .04	.3± .03	83.9± .76	9.1± .18	25.9	50.6	38.5
Basal air-fall--	8	.9± .04	.84± .01	.3± .01	84.4± .41	9.1± .09	25.7	50.9	38.6
Mean-----		0.9	0.94	0.3	84.0	9.1	25.9	50.7	38.5

[1]Weight percent Fe_2O_3 recalculated by the authors using the method of Carmichael (1967).
[2]Weight percent FeO recalculated by the authors using the method of Carmichael (1967).
[3]Molecular percent ulvospinel recalculated by the authors using the method of Carmichael (1967).

Table 3. Compilation of electron-microprobe analyses made by Hildreth (1977) of titanomagnetite microphenocrysts from samples of the Bishop Tuff of eastern California for only those samples known to occur in stratigraphic succession

[Analyses selected from samples listed by Hildreth (1977, table 3 and Appendix 1) that occur in stratigraphic succession; sample numbers, name of ash-flow lobe, and stratigraphic position from Hildreth (1977); Opx, orthopyroxene; Cpx, clinopyroxene; amounts of oxides in weight percent]

Sample No.	Ash flow lobe	Stratigraphic position	MnO	Al_2O_3	MgO	FeO	TiO_2	Sample contains Opx and Cpx
Locality 1:								
B-142	San Juan	Base of upper cooling unit	0.80	1.06	0.46	81.9	9.3	Yes.
B-143		Base of upper cooling unit	.69	1.15	.57	83.3	9.4	Yes.
B-141		Lower cooling unit -------	.84	.81	.26	83.0	9.1	No.
Locality 2:								
B-71	Adobe Valley	40 m above B-70 ----------	0.47	1.26	0.67	83.2	9.1	Yes.
B-70		Basal nonwelded ash flow	.62	1.06	.59	83.7	9.3	Yes.
Locality 3:								
B-120	Chidago	25 m above B-118 ---------	0.80	0.98	0.30	83.6	8.8	No.
B-117		25 m above B-118 ---------	.70	1.21	.37	82.8	9.2	No.
B-119		2 m above B-118 ----------	.78	1.05	.33	82.9	9.1	No.
B-118		25 m below B-117 and B-120	.83	1.00	.27	82.8	9.3	No.
Locality 4:								
B-19	Tableland	40 m above B-20 ----------	0.61	1.12	0.58	82.9	9.8	Yes.
B-20		Basal 3 m of nonwelded ash flow	.70	.95	.39	83.3	9.0	Yes.
Locality 5:								
B-63	Little Round Valley.	Upper cooling unit -------	0.65	1.28	0.67	83.1	9.2	Yes.
B-64		Nonwelded ash flow -------	1.05	.95	.28	82.8	9.1	No.
B-65		Middle of three cooling units	1.01	.93	.26	85.2	9.1	No.
B-67		Lowest of three cooling units	1.06	.97	.27	84.6	9.4	No.
Locality 6:								
B-134	Adobe Valley	15 m above B-135 ---------	0.59	1.13	0.58	82.5	9.4	Yes.
B-135		Base of densely welded ash flow	.67	1.13	.51	84.1	9.3	Yes.
Locality 7:								
B-58	Gorges	100 m above B-54, welded -	0.96	0.91	0.27	83.7	8.9	No.
B-57		65 m above B-54, welded --	1.07	.92	.26	83.6	9.2	No.
B-56		50 m above B-54, densely welded	1.05	.93	.25	84.6	9.1	No.
B-54		Partially welded ash flow	1.19	.93	.29	83.0	9.5	No.
Locality 8:								
B-81	Gorges	50 m above B-80 ----------	0.89	0.96	0.26	84.7	9.2	No.
B-80		Densely welded vitrophyre	.95	.95	.26	84.1	9.2	No.
Locality 9:								
B-90	Chidago	Poorly welded caprock ----	0.90	0.92	0.25	84.5	9.0	No.
B-89		15 m above B-88 ----------	.84	.94	.26	84.5	9.1	No.
B-88		Basal ash flow ----------	.79	.96	.27	84.0	9.4	No.
B-87		Basal air fall ----------	.84	.93	.27	84.7	9.2	No.
Locality 10:								
B-95	Gorges	A few meters above B-94 --	0.86	0.92	0.26	84.1	9.2	No.
B-94		Basal ash flow ----------	0.84	.91	.26	84.4	9.2	No.
B-93		Basal air fall ----------	0.85	.93	.25	85.0	9.2	No.

Also listed are the stratigraphic position, name of the ash-flow lobe as assigned by Hildreth (1977), and whether the samples contained orthopyroxene and clinopyroxene. As in table 2, the electron-microprobe analyses of titanomagnetite show that the lower unit, which does not contain orthopyroxene and clinopyroxene, contains titanomagnetite having less magnesium and more manganese than that of the upper unit. Within the two groups of samples—those of the lower unit that do not contain pyroxene and those of the upper unit that do contain pyroxene—there seemingly is little if any chemical compositional change in the titanomagnetite related to stratigraphic position. In contrast, Hildreth (1977, fig. 4) reported a systematic upward change in the chemical composition of titanomagnetite and associated ilmenite, and accordingly, an attendant systematic upward change in calculated equilibration temperatures. The method that Hildreth used for calculating temperatures of equilibration for titanomagnetite and ilmenite was based on the curves of Buddington and Lindsley (1964). On this basis, tephra of the lower part of the Bishop seemingly formed from magma that was distinctly cooler (720–773 °C) than was tephra of the upper part of the Bishop (763–790 °C).

A third mineralogical difference between the lower and upper parts of the Bishop was reported by Hildreth (1977, p. 16, 106). He concluded that allanite was absent in pumice from the upper part of the Bishop that yielded Fe-Ti-oxide mineral temperatures above 763 °C. In contrast to the conclusion reached by Hildreth, we found small amounts of glass-encrusted allanite crystals and broken crystals in pumice blocks from the uppermost ash flows of the Bishop at four localities of Hildreth (1977, p. 299) including B-77, B-137, B-138, and B-139. He (1977, p. 46) reported Fe-Ti-oxide temperatures of 790 °C, 770 °C, 778 °C, and 781 °C for samples at these four localities. The allanite crystals were found by making heavy-liquid separations using methylene iodide of individual white-cored pumice blocks carefully collected from nonwelded ash flows. After the rims of pumice blocks had been removed using a diamond saw, the resulting cores were cleaned using an ultrasonic scrubber to reduce the chance that foreign minerals, such as allanite, might have been introduced into vesicles of the pumice during or following the emplacement of the host ash flow. Our work suggests that allanite occurs in all units of the Bishop including the hottest, stratigraphically highest ash flows, but the amount of allanite in these ash flows seems to be much less than that in the lowest units of the Bishop.

Some of the mineralogical information presented in this report bears on the question of whether the pyroclastic material that comprises Bishop ash at localities of figure 1 was generated (1) during the initial Plinian stage of the Bishop eruption, (2) in conjunction with the emplacement of the successive ash flows of the Bishop, or (3) throughout the eruptive episode that produced the Bishop Tuff. Later in this report, we present considerable trace-element data that bear on this question and, more importantly, support the correlation of the ash beds of figure 1 with the Bishop Tuff.

Several mineralogical lines of evidence concerning the Bishop Tuff may be used to shed light on the problem of whether the pyroclastic material that now forms Bishop ash beds was produced during the Plinian stage, during the following ash-flow–producing stage, or throughout the eruptive cycle. One line of evidence pertains to the chemical composition of titanomagnetite microphenocrysts in Bishop ash beds. The composition of unaltered, primary titanomagnetite in samples of the least contaminated Bishop ash beds (table 4) is nearly identical to the composition of titanomagnetite in source-area tephra of the lower part of the Bishop (tables 2 and 3). Scores of individual glass-encrusted titanomagnetite microphenocrysts from the least contaminated Bishop ash beds were analyzed using the electron microprobe. All primary crystals in the ash beds were found to have compositions similar to the titanomagnetite from the lower part of the Bishop; not a single crystal was found to have a composition similar to the titanomagnetite of the stratigraphically highest ash flows of the Bishop. As previously mentioned, titanomagnetite crystals from the lower, pyroxene-free part of the Bishop contain significantly less magnesium and more manganese than do crystals of this mineral from the pyroxene-bearing upper part of the Bishop (tables 2, 3, and 4).

A second line of mineralogical evidence concerns the relative abundance of allanite in Bishop ash beds. Glass-coated or glass-mantled fragments of allanite microphenocrysts can be found in all samples of ash herein correlated with the Bishop, including those pervasively contaminated with detrital minerals. Furthermore, the amount of allanite in the ash, relative to the amount of other accessory minerals, is large. This observation, paired with the fact that allanite is apparently much more abundant in the lower part of the Bishop Tuff compared to the upper part, suggests to us that most of the material that forms Bishop ash beds was erupted early in the eruptive cycle.

A third mineralogical line of evidence concerns the absence of orthopyroxene and clinopyroxene in some samples and its paucity in other samples of Bishop ash. Most samples of ash herein correlated with the Bishop contain extremely rare primary crystals of glass-coated orthopyroxene. Curiously, glass-coated clinopyroxene, which is equally as common as orthopyroxene in the stratigraphically highest ash flows, was seen in only a few

Table 4. Electron-microprobe analyses of titanomagnetite microphenocrysts from some samples of Bishop ash and Bishop Tuff of eastern California

[Oxides in weight percent; operating conditions on electron microprobe as follows: operating voltage 15 kilovolts; beam current 25 nanoamps on benitoite, count time 10 seconds; analyst G.A. Izett]

Loc. No. (fig. 1)	Sample No.	Locality	MnO	Al_2O_3	MgO	FeO	TiO_2
		Bishop Tuff (air-fall pumice)					
1	64W96	Insulating Aggregates Co. quarry 10 km north of Bishop, Calif.	0.83	1.04	0.36	84.9	9.2
6	79G23	Toms Place, Calif. ----------	.89	1.02	.32	85.0	9.2
4	64W109	Benton Hot Springs, Calif. ----	.88	1.02	.35	85.9	9.2
		Bishop ash beds					
8	68W156	Shoshone quadrangle, Calif. ---	0.84	0.98	0.32	84.9	9.0
22	65W1	Paradox, Colo. ----------	.83	.89	.33	88.4	9.2
26	78W17	Gay Mines, Idaho ----------	.90	.98	.28	85.3	9.0
29	70W19	Clayton Valley, Nev. ----------	.84	1.06	.30	85.8	9.2
30	78G203	Jackass Flats, Nev. ----------	.92	.94	.30	82.3	8.7
31	79G4	Striped Hills, Nev. ----------	.90	1.00	.30	85.4	9.2
31	79W61	Skeleton Hills, Nev. ----------	.89	.98	.30	83.0	9.0
34	73W101	Grama Siding, N. Mex. ---------	.83	.89	.27	87.5	9.2
38	78G197	Polar Mesa quadrangle, Utah ---	.87	.98	.33	85.8	9.2
41	79G159	Cove Fort, Utah ----------	.87	1.02	.35	83.0	9.0
39	79G39	Delta, Utah ----------	.87	1.02	.33	82.9	9.0
46	74G20	Laramie, Wyo. ----------	.84	1.02	.30	84.4	8.8

ash samples. Perhaps clinopyroxene crystals were selectively dissolved from some ash beds by intrastratal solutions following deposition. The presence of relatively large amounts of orthopyroxene and clinopyroxene in pumice of the upper part of the Bishop Tuff in the source area and the paucity of these minerals in samples of Bishop ash suggest to us that the material that forms Bishop ash beds was formed early in the eruptive cycle. The combined mineralogical observations described above concerning the composition of titanomagnetite and the occurrence of allanite and orthopyroxene imply that a considerable amount of the material that forms Bishop ash beds probably originated during early stages of the eruptive cycle, mainly during the highly energetic Plinian phase.

Chemical Composition of Bishop Tuff and Bishop Ash Beds

In the past four decades, samples of volcanic ash beds and tephra have been extensively analyzed to establish their chemical fingerprint so they may be characterized and correlated. Among tephrochronologic studies involving the chemical analysis of ash beds are those done by Swineford and Frye (1946), Powers and others (1958), Powers and Malde (1961), Jack and Carmichael (1968), Izett (1968), Theisen and others (1968), Smith and Westgate (1969), Izett and others (1970), Borchardt and Harward (1971), Sarna-Wojcicki (1971, 1976), Borchardt and others (1972), Izett and others (1972), Nash and Smith (1977), Sarna-Wojcicki and others (1979, 1980, 1984); Izett (1982); and Scheidegger and others (1980).

The instrumental neutron activation method has proven to be particularly useful for the trace-element fingerprinting and correlation of silicic volcanic ash beds (Theisen and others, 1968; Borchardt, 1970). Results of chemical analyses by this method for a large number of Bishop ash beds and pumice samples are tabulated in table 5. Analyses were made of glass fragments separated from crushed pumice lumps of the Bishop Tuff from its source area and of glass shards separated from samples of ash suspected to be remnants of the Bishop ash fall at locations far downwind from the source area. The instrumental neutron activation analyses were made by three different analysts using slightly different methods at different times. Analyses were made by G. A. Borchardt of the California Division of Mines and Geology

in the early 1970's, by H. R. Bowman of the University of California (reported in Sarna-Wojcicki and others, 1980, 1984) in the late 1970's, and by D. M. McKown, R. J. Knight, and J. A. Budahn of the U.S. Geological Survey from 1975 to 1981. Some of the minor variations in the amounts of a few trace elements reported in table 5 might be attributed to intralaboratory bias. If there is intralaboratory bias among the chemical analytical data, it is small and does not seriously influence the identification and correlation of the ash beds of this report.

The ash beds, whose locations are shown on figure 1 and listed in table 1, are herein correlated with the Bishop Tuff on the basis of their similar mineralogy; chemical composition of glass shards (table 5); chemical composition of sanidine, titanomagnetite (table 4), and ilmenite microphenocrysts; and shape and refractive index of glass shards. Some of these chemical and petrographic data are not given in this report because they have been presented in earlier studies of Bishop ash beds (Izett and others, 1970) and the Bishop Tuff (Hildreth, 1977, 1979). It should be stressed that the probability of correlation of each ash bed with the Bishop Tuff made in this report is high, based on the agreement between many chemical and physical properties. However, correlations can never be absolutely certain because ash beds erupted from the same volcanic center but at slightly different times can have nearly identical properties. For example, the Glass Mountain-G and Glass Mountain-D ash beds of Izett (1981, p. 10217) and the Glass Mountain-T and Glass Mountain-U ash beds of this report almost surely were erupted from vents in the same region as the Bishop Tuff, but during earlier volcanic episodes. These ash beds have chemical and physical properties nearly identical to the Bishop, and their distinction from the Bishop, lacking stratigraphic, paleomagnetic, or geochronologic evidence, may not always be possible. Therefore, a slight chance exists that some ash beds here correlated with the Bishop actually are correlatives of the Glass Mountain family of ash beds. However, the eruptions that produced the Glass Mountain family of ash beds were probably small and did not result in the formation of thick beds of ash at localities far removed from the source area.

Only three standard gravimetric chemical analyses of Bishop ash beds have been made owing to the time-consuming process of preparing pure glass concentrates of the ash beds and the great expense of this type of analysis. Inspection of the analyses of the pure glass phases of the ash beds, which are given in table 6, shows that they are high silica rhyolite that contains small amounts of iron, calcium, and magnesium. Izett (1981) called this type of rhyolite, W-type, in reference to the dead white color of the ultrasonically cleaned glass from distal ash beds formed from this type of rhyolite. All analyses are nearly identical to an analysis of the glass phase of pumice of the basal air-fall unit of the Bishop Tuff from 10 km north of Bishop, Calif. (table 6, no. 1). Two of the analyses were made of ash samples from depths of 194 m and 197 m from a borehole drilled near Saltair, Utah (Eardley and Gvosdetsky, 1960; Eardley and others, 1973). The ash layers, which are separated by 3 m of Pleistocene Lake Bonneville sediments, are nearly identical in chemical composition. Perhaps the lower layer is composed of the ash that fell directly into ancient Lake Bonneville and settled to the bottom, whereas the upper layer is composed of ash washed into the lake. The source of this ash was the original Bishop ash-blanket that must have mantled the area adjacent to the lake.

Hildreth (1977, 1979) reported trace-element data for whole rock and glass concentrates of Bishop Tuff samples acquired using the neutron activation method.

Table 6. Standard gravimetric chemical analyses of the glass phases of Bishop ash beds and Bishop Tuff of the Western United States

[Contents in weight percent; analysts E.L. Brandt and Paula Montalto, U.S. Geological Survey; leaders (—), not determined]

	1	2	3	4
Lab. No.	D102955	D101150	E1819	E1820
Sample No.	64W96	67	57P132	57P133
SiO_2	72.42	71.83	73.61	73.61
Al_2O_3	13.24	11.88	11.81	11.81
Fe_2O_3	0.35	0.56	0.34	0.34
FeO	.40	.38	.38	.38
MgO	.07	.55	.11	.11
CaO	.40	.47	.60	.60
Na_2O	2.92	2.94	3.43	3.43
K_2O	5.06	5.30	4.63	4.63
H_2O+	4.51	4.28	4.42	4.42
H_2O-	.33	.45	.14	.14
TiO_2	.07	.09	.07	.07
P_2O_5	.01	.01	.02	.02
MnO	.04	.04	.04	.04
CO_2	---	.01	---	---
Cl	.08	.07	---	---
F	.06	.09	---	---
Total--	99.91	99.53	99.63	98.95

SAMPLE DESCRIPTIONS

1 Bishop Tuff, air fall; loc. 1 fig. 1; Insulating Aggregates Co. pumice quarry about 10 km north of Bishop, Calif.
2 Bishop ash; Lake Tecopa, Calif.; loc. 8, fig. 1; reported by Sheppard and Gude (1968, p. 13).
3 Bishop ash; Saltair, Utah; loc. 43, fig. 1; from 194 m depth in core of borehole near Saltair.
4 Bishop ash; Saltair, Utah; loc. 43, fig. 1; from 197 m depth in core of borehole near Saltair.

Based on sequences of samples collected in stratigraphic succession and samples that showed a progressive increase in Fe-Ti oxide mineral temperature, he concluded that the Bishop Tuff is compositionally zoned. For example, samples of pumice from the stratigraphically lowest unit (basal air-fall pumice unit) contain significantly less lanthanum, cerium, and europium and more uranium than do samples from the uppermost pyroxene-bearing units of the Bishop (table 5; Hildreth, 1977, fig. 22, 23).

As can be seen on table 5, the composition of glass shards of ash beds here assigned to the Bishop closely matches the composition of the glass fragments from pumice lapilli of the basal air-fall unit of the Bishop Tuff in its source area. In particular, analyses of ash from localities 8, 9 (samples S-1 and S-5), 12, 14, 25, 26, 29–33, 36, 38–39, and 41–50 show remarkable similarity to analyses of the air-fall unit of the Bishop Tuff (table 5). The composition of Bishop ash beds is also similar to the composition of most of the samples collected from the stratigraphically lowest ash flows of the Bishop Tuff (table 5). However, one sample (table 5, loc. 1, sample No. 79G15) of pumice from the basal ash flow of the Bishop Tuff contains slightly more lanthanum, cerium, and europium and less uranium than do other samples of the lower units of the Bishop.

Ash from several localities, including 9 (samples S-2 and S-2A), 10, 19, 21–24, 27–28, 34–36, 40, 43, 45, and 50 (table 5) herein assigned to the Bishop ash, contains slightly more lanthanum, cerium, and europium and less uranium than samples of the basal air-fall unit of the Bishop. Samples of ash from several of these localities (27, 34, 35, and 40) were reanalyzed (table 5) to determine if the larger amounts of lanthanum, cerium, and europium and smaller amounts of uranium might be attributed to variations arising from using imperfectly cleaned samples or to variations from using samples of slightly different grain size. However, in most instances reanalyzed samples of the ashes consistently mirror the analytical results of prior analytical runs and contain larger amounts of lanthanum, cerium, and europium and smaller amounts of uranium.

Several explanations are possible that might account for the fact that some ash beds contain less lanthanum, cerium, and europium and more uranium than the other Bishop ash beds. One possibility is that the samples with this trace-element fingerprint consist of material expelled during the earliest phase of the Bishop Tuff eruption cycle when the basal air-fall unit and the lowest ash flows were formed. In contrast, the ash samples that contain the largest amounts of lanthanum, cerium, and europium and the smallest amounts of uranium probably contain a small component of material generated in the late stages of the eruption cycle during the time of emplacement of the stratigraphically highest ash flows of the Bishop Tuff. Inspection of analyses (table 5) of samples from localities 31 (sample 79G4), 36 (sample 80G15), 38, 39, 43, 45, and 46, which were collected near the base of Bishop ash beds in a stratigraphic position suggesting they formed during the early phase of the Bishop ash fall, reveals that they contain the smallest amounts of lanthanum, cerium, and europium, and the largest amounts of uranium. Because these samples are nearly identical in trace-element composition to the basal air-fall pumice of the Bishop Tuff, they have similarity coefficients greater than 0.95. In general, samples of Bishop ash that contain the largest amounts of lanthanum, cerium, and europium and smallest amounts of uranium (characteristic of ash flows of the upper part of the Bishop Tuff) were collected from either the upper parts of thick ash beds or from thin impure ash beds (for example, samples from locs. 21–24, 27, and 34 in table 5). The stratigraphically highest parts of the ash beds have bed forms that indicate they formed from ash that was washed or blown into the depositional site following the deposition of the primary ash fall. These ash beds have similarity coefficients compared to the basal air-fall unit of the Bishop Tuff (table 5) that range from 0.77 to 0.85—so low that some might doubt that they are indeed Bishop ash beds.

Another possibility, which is not high in our opinion, is that samples of ash beds that contain the relatively largest amounts of lanthanum, cerium, and europium and the smallest amounts of uranium in the glass shards are not Bishop ash beds. The fact that they are petrographically, mineralogically, and stratigraphically similar to the Bishop as well as having a chemical composition, in most respects, similar to the Bishop suggests to us that they are Bishop ash beds, but have a slightly different trace-element chemical composition.

Table 5 shows that the composition of the glass shards of ash beds herein correlated with the Bishop match rather well (except for small differences in some rare-earth elements) the composition of the glass phase of tephra from the basal air-fall unit of the Bishop Tuff. On the other hand, the composition of glass shards of these ash beds markedly contrasts with the glass phase of tephra from the uppermost ash flows that contain orthopyroxene and clinopyroxene (table 5, loc. 7). Samples of the upper part of the Bishop Tuff that contain pyroxene have significantly less iron, manganese, scandium, tantalum, lutetium, uranium, rubidium, and cesium than samples of the lower part. Moreover, the highest ash flows contain about twice as much of the light, rare-earth elements lanthanum and cerium than do samples of the lower unit of the Bishop. Hildreth (1977, p. 175, 213) suggested that the concentration of iron doubled during the eruption of the Bishop. Thus, amounts of iron should be greater in samples from the upper part compared to samples from the lower part of the Bishop. This is indeed true for many of the whole-rock analyses listed by

Hildreth (1977, p. 176–184), especially for samples from the Adobe Valley and Mono lobes of the Bishop Tuff. In contrast, some analyses of only the glass phase of the tuff separated from the bulk pumice of the upper unit of the Bishop from Adobe Valley reported by Hildreth (1977, p. 200–203) and those listed in table 5 indicate that the glass shards from the upper part of the Bishop contain less iron than glass shards from the lower part.

The combined mineralogical and chemical evidence supports the idea that a large amount of the material that forms Bishop ash beds was generated early in the Bishop Tuff eruptive cycle. The mineralogical evidence for Bishop ash beds given in a previous part of this report, including the composition of titanomagnetite microphenocrysts, the lack of significant amounts of orthopyroxene and clinopyroxene, and the relatively large amount of allanite, is particularly important. Chemical evidence also supports the idea that a considerable amount of the pyroclastic material that forms Bishop ash beds was generated early in the Bishop Tuff eruptive cycle. Hildreth (1977) concluded that the Bishop Tuff is a chemically zoned ash-flow sheet. He showed that the earliest units of the Bishop Tuff contain the smallest amounts of lanthanum and cerium and the largest amounts of uranium. Progressively younger parts of the Bishop contain more lanthanum and cerium and less uranium. The fact that the chemical composition of many Bishop ash beds matches closely the composition of the air-fall tephra unit at the base of the Bishop supports the contention that a considerable amount of the material that forms Bishop ash beds was generated early in the eruptive cycle, perhaps mainly during the energetic Plinian phase of the eruption. Some samples of Bishop ash contain slightly more lanthanum and cerium and less uranium than samples of tephra from the basal air-fall unit of the Bishop Tuff (table 5). This fact suggests to us that some component of material that forms Bishop ash beds was generated during the eruption of the middle and upper ash flows of the Bishop, which contain more lanthanum and cerium and less uranium compared to air-fall tephra. The chemical composition of glass shards of the youngest, pyroxene-bearing ash flows is strikingly different than the bulk composition of glass shards of Bishop ash beds. This evidence rules out the possibility that the youngest eruptions, which produced pyroxene-bearing pumice, contributed much material to the formation of Bishop ash beds.

Bishop Ash Bed at Friant

A rhyolitic ash bed included in the Pleistocene Friant Pumice Member of the Turlock Lake Formation by Janda (1965) occurs near Friant, Calif. (MacDonald, 1941; Trauger, 1950). The ash bed has been mined by the California Industrial Minerals Company for more than 20 years. In the mine workings, the stratigraphic relationship between the ash and the enclosing sediments is well exposed. As seen in the walls of the mine, the ash bed is overlain by a unit of pumiceous conglomerate (Chesterman, 1956, p. 38, fig. 21). The cobbles in the conglomerate unit are composed of several types of stream-rounded volcanic rock including fresh, lightweight rhyolite pumice and dense, rhyolite welded tuff. The welded tuff cobbles resemble welded tuff of the Bishop (fig. 3) in its type area.

The bed of fine-grained volcanic ash within the Friant Pumice Member at the excavations of the California Industrial Minerals mine is here named, for discussion purposes only, the Millerton Lake ash bed. Millerton Lake lies a few kilometers east of the California Industrial Minerals mine. The name Millerton Lake, rather than Friant, was chosen to prevent confusion that might arise from using Friant for both the ash bed and for the formally named Friant Pumice Member. The chemical composition of the glass of the Millerton Lake ash is much like that of Bishop air-fall tephra (tables 5 and 11). However, the Millerton Lake ash differs in that it contains slightly less iron than the Bishop. Seemingly, the Millerton Lake ash bed is a slightly different variety of Bishop ash, but more analyses of the ash are needed to determine if the small difference in iron content is consistently different than that in Bishop air-fall tephra.

Sarna-Wojcicki and others (1980, table 1; 1984, table 2) obtained chemical analyses of pumice cobbles from the conglomerate unit that overlies the Millerton Lake ash bed and drew attention to their similarity in chemical composition with pumice of the Bishop Tuff (see also tables 5 and 11 herein). Because of small differences in the chemical composition (for example lanthanum and cerium) of the glass of the pumice cobbles in the Friant Pumice Member and glass of pumice of the air-fall unit of the Bishop Tuff, Sarna-Wojcicki and others (1980, p. 18–19; 1984) suggested that the cobbles represent a slightly different chemical type of Bishop tephra, which they called the Friant type.

The age of the Millerton Lake ash bed has not been established by isotopic methods. However, pumice cobbles in the overlying conglomerate unit at the California Industrial Minerals mine were dated by the K-Ar method (Janda, 1965, p. 131; Dalrymple, 1980) at about 0.62 m.y. Sarna-Wojcicki and others (1980, p. 21–23; 1984, p. 23–26) considered the K-Ar age of 0.62 m.y. for the pumice cobbles to be anomalous because the chemical composition of the cobbles (their Friant-type Bishop ash) is strikingly similar to that of tephra of the Bishop Tuff (0.74 m.y.)

To further explore the K-Ar ages of the pumice cobbles, three groups of cobbles were collected by G. A. Izett from the conglomerate unit, and sanidine separated from

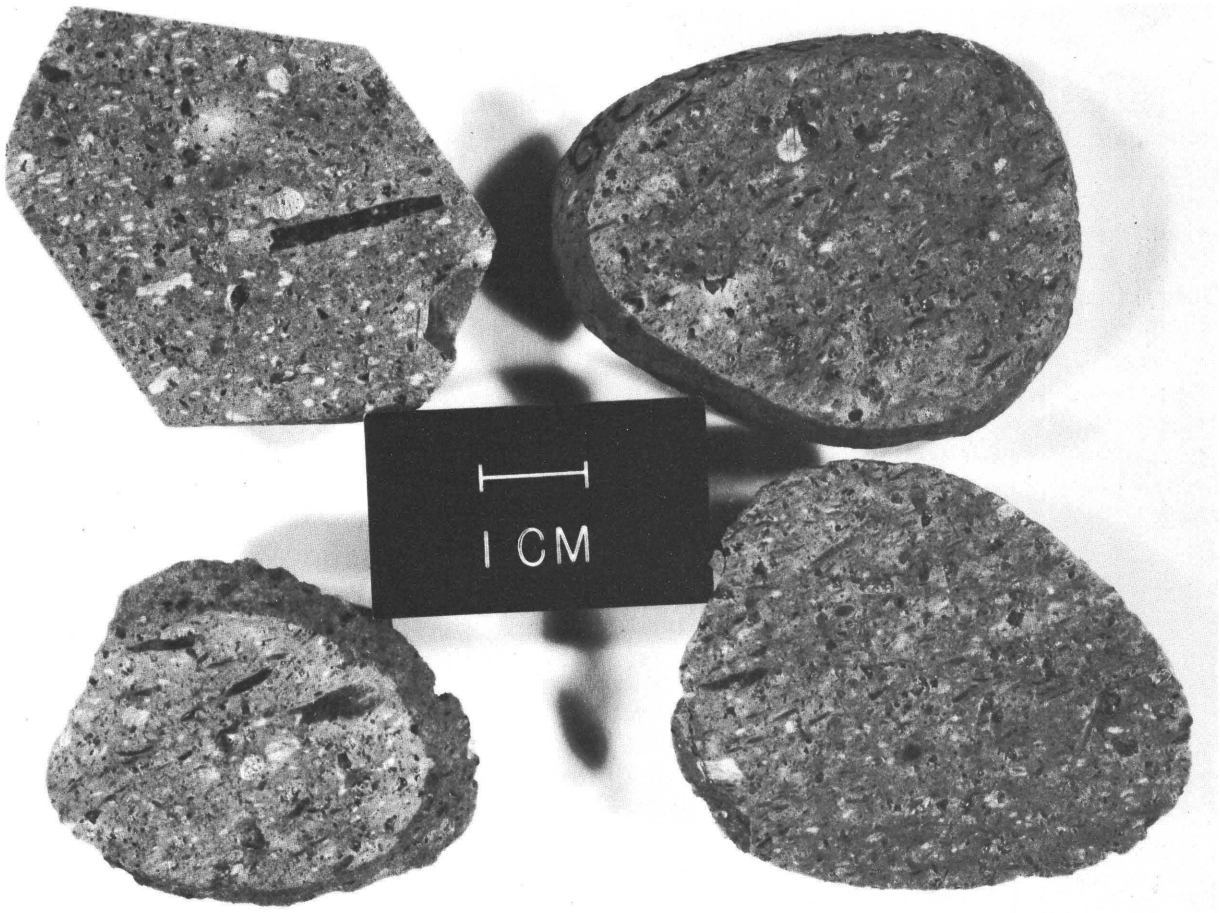


Figure 3. Stream-rounded cobbles of welded tuff (Bishop? Tuff) collected from conglomerate unit that lies above a Bishop ash bed at the California Industrial Minerals mine near Friant, Calif. Cobbles have fairly well developed eutaxitic structure. Xenolith of metamorphic rock of Sierran(?) age is in cobble in upper left corner of photograph.

them was dated (table 7). Sanidine separated from one group of pumice cobbles gave a K-Ar age of 1.78± 0.03 m.y.; sanidine from another group gave an age of 1.06±0.02 m.y.; and sanidine from a third group gave an age of 0.19±0.3 m.y.

The wide spread of K-Ar ages of the pumice cobbles reported here and of K-Ar ages reported by Dalrymple (1980) is very puzzling in view of the observation that the chemical composition and mineralogy of some pumice cobbles are nearly identical to the 0.74-m.y.-old Bishop Tuff tephra. One explanation for the wide spread of ages is that the K-Ar ages older than the Bishop result from dating random mixtures of pre-Bishop pumice cobbles, all of which chemically and mineralogically resemble Bishop tephra. Another condition that can result in unrealistically old K-Ar ages occurs when significantly older (two to three orders of magnitude) detrital potassium feldspar grains lodge in tubular vesicles in pumice cobbles while they are being transported by sediment-charged rivers. Various amounts of these older potassium feldspar grains are retained in sanidine concentrates separated from the pumice cobbles. The older detrital potassium feldspar grains cannot be removed from mineral concentrates during heavy-liquid separations of pumice fragments. The detrital, older potassium feldspar possibly can be removed from a feldspar concentrate by hand picking under a stereomicroscope. A K-Ar age obtained from a mixture of primary sanidine and significantly older detrital potassium feldspar obviously will be incorrect. The oldest K-Ar age (1.78±0.03 m.y.) was obtained on pumice cobbles that had been ultrasonically scrubbed in dilute hydrofluoric acid. Although this treatment may have removed detrital feldspar grains from the surface of the pumice, it could not remove detrital feldspar grains deeply lodged in vesicular tubes in some pumice cobbles. A second group of cobbles was prepared by grinding or sawing about 1–2 cm from the outer parts of the pumice cobbles so as

Table 7. Potassium-argon ages of pumice cobbles from the conglomerate unit of the Friant Pumice Member of the Turlock Lake Formation at the California Industrial Minerals mine near Friant, Calif.

[K-Ar ages determined by G.A. Izett, J.D. Obradovich, and H.H. Mehnert; ages calculated using decay constants and isotope abundances recommended by Steiger and Jäger (1977); ± is one sigma; potassium determined by flame photometry by V. Merrit, except for sample DKA3937, which was determined by the isotope dilution method by J.D. Obradovich]

Lab No.	Potassium (percent)	Sample weight (gram)	Radiogenic $^{40}Ar/g$ ($x10^{-11}$ mole)	Radiogenic ^{40}Ar (percent)	Age ($x10^6$ years)	Sample No. and dated material	Sample location and remarks
DKA3958	9.00	3.9908	1.6563	61.7	1.06±0.02	80G20S, sanidine.	Pumice cobbles from near the base of conglomerate unit at the California Industrial Minerals mine near Friant, Calif.
DKA3937	9.097	4.8105	2.8121	88.5	1.78±0.03	79G73, sanidine.	Do.
DKA4132	9.13	0.9713	0.3028	2.4	0.19±0.3	79G73A, sanidine.	Do.

to increase the possibility of dating primary phenocrystic sanidine only from the interiors of the cobbles. The K-Ar age of sanidine from this group of pumice cobbles yielded an age of 1.06±0.02 m.y. This age is similar to the K-Ar age of pumice and lava of the rhyolite of Glass Mountain (Metz, 1984), which have a chemical composition similar to the Bishop Tuff.

The K-Ar age (0.19±0.3 m.y., table 7) of sanidine separated from a third group of pumice cobbles seems to be anomalously young, considering the middle Pleistocene age of the Friant Pumice Member of the Turlock Lake Formation (Janda, 1965). Only a small amount of sanidine was available for this determination, and the amount of radiogenic ^{40}Ar obtained, relative to the total ^{40}Ar extracted (table 7), was small (2.4 percent). Naeser and others (1981, p. 30–31) recently emphasized the unreliability of K-Ar ages having a low ratio of radiogenic ^{40}Ar to total ^{40}Ar.

In summary, the spurious K-Ar ages of pumice cobbles from the conglomerate unit in the Friant Pumice Member of the Turlock Lake Formation provide little information on the age of the underlying Millerton Lake ash bed. Perhaps there are several age groups of pumice cobbles in the conglomerate unit. In contrast to the isotopic age data, stratigraphic relationships clearly show that the Millerton Lake ash bed is older than the overlying conglomerate unit that contains stream-rounded fragments of welded tuff here assigned to Bishop Tuff. Remnants of a once more extensive lobe of the Bishop Tuff (formerly called the tuff of Reds Meadow by Huber and Rinehart (1965)) are found on the west side of the Sierra Nevada crest in the drainage of the Middle Fork of the San Joaquin River (Hildreth, 1977, p. 296). Considerable time (perhaps 10,000 years) may have elapsed following the emplacement and welding of the Bishop ash-flow sheet 0.74 m.y. ago and the subsequent reintegration of the San Joaquin River drainage system to allow incision of the Bishop and accompanying transportation of welded tuff fragments of the Bishop to the Friant, Calif., area.

Thickness of Bishop Ash

The thickness of the Plinian pumice fall deposit at the base of the Bishop Tuff (fig. 2) can be determined at several localities north of Bishop, Calif., where it typically and uniformly is about 4 m thick. Good exposures occur at the Insulating Aggregates Co. pumice mine about 10 km north of Bishop; at the south end of the Volcanic Tableland in secs. 20 and 29, T. 6 S., R. 32 E.; and at a roadcut along California State Highway 395 about 1.5 km east of Toms Place, Calif. In general, the basal air-fall unit is fairly well sorted and consists of angular pumice fragments, most of which range from 0.5 to 6 cm in diameter. A few percent of dark-gray, lithic fragments only a few millimeters in diameter are evenly distributed in the unit. The basal air-fall unit is noticeably stratified and contains several subunits that are reversely graded (Bateman, 1953). The even distribution of the lithic fragments clearly indicates that the reverse graded bedding did not form as a result of pumice falling in standing water, as originally suggested by Bateman (1953). If the pyroclastic material that forms the air-fall unit had fallen in standing water, the lithic fragments would have been concentrated in a discrete layer at the bottom of the unit owing to their greater density compared to the pumice fragments (Bateman, 1965, p. 151–155).

There are thick, scattered pumice deposits along the west face of the White Mountains in the Bishop and White

Mountain Peak quadrangles, some of which were assigned to the Bishop Tuff basal air-fall unit by Bateman (1965, pl. 3). Other deposits of pumice similar to the basal air-fall of the Bishop occur in the Benton Hot Springs area in the Glass Mountain quadrangle. The origin of some of these deposits can be ascribed to air-fall or ash-flow mechanisms, but the origin of a few of the deposits is uncertain. For example, the pumice lumps that form the deposit at the Sacramento mine in sec. 3, T. 4 S., R. 34 E. were questionably assigned to the Bishop by Hildreth (1977, p. 296) and classified as air-fall material. However, the pumice fragments are unusually well rounded for air-fall material. In addition, the pumice lumps are unusually large (as much as 25 cm) and frothy compared to pumice fragments of typical air-fall material at the base of the Bishop Tuff nearby in the Volcanic Tableland area of the Bishop quadrangle. Moreover, the chemical composition of this pumice is slightly different than pumice of the basal air-fall unit (table 5). Much more work needs to be done to discriminate and correlate the Bishop-like deposits along the White Mountains front and other deposits in the Glass Mountain quadrangle.

Although the basal air-fall unit of the Bishop Tuff in its source area generally can be identified and its thickness determined, it is extremely difficult to find localities where the thickness of the primary air-fall component of Bishop ash beds can be identified and measured. At most places, Bishop ash beds are composed entirely of water- and wind-deposited ash, as opposed to primary air-fall ash (fig. 4). The beds are lenticular and only extend along the outcrop for a few tens of meters. Accordingly, the thickness of beds varies from a feather edge to as much as 3 m at any ash locality. Figure 5 shows localities where the total thickness (including the lower primary air-fall component and the upper reworked component) of Bishop ash beds has been measured. As shown on figure 5, there is a general trend, as would be expected, for ash beds to be thickest close to the source area at Long Valley, Calif. However, thicknesses of ash can vary markedly from locality to locality. For example, ash thicknesses at localities a few tens of kilometers apart in Nevada (fig. 5, locs. 30 and 31) range from 30 to 100 cm. Such marked changes in thickness result not so much from original thickness changes of the primary ash fall

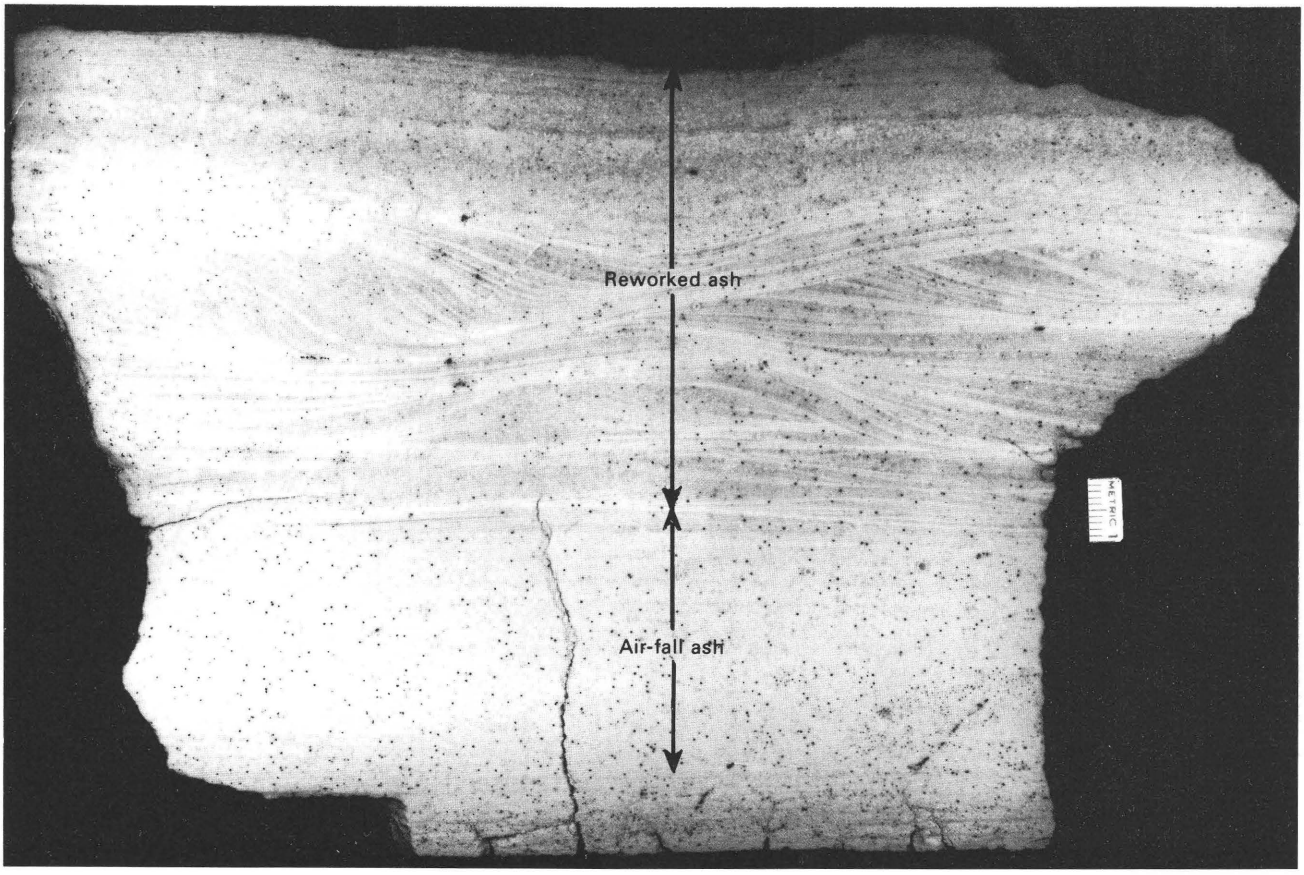


Figure 4. A sawed slab of ash collected from the lowermost part of a 1-m-thick Bishop ash bed at Onion Creek, Utah (fig. 1, loc. 38). Base of ash bed is at bottom of picture. Lowest 6 cm of ash bed may be primary air-fall ash ; upper 8 cm is crossbedded eolian? redeposited ash. Scale in photograph is 1 cm.

but rather from thickness changes caused by reworking by wind and water of the primary ash fall. Material of the primary ash fall can be blown or washed so as to cover other parts of the same ash fall or can be blown or washed to new deposition sites where the bed could consist entirely of reworked ash.

The thickness of the original Bishop ash fall can be determined with reasonable confidence at only a few localities. At these places, the beds consist of two depositional units—a lower unit of primary air-fall ash and an upper unit of secondary, water- or wind-deposited ash (fig. 4). One locality is on the west side of the Mineral Mountains in southwestern Utah (fig. 1 and table 1, loc. 36) about 500 km downwind from the vent area. At this locality, the Bishop ash bed is 3.0 m thick (fig. 5). However, we judge that the air-fall component of the 3.0-m-thick ash bed at this locality is only about 10 cm thick. Of course, this thickness (10 cm) is a compacted-ash thickness, and the original thickness of air-fall ash shortly after deposition must have been considerably thicker (perhaps 16 cm). At a second locality in eastern Utah (fig. 1 and table 1, loc. 38), about 800 km downwind from the vent area, the Bishop ash bed is about 1.0 m thick. We surmise that the air-fall component of the ash bed at this locality is only about 6 cm thick (fig. 5). Of course, this thickness (6 cm) also represents compacted ash, and the original air-fall ash may have been as thick as 10 cm.

Volume of Bishop Ash

Calculation of the volume of pyroclastic material ejected during historic volcanic eruptions can give insight into volcanological processes that should lead to a more systematic and accurate volcano hazard warning and assessment network in the United States. A compilation of the volume of particulate material ejected during some notable pyroclastic eruptions of late Cenozoic and Holocene time is given in table 8. Two different types of data are listed—the volume of tephra in the source area and the volume of ash carried far downwind. An accurate estimate for the volume of tephra in source areas is the more readily acquired of the two different components of pyroclastic eruptions. In contrast, an accurate assessment for the volume of ash carried away from the source area by high-altitude winds is much more difficult to make. Accurate assessment of the volume of pyroclastic material is contingent upon collecting large amounts of data so that maps showing distribution and thickness can be drawn. Thickness data can then be used to make contour maps, and the volume can be calculated from planimetered areas. For example, Thorarinsson (1958, 1967) calculated the volume of several pyroclastic eruptions originating at Hekla volcano in Iceland (table 8). Gorshkov (1959) and Gorshkov and Dubik (1970) calculated the volume of ash that fell during the March 30, 1956, eruption of Bezymianny volcano and the November 12, 1964 eruption of Shiveluch volcano on Kamchatka (table 8). A more recent example of calculating the volume of a pyroclastic eruption is that done by Sarna-Wojcicki and others (1981) following the May 18, 1980, eruption of Mount St. Helens volcano in Washington (table 8).

Calculation of the volume of ejected pyroclastic material is much more complex for prehistoric eruptions than for historic eruptions for several reasons. Within the source area, the areal distribution of the original pyroclastic material is never completely known because of posteruption erosion. Thicknesses of tephra must be adjusted for varying density following compaction and welding, and the amount of tephra concealed by younger deposits or in downdropped caldera blocks can only be estimated from drilling or geophysical studies, and then only with considerable uncertainty. Calculation of the volume of the ash carried far downwind is rarely known with accuracy, owing to incomplete knowledge of the original distribution of the ash, incomplete preservation of the original ash blanket, and unavailability of ash layers for observation and study due to lack of erosion of deposits containing the ash layers.

As suggested above, calculation of a minimum value for the volume of Bishop ash is contingent upon knowing (1) the areal distribution of the original ash fall and (2) the relationship between ash thickness and distance from source throughout the fallout area. The areal distribution of the Bishop ash is fairly well established (fig. 1), but not enough data on thickness are available to arrive at a reliable volume estimate. Using the distribution of the Bishop ash bed as it was known in the early 1970's (Izett and others, 1970) and assuming a logarithmic thinning (compare Williams and Goles, 1968; Walker, 1980, p. 76–77) away from the vent area, Bailey and others (1976, p. 730) estimated the volume of the Bishop ash fall to be about 300 km^3. Conversion of this volume to the volume of dense rock equivalent can be made by determining a value for the bulk density of the ash. To obtain a more accurate estimate of the volume of Bishop ash than that made by Bailey and others (1976) requires a far better understanding of the areal distribution of the original ash fall and a more detailed knowledge of the nature of the logarithmic thinning away from the vent area.

In conclusion, the number of localities of Bishop ash where the primary air-fall ash thickness can be measured is so small that the rate of thinning away from the vent cannot be accurately determined. This factor imposes a serious obstacle to those interested in calculating ash volumes produced from prehistoric pyroclastic eruptions such as the Bishop. Although there are insufficient

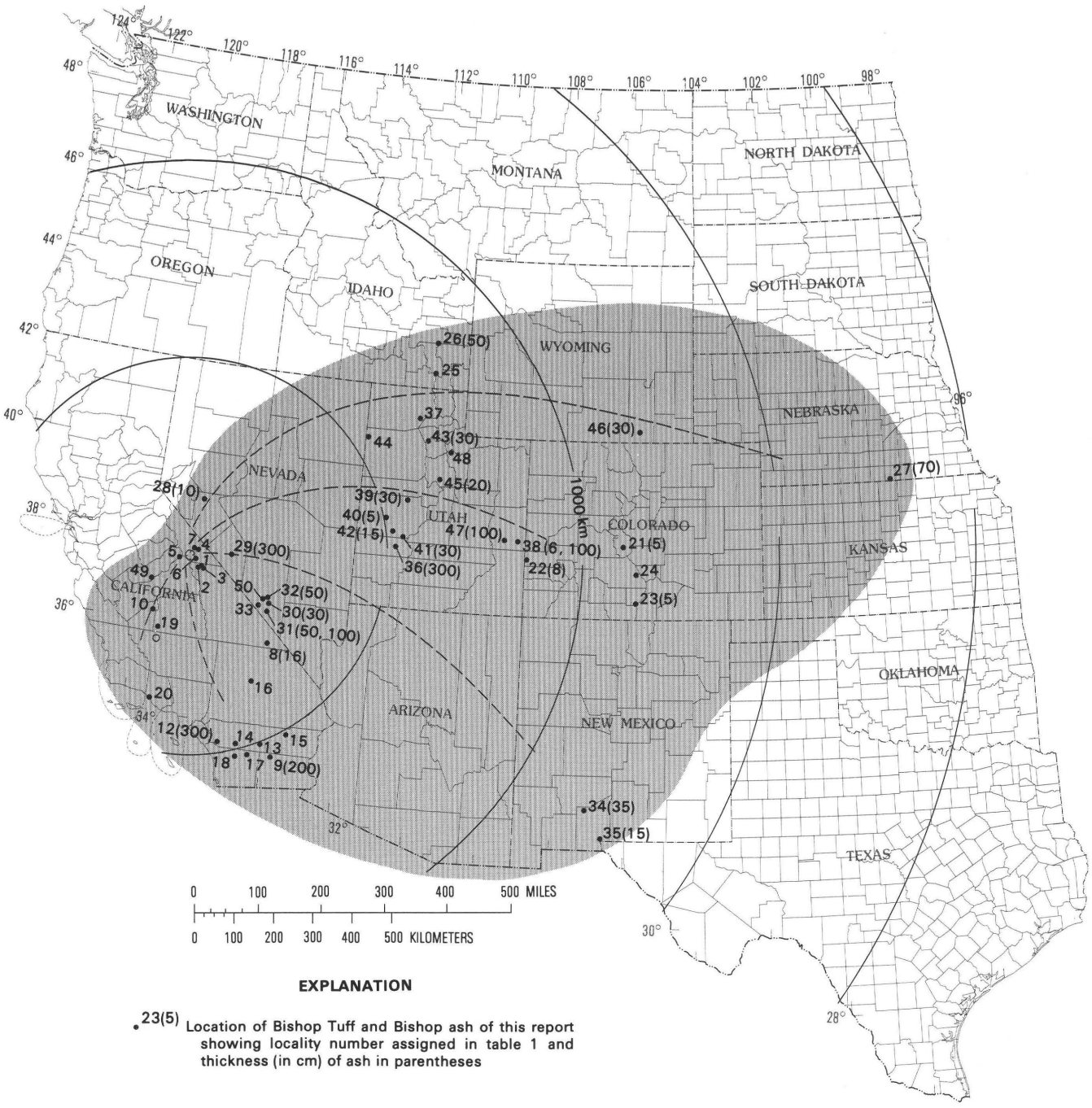


Figure 5. Map showing thicknesses of Bishop ash beds in the Western United States. Shaded area indicates inferred extent of original Bishop ash fall.

reliable thickness data to arrive at a meaningful volume for the Bishop ash fall, nevertheless, the volume must have been enormous considering the wide distribution of Bishop ash (fig. 1). The volume may have been several hundred cubic kilometers as suggested by Bailey and others (1976, p. 730).

Potassium-Argon Age of Bishop Tuff

The Bishop Tuff has been the object of repeated attempts to determine accurately its age by the K-Ar method (Evernden and others, 1957; Dalrymple and others, 1965; Hildreth, 1977, p. 327). Recalculation of

Table 8. Some large-scale silicic pyroclastic eruptions of the past, listing the estimated volume of material ejected during the Plinian and ash-flow-producing stages

[Leaders (---), lack of data]

Eruption unit or volcano	Eruption age or date	Location	Tephra volume of ash flows (in km^3)	Tephra volume of ash falls (in km^3)	References
Huckleberry Ridge Tuff.	2.01 m.y.	Wyoming	2,000	---	Christiansen, 1979, p. 36.
Toba Tuff------	75,000 B.P.	Sumatra	2,000	1000	van Bemmelen, 1949; Ninkovitch and others, 1978, p. 290.
Lava Creek Tuff	0.61 m.y.	Wyoming	1,000	---	Christiansen, 1979, p. 36.
Bishop Tuff----	0.74 m.y.	California	500	300	Bailey and others, 1976, p. 730.
Bandelier Tuff (upper).	1.15 m.y.	New Mexico	300	---	Smith, 1979.
Bandelier Tuff (lower).	1.47 m.y.	New Mexico	300	---	Smith, 1979.
Mesa Falls Tuff	1.27 m.y.	Idaho	280	---	Christiansen, 1979, p. 36.
Granadilla Pumice	32,000 B.P.	Canary Islands	5.5	35	Booth, 1973, p. 366-367.
Manganone------	30,000 B.P.	New Zealand	2.0	16.5	Howorth, 1975, p. 694.
Shikotsu-------	Pleistocene	Japan	90	25	Katsui, 1959.
Tambora--------	A.D. 1815	Tambora	25	125	Stothers and others 1983, p. 873.
Crater Lake (Mazama).	6,500 B.P.	Oregon	25-33	29-37	Williams and Goles, 1968, p. 40.
Santorini------	1500 B.C.	Thera	---	28	Watkins and others, 1978, p. 125.
Taupo----------	1,820 B.P.	New Zealand	70	23	Froggatt, 1982; Froggatt and others, 1981; Walker, 1980.
Katmai---------	A.D. 1912	Alaska	11-15	20	Curtis, 1968, p. 207; Hildreth, 1983, p. 1.
Krakatoa-------	A.D. 1883	Java	12	8.5	Self and Rampino, 1981, p. 703.
Oraefajokull---	1362	Iceland	---	10	Thorarinsson, 1958, p. 81.
Vesuvius-------	A.D. 79	Italy	---	2.6	Lirer and others, 1973, p. 770.
Hekla----------	A.D. 1104	Iceland	---	2.5	Thorarinsson, 1967, p. 34.
Avellino-------	1,100 B.P.?	Italy	---	2.1	Lirer and others, 1973, p. 770.
Hekla----------	A.D. 1300	Iceland	---	0.5	Thorarinsson, 1967, p. 48.
Bezymianny-----	3/30/56	Kamchatka	1.8	0.5-0.4	Gorshkov, 1959, p. 87 and 95.
Hekla----------	A.D. 1766	Iceland	---	0.40	Thorarinsson, 1968, p. 116.
Hekla----------	A.D. 1510	Iceland	---	0.32	Thorarinsson, 1968, p. 62.
Hekla----------	A.D. 1693	Iceland	---	0.30	Thorarinsson, 1968, p. 94.
Hekla----------	A.D. 1845	Iceland	---	0.23	Thorarinsson, 1968, p. 136.
Shiveluch------	11/12/64	Kamchatka	0.3-0.5	0.3	Gorshkov and Dubik, 1970, p. 277.
Mount St. Helens	5/18/80	Washington	0.1	1.1	Sarna-Wojcicki and others, 1981.
Chichonal------	3/82; 4/82	Mexico	0.03-0.06	[1]0.25	Silva and others, 1982.

[1]Volume cited is dense rock equivalent of pyroclastic material.

K-Ar ages for the Bishop using the analytical data of Dalrymple and others (1965) and decay constants and isotope abundances being used in 1976 resulted in a weighted mean age of 0.708 ± 0.015 m.y. at the 95 percent confidence level (Bailey and others, 1976, p. 731). The K-Ar age of the Bishop Tuff was recalculated by Mankinen and Dalrymple (1979, p. 619). They used decay constants and isotope abundances advocated by Steiger and Jäger (1977) and analytical data of Dalrymple and others (1965) to arrive at an age of 0.727 m.y. for the Bishop. Recently, Hurford and Hammerschmidt (1985) dated sanidine from the Bishop Tuff using the conventional K-Ar method and the $^{40}Ar/^{39}Ar$ step-heating method. They reported a total degassing age of 0.740 ± 0.014 m.y. and a $^{40}Ar/^{39}Ar$ plateau age of 0.734 ± 0.024 m.y. The sanidine concentrate they used was a split of a large amount (625 g) recovered from a large boulder of pumice from the upper part of the Bishop Tuff in Adobe Valley, Calif., collected by G. A. Izett (table 9, sample 79G94).

Because considerable progress has been made in the techniques and equipment used for K-Ar dating since Dalrymple and his coworkers dated the Bishop in the middle 1960's (Dalrymple and others, 1965), 17 new K-Ar age determinations for the Bishop have been made. Samples were collected from the stratigraphically lowest and uppermost parts of the Bishop Tuff to determine if the lowest part (nonpyroxene-bearing pumice unit) might

Table 9. Potassium-argon ages of the Bishop Tuff of eastern California

[Underlined ages previously reported by Dalrymple and others (1965) or Hildreth (1977); all other ages determined by G.A. Izett, J.D. Obradovich, and H.H. Mehnert; ages calculated using decay constants and isotope abundances recommended by Steiger and Jäger (1977); ± is one sigma; qtz, quartz; plag, plagioclase; potassium concentrations determined by flame photometry by V. Merrit, U.S. Geological Survey, except sample DKA 3876, which was determined by isotope dilution methods by J.D. Obradovich]

Lab No.	K_2O (pct)	Sample weight (grams)	Radiogenic $^{40}Ar/g$ $\times 10^{-11}$ mole	Radiogenic ^{40}Ar (pct)	Age x 10^6 years	Sample No. and dated material	Sample locality and remarks
				Upper part of Bishop Tuff (orthopyroxene- and clinopyroxene-bearing pumice)			
DKA3865	10.97 11.11	6.0378	1.1242	66.0	0.71±0.013	79G88S, sanidine.	Pumice cobbles and blocks from near the base of nonwelded ash-flow tuff in the NW1/4NW1/4 sec. 25, T. 1 S., R. 29 E., Glass Mountain 15-minute quadrangle, Mono County, Calif.; collector, G.A. Izett.
DKA3953	10.96 10.99 11.04	5.1749	1.2049	59.5	0.76±0.016	79G88S-1, sanidine.	Do.
DKA3954	10.96 10.99 11.04	4.7969	1.1734	50.0	0.74±0.015	79G88S-2, sanidine.	Do.
DKA4124	11.24 11.22	7.7476	1.2162	52.9	0.75±0.007	79G94S, sanidine.	Rounded pumice block about 1 m in diameter from near the base of nonwelded ash flow in the NE1/4 sec. 27, T. 1 S., R. 29 E. in the Glass Mountain 15-minute quadrangle, Mono County, Calif.; near locality B-137 of Hildreth (1977, p. 299); collector, G.A. Izett.
	10.94 10.97	7.533 8.535	1.160	42.2 60.9	0.691±0.025	64G003, sanidine.	Pumice blocks from upper surface of Bishop Tuff in the SE1/4SE1/4 sec. 28, T. 1 S., R. 29 E., Cowtrack Mountain 15-minute quadrangle, Mono County, Calif.; collector, C.M. Gilbert; see Dalrymple and others (1965) and Dalrymple (1980).
KA2899	9.09	3.8485	0.8863	77.1	0.700±0.014	B-96, sanidine.	Pumice blocks from the Bishop Tuff at Gas Pipe Springs at Bench Mark 7974 in the NW1/4NW1/4 sec. 1, T. 1 S., R. 28 E., Cowtrack Mountain 15-minute quadrangle, Mono County, Calif. (Hildreth, 1977).
DKA3876	1.309	3.6567	0.1394	10.4	0.74±0.054	79G88P, plag.	Pumice cobbles and blocks from near the base of nonwelded ash flow in the NW1/4NW1/4 sec. 25, T. 1 S., R. 29 E., Glass Mountain 15-minute quadrangle, Mono County, Calif.; collector, G.A. Izett.
DKA3867	5.09	4.2492	0.6794	2.3	0.93±0.312	77G88G, glass.	Do.
DKA3866	6.50	1.9207	1.2427	1.7	1.10±0.52	77G88B, biotite.	Do.
DKA3941	6.28	0.2658	0.3113	0.7	0.34±0.252	77G88B, biotite.	Do.
DKA4130	1.16 1.19	5.3866	1.4084	4.4	0.83±0.10	79G94P, plag.	Rounded pumice block about 1 m in diameter from near the base of nonwelded ash flow in the NE1/4 sec. 27, T. 1 S., R. 29 E. in the Glass Mountain 15-minute quadrangle, Mono County, Calif.; near locality B-137 of Hildreth (1977, p. 299); collector, G.A. Izett.

					Lower part of Bishop Tuff (nonpyroxene-bearing pumice)		
DKA3877	10.07 10.13	4.6850	1.0739	72.5	0.74±0.012	79G14S, sanidine.	Handpicked pumice lapilli from basal air-fall unit of the Bishop Tuff at the California Insulating Aggregates Co. pumice quarry in the NW1/4NW1/4 sec. 4, T. 6 S., R. 33 E., Bishop 15-minute quadrangle, Inyo County, Calif.; collectors, G.A. Izett, G.T. Cebula, and J.G. Honey.
DKA3955	10.01 10.08	4.0810	1.0817	54.2	0.75±0.017	79G14S-2, sanidine.	Do.
DKA4116	10.82 10.83	5.7623	1.1541	45.4	0.74±0.008	80G24, sanidine.	Pumice lapilli from prominent, thick ash flow of the Bishop Tuff at the California Insulating Aggregates Co. pumice quarry in the NW1/4NW1/4 sec. 4, T. 6 S., R. 33 E., Bishop 15-minute quadrangle, Inyo County, Calif.; collector, G.A. Izett.
DKA4117	10.93 10.89	5.1063	1.1230	38.2	0.71±0.009	80G24S, sanidine.	Do.
DKA4125	11.02 11.06	6.0520	1.1648	40.4	0.73±0.009	80G21, sanidine.	Pumice lapilli from thin, basal lenticular ash flow of the Bishop Tuff at the California Insulating Aggregates Co. pumice quarry in the NW1/4NW1/4 sec. 4, T. 6 S., R. 33 E., Bishop 15-minute quadrangle, Inyo County, Calif.; collector, G.A. Izett.
	10.63 10.56	6.734 7.837	1.180	61.6 45.8	0.764±0.027	64G001, sanidine.	Pumice blocks from near base of nonwelded ash-flow tuff at the California Insulating Aggregates Co. pumice quarry in the NW1/4 sec. 4, T. 6 S., R. 33 E., Bishop 15-minute quadrangle, Mono County, Calif.; collectors, A. Cox and G.B. Dalrymple; see Dalrymple and others (1965) and Dalrymple (1980).
	10.69 10.72	5.671 6.799	1.154 1.180	56.0 78.6	0.726±0.025	64G002, sanidine.	Pumice fragments from basal air-fall unit of the Bishop Tuff in a roadcut along U.S. Highway 395 near Toms Place in the W1/2 sec. 34, T. 4 S., R. 30 E., Casa Diablo Mountain quadrangle, Mono County, Calif.; collector, R.J. Janda; see Dalrymple and others (1965) and Dalrymple (1980).
KA2936	9.87	2.5161	1.0331	61.0	0.75±0.007	B-105, sanidine.	Pumice fragments from basal air-fall unit of the Bishop Tuff in NE1/4SW1/4 sec. 28, T. 2 S., R. 32 E., White Mountain Peak 15-minute quadrangle, Mono County, Calif.; collector, E.W. Hildreth; see Hildreth (1977).
KA2935	10.40	2.1250	1.0780	42.8	0.74±0.005	B-109, sanidine.	Pumice fragments from ledge of poorly welded ash flow of lower cooling unit of the Bishop Tuff in SW1/4 sec. 6, T. 6 S., R. 33 E., Bishop 15-minute quadrangle, Mono County, Calif.; collector, E.W. Hildreth; see Hildreth (1977).
DKA3957	6.92 6.94	0.4244	1.1355	2.1	1.14±0.60	79G14B, biotite.	Handpicked pumice lapilli from basal air-fall unit of the Bishop Tuff at the California Insulating Aggregates Co. pumice quarry in NW1/4NW1/4 sec. 4, T. 6 S., R. 33 E., Bishop 15-minute quadrangle, Inyo County, Calif.; collectors, G.A. Izett, G.T. Cebula, and J.G. Honey.
DKA3958	0.90 0.89	3.3959	1.7537	11.4	1.36±0.13	79G14PQ, plag and qtz.	Do.
DKA4122	0.83 0.85	11.1766	0.8005	6.8	0.66±0.04	80G21P, plag.	Pumice lapilli from thin, lowermost lenticular ash flow (fig. 2) of the Bishop Tuff at the California Insulating Aggregates Co. pumice quarry in NW1/4NW1/4 sec. 4, T. 6 S., R. 33 E., Bishop 15-minute quadrangle, Inyo County, Calif.; collector, G.A. Izett.

yield consistently older ages than the stratigraphically youngest part (orthopyroxene- and clinopyroxene-bearing ash flows). Newly determined K-Ar ages are reported here (table 9), as well as ages determined by Dalrymple and others (1965) and Hildreth (1977). All ages listed in table 9 were calculated or recalculated using the decay constants and isotope abundances recommended by Steiger and Jäger (1977).

The weighted mean age calculated from all determinations in table 9 made on sanidine, plagioclase, and biotite from the lower nonpyroxene-bearing part of the Bishop is 0.738±0.003 m.y. at the 1 sigma level. The weighted mean age calculated from the data obtained from all the sanidine determinations (0.738±0.003 m.y.) from the lower unit is identical to the weighted mean calculated for all minerals. The weighted mean age calculated from only the sanidine ages determined in this study (0.731±0.004 m.y.) is not statistically significantly different from the weighted mean ages for all minerals and for all sanidine ages of the lower unit.

The weighted mean age calculated from all determinations listed in table 9 made on sanidine, plagioclase, biotite, and glass from the upper pyroxene-bearing part of the Bishop is 0.736±0.005 m.y. at the 1 sigma level. This mean age is not statistically different from the weighted mean age calculated for the lower unit. The weighted mean age calculated for only sanidine ages (0.722±0.007 m.y.) from the upper unit is slightly younger than the weighted mean age of all minerals. A slightly younger weighted mean age for sanidine is a consequence of three of the six sanidine ages clustering around 0.70 m.y. and the other three clustering around 0.74 m.y. The weighted mean age calculated for the four sanidine ages determined in this study is 0.743±0.005 m.y., slightly older than the weighted mean age for all sanidine ages. Perhaps the younger sanidine ages resulted from the less than complete expulsion of argon from the samples during heating and gas extraction.

The only age (1.36±0.13 m.y.) that seems anomalous is one determined on plagioclase from the lower unit of the Bishop (table 9, sample DKA3958). The most likely explanation for the anomalous age is that the plagioclase sample prepared for the age determination was so inhomogeneous that the sample splits used for potassium and argon analyses differed in potassium content. A large amount of quartz could not be completely removed from the plagioclase during the mineral separation process, and the amount of the potassium-bearing phase (plagioclase) relative to the nonpotassium-bearing phase in the sample was small.

The ages determined on biotite and glass (table 9) have large analytical uncertainties owing to the small amount of radiogenic ^{40}Ar obtained relative to the total ^{40}Ar extracted (table 10). Naeser and others (1981, p. 30–31) recently emphasized the unreliability of K-Ar ages having a low ratio of radiogenic ^{40}Ar to total ^{40}Ar.

Table 10. Potassium-argon analytical data used for isochron plot of figure 6

[Laboratory numbers are those of table 9; CV, coefficient of variation; leaders (---), coefficient of variation not calculated]

Lab No.	Analyzed material	$^{40}Ar/^{36}Ar$	CV	$^{40}K/^{36}Ar$ ($X10^4$)	CV
Upper unit of Bishop Tuff (pyroxene-bearing pumice)					
DKA3865	Sanidine	869.6	1.11	1390.4	1.73
DKA3953	Sanidine	730.0	1.24	984.8	1.43
DKA3954	Sanidine	592.4	1.25	687.8	1.44
DKA3941	Biotite	298.2	1.04	10.8	1.62
DKA3866	Biotite	301.2	1.13	8.0	2.19
DKA3876	Plagioclase	330.3	0.87	79.4	1.66
DKA4130	Plagioclase	309.7	1.11	28.1	1.17
DKA3867	Glass	302.9	0.87	12.7	1.67
Lower unit of Bishop Tuff (nonpyroxene-bearing pumice)					
DKA3877	Sanidine	1077.8	0.80	1820.9	1.62
DKA3955	Sanidine	645.6	1.25	801.6	1.82
DKA4116	Sanidine	541.7	---	570.9	---
DKA4117	Sanidine	479.1	---	440.5	---
DKA4124	Sanidine	627.6	---	758.4	---
DKA4125	Sanidine	496.1	---	469.9	---
DKA3957	Biotite	302.3	1.24	9.5	1.81
DKA4122	Plagioclase	317.7	---	56.3	---
DKA3958	Plagioclase	334.1	1.25	48.1	1.82

A plot of $^{40}Ar/^{36}Ar$ against $^{40}K/^{36}Ar$ using the analytical data (table 10) acquired from sanidine, plagioclase, biotite, and glass from the lowermost and uppermost parts of the Bishop is shown on figure 6. The intersection of the isochron along the ordinate is about 298, which suggests that there is no analytically detectable amount of excess ^{40}Ar in the sanidine, plagioclase, biotite, or glass. The isochron age of the Bishop, including samples from the stratigraphically lowest and highest units, is 0.74 m.y.

The following conclusions are made from study of the K-Ar ages of the Bishop:

1. The weighted mean age of previously reported and newly determined K-Ar ages for the lower and upper units of the Bishop Tuff, 0.738±0.003 m.y. and 0.736±0.005 m.y., respectively, are not statistically different from the mean age (0.727 m.y.) of the Bishop reported by Mankinen and Dalrymple (1979, p. 619).
2. There is no significant age difference between the lowest nonpyroxene-bearing and the uppermost pyroxene-bearing parts of the Bishop.
3. The average K-Ar age of 0.738±0.003 m.y. of the lower air-fall unit of the Bishop Tuff as determined in this study is nearly identical to the average zircon fission-track age (0.74±0.05 m.y.) from the same unit reported by Izett and Naeser (1976).

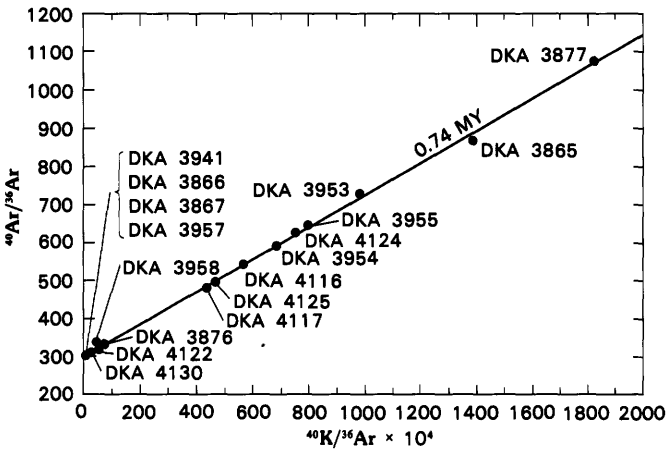


Figure 6. Plot of argon and potassium isotopes ($^{40}Ar/^{36}Ar$ vs $^{40}K/^{36}Ar$) measured in samples of sanidine, plagioclase, biotite, and glass separated from samples of the Bishop Tuff. Sample numbers are those of tables 9 and 10.

4. Minerals and glass that comprise the Bishop Tuff do not contain analytically significant amounts of excess radiogenic argon.
5. The K-Ar age of the Bishop Tuff is 0.738 ± 0.003 m.y. at the 1 sigma level. This composite of ages from the lower and upper units of the Bishop was calculated using only the analytical data for sanidine, which are considered by us to be the most reliable.

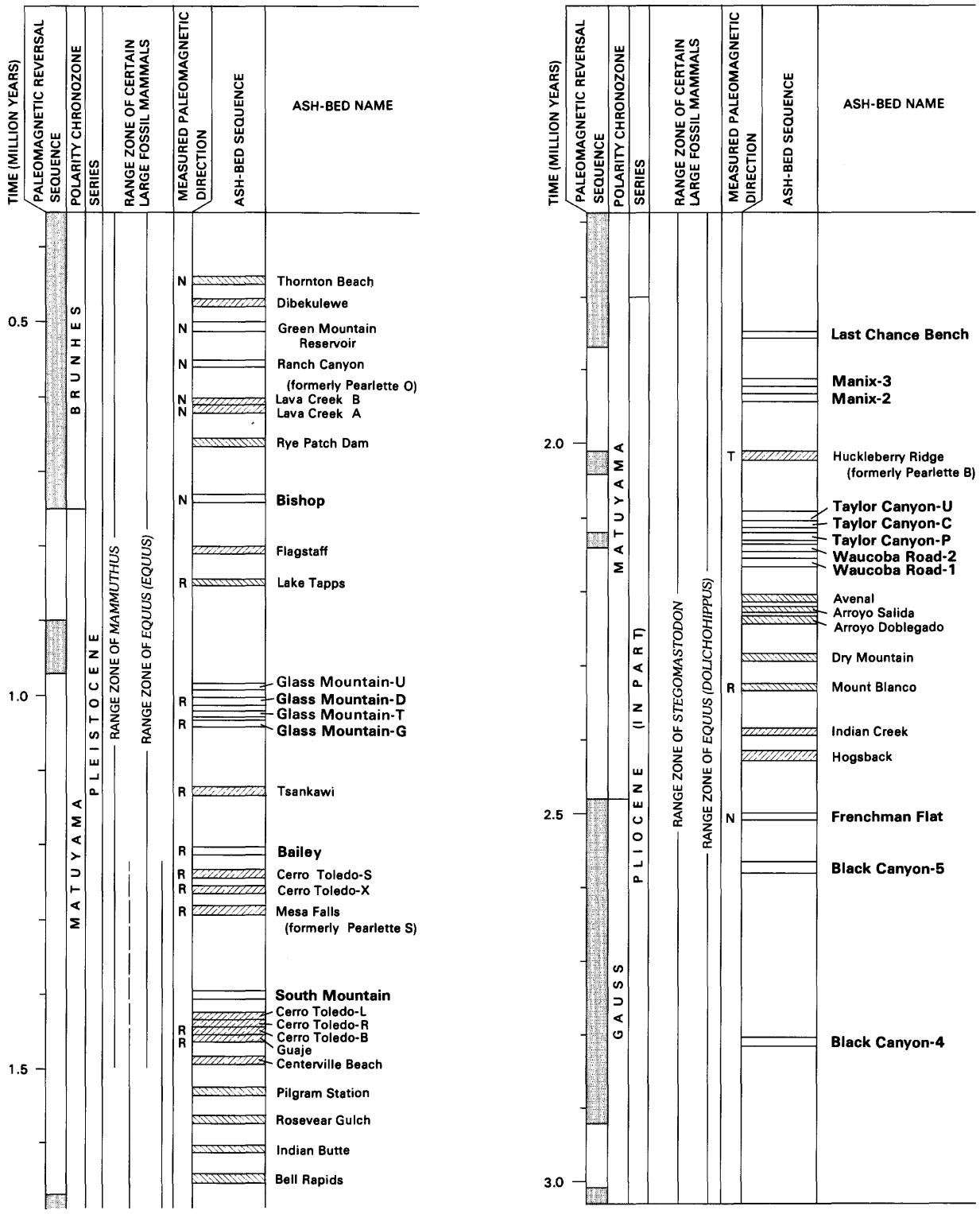
Preparation of samples for K-Ar dating.—In the field, pumice lapilli and blocks collected for K-Ar age determinations were handpicked from the walls of pumice quarries. In the laboratory, groups of pumice lapilli were ultrasonically scrubbed in dilute hydrofluoric acid (about 1 percent), washed in water, and dried. Only those pumice lapilli that would float in water were selected for mineral separation; heavier accidental lithic fragments were excluded using this technique. The outer rinds of large pumice blocks from ash-flow units of the Bishop were ground away or trimmed off with a rock saw to reduce the possibility of contamination by xenocrystic material in the outer vesicles and tubes of the pumice. Following crushing, washing, drying, and sizing of the pumice fragments, mineral separations were made using standard heavy-liquid techniques. The purity of the concentrates resulting from the heavy-liquid separations was improved by removing glass coatings on the minerals with dilute hydrofluoric acid (10 percent) and recycling the mineral concentrates through heavy liquids. The purity of the mineral concentrates was further improved by use of a magnetic separator. After the samples were sized for the final time, they were split, using a Jones-type microsplitter, into fractions for argon and potassium analyses. Argon was extracted from melted mineral concentrates by G. A. Izett, J. D. Obradovich, and H. H. Mehnert; argon isotopic ratios were measured by H. H. Mehnert and J. D. Obradovich using a mass spectrometer at the U.S. Geological Survey's K-Ar laboratory at Denver, Colo. Potassium was determined by flame photometry using a lithium internal standard and by isotope dilution techniques.

ASH BEDS AND TEPHRA UNITS OLDER THAN BUT SIMILAR TO THE BISHOP TUFF

For many years it has been known that the Long Valley area north of Bishop, Calif., was the location of vents from which tephra that now forms the Bishop Tuff was erupted (Gilbert, 1938, p. 1860; Smith and Bailey, 1968, p. 629; Bailey and others, 1976; Hildreth, 1977, 1979). The amount of erupted tephra was enormous (about 500 km^3) and now forms the basal air-fall and overlying, sequential ash flows of the Bishop. From north to south, remnants of the ash flows extend about 70 km from Aeolian Butte to near Bishop, Calif. From east to west, the ash flows extend from Owens Valley for about 60 km to about 10 km west of Mammoth Mountain (Hildreth, 1977, fig. 1).

It is becoming increasingly clear that the episode of rhyolitic, pyroclastic volcanism that produced the Bishop Tuff was not the only one that occurred in the uppermost Cenozoic in the Long Valley–Glass Mountain area, although it certainly was the largest. Evidence is accumulating (Sarna-Wojcicki and others, 1980, 1984; Izett, 1981, 1982; Metz and Mahood, 1983, p. 883; Metz, 1984) that at least 17 and probably many more small pyroclastic eruptions took place episodically in the 2.0 m.y. period prior to the cataclysmic eruption of the Bishop Tuff 0.74 m.y. ago. The tephra formed during the many different episodes of rhyolitic volcanism are united by a common set of chemical (table 11) and mineralogical properties that distinguishes them from tephra generated at other uppermost Cenozoic volcanic centers of the Western United States (Izett and others, 1970; Sarna-Wojcicki and others, 1980, p. 4; 1984; Izett, 1981, 1982). Because of the protracted history of pyroclastic eruptions in the Long Valley–Glass Mountain region, it seems probable that more pyroclastic eruptions will occur in the future. This pyroclastic volcanism is the surface manifestation of the buoyant rise into high levels of the crust of a large granitic batholith that has been chemically and mineralogically evolving beneath the Long Valley–Glass Mountain region in late Cenozoic time.

The relative stratigraphic positions of Pliocene and Pleistocene volcanic ash beds of this report that are chemically and mineralogically similar to Bishop ash beds and the Bishop Tuff are plotted on figure 7. Their geographic locations are shown on figure 8, and pertinent stratigraphic and other data are given in table 12. Also plotted on figure 7 are the stratigraphic positions



EXPLANATION

W-TYPE RHYOLITE ASH BED—White volcanic ash that generally has phenocrystic biotite and contains less than 0.55 weight-percent iron in the glass shards

G-TYPE RHYOLITE ASH BED—Gray volcanic ash that lacks phenocrystic biotite and contains more than 0.55 weight-percent iron in the glass shards

DACITIC ASH BED—White to light-gray volcanic ash that commonly has phenocrystic clinopyroxene and orthopyroxene and, in some instances, amphibole, and whose glass shards contain more than 0.55 weight-percent calcium and 0.55 weight-percent iron

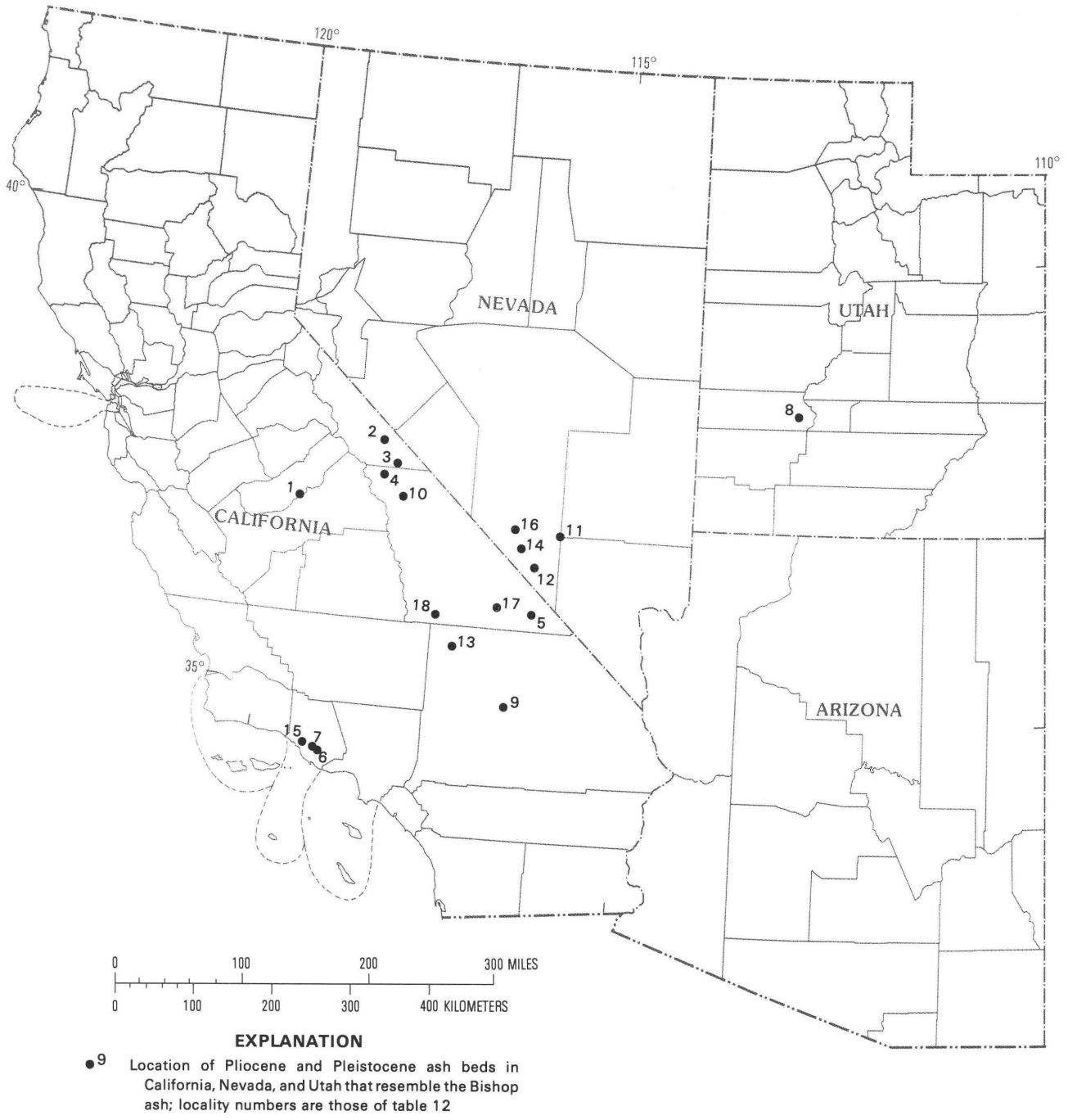


Figure 8. Locations of Pliocene and Pleistocene ash beds in California, Nevada, and Utah that resemble the Bishop ash.

Figure 7 (facing page). Stratigraphic positions of volcanic ash beds of this report relative to some other silicic ash beds of Western United States (modified from Izett, 1981, pl. 1). Also shown are paleomagnetic polarity of some ash beds, geomagnetic time scale of Mankinen and Dalrymple (1979), and range zones of certain fossil mammals. Ash beds of this report shown in bold type. Paleomagnetic polarity as follows: N, normal; R, reverse; T, transitional.

of some other regionally important volcanic ash beds of the Western United States that are chemically and mineralogically distinct from Bishop ash beds, as well as the paleomagnetic time scale of Mankinen and Dalrymple (1979), the paleomagnetic polarity of some ash beds, and the range zones of a few fossil mammals important for correlation and dating. The relative stratigraphic positions of most of the ash beds of figure 7 are known with confidence from field study. However, the relative

stratigraphic positions of a few are inferred, owing to a lack of definitive field relationships or geochronologic data. Figure 7 is an updated, abbreviated version of an attempt by Izett (1981) to construct a stratigraphic summary revealing the record of major, pyroclastic eruptions that took place in the Western United States from 4.0 to 0.1 m.y. ago. Continual revision of such stratigraphic charts becomes necessary as new stratigraphic and geochronologic information becomes available.

Figure 7 differs in the stratigraphic arrangement of the ash beds from that shown by Izett (1981, pl. 1) in the following ways. In 1981, the Frenchman Flat ash bed of southern Nevada was inferred to be about 2.35 m.y. old, and therefore was thought to have been erupted during the Matuyama Reversed Polarity Chron. It is now known that this ash has normal paleomagnetic polarity (W. J. Carr, written commun., 1978), and so is inferred on figure 7 to be in the Gauss Normal Chronozone at about 2.5 m.y. Two samples of volcanic ash from outcrops only a few meters apart collected by J. D. Obradovich in the Kettleman Hills, Calif., were informally named by Izett (1981) the Arroyo Doblegado-1 and Arroyo Doblegado-2. Restudy of the field relationships by G. A. Izett in Arroyo Doblegado now suggests that there is arguably only one ash in Arroyo Doblegado. The Rye Patch Dam ash bed of Nevada was inferred by Izett (1981) to lie below the Dibekulewe ash bed and above the Green Mountain Reservoir ash bed. It is now known with confidence that the Rye Patch Dam bed lies below the Lava Creek B bed (J. O. Davis, written commun., 1982). Three new informal tephra bed names have been introduced in this report and are shown on figure 7. They are the Taylor Canyon-U bed that occurs near Benton Hot Springs, Calif., and the Glass Mountain-T and Glass Mountain-U beds that are about 7 km northwest of Bishop, Calif.

Within and adjacent to the Long Valley–Glass Mountain volcanic field, stratigraphic information and K-Ar ages clearly indicate that there are a minimum of 11 tephra units older than the 0.74-m.y.-old Bishop Tuff. The 7 oldest of these 11 formed during pyroclastic eruptions that occurred in the Long Valley–Glass Mountain area from about 2.8 to 2.0 m.y ago. In ascending order, these tephra beds named by Izett (1981) are the Black Canyon-4, Black Canyon-5, Waucoba Road-1, Waucoba Road-2, Taylor Canyon-P, Taylor Canyon-C, and Taylor Canyon-U (fig. 7). Perhaps the stratigraphically most

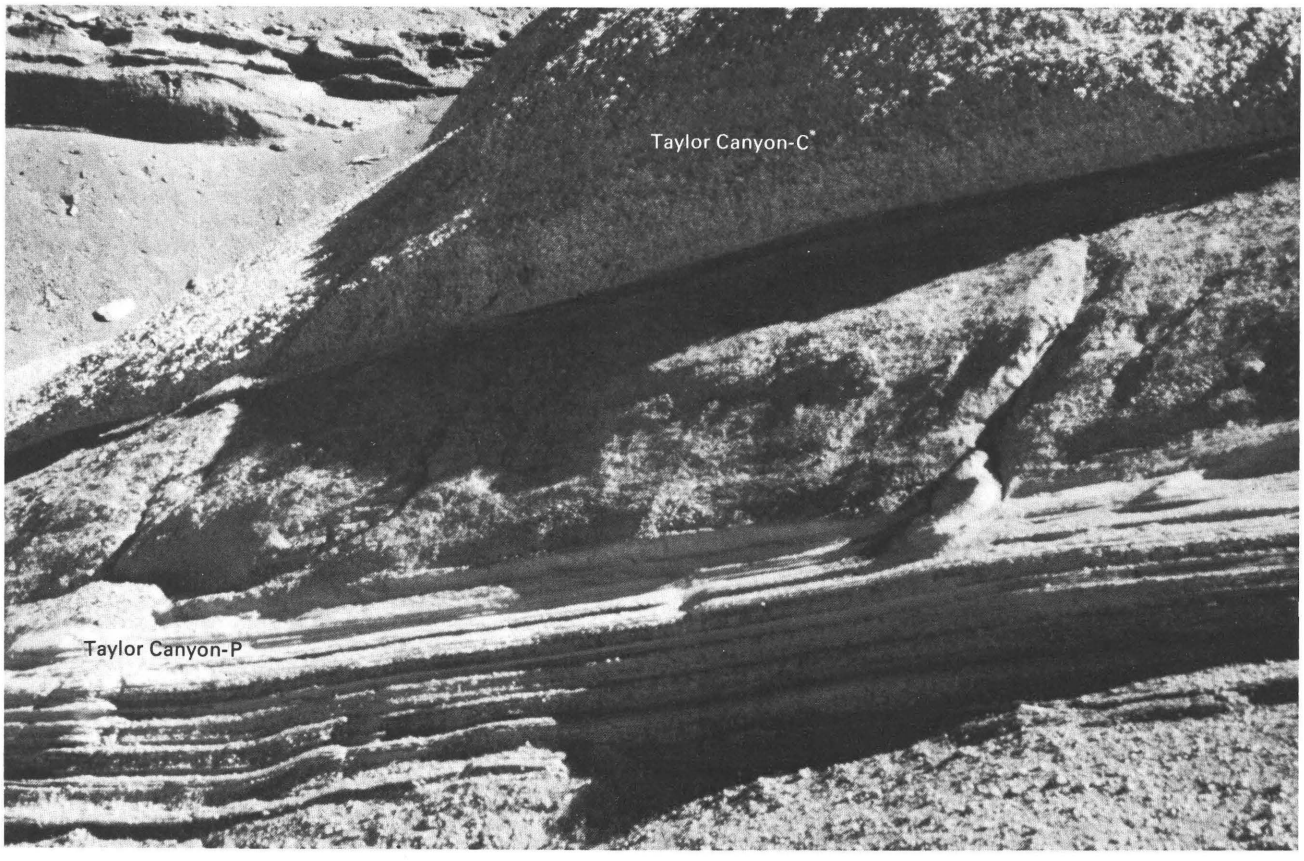


Figure 9. Two tephra units informally named the Taylor Canyon-P and Taylor Canyon-C exposed in pits at the Cowan pumice mine about 4 km south of Benton Hot Springs, Calif. Tephra units separated by 1–2 m of tuffaceous sediments. Taylor Canyon-C, the upper tephra unit, was dated by the K-Ar method at 2.10 m.y. (Izett, 1981, p. 10215).

important of these are in pumice pits near Benton Hot Springs, Calif., where several closely related superposed layers of coarse-grained tephra occur. Three layers of tephra separated by tuffaceous sediments occur at Blind Spring Hill (Chesterman, 1956, p. 54), 12 km southeast of Benton Hot Springs. Two superposed tephra layers separated by tuffaceous sediments occur at the Cowan mine (fig. 9), 4 km south of Benton Hot Springs. Two superposed air-fall tephra units separated by tuffaceous sediments occur in a pit about 3.0 km south of Benton Hot Springs (fig. 10). The two air-fall pumice units at the Cowan mine and at the pumice pit 3.0 km south of Benton Hot Springs are similar to the lower two tephra units at Blind Spring Hill. These tephra beds record closely spaced episodes of pyroclastic volcanism within the volcanic field. The middle of these three tephra beds, the Taylor Canyon-C, was dated by the K-Ar method at 2.10 m.y. (Izett, 1981, p. 10215).

The youngest 4 of the 11 ash beds are interlayered in middle Pleistocene sedimentary rocks that lie 15–20 m below the Bishop Tuff along the Owens River about 7 km north of Bishop, Calif. These four ash beds are very similar chemically and mineralogically and record closely spaced episodes of pyroclastic volcanism in the volcanic field at about 1.0 m.y. ago. In ascending stratigraphic order, these four ash beds are the Glass Mountain-G, Glass Mountain-T, Glass Mountain-D, and Glass Mountain-U.

At locations far distant from the Long Valley–Glass Mountain volcanic field, in California, Nevada, and Utah, six other rhyolite volcanic ash beds have been found that have chemical (tables 5 and 11) and mineralogical properties strikingly similar to the Bishop Tuff and older tephra units in the volcanic field. In most instances, these ash and tephra beds can be shown to occupy older stratigraphic positions relative to the Bishop ash. The chemical and mineralogical similarities of these ashes with the Bishop Tuff and other older tephra units of the volcanic field suggest to us that they probably had their source in that area. These six ash beds, listed in ascending stratigraphic order, are the Frenchman Flat, Manix-2, Manix-3, Last Chance Bench, South Mountain, and Bailey. They range in age from about 2.5 to 1.2 m.y. Sarna-Wojcicki and others (1980, 1984) and Izett (1981, 1982) discussed certain features of these beds and pointed out their mineralogical and chemical affinity with Bishop ash beds.

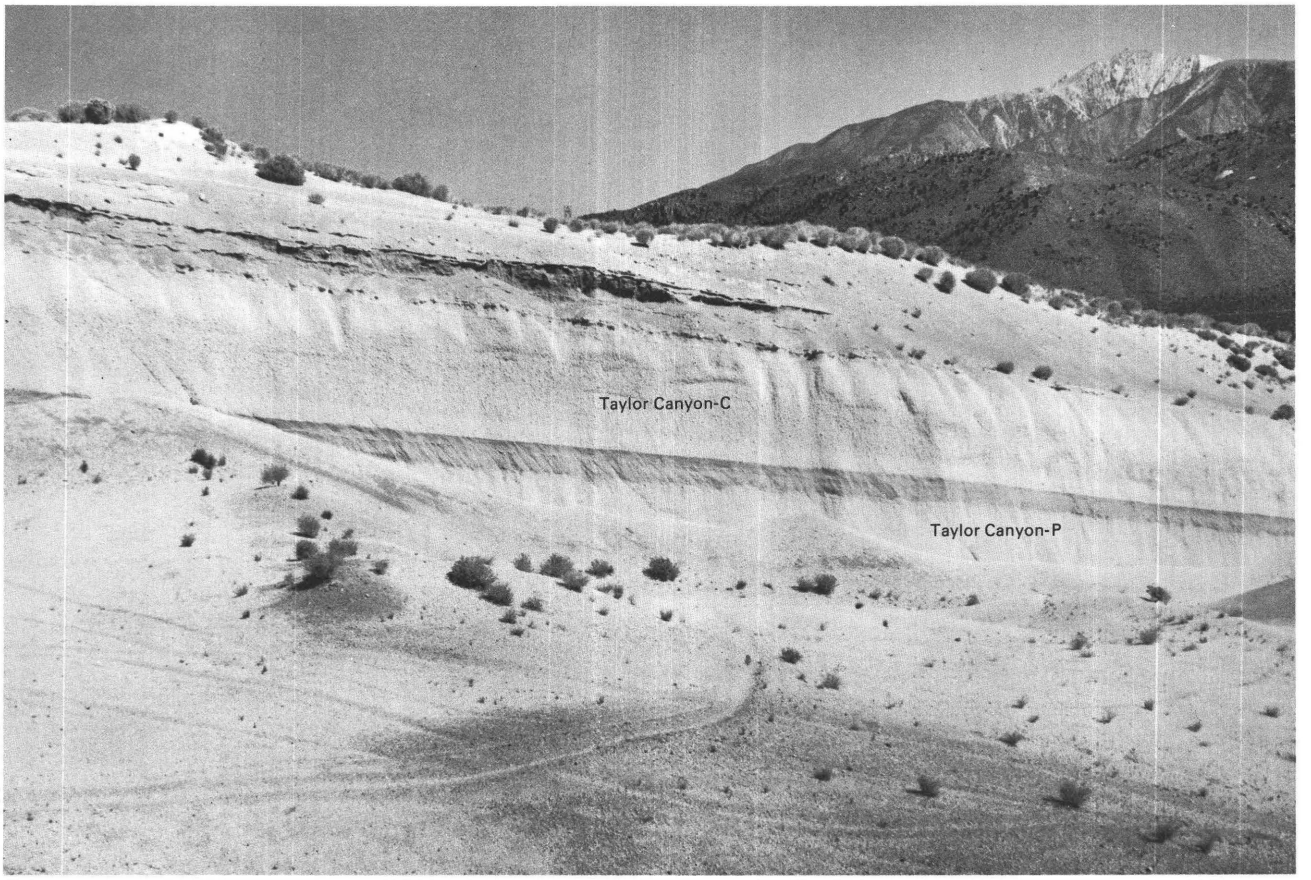


Figure 10. Two unstudied tephra units exposed in abandoned pumice mine about 3 km south of Benton Hot Springs, Calif. The upper tephra unit, which is about 3 m thick, may correlate with the Taylor Canyon-C tephra layer. The lower tephra unit may correlate with the Taylor Canyon-P tephra bed. Tephra units separated by about 1 m of tuffaceous sediments.

In addition to the middle Pleistocene and late Pliocene volcanic episodes, small eruptions of silicic tephra occurred in latest Pleistocene and Holocene time (Bailey and others, 1976, p. 735; Wood, 1977; Sieh and others, 1983, p. 889; Miller, 1983, p. 900) at the Mono-Inyo Craters near Mono Lake, Calif. Lajoie (1968) reported that the late Pleistocene deposits near Mono Lake, Calif., contain 18 different tephra beds generated during eruptions at Mono-Inyo Craters.

In the following sections of this report, the pre-Bishop ash beds are described in ascending stratigraphic succession. Instrumental neutron activation analyses of the glass phases of the ashes are listed in table 11, and locality data, along with pertinent comments, are given in table 12. The ash beds are grouped in table 11 on the basis of similar elemental composition and are arranged from youngest to oldest.

Black Canyon-4 and Black Canyon-5 Ash Beds

Two Pliocene ash beds collected and studied by R. E. Wilcox (written commun., 1971) were named the Black Canyon-4 and Black Canyon-5 by Izett (1981). They are the fourth and fifth beds from the base in a sequence of six ash beds separated by sediments at Black Canyon, about 14 km southeast of Bishop, Calif. Bateman (1965, p. 154) first called attention to one of these ash beds (the Black Canyon-2 ash bed of Izett, 1981) and incorrectly assigned it to the basal air-fall unit of the Bishop Tuff. The chemical composition of this ash bed is unlike Bishop Tuff air-fall tephra.

An ash bed in upper Cenozoic deposits near Airport Lake in the Mountain Springs Canyon 15-minute quadrangle, California (table 12), is here tentatively correlated with the Black Canyon-5 ash bed. The trace-element fingerprint of the ash is similar although the amounts of a few elements do not match exactly.

Analyses of the glass shards of these ash beds indicate that they contain slightly less iron and more manganese than Bishop air-fall tephra (tables 5 and 11). Although the differences in the amounts of these elements are small, they are consistent and significant. Based on a fission-track age of an ash bed that occurs stratigraphically below these two ash beds at Black Canyon (Black Canyon-2 ash bed of Izett, 1981, table 5, bed no. 64) and on a K-Ar age of a tephra bed suspected to overlie it (Taylor Canyon-C of Izett, 1981, pl. 1, bed no. 38), the Black Canyon-4 and Black Canyon-5 ash beds are inferred to be about 2.5 to 2.8 m.y. old. The source of the ash beds is not known, but based on the coarse particle size of the pyroclasts and their chemical composition and mineralogy, it possibly was the Glass Mountain area north of Bishop, Calif.

Frenchman Flat Ash Bed

The Frenchman Flat ash bed was named by Izett (1981, pl. 1, bed no. 47) for an ash at a depth of 195 m (W. J. Carr, written commun., 1978) in a drill hole in Frenchman Flat at the Nevada Test Site. An ash bed (table 11) in a drill hole in Pliocene deposits at Searles Lake, Calif. (Sarna-Wojcicki and others, 1980, table 1, sample 49; 1984), and an ash bed (table 11) in the Lathrop Wells 15-minute quadrangle, Nye County, Nev., collected by Swadley (1983) of the U.S. Geological Survey are correlated with the Frenchman Flat ash bed on the basis of their similar chemical composition (table 11). This ash bed differs from Bishop air-fall tephra because it contains more manganese and less uranium and differs from the Black Canyon-4 ash bed because it contains significantly more iron. A fission-track age determination made by Izett on glass shards separated from the ash bed at its type locality at Frenchman Flat, Nev., yielded an age of 2.2 ± 0.4 m.y. However, glass fission-track ages generally yield only minimum ages owing to track annealing (Naeser and others, 1980), and the ash is somewhat older than 2.2 m.y. W. J. Carr (written commun., 1982) reported that the ash at Frenchman Flat has normal magnetic polarity. Because the ash has normal polarity, it suggests to us that it formed in the age span 2.5–2.9 m.y. during the Gauss Normal Chronozone. Previously, Izett (1981, pl. 1) estimated the age of the ash to be about 2.3–2.4 m.y., but because the ash is now known to have normal polarity, its age is probably older than 2.4 m.y. The source area of this ash bed is not known, but it is suspected to be the Glass Mountain area north of Bishop, Calif., because the glass shards of these ash beds have chemical affinity with tephra known to have originated near Glass Mountain (tables 5 and 11).

Waucoba Road-1 and Waucoba Road-2 Ash Beds

Coarse-grained tephra units in Pliocene sedimentary deposits adjacent to Waucoba Road in the Waucoba Mtn. 15-minute quadrangle, California, were named the Waucoba-1 and Waucoba-2 by Izett (1981, pl. 1, bed nos. 40 and 39). The glass of these tephras contains significantly more manganese than does Bishop air-fall tephra (tables 5 and 11). The Waucoba-1 ash bed contains more cesium, rubidium, tantalum, and uranium than the Bishop; the Waucoba-2 contains slightly more tantalum than the Bishop, but less than the Waucoba-1 ash bed. The age of the Waucoba-1 and Waucoba-2 ash beds is 2.1 to 2.2 m.y., as inferred from stratigraphic relationships with other ash beds. The source area of these tephra units is not known, but based on their coarse grain size and their chemical composition, the Glass Mountain area north of Bishop, Calif., seems probable.

Taylor Canyon-P, Taylor Canyon-C, and Taylor Canyon-U Ash Beds

A group of tephra beds, lava flows, and ash flows older than the Bishop Tuff was mapped and named the tuff of Taylor Canyon by Krauskopf and Bateman (1977) near Benton Hot Springs, Calif., in the Glass Mountain 15-minute quadrangle. The tuff of Taylor Canyon is presumably part of a complex volcanic unit called the rhyolite of Glass Mountain by Bailey and others (1976, p. 729–730). The tephra beds included in the tuff of Taylor Canyon have chemical and mineralogical properties similar to certain Pliocene ash beds at various localities in California, Nevada, and Utah (tables 5 and 11), and because of these similarities they were correlated with the tuff of Taylor Canyon by Izett (1981). In some instances, correlation of ash beds in California, Nevada, and Utah with a specific air-fall tephra unit of the tuff of Taylor Canyon is tentative because many of the tephra beds comprising the unit have not been studied and the chemical and mineralogical properties of those that have been studied are nearly identical.

The principal locality of the Taylor Canyon-P tephra layer is at the Cowan pumice mine 4 km south of Benton Hot Springs, Calif. (fig. 9). It is the lowest of two coarse-grained air-fall pumice units separated by tuffaceous sedimentary rocks. This bed seemingly correlates with the lowest of three coarse-grained air-fall pumice units at the south end of Blind Spring Hill (Tucker, 1927, p. 403–404) near Yellowjacket Canyon, 12 km southeast of Benton Hot Springs, Calif. Results of chemical analyses of samples of the lower bed at the Cowan mine (sample no. 79G11) and the lower of three beds at pumice pits at Blind Spring Hill (sample no. 79G17) are listed in table 11 and locality information is given in table 12. The Taylor Canyon-P ash beds consistently contain less iron and calcium and more manganese, tantalum, cesium, rubidium, and uranium than Bishop air-fall tephra. Ash beds that seemingly correlate with the Taylor Canyon-P ash bed are found southeast of Bishop, Calif., at Black Canyon (sixth ash bed from the base of the ash-bed sequence) and in the Amargosa Valley, Nev., (W. J. Carr, written commun., 1981; tables 11 and 12).

The principal locality for the Taylor Canyon-C tephra bed is also at the Cowan pumice mine 4 km south of Benton Hot Springs (fig. 9). It is the upper of the two air-fall tephra layers in the pumice mine area and probably correlates with the middle of the three tephra layers at Blind Spring Hill. Results of chemical analyses of samples of the upper bed at the Cowan mine (sample nos. 79G10 and 74W60) and the middle of three beds (sample nos. 74W5 and 79G18) at pumice pits at Blind Spring Hill in the White Mountain Peak 15-minute quadrangle are listed in table 11, and locality information is given in table 12. Other correlatives of the Taylor Canyon-C tephra in the Bishop, Calif., area are in the Waucoba Mtn. 15-minute quadrangle (tables 11 and 12, sample nos. 79G25 and 79G29) and in the White Mountain Peak 15-minute quadrangle (tables 11 and 12, sample no. 74W80). Downwind correlatives of the Taylor Canyon-C tephra were found near Beaver, Utah (tables 11 and 12, sample nos. 78G174, 78G167, 79W98, and 79W99). These ash beds in the Beaver, Utah, area occur stratigraphically below the Huckleberry Ridge ash bed (previously called the Pearlette type B ash) of Izett and Wilcox (1982).

The composition of glass shards of the Taylor Canyon-C tephra is nearly identical to the composition of glass of the Taylor Canyon-P tephra. The Taylor Canyon-C seemingly contains slightly less cesium and uranium than the Taylor Canyon-P, and distinction between these chemically similar tephra units is perhaps not always possible. The Taylor Canyon-C tephra was K-Ar dated (sample no. DK 3808) using sanidine at 2.10± 0.02 m.y. by Izett (1981, table 4). The Taylor Canyon-P ash bed, which occurs stratigraphically just below the Taylor Canyon-C ash bed, is probably also about 2.1 m.y. old.

Coarse-grained tephra that forms the uppermost of three stratigraphically superposed air-fall units at Yellowjacket Canyon at Blind Spring Hill southeast of Benton Hot Springs, Calif., is here named the Taylor Canyon-U tephra bed. It is similar in chemical composition (tables 11 and 12, sample nos. 79G20 and 74W6) to the other two Taylor Canyon tephra units except that it apparently contains slightly less uranium. The age of this tephra unit is presumably about 2.1 m.y. because of its stratigraphic nearness to the dated Taylor Canyon-C tephra.

Manix Lake-2 and Manix Lake-3 Ash Beds

Two ash beds separated by only a few meters of Pliocene sedimentary rocks occur along the banks of the Mojave River at Manix Lake, San Bernardino County, Calif. These ash beds were collected and studied by Merriam and Bischoff (1975) and Sarna-Wojcicki and others (1980, 1984) and named by Izett (1981, pl. 1, bed nos. 34 and 35). The chemical composition of the glass shards of the ash beds differ from the chemical composition of Bishop air-fall tephra in that they have a higher manganese content (tables 5 and 11). The Manix Lake-2 ash bed contains nearly twice as much uranium, slightly more cesium and rubidium, and less iron than Bishop air-fall tephra. The Manix Lake-3 ash bed can be distinguished with confidence from the Manix Lake-2 by its lower uranium content and differences in the amounts of several

other elements. The age of these two stratigraphically close ash beds is probably slightly less than 2.0 m.y. because they seemingly overlie an ash, correlated by Sarna-Wojcicki and others (1980, p. 39) with the 2.0-m.y.-old Huckleberry Ridge ash of Izett and Wilcox (1982). The source-area tephra units of the Manix Lake-2 and Manix Lake-3 ash beds are not known. Because the glass shards of these beds are similar to tephra of the Bishop Tuff and the rhyolite of Glass Mountain of Bailey and others (1976, p. 729–730), the source area for the ash beds may be in the Glass Mountain area north of Bishop, Calif.

Last Chance Bench Ash Bed

An ash bed in Pliocene sedimentary rocks that lies about 20 m stratigraphically above the Huckleberry Ridge ash bed of Izett and Wilcox (1982) near Beaver, Utah, was named the Last Chance Bench bed by Izett (1981, p. 10217–10218). This ash is nearly identical to Bishop air-fall tephra in chemical composition (tables 5 and 11). The age of this ash may be about 1.8 to 1.9 m.y. as judged by its stratigraphic nearness to the underlying well-dated Huckleberry Ridge ash bed (2.0 m.y.). The source-area tephra unit of this ash bed is not known; however, the Glass Mountain area north of Bishop, Calif., seems likely because of the similarity in chemical composition of glass shards of this ash bed and tephra units of the Bishop Tuff and the rhyolite of Glass Mountain of Bailey and others (1976, p. 729–730).

South Mountain Ash Bed

A thin, lenticular ash bed in Pliocene to Pleistocene marine sedimentary rocks of the Pico Formation near Ventura, Calif. (Sarna-Wojcicki and others, 1980, p. 36, sample 27; 1984, p. 30–31), was named the South Mountain by Izett (1981, p. 10217). It is nearly identical in chemical composition to Bishop air-fall tephra (tables 5 and 11). Sarna-Wojcicki and others (1984, p. 30–31) reported that the ash bed occurs about 245 m below the Bailey ash. The glass shards contain slightly more cesium, rubidium, and manganese than the glass phase of Bishop air-fall tephra. Its age is presumably about 1.5 m.y. (Sarna-Wojcicki and others, 1984, p. 30–31) based on its stratigraphic position below the overlying Bailey ash bed dated about 1.2 m.y. by Izett and others (1974). The source-area tephra unit for this ash bed is not known; however, the Glass Mountain area north of Bishop, Calif., seems likely because of the similarity in chemical composition of glass shards of this ash bed and tephra units of the Bishop Tuff and the rhyolite of Glass Mountain of Bailey and others (1976, p. 729–730).

Bailey Ash Bed

An ash bed in marine Pliocene and Pleistocene sedimentary rocks of the Pico Formation near Ventura, Calif. (Izett and others, 1974; Sarna-Wojcicki and others, 1980, 1984, p. 28–30; Izett, 1981, p. 10217), was called the Bailey ash by Yeats and McLaughlin (1970). Glass shards of this ash bed contain significantly more cesium, rubidium, uranium, and manganese (Izett and others, 1974) than do glass shards of Bishop air-fall tephra (tables 5 and 11). The chemical composition of the Bailey ash is nearly identical to the South Mountain ash. Based on the analyses at hand (table 11), the Bailey seemingly contains more thorium than the South Mountain; however, the thorium-to-uranium ratio of the South Mountain bed seems anomalously low compared to most other Bishop-like ash beds. The Bailey seems to contain less scandium than does the South Mountain. The age of the Bailey ash was determined by Izett and others (1974) at about 1.2 m.y. using the fission-track method on zircon crystals. The ash is reversely magnetized (G. A. Izett, 1985, unpublished data) and was erupted during the Matuyama Reversed Polarity Chron. The source-area tephra unit for this ash bed is not known; however, the Glass Mountain area north of Bishop, Calif., seems likely because of the similarity in chemical composition of glass shards of this ash bed and tephra units of the rhyolite of Glass Mountain of Bailey and others (1976, p. 729–730).

Glass Mountain Family Ash Beds

Four chemically and mineralogically similar volcanic ash beds, here informally called the Glass Mountain family ash beds, occur in Pleistocene sedimentary rocks 15–20 m below the Bishop Tuff about 7 km north of Bishop, Calif. (fig. 11). The ash beds are separated by several meters of sedimentary rocks and record separate pyroclastic eruptive events. Two of these ash beds were named the Glass Mountain-G and Glass Mountain-D by Izett (1981, p. 10217). The other two Glass Mountain family ash beds of this report are here informally named the Glass Mountain-T and Glass Mountain-U. Other ash beds correlated with the Glass Mountain family of ash beds are shown on figure 8, and locality information is given in table 12. One of these ash beds, which is suspected to be a Glass Mountain-G or a Glass Mountain-D ash bed, occurs about 10 m below the Bishop ash bed in sedimentary deposits of ancient Lake Tecopa near Shoshone, Calif. (Sheppard and Gude, 1968, fig. 6). Because the chemical and mineralogical fingerprints of the Glass Mountain family ash beds are so similar, the probabilities for exact correlation among

them are not large. Furthermore, the chemical composition of the Glass Mountain family ash beds is nearly identical to that of Bishop air-fall tephra, and the ability to confidently distinguish them from the Bishop, based on the data at hand, may not be great. Of equal importance, the mineralogy and the chemical composition of the phenocrysts in the Glass Mountain family ash beds are also nearly identical to those in Bishop air-fall tephra. Although the ash beds may not be distinguished from Bishop ash beds on the basis of chemical composition and mineralogy, Glass Mountain ash beds should have reverse paleomagnetic polarity, whereas Bishop ash beds should have normal magnetic polarity. The Glass Mountain family ash beds formed during pyroclastic eruptions associated with the emplacement of the many rhyolite lava flows (Bailey and others, 1976, p. 729–730) that form Glass Mountain (Metz, 1984).

MATUYAMA AND BRUNHES PALEOMAGNETIC BOUNDARY

Considerable geochronologic work has been done in the last 25 years to establish and refine a geomagnetic polarity time scale by K-Ar dating lavas and tuffs that had been paleomagnetically studied. Some of the more important papers recording this work are those by Rutten (1959); Cox and others (1963a, 1963b, 1964, 1968); McDougall and Tarling (1963); Dalrymple and others (1965); Doell and Dalrymple (1966); Doell and others (1966); McDougall and Chamalaun (1966, 1969); Cox (1969); Dalrymple (1972); McDougall (1977); and Mankinen and Dalrymple (1979).

One of the first rocks to be intensively studied by both paleomagnetic and geochronologic methods was the Bishop Tuff. Evernden and others (1957, p. 14; 1964), Evernden (1959), and Evernden and Curtis (1965)

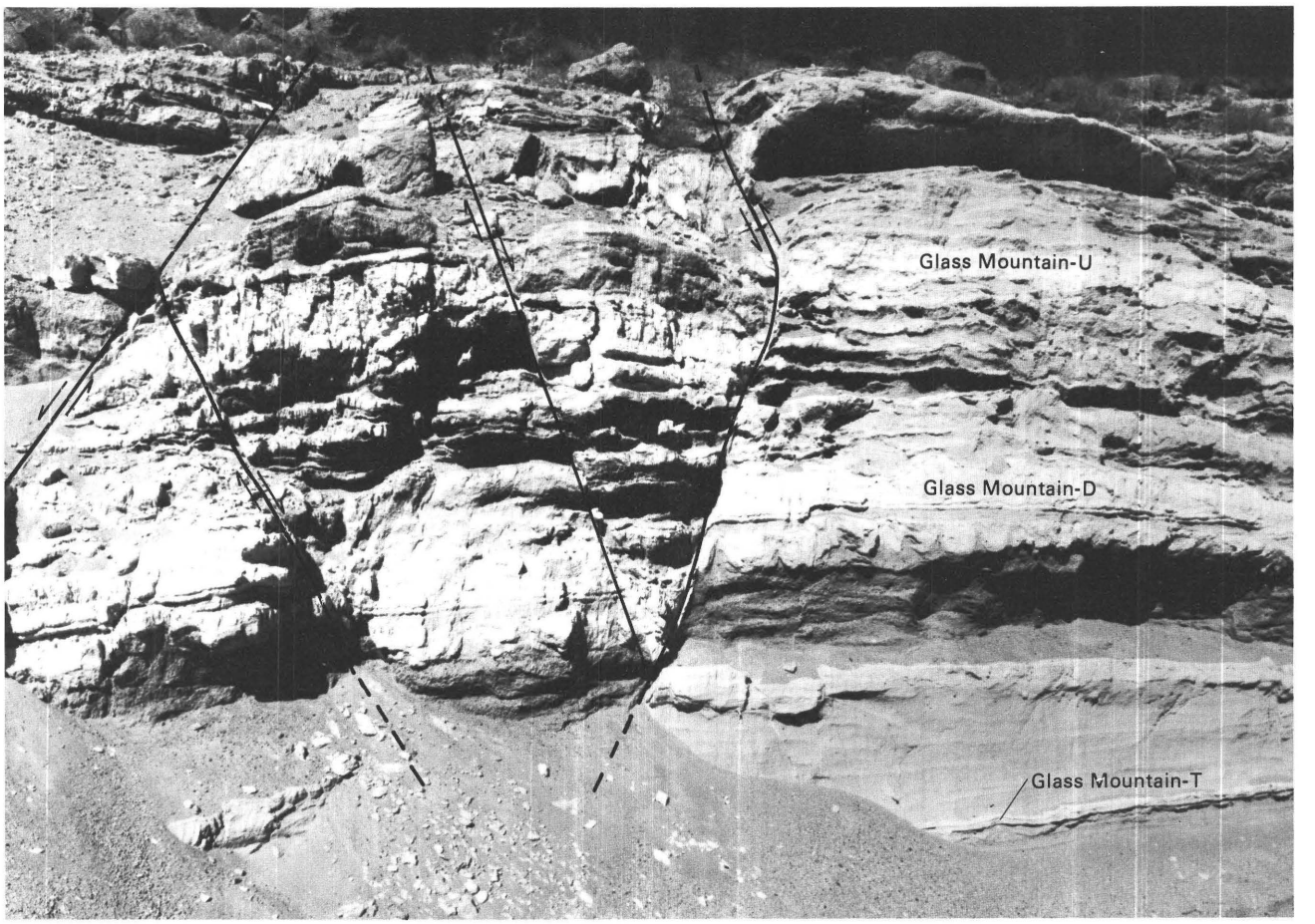


Figure 11. Tephra beds exposed in roadcut along the Owens River about 7 km north of Bishop, Calif. At least four tephra layers occur at this locality within middle Pleistocene sedimentary deposits that lie stratigraphically below the Bishop Tuff. Glass Mountain-T, Glass Mountain-D, and Glass Mountain-U are shown in photograph. Glass Mountain-G is below road level out of the photograph. Several small faults can be seen in the left part of the photograph.

measured K-Ar ages of tuff samples of the Bishop that ranged from 0.9 to 1.2 m.y. Cox and others (1963a, p. 1050) established that the Bishop was erupted at a time just following the last change in polarity of the Earth's magnetic field from reverse (Matuyama Reversed Polarity Chron) to normal (Brunhes Normal Polarity Chron). Thus, an isotopic age could be assigned to the Matuyama and Brunhes boundary of about 1.0 m.y.—providing that the K-Ar age of the Bishop Tuff had been accurately determined. The Bishop Tuff was a particularly important target for efforts to establish the Matuyama and Brunhes boundary because it is a rhyolite that contains sanidine, one of the best materials for precise K-Ar dating.

Dalrymple and his colleagues (1965) were aware that many ash-flow tuffs, such as the Bishop, contain xenocrystic potassium feldspar incorporated in tuffs during their emplacement. They recognized the possibility that feldspar concentrates used by Evernden and others (1957, p. 14), Evernden (1959), Evernden and others (1964), and Evernden and Curtis (1965) to date the Bishop might be contaminated with xenocrystic, Sierran-age potassium feldspar. Because of this possibility, Dalrymple and others (1965) determined a new set of K-Ar ages for the Bishop. Instead of using samples of welded tuff as a source for sanidine, as had been done in previous experiments, individual pumice lumps were used to obtain sanidine concentrates. The probability is moderately high that individual pumice lumps in the ash flows of the Bishop Tuff are free of xenocrystic feldspar. Nevertheless, the posssibility exists that xenocrystic potassium feldspar can be forced fairly deep into vesicles of pumice lumps during emplacement of the ash flows. The probability is even higher that pumice lumps in the air-fall unit at the base of the Bishop are xenocryst free. The K-Ar age of sanidine separated from the pumice proved to be slightly younger (about 0.7 m.y.) than ages (0.9–1.2 m.y.) determined by Evernden and his coworkers. In 1976, Dalrymple (in Bailey and others, 1976) recalculated the K-Ar age of the Bishop using the analytical data collected by Dalrymple and others in 1965. They reported a weighted-mean age of 0.703 ± 0.015 m.y. for the Bishop. The K-Ar age of the Bishop again was recalculated at 0.727 m.y. by Mankinen and Dalrymple (1979, p. 619) using the original analytical data of Dalrymple and his coworkers and the newly recommended decay constants of Steiger and Jäger (1977).

Mankinen and Dalrymple (1979, p. 624) assigned an age of 0.73 m.y. to the Matuyama and Brunhes boundary based on analysis of statistically acceptable (Cox and Dalrymple, 1967) K-Ar ages of normally and reversely magnetized rocks near the boundary. Most of the ages used to bracket the Matuyama and Brunhes polarity boundary were obtained by dating whole rock samples of basalts or, in a few instances, obsidian (Mankinen and Dalrymple, 1979, p. 619). Basalts in general contain only

Table 13. Potassium-argon ages of reversely magnetized rhyolite domes from the Jemez Mountains, New Mexico

[Ages calculated or recalculated using decay constants and isotope abundances recommended by Steiger and Jäger (1977); ± is one sigma; potassium determined by flame photometry by E.L. Brandt, U.S. Geological Survey]

Lab No.	Potassium (percent)	Sample weight (gm)	Radiogenic ^{40}Ar/gm ($\times 10^{-11}$ mole)	Radiogenic ^{40}Ar (percent)	Age($\times 10^6$ years)	Sample No. and dated material	Sample location and remarks
DKA4376	6.86	6.8283	0.8967	40.4	0.75±0.02	82W8, sanidine.	Pumice from rhyolite of Cerro San Luis, Jemez Mountains, N. Mex.; sample collected by R. L. Smith, U.S. Geological Survey.
DKA4377	6.80	5.7302	0.9458	33.2	0.80±0.03	82W8A, sanidine.	Do.
3X122	7.20	7.043	1.054	71.3	0.845±0.074	S41, sanidine.	Pumice from rhyolite of Cerro San Luis, Jemez Mountains, N. Mex.; data from Doell and others (1968, p. 236-238).
4D214	7.17	9.426	0.8100	42.4	0.710±0.015	S41 sanidine.	Do.
	7.16	11.266	0.8740	68.3			
		10.834	0.9179	63.8			
		11.244	0.9296	76.7			
4D003	7.03	10.495	0.8663	79.7	0.726±0.019	S40, sanidine.	Pumice from rhyolite of Santa Rosa II, Jemez Mountains, N. Mex.; data from Doell and others (1968, p. 236-238).
	7.09	10.625	0.9101	63.2			
4D001	7.10	10.827	0.9130	52.7	0.745±0.015	S39, sanidine.	Pumice from rhyolite of Cerro Seco, Jemez Mountains, N. Mex.; data from Doell and others (1968, p. 236-238).
	7.11	10.505	0.9237	60.8			

small amounts of potassium and rarely contain minerals rich in that element; therefore, if basalts are to be dated by the K-Ar method, the whole rock method is generally used. Because of their young age and their low potassium content, basalt flows yield K-Ar ages that have relatively large uncertainties owing to their small content of radiogenic ^{40}Ar relative to atmospheric ^{40}Ar. However, if only sanidine ages, which generally are more reliable than whole rock basalt or obsidian ages, are used to establish the boundary, then the boundary must be older than the age of the normally magnetized Bishop Tuff herein dated at 0.74 m.y. (table 9).

Doell and others (1968) added important geochronologic and paleomagnetic information bearing on the age of the Matuyama and Brunhes boundary. They K-Ar dated sanidine-bearing, reversely magnetized rhyolite domes in the Jemez Mountains, N. Mex. The published sanidine ages of Doell and others (1968) recalculated using the decay constants recommended by Steiger and Jäger (1977) for the Cerro San Luis, Cerro Santa Rosa II, and Cerro Seco domes and two new K-Ar ages from Cerro San Luis are given in table 13. The K-Ar ages range from 0.710 ± 0.015 to 0.84 ± 0.074 m.y.

Statistical analysis of the analytical data (table 13) from the three reversely magnetized domes with the hope of establishing a more precise age for the Matuyama and Brunhes boundary is not warranted, in our opinion, for two reasons. The relative geologic age of the Cerro Seco, Cerro Santa Rosa II, and Cerro San Luis domes cannot be established using field relations, according to Doell and others (1968, p. 216), and therefore, averaging the K-Ar age data for the three domes, which are of uncertain relative age, is inappropriate. Although their relative ages cannot be established, they must have been intruded at nearly the same time based on other geologic relations and the K-Ar age data.

Four age determinations (table 13) are available for one of the reversely magnetized rhyolite domes, Cerro San Luis. Inexplicably, the K-Ar ages have a wide range, from 0.845 to 0.71 m.y. If the wide range is overlooked, however, and the four ages averaged, the age can be used to bracket the Matuyama and Brunhes boundary. The age of the boundary probably lies between the average K-Ar age of the reversely magnetized rhyolite of Cerro San Luis (0.78 m.y.) and the K-Ar age of the normally magnetized Bishop Tuff (0.74 m.y.). The K-Ar age of the other two reversely magnetized domes in the Jemez Mountains (table 13) are 0.726 ± 0.19 m.y. and 0.745 ± 0.15 m.y. These K-Ar ages of Cerro Santa Rosa II and Cerro Seco suggest that the Matuyama and Brunhes boundary is very close to the age of the 0.74-m.y.-old, normally magnetized Bishop Tuff.

In summary, the age of the boundary may be close to 0.75 m.y. This conclusion is reached based on the K-Ar ages of the reversely magnetized domes in the Jemez Mountains (table 13) and the fact that the Matuyama and Brunhes boundary occurs 65 cm below the Bishop ash (0.74 m.y. old) in sediments of ancient Lake Tecopa (Hillhouse and Cox, 1976, p. 56) and 183 cm below the Bishop ash in sediments of ancient Lake Bonneville (Eardley and others, 1973, p. 212).

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