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# Distribution, correlation, and radiocarbon dating of late Holocene tephra, Mono and Inyo craters, eastern California

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## ABSTRACT

Two pumiceous tephra layers, widespread in meadow topsoils of the southern Sierra Nevada, are correlated on the basis of radiocarbon dates and trace-element analyses with two eruptive centers at the northern and southern ends of the Mono Craters–Inyo craters volcanic chain in eastern California. Pumice and obsidian that were erupted in the northern part of the chain are uniform in trace-element content, whereas those erupted from the southern part are nonuniform and distinctly different, particularly in Sr content. Similar differences are recognized in the two most recent and widespread tephra layers originating from these sites. These tephra layers are the deposits of the most recent explosive eruptions of magma from the Mono Craters and the Inyo craters.

Tephra 1, characterized by sanidine microphenocrysts and a Sr content of about 215 ppm, was erupted 720 ± 60 yr B.P. Its distribution defines a south-trending lobe extending over the Sierra Nevada from the upper San Joaquin drainage area to the Little Kern drainage area. Sr, Rb, and Zr contents of the ash are similar to those of a tephra-ringed obsidian dome at the south end of the Inyo craters.

Tephra 2, characterized by a lack of microphenocrysts and a Sr content of less than 20 ppm, was erupted 1190 ± 80 yr B.P. It is encountered as a fine ash layer in the Sierra Nevada from northernmost Yosemite to Kings Canyon. Its low Sr content indicates geochemical affinity with the Mono Craters. Panum Crater, a tephra-ringed dome at the north end of the chain, appears to be its most likely source vent.

## INTRODUCTION

The Mono and Inyo craters are a late Quaternary volcanic chain extending from Mono Lake to the Long Valley caldera (Mayo and others, 1936; Putnam, 1938; Kistler, 1966; Huber and Rinehart, 1967). The chain includes the basaltic tephra cone of Black Point, the dacitic to rhyodacitic Mono Lake islands, the rhyolitic Mono Craters, and the rhyolitic and rhyodacitic Inyo domes. This paper is a report on the most recent pyroclastic eruptions from the chain and correlates their widespread tephra deposits with specific eruptive centers.

The Mono Craters are a 17-km-long arcuate chain of late Quaternary domes, flows, and tephra deposits. They are composed of chemically homogeneous rhyolite (Carmichael, 1967; Jack and Carmichael, 1968) except for an older rhyodacite dome on the northwest side (Lajoie, 1968). Kistler (1966) suggested that the arcuate shape of the Mono Craters chain is related to a mylonitized ring-fracture system about 12 km in diameter in the June Lakes area. Bailey and others (1976) suggested that a magma chamber lies beneath this ring-fracture zone. More recent mapping by Bailey (U.S. Geol. Survey, 1976) of more extensive, concentric fractures and faults shows that the ring-fracture zone is nearly 18 km in diameter and that it has been displaced downward toward the center at least 200 m since the time the Bishop tuff was deposited [Bishop tuff has been dated as 0.7 m.y. by Dalrymple and others (1965)].

The Inyo craters form an 11-km-long discontinuous straight chain of chemically and physically heterogeneous domes (Lajoie, 1968) and tephra deposits. Bailey and others (1976) suggested that the Inyo domes represent mixing along a north-south fissure system of rhyodacitic magma from the Long Valley chamber with rhyolitic magma from a chamber beneath the Mono Craters. Evidence presented in this paper indicates that the north and south extremities of the Mono-Inyo chain have been the most recently active parts.

### Eruptive Sequence

The sequential development of eruptive forms of the Mono and Inyo craters type was outlined by Williams (1932) and extended by Putnam (1938). The initial stage forms an explosion crater rimmed by tephra. This is followed by extrusion of a dome on the crater floor, and, if extrusion continues, it overflows the tephra rim to form a coulee that may extend several kilometres from the vent. In some instances the dome itself may be subsequently cratered by collapse or explosion, producing a double crater (Smith, 1973). The most recent sequences commenced with violent pyroclastic eruptions of pumice. The only exceptions are a few small domes (<300 m diam) in the Mono Craters.

Reports of direct observations of an eruptive sequence producing forms like those seen in the Mono-Inyo chain are rare in the literature; however, events occurring during the 1912 eruptions in the Valley of Ten Thousand Smokes, Alaska, are enlightening, because the resulting form of the major volcanic vent, Novarupta, resembles in size and shape the tephra-ringed dome of Panum Crater on the south shore of Mono Lake (Green and Short, 1971). The Novarupta vent erupted a voluminous (10.9 km$^3$), incandescent tuff flow; this was followed by several equally voluminous eruptions of pumiceous tephra totaling 19.8 km$^3$ of expanded tephra (Curtis, 1968). The resulting tephra-ringed crater was then invaded by a viscous plug of banded pumiceous obsidian 400 m in diameter and 100 m high (Fenner, 1923, 1950). Major eruptive activity commenced on June 6 and had apparently entirely ceased by the end of July 1912. It is not known precisely when or how long Novarupta was extruded, because the valley was not visited until 1915; however, it clearly was extruded during that period of less than three years. The area has been dormant since that time. In contrast, extrusion of the Santiaguito dome in Guatemala did not commence until 20 yr after the two-day violent eruptions of 5.5 km$^3$ of dacitic pumice in 1902 (Williams, 1932; Rose, 1972). Extrusion of the dome has continued in a crudely cyclic manner to the present — a period of 51 yr (Rose, 1973). Both analogies suggest that it is the initial explosive stage that supplies large volumes of pumiceous tephra and that some eruptive sequences involving a tephra ring and a subsequent dome may occur in a relatively short geologic time.

### Geochronology of the Volcanoes

Volcanoes have been dated by a variety of methods in recent years. The most reliable ages, including newly obtained data from this work (Table 1), are summarized

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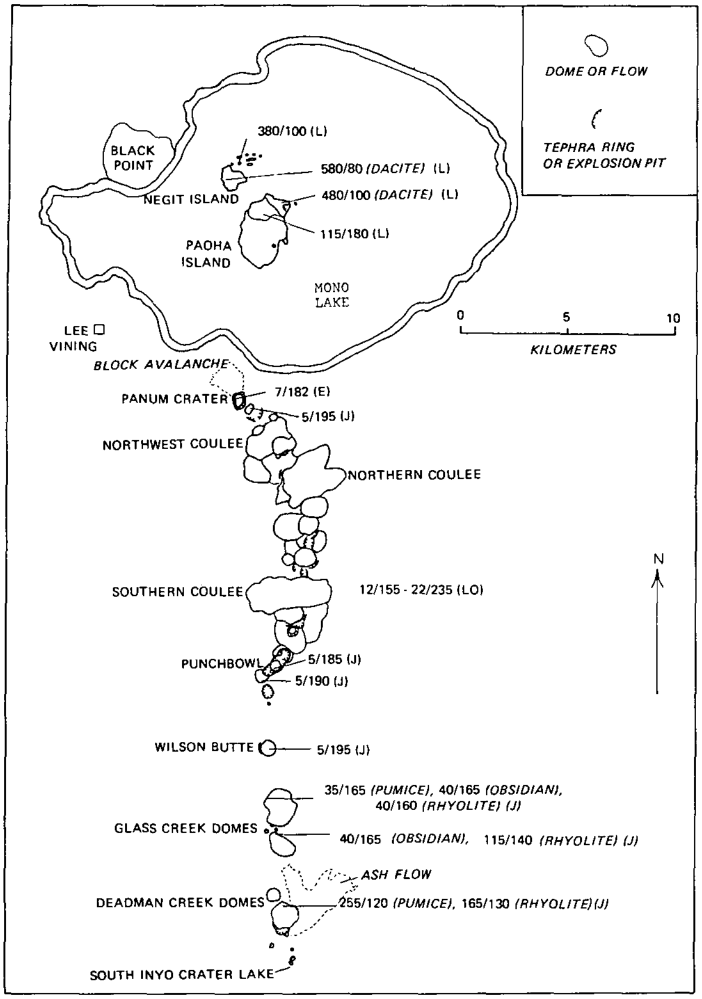

**Figure 1.** Compilation of radiocarbon and hydration-rind ages on the Mono and Inyo craters. Map based on Lajoie (1968) and reconnaissance mapping. Source of radiocarbon ages: R = Rinehart and Huber (1965); L = Lajoie (1968) and Denham and Cox (1971); W = this study. Hydration-rind ages: F = Friedman (1968). Newly obtained radiocarbon ages given in Table 1.

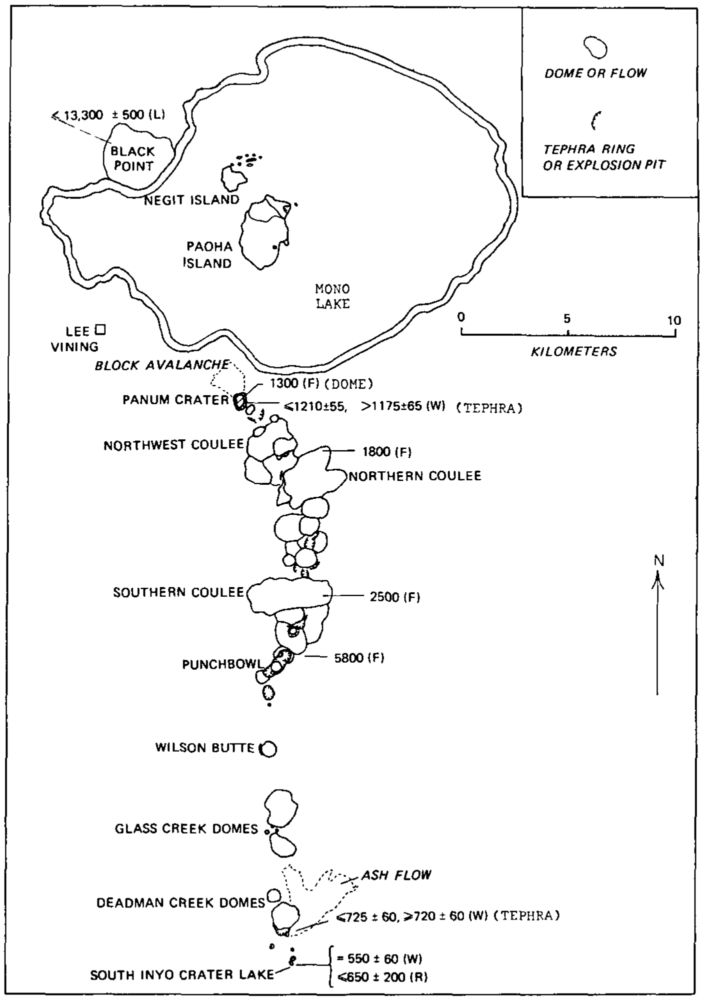

**Figure 2.** Compilation of Sr and Rb analysis on extrusive rocks of the Mono and Inyo Craters; rocks are rhyolite except as noted. Sr/Rb values in ppm followed by data source. X-ray fluorescence analyses: J = Jack and Carmichael (1968); L = Lajoie (1968) LO = Loney (1968). Isotope dilution analyses: E = T. O. Early, unpub. data.

in Figure 1. I omitted the K-Ar dates obtained by Dalrymple (1967). Individual K-Ar determinations have poor reproducibility owing to low radiogenic argon content, although several of the analyses are consistent and indicate ages on the order of 10,000 yr or less.

Friedman (1968) dated obsidian samples from the northern Mono Crater group by the hydration-rind method. Lacking radiocarbon calibration of the hydration rate for the Mono Craters area, he used data from Medicine Lake, northern California, which yielded late Holocene ages for several Mono Craters obsidian bodies. The method establishes relative temporal relationships within these volcanoes, and absolute ages may be assigned if the hydration rate can be locally calibrated to a few radiocarbon or dendrochronologically dated materials.

A radiocarbon age of 650 ± 200 yr (Sample W-1431) was reported by Rinehart and Huber (1965) for the steam explosion that excavated the south Inyo Crater Lake. They reported a maximum radiocarbon age of 1,440 ± 150 yr (sample W-727) for the eruption of the pumice lapilli layer that blankets the Mammoth Mountain area, but they did not identify the vent from which the pumice erupted.

Batchelder (1970) reported that five pumiceous tephra layers were found in piston cores of the organic lacustrine silts of Black Lake, Adobe Valley, which is 16 km east of the volcanic chain. Two layers are stratigraphically above a radiocarbon date of 2190 ± 130 B.P., and three layers occur between sediment dated at 4580 ± 130 and 4230 ± 110 B.P. No tephra has been reported from the sediment between 5230 ± 110 and 11,350 ± 350 B.P.

Lajoie (1968) studied the 17 rhyolite tephra layers in the lacustrine silts deposited during the late Wisconsin high stand of Mono Lake. Ages of the 17 tephra layers range from 13,100 to 30,310 yr [on the basis of extrapolations from two radiocarbon dates for ostracode tests of 13,300 ± 300 and 23,300 ± 300 B.P. (Denham and Cox, 1971)]. Two basaltic tephra layers occur in the section. The most prominent basaltic tephra is dated at 13,100 B.P. and was correlated by Lajoie (1968) with the Black Point basaltic cone.

## Trace-Element Geochemistry of the Volcanic Rocks

The trace-element contents of the northern group of Mono Crater bodies are relatively uniform and homogeneous (Jack and Carmichael, 1968). Trace-element contents of the southern Inyo group of extrusive rocks and recent extrusive rocks on the islands in Mono Lake are distinctly different and seemingly unique for each eruptive vent, particularly in Zr, Sr, and Ba contents (Jack and Carmichael, 1968; Lajoie, 1968).

Existing data for Rb and Sr on the extrusive materials are compiled in Figure 2. Sr shows large variation throughout the volcanic chain, with values ranging from 5 to 580 ppm. The Sr content of the Inyo craters and the island volcanic rocks appears distinctive for each eruptive center. The Mono Craters, including Wilson Butte, have remarkably low Sr contents (less than 22 ppm), and individual centers are indistinguishable by trace-element contents. Rb content variations through the volcanic chain are not large, all of the analyses lying between 80 and 195 ppm. Analyses by Jack and Carmichael (1968) of pumice, rhyolite, and obsidian from the same vent suggest that trace-element chemistry does not vary greatly throughout an eruptive sequence, although many more analyses of this type are needed to ascertain the reliability of this conclusion.

Seventeen rhyolitic tephra layers in a section of late Wisconsin Mono Lake sediments were analyzed by Lajoie (1968) and found to have a uniform trace-element content similar to the Sr-poor Mono Craters bodies. No tephra was found in that section with the higher Sr content characteristic of the Inyo craters and the Mono Lake island volcanic rocks.

TABLE 1. LOCATION OF RADIOCARBON-DATED SECTIONS WITH TEPHRAS 1 AND 2

| Locality | Material | Radiocarbon no. | Date (yr B.P.) |
|---|---|---|---|
| Southernmost Inyo Crater Lake,<br>Devils Postpile quadrangle<br>lat 37°41.8'N, long 119°0.6'W | Pine log | UGa-603[*] | 710 ± 60 |
| Lower Cabin Meadow,<br>Huntington Lake quadrangle<br>lat 37°3.2'N, long 119°6.8'W | Fir log | UGa-602[*,†] | 760 ± 60 |
| West fork, Long Meadow Creek,<br>Patterson Mountain quadrangle<br>lat 36°58.8'N, long 119°0.8'W | Fir stump<br>Fir log | UGa-450[*]<br>UGa-451[*] | 1,210 ± 55<br>1,175 ± 60 |
| Devils Postpile Road,<br>Devils Postpile quadrangle<br>lat 37°39.5'N, long 119°04.3'W | Charcoal | UGa-449[*] | 3,375 ± 140 |
| East Meadow of Aspen Valley,<br>Yosemite National Park,<br>Hetch Hetchy quadrangle<br>lat 37°50.0'N, long 119°44.5'W | Charcoal | I-6049[‡] | 1,545 ± 90 |

[*] Brandau and Nokes (1974).

[†] Stratigraphic relationship of UGa-602 and tephra 1 is incorrectly reported in Brandau and Nokes (1974) and is correct in this paper.

[‡] Wood (1972).

## DISTRIBUTION AND CHARACTER OF TEPHRAS 1 AND 2

Two recent ash and lapilli layers, a few centimetres thick, are recognized in meadow topsoils of the southern Sierra Nevada at widely distributed localities (Figs. 3, 4). These layers are the only significant tephras found within meadow-deposit sections on the west Sierra slope between 36° and 38°N, with the exception of two older layers recognized only in the upper San Joaquin River drainage area (Wood, 1975).

Tephra 1 commonly occurs at a depth of 10 to 30 cm in mountain-meadow topsoils as a 0.5- to 3-cm-thick layer of white to tan, fine lapilli and ash. Some lapilli and coarse ash grains are porphyritic pumice. Tephra 2 occurs at a depth of 30 to 60 cm as a 0.5- to 2-cm-thick layer of white ash. Tephra 2 is entirely aphyric fine ash; no grains of lapilli size (4 mm) are found in the Sierra Nevada.

### Distribution

**Tephra 1.** The distribution of remnants of the youngest tephra defines a south-trending lobe extending 190 km (120 mi) from the Inyo craters (Fig. 3). This tephra forms the ubiquitous pumice mantle in the Mammoth Lakes area and can be traced from the upper San Joaquin drainage area south to the valley of the Little Kern River. Pumice fragments concentrated in natural depressions and increasing in abundance northward in the eastern half of the Mount Abbot and the western half of the Kaiser Peak quadrangles were reported by Lockwood and others (1972) and probably represent tephra 1. The volcanic ash that F. E. Matthes found in bedrock potholes in Sequoia National Park (Stewart, 1929; Elsasser, 1965) is probably also tephra 1. Janda (1966) reported that pumice lapilli occur on all moraines of the Ritter Range except those of the Matthes-age neoglacial advance. Thus, the maximum age for the Matthes-age moraines allowed by the absence of a tephra 1 mantle is 720 ± 60 yr, which is consistent with lichenometric ages on the moraines of between 55 and 690 yr obtained by Curry (1971).

**Tephra 2.** Tephra layer 2, to the extent that it has been mapped, does not delineate a lobe. The principal direction of transport may have been to the east in the less well investigated Great Basin area. Several tephra occurrences are known to the east in the vicinity of Hawthorne, Nevada, but they have not yet been positively correlated with tephra 2. In the Sierra Nevada, tephra 2 commonly occurs in meadow topsoils from northernmost Yosemite National Park to the south side of Kings Canyon. Within the Mono basin, it forms a 2- to 20-cm-thick bed of white ash with a basal layer of coarse ash a few millimetres to 1 cm thick, particularly in colluvial deposits in Lee Vining Canyon and in the Bodie Hills.

### Characteristics of the Tephra

**Texture.** The distribution of maximum grain size of the tephra layers is indicated (Figs. 3, 4) by an isopleth delineating the area with fragments coarser than 1 mm. The size of the largest pumice fragment denoted at each locality indicates the principal direction of transport and shows there is a significant textural difference between these two tephras. Tephra 1 is predominantly lapilli; particles as large as 4 mm are found 80 km south of the vent. In contrast, tephra 2 is composed entirely of fine ash (<1 mm) beyond a distance of 10 km. The latter differences may reflect differences in temperature of the two magmas — the hotter aphyric magma being less viscous and more easily disrupted into fine ash. The textural variations and limited isopach data suggest that tephra 1 erupted from the southern part of the volcanic chain and tephra 2 from near the northern end.

**Petrography.** The microphenocryst content of the two tephras is distinctly different (Wood, 1972). In tephra 1, square, prismatic, commonly twinned microphenocrysts of sanidine occur in about 30 percent of the grains examined under crossed nichols. Tephra 1 also gives a strong 3.27-A x-ray diffraction peak of sanidine. Other shards and matrix associated with the microphenocrysts are of pumiceous glass. Vesicles are predominantly round or oval, but in about 30 percent of the shards, vesicles are very elongate and have been strongly attenuated by shearing.

Tephra 2 is devoid of microphenocrysts although powder x-ray diffraction shows a weak 3.37-A peak of biotite. More than 50 percent of the pumice grains have very elongate vesicles. Refractive indices of glass in both tephras are similar and range from 1.496 to 1.500; hence, indices are not a useful criteria for distinction between these tephra.

**Trace-Element Chemistry.** Glass separates from tephras 1 and 2 have been analyzed for Sr, Rb, and Zr by the rapid-scan x-ray fluorescence methods of Sarna-Wojcicki (1971); procedures are given in Wood (1975). Results are shown in

Table 2. The large difference in Sr content and the lesser difference in Zr content seems to provide a firm basis for distinguishing between the two tephras. Tephra 1 has a Sr content of more than 200 ppm and a Zr content of about 400 ppm. The Sr content of tephra 2 is an order of magnitude less, and Zr content is less by a factor of about 3. Rb contents are nearly the same in both tephras.

These trace-element data, together with stratigraphic, mineralogic, and textural relations, provide a means of correlating isolated occurrences of these tephras in eastern California.

## AGE

Ages of Tephras 1 and 2 can be established by radiocarbon dates on well-preserved conifer logs stratigraphically associated with the tephras. It is useful to refine these by sampling from growth increments of logs and then counting annual rings to the center and to the exterior rim to date the establishment and death of the tree. Suess (1965) has shown that there is no transfer of radiocarbon into the sapwood of earlier grown annual rings. Therefore, radiocarbon activity of a known growth interval is unique (except for secular variations of radiocarbon in the atmosphere), and the radiocarbon age can be extended by annual rings throughout the lifetime of the tree.

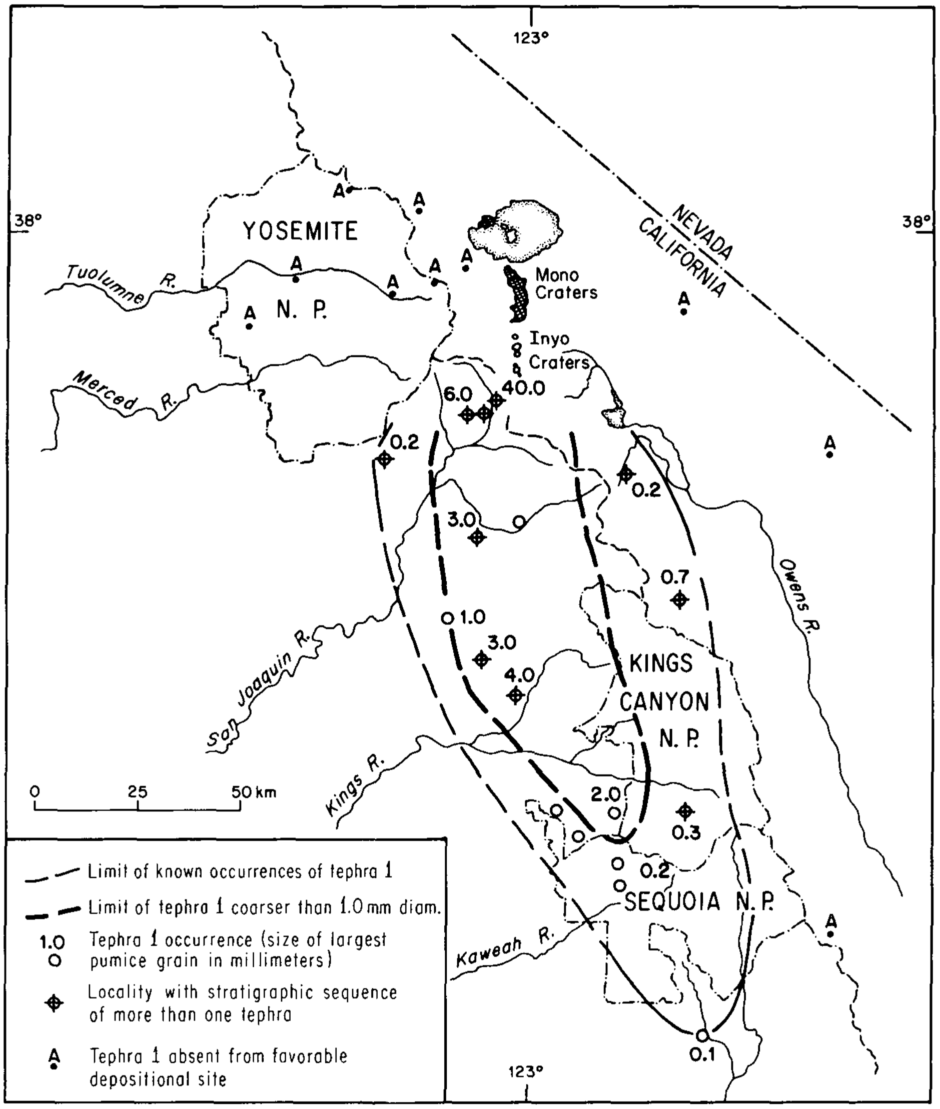

Figure 3. Distribution of tephra 1 (720 ± 60 B.P.).

### Revision of the Inyo Crater Lakes Age

Exposed in the walls and rim of the southern Inyo Crater Lake explosion pit is a heterogeneous mixture of mud and rock apparently erupted from the pit without any associated magma. The rim material overlies a 1.2-m-thick bed of pumice lapilli, identified as tephra 1. Incorporated into the rim material are uncharred, well-preserved conifer logs. Rinehart and Huber (1965) obtained a date of 650 ± 200 B.P. on one of these (sample W-1431). This age is often quoted as the youngest expression of volcanism in the area.

Because of the improved counting precision now available in radiocarbon laboratories, a second log sample from within the crater rim material was dated. This log has 185 annual rings and is probably the same log sampled by Rinehart and Huber (1965). Analysis of the 15- to 35-yr-old growth increment of heartwood yielded a radiocarbon date of 710 ± 60 B.P. (sample UGa-603). Counting annual rings both directions from the dated growth increment shows that this tree was established as a seedling 725 ± 60 radiocarbon yr ago and died 550 ± 60 radiocarbon yr ago. If the eruption at the southern Inyo crater site killed this tree (that is, it did not incorporate a dead log lying on the surface), then the death of the tree virtually dates that eruption as occurring between the years A.D. 1340 and 1460 (conversion to calendar age using the curve of Suess, 1970).

### Age of Tephra 1 and the South Deadman Creek Eruptive Sequence

The vent just south of Deadman Creek from which tephra 1 was erupted (correlation of tephra to vent is discussed below) lies 1.5 km north of the Inyo Crater Lakes. It is almost certain that this pumice eruption would have killed, or at least charred, vegetation within several kilometres of the vent, especially in the direction of the Inyo Crater Lakes, which lie along the axis of the main lobe of tephra distribution. The dated log and other logs in the rim material of the crater lake are uncharred (Rinehart and Huber, 1965) and therefore must have been established in the area after eruption of tephra 1. Thus, the date of 725 ± 60 B.P. indicates a minimum age for the eruption of tephra 1.

On the west slope of the Sierra Nevada near the village of Dinkey Creek is a meadow soil sequence (Lower Cabin meadow, Table 1) containing tephra 1 that rests directly on a fir log with 70 annual rings. This log apparently fell into the meadow when it died of natural causes and was then buried by tephra 1. A wood sample consisting of the 40th and 50th annual rings inward from the outermost ring of the log yielded a radiocarbon date of 760 ± 60 B.P. (sample UGa-602); this date corrected to the death age gives a maximum of 720 ± 60 B.P. for the date of the eruption and deposition of tephra 1. This remarkable agreement in bracketing dates, obtained at sites 63 km apart, confirms the radiocarbon date of this pyroclastic eruption of 720 ± 60 B.P. Applying a small radiocarbon secular-variation correction from Suess (1970, Pl. 1), the eruption of tephra 1 is established as occurring between A.D. 1180 and 1300. Other investigators have obtained radiocarbon ages from material within the soil or alluvium that immediately

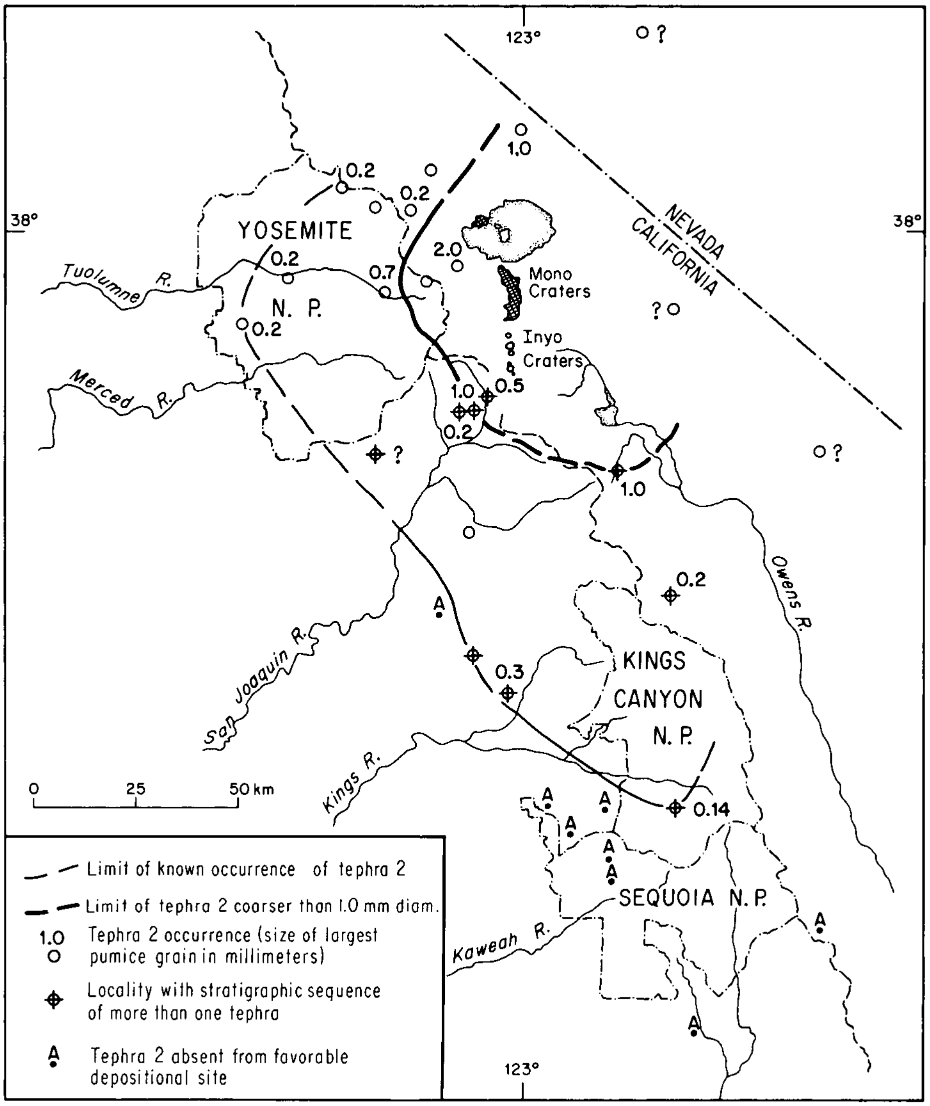

**Figure 4.** Distribution of tephra 2 (1190 ± 80 B.P.).

underlies the surficial pumice in the west moat area of the Long Valley caldera. Rinehart and Huber (1965) gave a date of 1140 ± 150 B.P. (sample W-727) for charred wood fragments in alluvium beneath the pumice. Charcoal from beneath this pumice was also collected during construction of the Mammoth Mountain Inn and dated by Berger and Libby (1966) at 920 ± 80 B.P. (sample UCLA-908). R. Koeppen and R. Bailey (1976, written commun.) collected a piece of a partially charred log in the basal part of the surficial pumice exposed in a borrow pit at Minaret Summit. This log yielded a date of 1040 ± 250 B.P. (sample W-2981). The surficial pumice at these sites is composed of two different units. The basal unit is a set of several thin tephra layers of mixed lithology, probably derived from the Glass Creek area (discussed in the section on correlation of tephras). The surficial unit is the white pumice of tephra 1. Thus, the latter two ages, 920 ± 80 and 1,040 ± 250 yr, relate to the age of the basal tephra layers and not to the age of tephra 1.

TABLE 2. X-RAY FLOURESCENCE ANALYSES

| Locality | Sr (ppm) | Rb (ppm) | Zr (ppm) | Tephra layer |
|---|---|---|---|---|
| East Meadow of Aspen Valley (see Table 1) | 5 ± 3 | 195 ± 10 | 125 ± 10 | 2 |
| West fork Long Meadow Creek (see Table 1) | 20 ± 10 | 206 ± 10 | 120 ± 10 | 2 |
| Devils Postpile Road (see Table 1) | 225 ± 15 | 205 ± 10 | 400* | 1 |
| Boggy Meadow, Kings Canyon National Park, Triple Divide Peak quadrangle lat 36°43.5′N, long 119°30.0′W | 210 ± 15 | 204 ± 10 | 375* | 1 |

*Note:* Uncertainty refers to estimated precision of repeated analyses on samples and standards.
* Linear extrapolation of calibration curve for high Zr.

### Age of Tephra 2

The age of tephra 2 is established by the fortuitous occurrence of this fine ash directly on a buried stump and beneath a log in a section of meadow deposits near the North Fork of the Kings River. The outermost wood from the stump and from the log yielded radiocarbon dates of 1210 ± 55 (sample UGa-450) an1175 ± 65 B.P. (sample UGa-451), respectively, which may be averaged and rounded to 1190 ± 80 B.P. Thus, applying the secular-variation correction from Suess (1970, Pl. 1), the eruption of tephra 2 occurred between A.D. 680 and 940. A previously reported age of 1,545 ± 90 yr (sample I-6049) for tephra 2 at a site in western Yosemite National Park (Wood, 1972) was based on charcoal derived from material that probably had already aged several hundred years before incorporation into the water-laid tephra layer.

An age of 700 ± 200 yr (sample W-629) was obtained from carbonized wood reported to be from between two ash layers in a bank along Bodie Creek (Rubin and Alexander, 1960). Stratigraphic details of the exact site are not published, and it is uncertain whether the upper ash layer is not just slope-washed ash deposited upon the original airfall ash or whether this represents another young eruption not detected in the Sierra Nevada, from which ash blew to the northeast.

## CORRELATION OF TEPHRAS WITH THEIR ERUPTIVE VENTS

A comparison of the Sr, Rb, and Zr data for the tephras with the data for the Inyo and Mono domes and flows is shown in Figure 5. Trace-element content of tephra 1 is similar to that of the obsidian dome just south of Deadman Creek, which partially covers a 1-km-diam tephra-ringed crater. Although the trace-element match is not perfect and the analyses of Jack and Carmichael (1968) show some variability among the several samples from this vent, this is the only Holocene vent known to have produced ejecta with Sr contents on the order of 200 ppm. Pumice from the tephra ring of this vent contains sanidine and is petrographically similar to that of tephra 1. Tephra 1 is very thin to nonexistent north of Deadman Creek, indicating that north winds carried most of this tephra south over the Sierra Nevada. Eruptions at the Deadman Creek vent also produced a hot ash flow that spread 2.4 km to the northeast of the vent and mantled a 5.5-km$^2$ area (Fig. 1). The ash-flow eruption was probably very close in age to the eruption of tephra 1. The obsidian dome that was extruded over the tephra is not mantled by tephra and is therefore younger than tephra 1.

Another set of tephras occurs locally within the west moat of the Long Valley caldera. This tephra set immediately underlies tephra 1. It contains a succession of as many as 10 air-fall layers of mixed lithology composed mostly of lapilli of white pumice, gray pumiceous rhyolite, and lithic fragments of andesite and granodiorite. This tephra set rests on a charcoal-rich soil and overlies the fine white ash of tephra 2. Preliminary trace-element analyses of pumice from this tephra set (manuscript in prep.) indicate that the Glass Creek vents are the source. This tentative correlation and the above discussion of ages suggest that the last major pyroclastic eruptions from the Glass Creek area are bracketed in age between tephra 1 and tephra 2 and probably commenced 1040 ± 250 B.P. and include 920 ± 80 B.P.

Tephra 2 correlates best with the Mono Craters, both of which are characteristically very low in Sr content. Solely on the basis of trace-element chemistry it is not possible to identify specifically which of the tephra-ringed centers of the Mono Craters is the source of tephra 2. Mapping of the several tephra sources within the Mono chain during the summer of 1975 indicates that Panum Crater is the most likely source. A surficial layer of white aphyric pumice bombs and lapilli, about 1m thick, is found in the area surrounding the Panum tephra ring. Vesicles in the pumice are very elongate and cause it to break into elongate blocks, a feature common (on a microscopic scale) to the fine ash of tephra 2. A 1.5-km$^2$ area northwest of the vent is overlain by deposits of partly agglutinated blocky avalanche composed of large blocks of gray pumiceous rhyolite and black obsidian. The coarse white pumice is not present on the avalanche deposits, but it mantles the area to either side of the avalanche. Both the pumice and the avalanche deposits are locally overlain by one or more base-surge deposits of fine ash and lapilli originally noted by Crowe and Fisher (1973). These stratigraphic relations suggest the following eruptive sequence: (1) initial eruption of white pumice giving rise to local block and ash flows adjacent to the vent, an air-fall pumice lapilli blanket about the vent, and a thin basal layer of coarse ash overlain by fine ash at distant sites (tephra 2); (2) extrusion of viscous, pumiceous rhyolite and obsidian in the form of an incipient dome, followed by violent pyroclastic eruptions of ash that caused the incipient dome to break up and form the block avalanche; this last ash eruption culminated in local base surges and, at distant sites, the fine ash of tephra 2; and (3) finally, the extrusion of the obsidian dome within the tephra ring. Large blocks of obsidian scattered about the surface within 1 km of the vent suggest that the extrusion of the obsidian dome was accompanied by minor explosions. The dome is free of tephra and appears to be the most recent feature of the Mono chain. If tephra 2 erupted from Panum Crater, then the radiocarbon age of 1,190 ± 80 yr is in reasonable agreement with the age from obsidian hydration rinds of 1,300 yr obtained by Friedman (1968) on the dome within the crater. This suggests that other ages obtained by Friedman on the coulees in the Mono Craters complex (Fig. 2) may also be relatively accurate. The entire eruptive sequence at Panum may well have occurred within a few years to a few tens of years if the eruptions of Novarupta in Alaska and of Santiaguito in Guatemala can be used as a measure of typical eruption spans.

## VOLUME OF ERUPTED MAGMA

Volume estimates are based on crude isopach data at localities shown in Figures 4 and 5. It is not always possible to discriminate between primary air-fall deposits and those that have been secondarily thickened by slope wash or slumping. In all cases, conservative judgments have been made, and the estimates should be considered minimums. Volumes have been adjusted for porosity and intergranular space on the basis that fine ash deposits have densities of about 1.5 g/cm$^3$ and coarse lapilli beds about 0.5 g/cm$^3$. Reduced volumes are given in terms of an assumed obsidian density of 2.3 g/cm$^3$. The depositional lobe of tephra 1 is well delineated, and 0.1 km$^3$ is a good estimate of the reduced volume of erupted tephra including the ash flow. Tephra 2 is delineated only west of its source, and the main lobe may have extended to the east. Thus, its reduced volume may be considerably more than 0.2 km$^3$.

## CONCLUSIONS

Radiocarbon ages obtained in this study and tephra correlations by means of trace-element chemistry and petrography provide firm dates on four recent eruptions within the Mono and Inyo craters chains. The last major eruption of aphyric pumice, probably from Panum Crater, is dated between A.D. 680 and 940 and involved at least 0.2 km$^3$ of magma. Ash from this eruption is widespread in the southern Sierra and probably in the Great Basin area east of the Mono Craters. Eruptions of porphyritic pumice and lithic lapilli commenced more recently than A.D. 680 in the Glass Creek area of the Inyo craters. Tephra from the Glass Creek vents is mostly confined to the west moat area of the Long Valley caldera. Porphyritic pumice erupted from the vent just south of Deadman Creek between A.D. 1180 and 1300. This eruption involved a hot ash flow that spread over a 5.5-km$^2$ area northeast of the vent and an air-fall tephra distributed in a south-trending lobe over the southern Sierra, Nevada. The total volume of magma probably did not exceed 0.1 km$^3$. A phreatic explosion excavated the southernmost Inyo Crater Lake between A.D. 1340 and 1460. The two recent

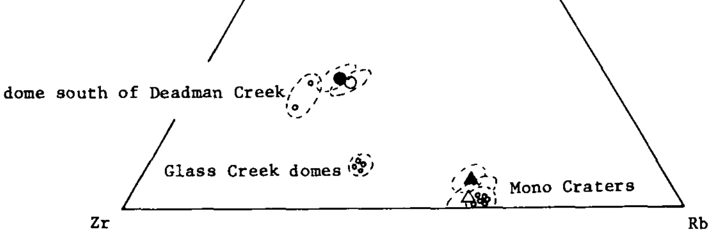

Figure 5. Trace-element correlation diagram for tephra layers in the southern Sierra Nevada. Small open circles represent analyses by Jack and Carmichael (1968) of rocks from the Mono and Inyo Craters. Corners of the ternary plot are concentrations in ppm normalized to the sum of concentrations of Zr, Rb, and Sr. Dashed lines represent estimated precision of analysis. Large circles are tephra 1: solid circle represents lapilli from Devils Postpile Road; open circle represents volcanic ash from Boggy Meadow, Kings Canyon National Park. Triangles are tephra 2: Solid triangle represents volcanic ash from west fork of Long Meadow Creek, north fork of Kings River drainage area; open triangle represents volcanic ash from East Meadow of Aspen Valley, Yosemite National Park.

obsidian domes on either side of Glass Creek and the obsidian dome south of Deadman Creek are not mantled by tephra and are younger than A.D. 1180.

This sequence shows that the north and south extremities of the chain have been the most recently active. Distinctive trace-element chemistry of the most recent tephras shows that both the Mono Craters magma chamber and the residual magma chamber of the Long Valley caldera have recently erupted. It is reasonable to expect that the Mono Craters and Inyo craters chains are capable of future eruptions. Judging from deposits of recent eruptions from these chains, future eruptions may produce volcanic hazards such as hot ash flows or glowing avalanches that flow downslope and into valleys several kilometres from the vents and tephra falls, as much as 1m thick that could mantle the area several kilometres downwind from the vents [terminology for volcanic hazards follows Macdonald (1975)].

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