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Chronology of Late Pleistocene and Holocene Volcanics, Long Valley and Mono Basin Geothermal Areas, Eastern California

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U.S. DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Chronology of Late Pleistocene and Holocene Volcanics, Long Valley and Mono Basin Geothermal Areas, Eastern California

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1983

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Project Information

This report represents the results of the U.S. Geological Survey's Geothermal Research Program Contract No. 14-08-0001-15166 with Occidental College. Principal Investigator was Dr. Spencer W. Wood, and the period of the study was from June 25, 1975, to June 25, 1976. Its objective was to establish a tephrachronology for the Mono and Inyo craters, date and map the distribution of Holocene eruptives, and obtain a local radiocarbon calibration of the obsidian hydration-rind dating method.

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ABSTRACT

Hydration-rind ages based on hydration-rind thicknesses of obsidian and an assumed hydration rate of 5 microns^2/1000 yrs have been determined for the 26 exposed Mono domes and coulees. Hydration-rind thickness data give good estimates of relative age differences between the domes, but determination of absolute ages will depend upon calibration to radiometric ages.

The first extrusion of highly differentiated, sparsely porphyritic rhyolite occurred an estimated 32,000 to 40,000 yrs ago and consists of a small dome at the northwest end of the contiguous chain. The next major extrusive event occurred about 24,000 yrs ago and is represented by two domes and a major tephra. About 10,000 yrs ago, the frequency of eruptive activity increased, and rhyolite lava was extruded at an average rate of 0.2 km^3/1000 yrs; periods of dormancy ranging in length from 300 to 2000 yrs. About 2000 to 3000 yrs ago the rate of extrusion increased dramatically to 0.8 km^3/1000 yrs beginning with the eruption of the South Coulee and its associated tephra. At the same time, the nature of erupted magma changed from sparsely porphyritic (3 to 10 per cent sanidine) to aphyric rhyolite. All eruptions since 2000 radiocarbon yrs BP have produced magma that is aphyric but is of the same chemical composition as the earlier porphyritic magma. Volumes of porphyritic and aphyric extrusives, each of which includes volumes of lava and volumes of pumiceous pyroclastics reduced for porosity, are nearly equal and together total about 4 km^3. Projecting the recent rate of extrusion over

the time since the last major eruption, 1185 radiocarbon yrs ago suggests that a future eruption in the Mono Chain could release as much as 1 km^3 of magma. The rècent increase in extrusion rate and the contemporaneous change in the nature of the magma are attributed to an event in the magma chamber that allowed the release of hotter, more fluid, crystal-free magma.

The young age for the beginning of rhyolite volcanism from the Mono magma chamber suggests that rhyolite magma may have been emplaced in the shallow crust as recently as 32,000 to 40,000 yrs ago. Calculations by Lachenbruch et al. (1976, Jour. Geophys. Research, v. 81, p. 769-784) that a thermal distubance at this age would have propagated upward by solid conduction only 4 km and offer an explanation for the lack of a heat-flow anomaly and surface indications of hydrothermal activity over the Mono magma chamber and its associated ring-fracture system.

This report also contains new information on the age and chemistry of volcanics on the Mono Lake islands, the Inyo domes, and tephras within the Long Valley Caldera.

A newly discovered rhyolite tuff ring of late Quaternary age in the Toowa volcanic field of the southern Sierra Nevada is briefly described for it represents a new area that should be examined for potential as a geothermal area.

ACKNOWLEDGEMENTS

I am especially grateful to Roy Bailey, U.S. Geological Survey, for help and encouragement throughout the course of the study and for serving as technical monitor of the contract. The study benefited ftom discussions with Irving Friedman, Rodd May, John Harmening, Joe Ritchy, Ken Lajoie, Steve Lipshie, Robert Koeppen, and Layle Wood. I wish to thank John and Mary Harmening of Mammoth Lakes for their help and hospitality. Members of the Geology Department of Occidental College and the Center for Volcanolgy of the University of Oregon generously supplied facilities and helpful discussions. Ira Pasternack and Matt LaRoche were a great help with the hydration-rind dating.

INTRODUCTION

The Mono Basin and the Long Valley Caldera geothermal areas contain numerous volcanic features of late Quaternary age. The objective of this study was to obtain the ages of the volcanoes and their associated tephra deposits. A relatively complete chronology of the eruptive history of the Mono domes is presented in this report. Estimates of ages of the Inyo domes and some of the Mono Lake Island volcanics are also reported. The chronology presented in this paper is based upon relative ages determined by field relationships, ages estimated from hydration-rind dating of obsidian, and ages from radiocarbon dating and trace-element correlations of stratigraphic accumulations of tephra. Interpretation of this chronology of volcanism leads to an increased understanding of the nature of the present magma at depth, some implications for the geothermal resource potential of the area, and a preliminary assessment of potential hazards from these volcanoes if they were to erupt in the future.

The Mono and Inyo craters and the volcanoes of western Mono Lake are a late Quaternary volcanic chain extending from Mono Lake to the Long Valley Caldera (Mayo *et al.* 1936; Putnam, 1938, Kistler, 1966; and 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 (fig. 1; Pl. 1). Although the volcanoes appear to lie along a chain, field studies and geochemical data interpreted by Bailey *et al.* (1976) and Bailey (verbal comm., 1975) suggest that the volcanoes are tapping three different magma sources: the chamber beneath the Long Valley Caldera, the postulated chamber beneath the Mono craters, and possibly a third source beneath western Mono Lake.

The Mono craters are a 17 km-long, arcuate chain of late Quaternary

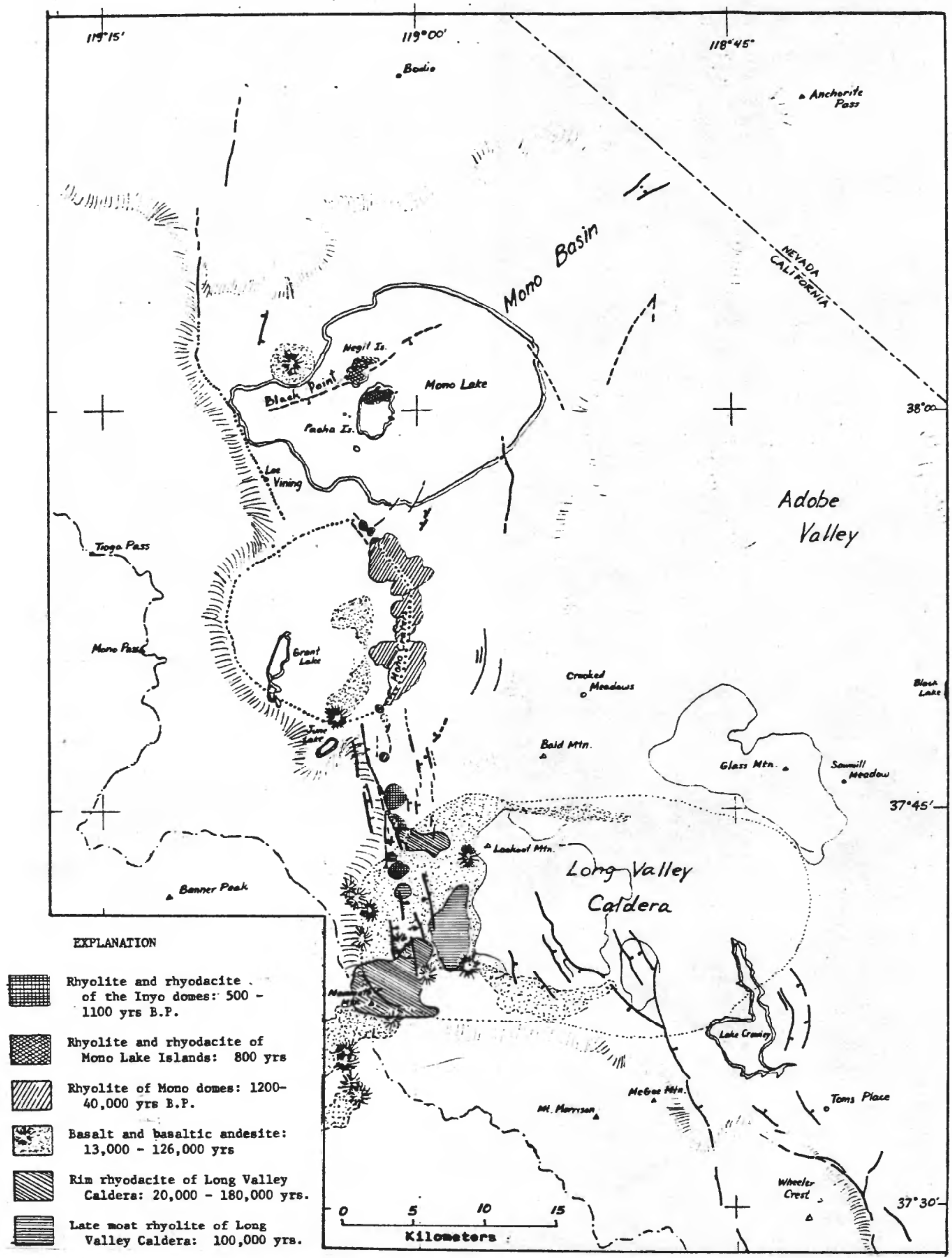

Figure 1. Geologic map of the volcanic rocks generally younger than 200,000 years and recent faults and fissures in the Mono Basin and Long Valley Caldera areas. Heavy lines denote faults: thin lines denote fissures. Recent fault mapping is incomplete east of the volcanoes. Map and geochronology of the caldera area are from Bailey et al. (1975). The Mono Basin area is mapped on the basis of data from Jenkins (1963), Kistler (1966), Scholl et al. (1967), Gilbert et al. (1968), Lajoie (1968), and this report. Faults south of Long Valley Caldera are from Jenkins (1967).

domes, flows, and tephra deposits (figures 2, 3) composed of chemically homogeneous rhyolite (Carmichael, 1967; Jack and Carmichael, 1969) except for an older rhyodacite dome on the northwest side (Lajoie, 1968). Kistler (1966) suggested that the arcuate shape of the Mono raters chain is related to a mylonitized ring-fracture system about 12 km in diameter in the June Lakes area. Bailey et al. (1976) have recently suggested a magma chamber lies beneath this ring-fracture zone. Recent mapping by Bailey (U.S. Geological Survey, 1976) of more extensive, concentric fractures and faults shows that the ring-fracture zone is nearly 18 km in diameter and has been displaced downward toward the center at least 200 m in post-Bishop Tuff time [Bishop Tuff is dated 0.7 x 10^6 years by Dalrymple et al. (1965)].

The Inyo craters form an 11-km-long discontinuous straight chain of chemically and physically heterogeneous domes (Lajoie, 1968) and tephra deposits. Bailey et al. (1976) suggested that the Inyo domes represent mixing along a north-south fissure system of rhyodacitic magma from the residual magma chamber beneath the Long Valley Caldera with rhyolitic magma from a chamber beneath the Mono craters.

The Island volcanics appear to be from another center producing lavas chemically different from either the Mono craters center or the Long Valley center (Lajoie, 1968). Hot springs and fumarolic activity on Paoha Island in Mono Lake suggest the Island volcanic system may contain a hydrothermal system (Smith and Shaw, 1975, p. 69). The nature and extent of this system have not been evaluated. The Long Valley Caldera has abundant hot spring activity and a thermal anomaly indicating a large convective hydrothermal system (Muffler and Williams, 1976). It is currently a target for geothermal resource exploration.

The area associated with the Mono domes and the ring-fracture system is

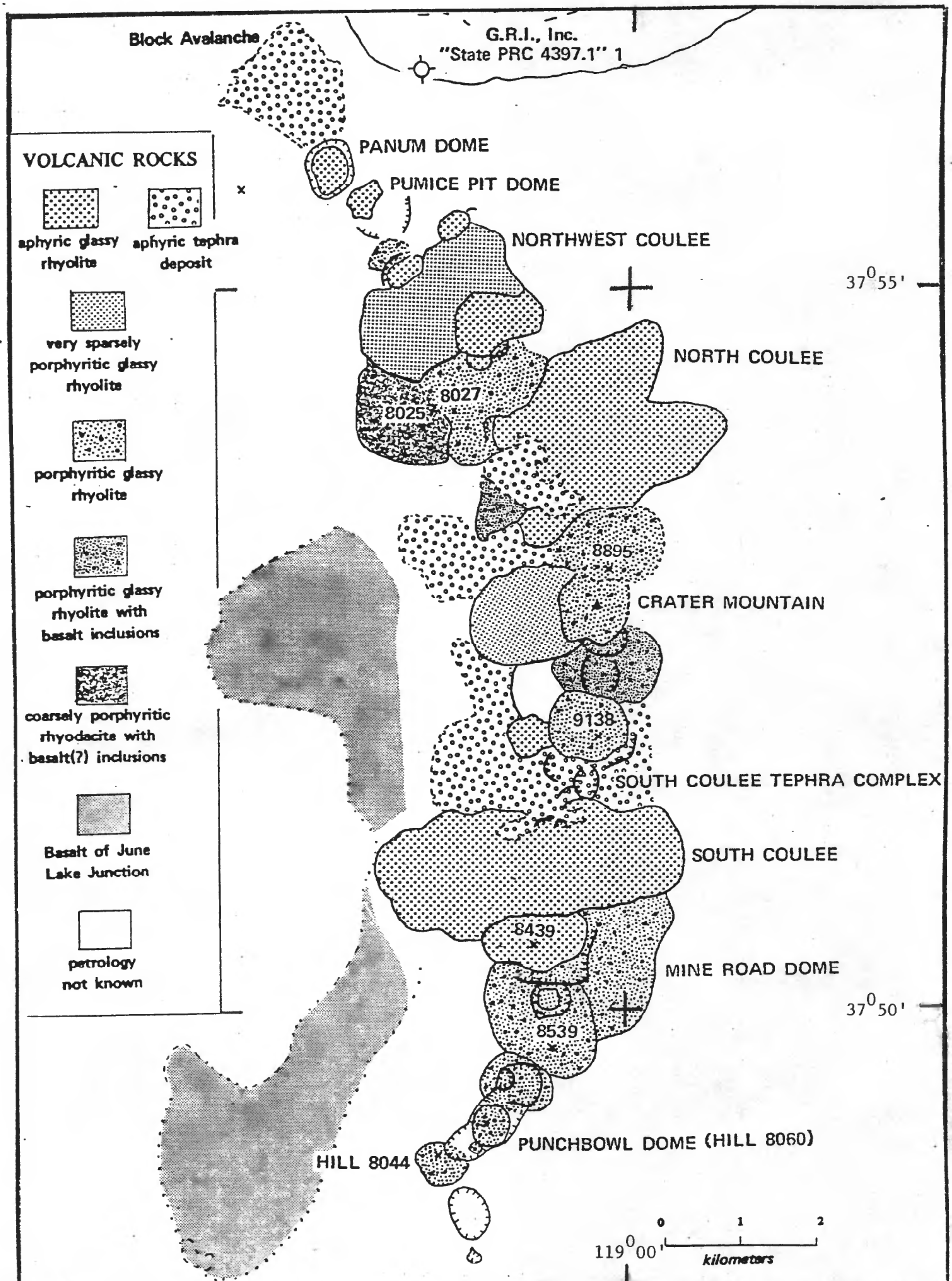

Figure 2. Geologic map of the Mono craters and domes.

Figure 3a. Wind-etched outcrop of porphyritic rhyolite with basalt inclusions that comprises the cratered dome (no. 18, plate 1) between Crater Mountain and hill 9138. Basalt inclusions protrude about 4 cm demonstrating the amount of rhyolite eroded by wind-driven sand on an older dome. Flow banding is horizontal. White specks about 1.5 mm diameter are sanidine phenocrysts. Scale is 15 cm long.

Figure 3 b. Three pyroclastic units that mantle the Pumice pit dome . Starting at the base of the section are 1)an ash flow deposit of unsorted and unstratified pumice and ash, 2)a layer of well-sorted , unstratified coarse-pumice lapilli and bombs, and 3) a stratified and cross-bedded sequence of two base-surge units separated by a thin air-fall pumice lapilli tephra. The pyroclastics erupted from the adjacent Panum Crater vent.

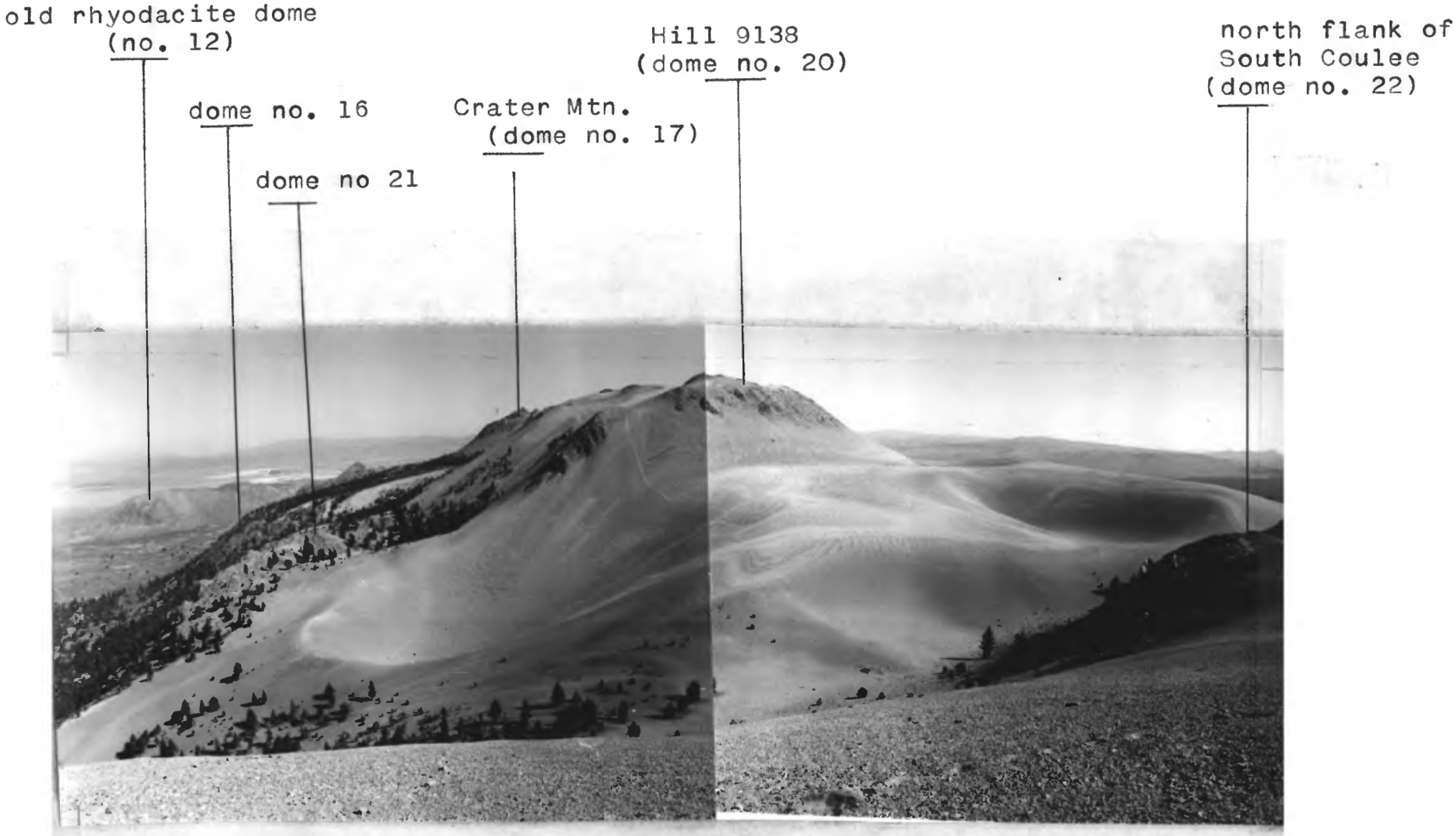

Figure 3c. Photograph looking north from the South Coulee across the thick pumice mantled craters of the "South Coulee Tephra Complex". Wind erosion has exposed layered tephra on the crater rims. Pumice mantle in the foreground erupted out of the side of the coulee.

Figure 3d. Low sun-angle air-photo of Panum and Pumice Pit domes and craters. Hummocky topography northeast of the domes is block avalanche deposits probably associated with eruptions of the Pumice Pit' dome. These deposits are cut by prominent fault scarps of a northeast and a northwest-striking system that intersect at the dome. The Panum crater sequence erupted on top of these deposits.

A block avalanche from the Panum eruption was channelled by the northwest striking scarp and deposited in the area off to the northwest. The dark, northwest-striking stripes in the pumice flat in the lower left (southwest) corner of the photo appear to be recent fissures or faults.

Picture is oriented with north up.

notably lacking in hot springs and a heat flow anomaly (Lachenbruch et al., 1976, p. 780-781). The lack of a near-surface thermal expression would appear in conflict with the young age and areal extent of the Mono volcanoes and ring-fracture system. However, if the Mono system is only 40,000 years old as estimated in this study, the thermal anomaly from magma emplaced several km deep in the crust would not have reached the surface by solid conduction in this time (Lachenbruch et al., 1976).

The most interesting contribution of this study has been the determination of the rates of extrusion of lavas in the Mono Chain over their estimated 40,000-year history. Both the rates of extrusion and the nature of the magma changed dramatically about 3000 years ago. Geologic mapping and hydration-rind determinations have identified the oldest exposed Mono Domes.

A considerable amount of new data was obtained on tephrachronology and the trace-element content of tephra in this area. A paper by Wood about the most recent tephra eruptions of the Mono and Inyo craters was published in 1977.

Interpretation of some of the trace-element analysis on tephra from the Long Valley Caldera depends upon petrochemical studies in progress by R. Bailey and R. Koeppen. The section descriptions and trace-element contents are given in Appendix II and can be drawn on by others or interpreted at a later date.

Included in this report is a brief description and chemical analysis (Appendix I) of a previously undescribed Quaternary rhyolitic pumice eruption in the Toowa volcanic field of the southern Sierra. Because of the association of geothermal systems with recent rhyolite eruptions and proximity to the Coso geothermal area, this feature is worthy of further examination.

OBSIDIAN HYDRATION-RIND DATING

The method of dating obsidian by the hydration rind method was described by Friedman and Smith (1960) and has been recently applied to dating geological materials by Friedman (1968) and Pierce and others (1976). The method is based upon the fact that the thickness of the hydrated obsidian layer increases as the square root of time, or:

$$t = kx^2$$

where t is time in years, x is the thickness of the hydrated layer, commonly expressed in microns, and k is the hydration rate, which is related to the diffusion constant. The hydration rate is independent of the water content of the soil or air but is strongly dependent upon the temperature history of the sample (Friedman and Long, 1976).

Hydration rinds are recognized along hairline cracks and on surfaces of obsidian by two properties of the hydrated layer: 1) the hydrated layer has a slightly higher refractive index producing a line of relief marking the diffusion front of the water into the glass, and 2) when observed under crossed nichols, the hydrated layer has low, 1st-order, strain birefringence owing to a slight volume increase in the hydrated layer.

Samples were prepared by standard thin-sectioning techniques, although they were not finished as carefully as petrographic slides, for all that was needed was a near-transparent section with sufficient optical thickness to see the strain birefringence. Thin sections used in this study ranged in thickness from 0.005 to 0.024 inches (130 to 610 microns).

Measurements were made with a petrographic microscope equipped with a filar micrometer eyepiece. Measurements using a 40x objective were easily reproducible to 0.3 microns. The measurements were made on the hydrated layers on both sides of a hairline crack in the obsidian. The exterior surfaces of obsidian pieces also have hydrated layers, but these exterior hydration rinds are easily chipped during sawing and lapping and are not always reliable. Only the cracks with near vertical orientation to the stage of the microscope were used for measurement. It was not possible to use just cracks that emanate from an exterior cooling crack, for these are rarely found in practice. Hydration rinds on all vertical cracks were recorded. It was found that some rinds vary by a factor of 1.2 when compared on either side of some cracks. Most rinds, however, agreed within 0.4 microns on either side of a crack.

The measured hydration rinds are plotted on histograms in the manner suggested by Pierce and others (1976). Examination of figure 4 shows that measurements on samples from the same geologic feature usually have a normal, or perhaps a log-normal, distribution about a mode with a standard deviation on the order of one micron. However, some determinations of rinds on obsidian from the same geologic feature vary widely from one another. The causes of variation in rind thickness are not well understood. There is clearly a need for an analysis of the uncertainties in obtaining a representative rind thickness and a meaningful standard deviation for determinations on a single geologic feature. Such an analysis was not attempted in this study, but an exhaustive sampling and hydration-rind determination on a young dome would be a useful contribution.

Two obvious causes of widely ranging rind thicknesses are 1) cracks of different ages or 2) samples collected from dissimilar temperature environments where they hydrated at different rates. The initiation of cracks in obsidian can occur in a number of ways: 1) cooling cracks, 2) cracks related to subsequent explosive volcanism in the vicinity, 3) crack related to warping, tectonic deformation, or collapse of supporting magma beneath a dome, or 4) subsequent

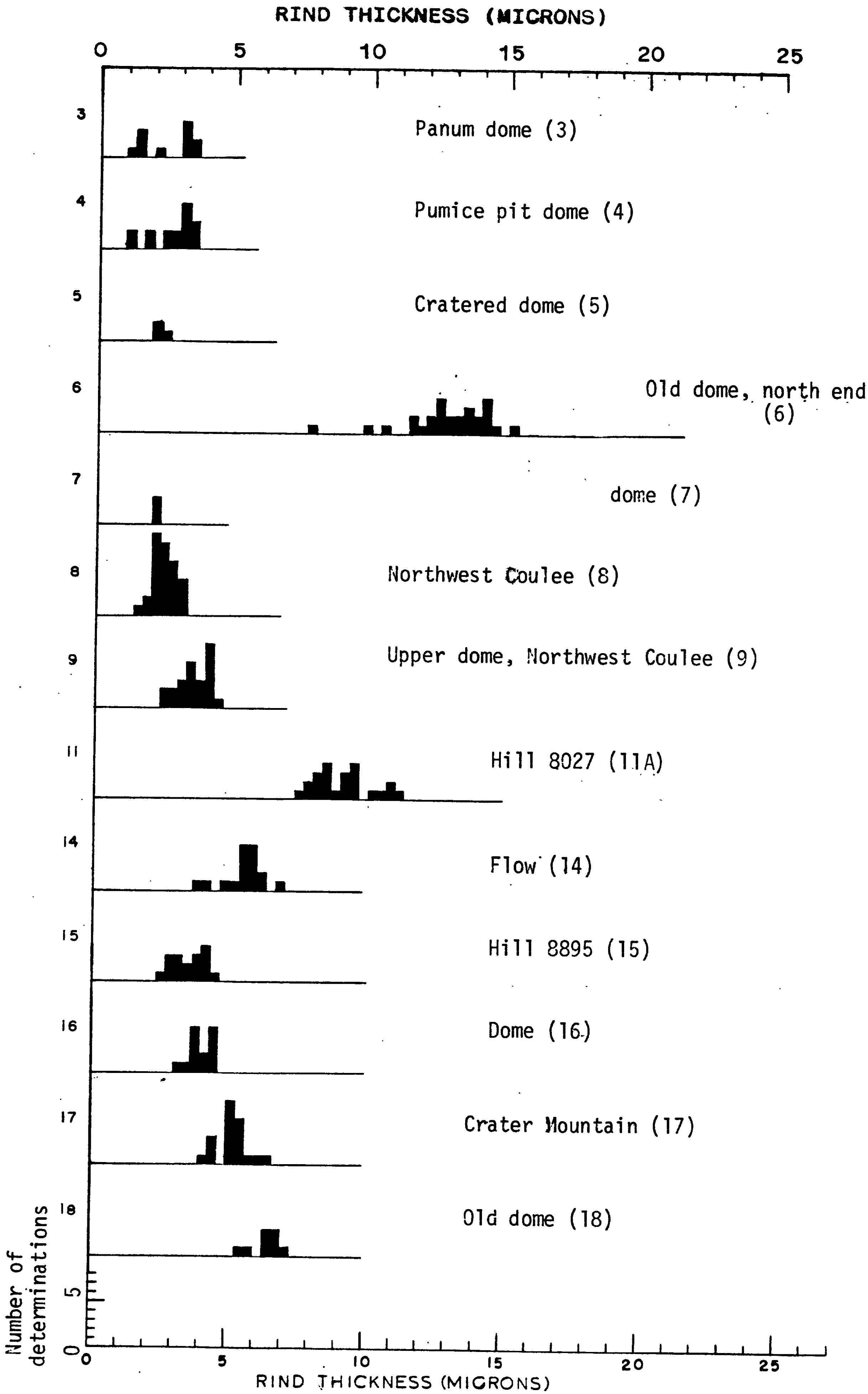

Fig. 4a. Histograms of hydration-rind thicknesses on the Mono domes (continued next page). Dome locations are shown in Plate 1.

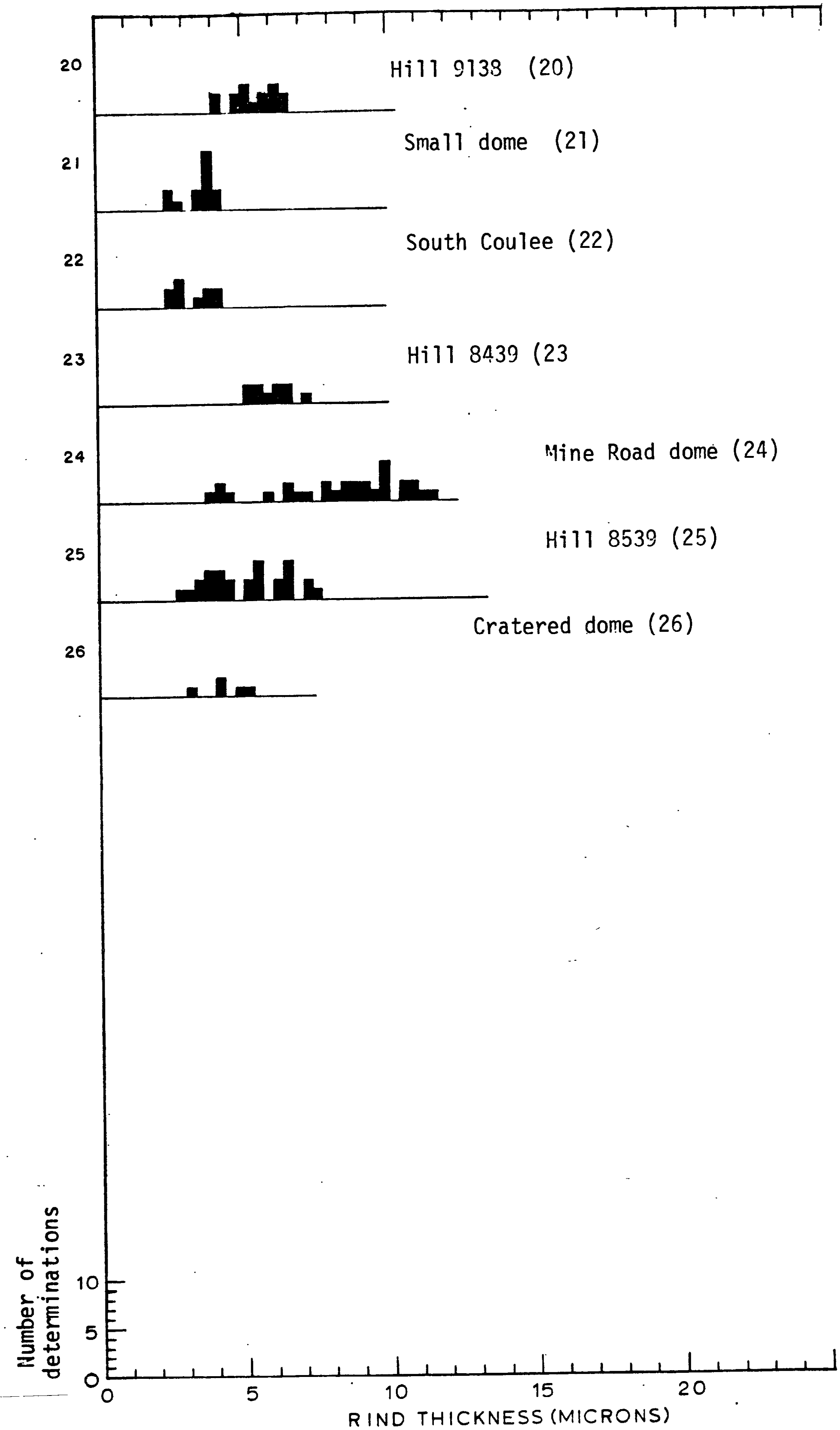

Fig. 4a. Histograms of hydration rind thicknesses on the Mono domes -- continued.

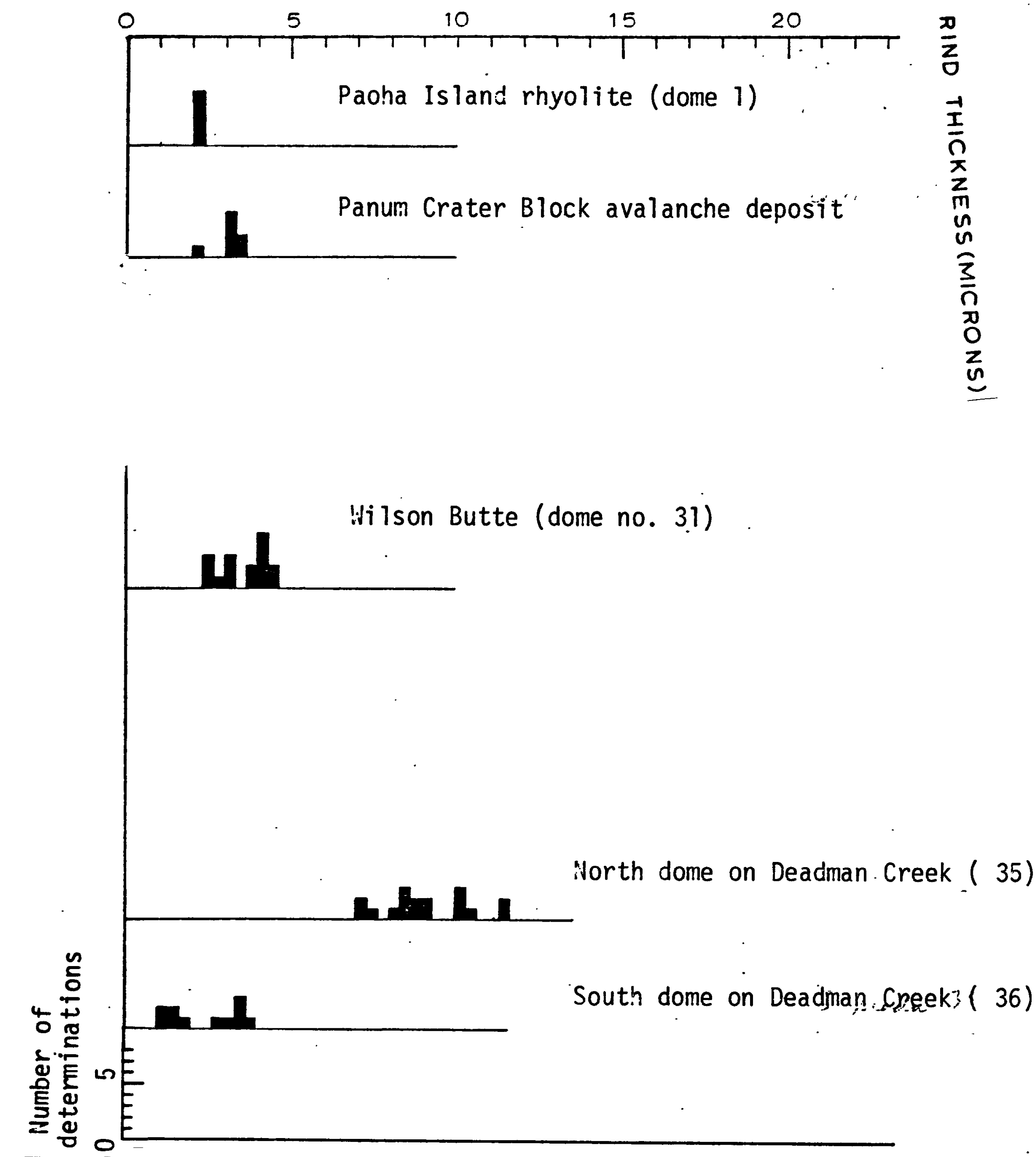

Figure 4b. Histograms of rind thicknesses, Mono Lake islands and Inyo domes. Dome locations are shown in Plate 1.

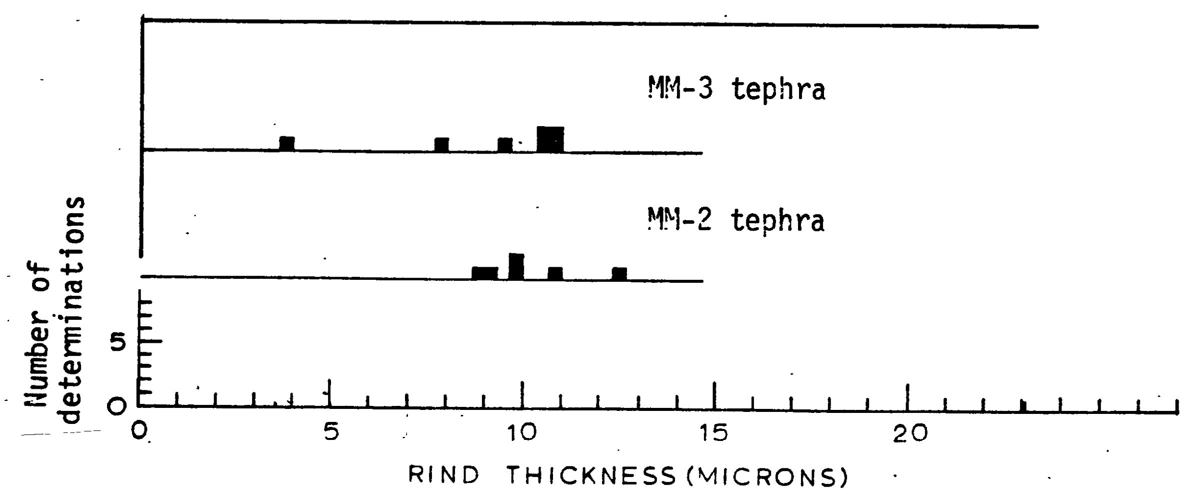

Figure 4c. Histograms of rind thicknesses, older tephras (Mammoth Mountain area, MM section). Location of Mammoth Mountain is shown in figure 1, and MM section is described in Appendix II, p. 163.

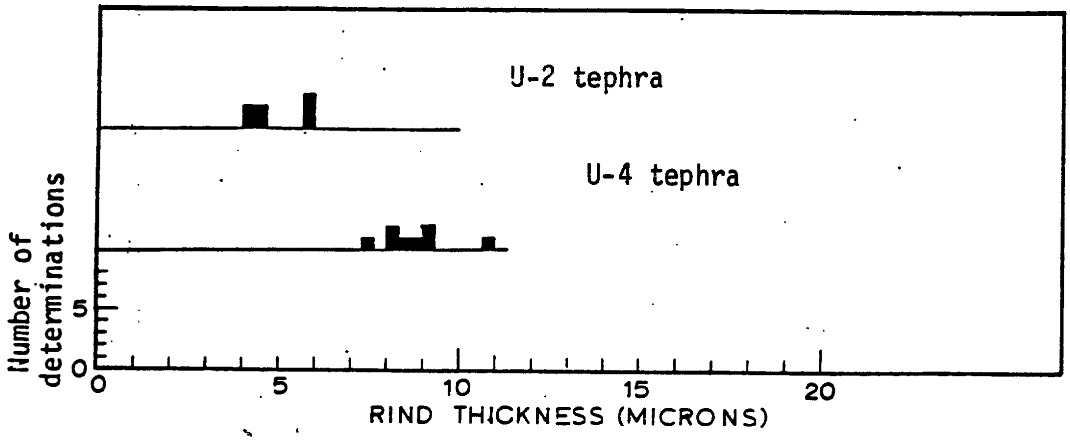

Figure 4d. Histograms of rind thicknesses (Section U, Highway US 395). Section U is described in Appendix II, p. 66-69.

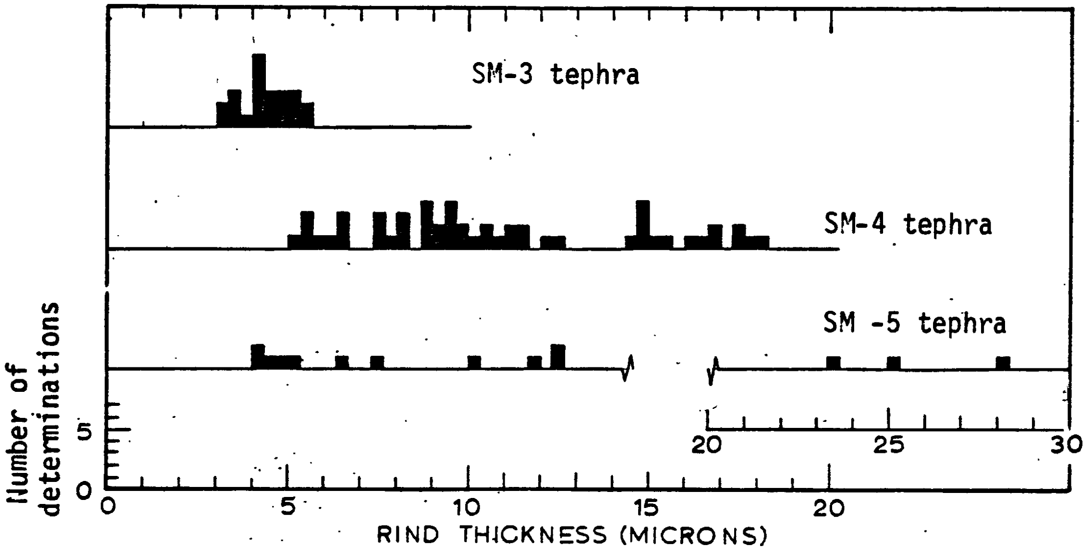

Figure 4 e. Histograms of rind thicknesses (Sawmill Meadow, SM section). SM section is described in Appendix II, p. 70-72.

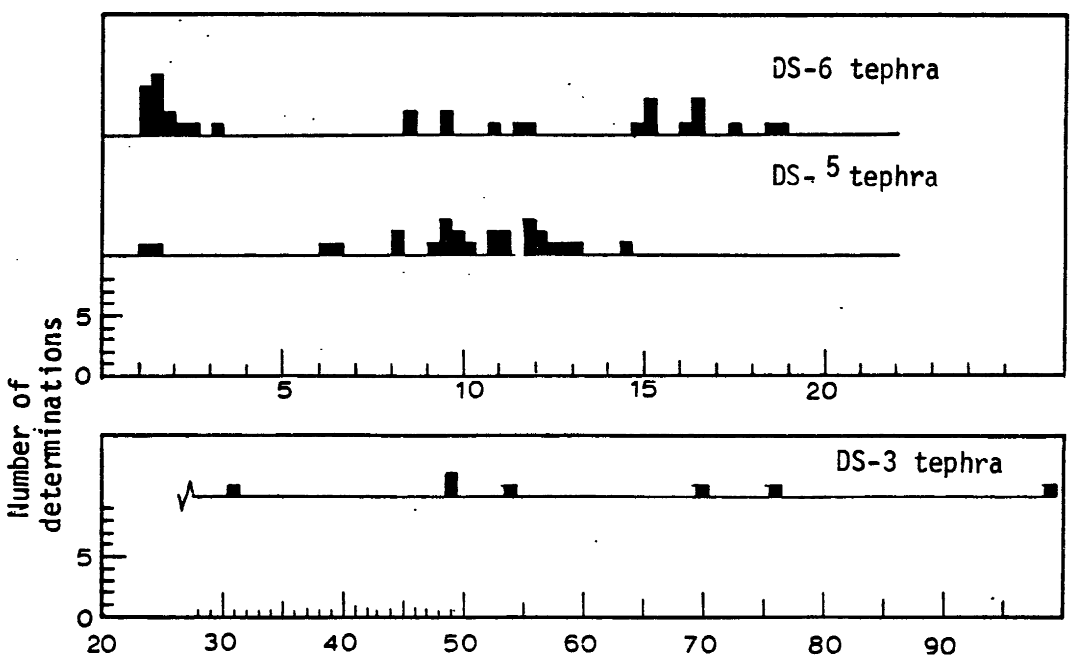

Figure 4f. Histograms of rind thicknesses (borrow pit on US 395, DS section). DS section is described in Appendix II, p. 60.

cracks related to expansion of hydrated glass. Since it is not possible to discern the origin of cracks in the thin sections, one can only interpret a mode of thick hydration rinds on the histogram and assume that mode is representative of hydration of cracks formed during rapid cooling.

Local variations in temperature environment are difficult to assess unless one can do a detailed study of the local micrometeorology as suggested by Friedman and Long (1976). One would not expect much variation within one obsidian sample; however, samples from different sun exposures may have different temperature histories and would be expected to have different hydration rates.

Discrepancies may arise in assigning significant age differences to very young obsidian domes because of an initial rind thickness acquired during cooling from 100°C down to ambient temperatures. J. L. Ritchy (University of Oregon, unpub. data, 1976) has computed this effect for obsidian cracked during cooling and undergoing hydration from 100°C to 20°C using cooling curves from Jaeger (1967) and rate constants from Friedman and Long (1976). At the center of a 1-meter block of obsidian, an initial hydration rind on the order of 0.6 microns will be produced. Therefore, variations of this order can be expected on samples taken from an outcrop.

All samples of outcrop obsidian used in this study were taken from north facing shaded outcrops or shaded crevasses in the domes. I did not always sample from an exterior cooling surface (i.e., some samples could have originally been from one or two meters deep in the dome during cooling and could have acquired an initial rind on the order of 0.6 microns).

In an attempt to standardize the temperature environment, all samples from domes and flows were taken from north-facing, wholly or partly shaded outcrops above ground. Sampling sites ranged from 2200 to 2700 m in altitude which may introduce additional small differences in temperature environments. Tephra samples, however, have been buried at least several centimeters since deposition, and buried at least 0.5 meter over most of their history. Differences in the temperature environments of the samples are probably small, but they constitute an important uncertainty in the dating method. A useful approach for future studies will be to exhaustively sample a dome and obtain samples from outcrops at different exposures and albedos in order to determine the extent to which variable temperature environments can affect the spread of the hydration-rind-thickness data.

In order to obtain a range of hydration-rind thicknesses thought to be representative of the rind developed since cooling of the rhyolite lava, modes have been chosen from the histograms in figures 4a and b and are listed in table 1. Where several modes appear on the histogram, and no single value predominates, the thickest rind has been chosen provided more than two hydrated cracks (four measurements) have this value. Where there is clearly one mode, the error range is given as the measurement precision of ± 0.3 microns. Where values are spread, the range of values that appear to be somewhat clustered is given in table 1. Table 1 also shows estimated ages and lava volumes of the Mono domes; these data are graphed in figure 5.

THE OBSIDIAN HYDRATION RATE

A number of stratigraphic sections (figure 6) containing pumice and obsidian tephra were dated by radiocarbon by Meyer Rubin (U.S. Geol. Survey, Reston, Va.) in hopes of providing a calibration of the hydration rate for obsidian in this region. Apparent difficulties with this approach are that 1) the obsidian is not necessarily of the same age as the pumice eruption into which it was incorporated and 2) buried tephra may undergo a different temperature environment than exposed obsidian outcrops on the domes. Figures 4d and 4e are rind measurements on tephra for which there is radiocarbon control. Radiocarbon age of the U-2 tephra eruption is 1695 ± 200 years B.P.*, and the hydration-

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*This age is derived from the heartwood of a charred log with 295 annual growth-rings exterior to the dated growth increment. (See Appendix II, p. 65-69.) Thus the C-14 date (W-3469) of 1990 ± 200 years B.P. is adjusted by subtracting 295 years.

TABLE 1.

HYDRATION-RIND THICKNESSES, AGE ESTIMATES, AND VOLUMES OF THE MONO DOMES AND KNOWN TEPHRA (LISTED FROM OLDEST TO YOUNGEST)

Dome Number (Plate 1)	Feature	Hydration-Rind Thickness (x)[1] (microns)	Estimated Age ($x^2 * 200$) (years)	Lava Volume (km^3)
12	Rhyodacite Dome	----	>22,500	0.23
6	Old dome, n. end	12.7 - 14.2	32,000 - 40,000	0.01
11	Hill 8027	10.9 ± 0.3	22,500 - 25,000	0.23[2]
24	Mine Road Dome	10.0 - 11.4	20,000 - 26,000	0.18
18	Old dome	6.6 - 7.7	8,700 - 10,400	0.13
25	Hill 8539	6.3 - 7.0	8,000 - 9,800	0.26
19[3]	- - - -	- - - -	>8,700[3]	0.08
30	Hill 8044	6.6 ± 0.3[4]	7,900 - 9,500[4]	0.015
23	Hill 8439	6.0 - 6.6	7,200 - 8,700	0.12
20	Hill 9138	5.8 - 6.4	6,700 - 8,200	0.08
14	- - - -	5.6 - 6.1	6,300 - 7,400	0.03
17	Crater Mountain	5.2 - 5.8	5,400 - 6,700	0.09
27	Caldera Dome	5.4 ± 0.3[4]	5,200 - 6,500[4]	0.03 (dome) 0.01 (local tephra)
28	Punchbowl Dome	- - - -	< (5200 - 6500)	0.01

(CONTINUED)

1. The manner by which the ranges of hydration-rind thicknesses are selected from data in figures 4a and 4b is discussed on page 16.

2. Volume does not include a substantial amount of tephra erupted about 23,300 years BP described by Lajoie (1968) in the Wilson Creek Formation.

3. Dome no. 19 is entirely covered by tephra, but appears to underlie Dome no. 18.

4. Hydration-rind thicknesses not determined in this study but taken from Friedman (1968).

TABLE 1. (CONTINUED)

Dome Number (Plate 1)	Feature	Hydration-Rind Thickness (x) (microns)[1]	Estimated Age (x^2 * 200) (years)[2]	Lava Volume (km^3)[3]
26	West Control Cratered Dome (Smith, 1973)	4.1 - 4.7	3,300 - 4,400	0.005
16	- - - -	4.3 ± 0.3[4]	3,200 - 4,200[4]	0.23
15	Hill 8895	3.8 - 4.4	2,900 - 3,900	0.16
22	South Coulee	4.0 ± 0.3[4]	2,700 - 3,700[4]	0.56 (flow) 0.20 (local tephra)[5]
21	- - - -	3.1 - 4.2	2,600 - 3,500	0.03
13	North Coulee	3.4 ± 0.3[4]	1,900 - 2,700[4]	0.75
8[6]	Northwest Coulee (Lower flow)[6]	2.7 ± 0.3	1,200 - 1,800	0.34
4	Pumice Pit Dome	2.8 - 3.3	1,550 - 2,200	0.05 (local tephra and dome)
9[6]	Northwest Coulee (Upper Dome)[6]	3.1 ± 0.3	1,550 - 2,300	0.05
7	- - - -	2.1 - 2.3	900 - 1,100	0.01
3	Panum Dome and Tephra	1.2 - 3.0	300 - 1,800	0.2 + (includes distant tephra shown in Wood [1977])
5	Cratered Dome of Smith (1973)	1.4 - 2.6	400 - 1,400	0.01

5. South Coulee may have produced an additional 0.1 to 0.2 km^3 of distant tephra not accounted for here.

6. Field evidence indicates Dome 8 preceded Dome 9. In all other cases where good field evidence for relative age exists there are no conflicts with the relative age determined by hydration rinds.

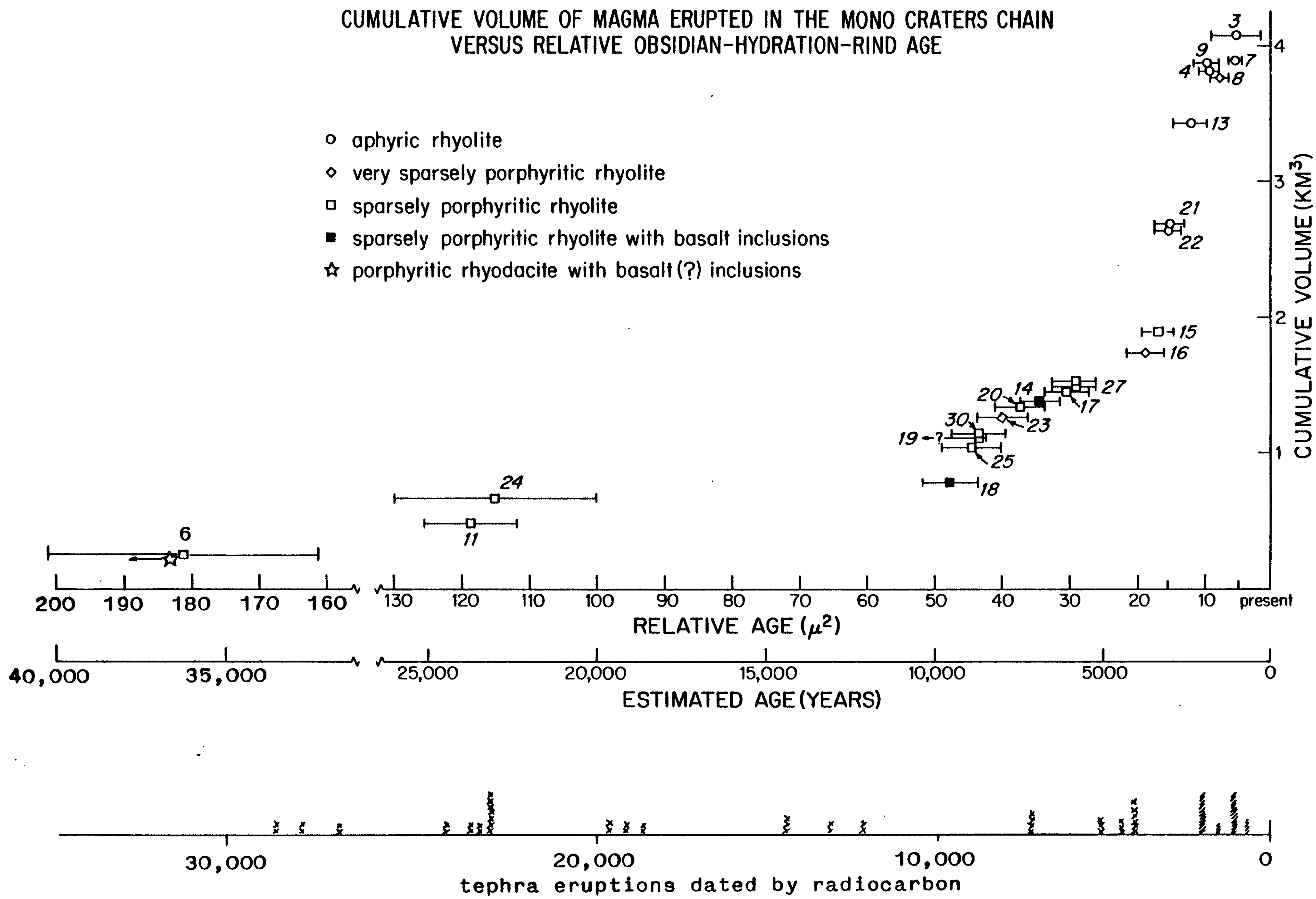


Figure 5. Plot of age versus cumulative volume for the Mono craters and domes. Average extrusion rates are derived from the slopes of the curve drawn through the points. Numbers on points refer to the dome numbering system shown on Plate 1. Tephra eruption are shown on the radiocarbon time scale; see figure 6c for radiocarbon control. Height of tephra symbol indicates relative magnitude of tephra eruption.

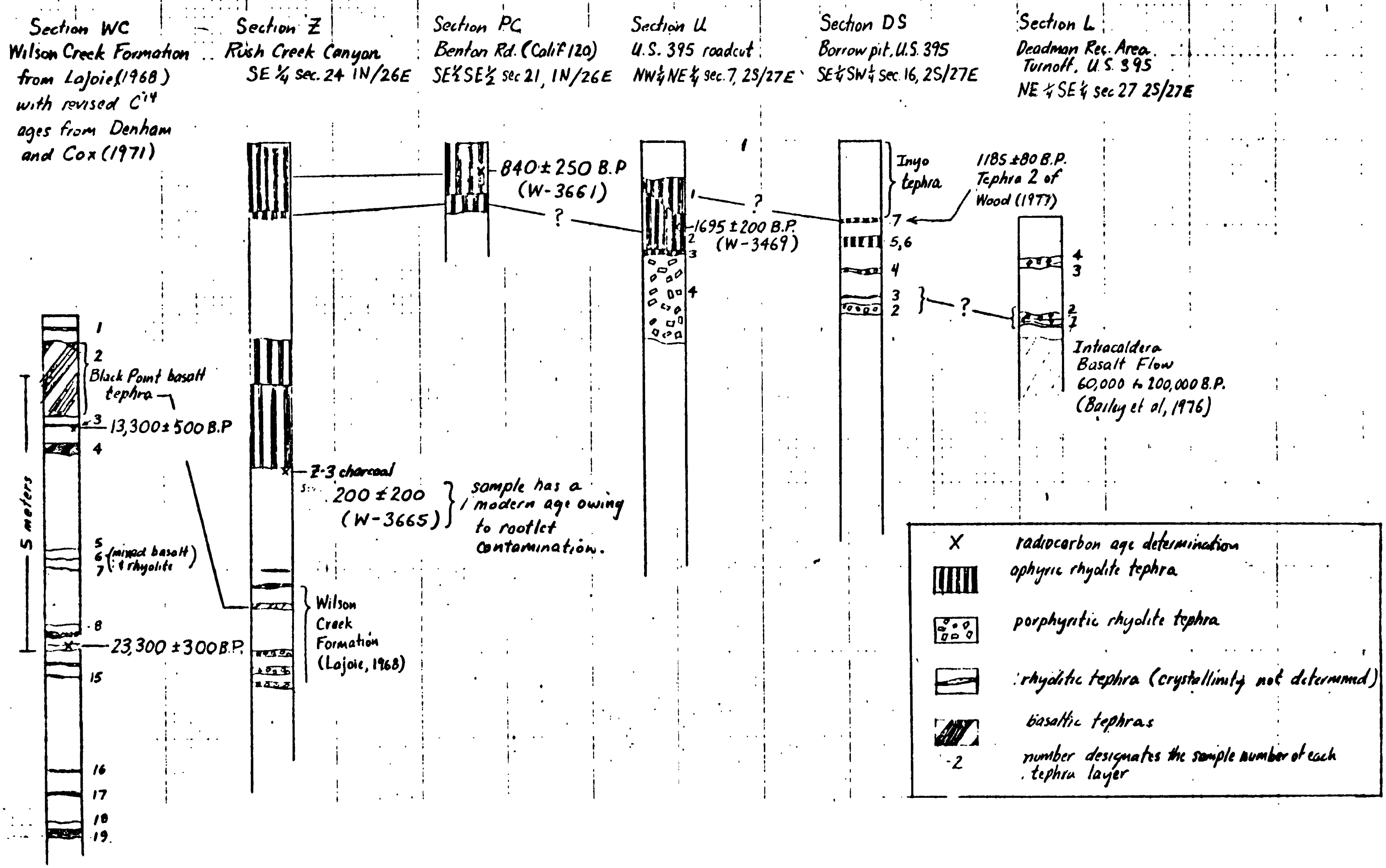


Figure 6a. Stratigraphy of Mono tephra east of the Mono craters. All tephra are of Mono crater type trace element chemistry except basalts and the Inyo tephra in section DS.

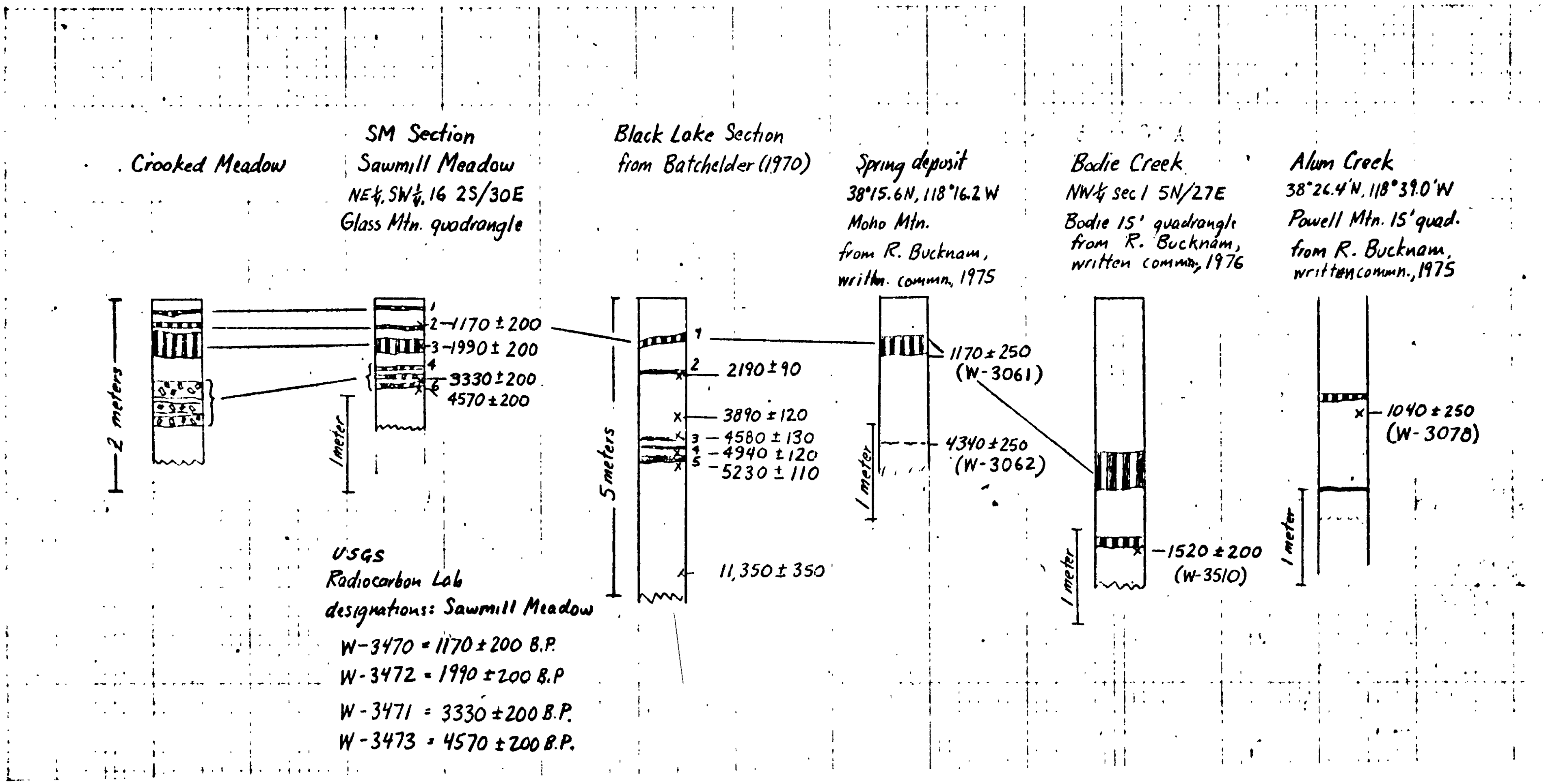


Figure 6b. Stratigraphy of Mono tephra in the Mono Basin and the northwestern Long Valley Caldera.

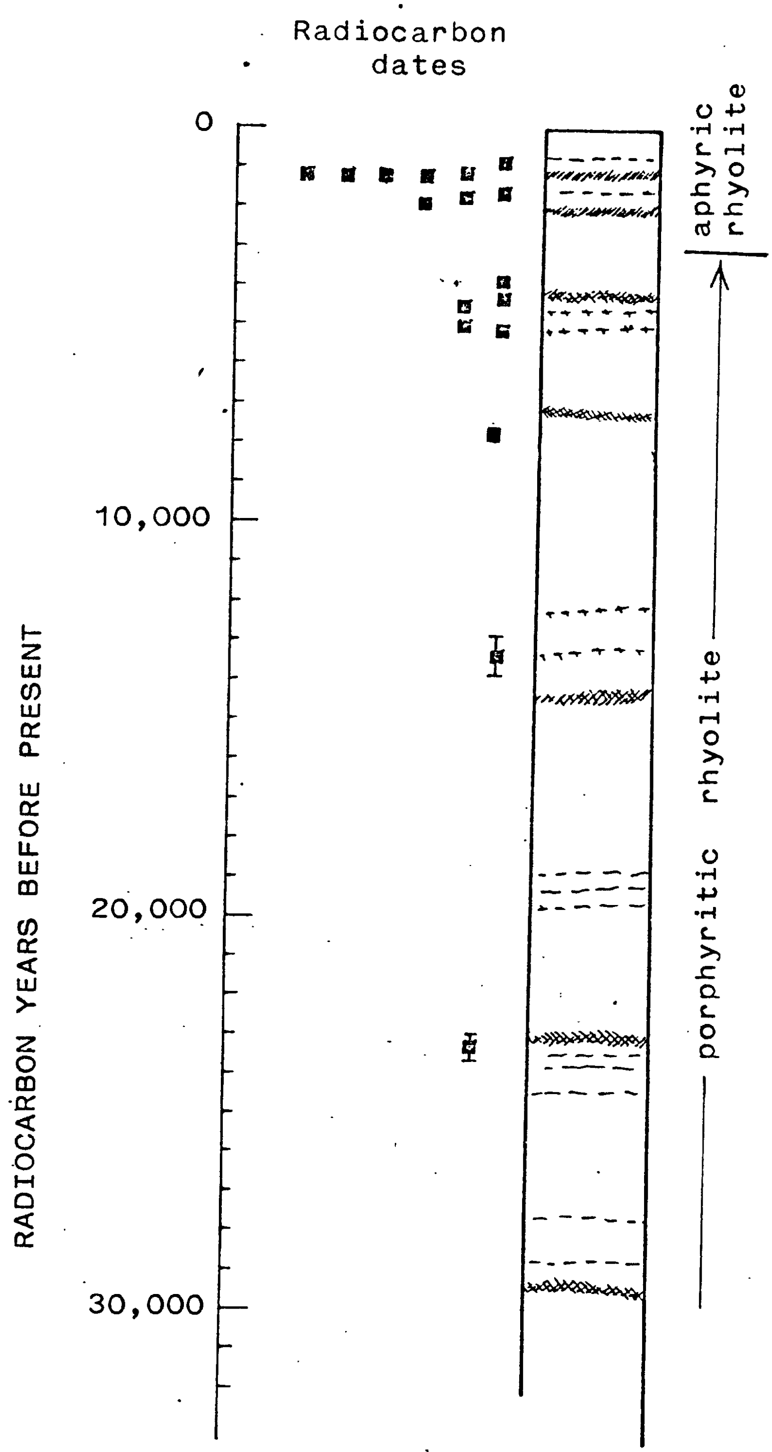


Figure 6c. Summary of radiocarbon dates on tephra from the Mono craters. Major eruptions are shown as thicker lines on the diagram.

rind thickness of obsidian fragments in the tephra ranges from 4.2 to 5.9 microns. Radiocarbon age of SM-3 (ash and lapilli layer 3 in section SM, Appendix II, p. 72) tephra is 1990 ± 200 years B.P. and a value of 4.2 microns would be interpreted from the histogram (fig. 4e), although the rind thicknesses range from 3.2 to 5.6 microns. SM-3 and U-2 are petrologically similar tephras and close agreement of radiocarbon ages and hydration rinds suggest they are the same tephra. Using an average radiocarbon age of 1840 years B.P. and a hydration-rind thickness of 4.2 microns yields a hydration rate of 9.6 microns^2/1000 years. If the thinnest rind measured (3.2 microns) is used, to date the tephra eruption, then the calculated rate is 5.5 microns^2/1000 years.

The rind-thickness data on the next oldest tephra in the SM section (SM-4) are widely spread (figure 4e). The thinnest rind is interpreted as 5.6 microns. There is also uncertainty with the radiocarbon age of this tephra, for the age on the SM section indicates 3330 ± 200 years B.P. (Appendix II, p. 65), yet there appears to be a stratigraphic correlation between the 3 lowest tephras found in Crooked Meadow, Sawmill Meadow, and the lacustrine sediments at Black Lake (fig. 6b). Radiocarbon ages obtained by Batchelder (1970) indicate that these 3 lowest tephras erupted between 4580 ± 130 and 5230 ± 110 years B.P. (fig. 4b) and the one correlative with SM-4 erupted prior to a radiocarbon age of 4940 ± 120 years B.P. Using 3330 years and 5.6 microns yields a hydration rate of 9.4 microns^2/1000 yrs. and using 4940 years yields 6.3 microns^2/1000 years. All that one can conclude from this exercise is that the rate for these buried tephras lies between 5.5 and 9.6 microns^2/1000 years.

Another possibility for calibration is the Panum Dome extrusion which must be younger than a radiocarbon age of 1185 ± 80 years B.P. (Wood, 1977), and possibly younger than a newly obtained radiocarbon date of 840 ± 250 B.P. [see p. 31-32 for discussion of Mono tephra and C^{14} sample W-3661 from section P_c; see also fig. 6a and Appendix II, p 73-74]. Range of rind thicknesses on Panum obsidian (Dome no. 3, fig. 4a) is 1.2 to 3.0 microns, and 3.0 appears to be the commonest value obtained (Friedman, 1968, reported a rind thickness of 2.5 $\pm$ 0.3 microns for Panum). Using 1185 yrs. and 3.0 microns, one obtains a rate of 7.6 microns^2/1000 yrs. Using 2.5 microns, one obtains 5.3 microns^2/1000 years. Rind thicknesses were not exhaustively determined for Panum Dome in this study, for it was decided to accept Friedman's original data. It now appears that at least 30 or more rind thicknesses should be determined from several samples in order to understand the spread of the data, and the accuracy to which the hydration rate can be determined from a young dome.

Recent success in calibrating the method in the Yellowstone area (Pierce et al., 1976) by using K-Ar dated flows indicates that K-Ar ages on sanidine from oldest domes of the Mono Chain offer the best hope for calibration. These domes are numbered 6, 11, and 24 in Plate 1. Unfortunately, Dalrymple (1968) did not date the oldest bodies, but chose more prominent domes of intermediate age. Table 2 compares Dalrymple's K-Ar ages with those estimated from the hydration rinds assuming a hydration rate of 5 microns^2/1000 yrs. There is no consistent agreement, or even a suggestion that the ages differ by a constant factor. Therefore it is not reasonable to use the existing K-Ar data for calibration. These older domes are being dated by the thermoluminescence technique (May, 1976) and will probably be dated by K-Ar (May, personal communication, 1976).

Friedman and Long (1976) suggested that knowledge of the effective hydration temperature and the laboratory measured constants on obsidian for the Arhennius equation allow computation of the hydration rate. They published a hydration rate versus temperature curve for Mono crater obsidian (Panum Dome). Shaded outcrop samples should hydrate at air temperatures. If hourly tempera-

TABLE 2.

COMPARISON OF K-AR AND HYDRATION-RIND AGES
FOR THE MONO CRATERS

Dome Number (Plate 1)	Dalrymple's Sample No.	K-Ar Age (in years)	Estimated Age From Hydration Rind (in years)
17	6G016	11500 ± 2900	5400 - 6700
		9000 ± 1800	
		10900 ± 4200	
15	6G017	8400 ± 2400	2900 - 3900
		9100 ± 1000	
26	6G008	12400 ± 4200	3300 - 4400
25	5G204	6900 ± 1600	8000 - 9800
		6300 ± 1400	
20	5G203	2900 ± 2800	6700 - 8200
		6800 ± 2000	
36	6G014	3900 ± 1300	Less than 720 ± 60 B.P. by C-14

[K-Ar ages from Dalrymple (1968); hydration-rind ages from table 1.]

ture readings were available for the Mono Basin, a rate of hydration could be computed. Judging from the few examples discussed in Friedman and Long (1976), buried tephra samples should hydrate at a slightly lower rate. There are many uncertainties in a computed hydration rate particularly because some materials dated in this study endured late Wisconsin and Holocene climatic fluctuations. Since Friedman and Smith (1960) found that most radiocarbon calibrations of the hydration rate in northern temperate and continental climates ranged from 4.5 to 6.5 $microns^2$/1000 years, use of a rate within this range is the best choice until detailed temperature measurements and radiometric calibration become available.

Because of the difficulty in obtaining radiometric calibration of the hydration rate, I have simply used the rate originally assumed by Friedman (1968) of 5 $microns^2$/1000 years to convert relative hydration-rind ages to an estimated age. The radiocarbon control on tephra sections and on Panum Dome would suggest a greater rate and would produce younger ages than those reported here. For instance, a rate of 9.5 $microns^2$/1000 yrs. would produce ages a factor of 0.53 smaller than the estimated ages reported here.

More significance can be attached to relative ages reported as the square of the hydration-rind thickness in figure 5. Ages reported in this manner should differ from true age by the same constant factor provided the temperature history and the major-element chemistry of the samples are the same, and provided the basic assumptions of the hydration-rind dating method are correct (Friedman and Long, 1976). All of the data on figure 4a are on obsidians of the same chemistry. Obsidians from the Inyo domes and Paoha Island (figure 4b) are chemically different. However, the effect of different chemistry on the hydration rate is probably insignificant compared to the effect occasioned by small differences in the temperature environment of different samples.

THE MONO DOMES AND CRATERS

Petrology of the various domes and flows is shown in figure 2. The oldest dome appears to be the rhyodacite dome on the northwest side originally described and analyzed for major-element chemistry by Lajoie (1968). It contains large phenocrysts of andesine plagioclase and sub-angular inclusions of dark reddish-grey volcanic rock that resembles andesite, although the inclusions have not yet been chemically analyzed. Lajoie (1968) noted lacustrine tufa deposits on the dome indicating it erupted prior to the late-Wisconsin high stand of Mono Lake. No dating techniques have been applied to the dome.

The next oldest are the 12 or more porphyritic rhyolite domes, commonly one to two kilometers in diameter. These domes contain 3 to 10 per cent sanidine phenocrysts, and some contain minor amounts of phenocrysts of plagioclase, quartz, amphibole, and biotite. The ground mass is mostly grey pumiceous obsidian with densities ranging from 0.5 to 2.0 gm/cc.

Material suitable for hydration-rind determination was difficult to obtain from many of these domes and occurred only as thin streaks or minute lenses of non-pumiceous black glass. Estimated hydration-rind dates on the porphyritic rhyolite domes range from 40,000 to 2,900 years and suggest two major periods of activity 25,000 to 20,000 years ago and during the last 10,000 years (table 1 and figure 5). Field relationships indicate that the porphyritic rhyolites are older than the aphyric and very sparsely porphyritic rhyolites. Aphyric rhyolite flowed over the porphyritic domes. Very sparsely porphyritic and aphyric domes occupy craters within porphyritic domes or appear to have erupted from the flanks of porphyritic domes. All flat areas of porphyritic domes are fluted and etched by wind-driven sand derived from pyroclastic deposits (figure 3a).

Two of the porphyritic rhyolite domes have numerous, sub-angular inclusions of vesicular olivine basalt (fig. 3a), indicating that they erupted through an older basalt flow. Basalts under the Mono Chain are probably the Basalt of June Lake Junction (Kistler, 1966) bracketed in age between glacial moraines of Tioga and Tahoe advances (Putnam, 1938). Alternatively the inclusions could be from some older basalts not exposed at the surface. Major-element chemistry of a typical basalt inclusion is given in Appendix I and is similar to analysis from the June Lake Junction Flow by Lajoie (1968).

Four domes of intermediate age (nos. 8, 16, 23, and 26, Plate 1) and also Wilson Butte* are composed of very sparsely porphyritic rhyolite (about 1 sanidine phenocryst per 20 cm^2 of outcrop area). Estimated hydration-rind ages on these domes range from 1200 to 8700 years (table 1).

All aphyric rhyolite domes and flows are judged on field evidence to represent the most recent eruptions of the Mono Chain. These features have fresh and jagged outcrops and lack the thick tephra mantle present on the porphyritic rhyolite domes. Hydration rinds are all less than 4.3 microns (table 1), suggesting an age less than 3700 years. Extrusions of the South Coulee, the North Coulee, the Pumice Pit dome, and Panum crater were each preceded or accompanied by eruptions of aphyric tephra. The Northwest Coulee (Dome no. 8) is entirely mantled by aphyric tephra indicating it erupted prior to tephra eruptions at the north end of the chain at Panum and Pumice Pit domes. The North Coulee is partially mantled by a ridge of angular obsidian tephra that erupted from a fissure within the coulee that developed above the trace of the main ring-fracture zone. Much of the North Coulee, however, appears to be free of a tephra

* Although Wilson Butte (Dome no. 31) geographically appears to be associated with the Inyo craters, major- and trace-element chemistry match those of the Mono Chain and Lajoie (1968) considered it geochemically part of the Mono Chain.

mantle and may be younger than the main eruptions of aphyric pumice. The South Coulee is mantled by patches of tephra (now forested with pines) that are a chaotic mixture of large blocks and finer pumice and obsidian fragments. There is no coherent bedding and it is likely that the flow was being extruded during pyroclastic eruptions that came from centers adjacent to the north side of the flow labelled in Plate 1 as the "South Coulee Tephra Complex".

The "South Coulee Tephra Complex" is in the area between Hill 9138 and the South Coulee. It is entirely mantled by thick deposits of stratified and wind-reworked, aphyric, pumice tephra and contains three prominent craters that were probably source vents for major eruptions of aphyric tephra (figure 3c). In particular the 2-meter thick set of stratified tephra layers found on domes just south of the South Coulee, but not on it, is probably from this source.

Panum crater and the low-lying Pumice Pit dome (no. 3 and 4, Plate 1) lie within tephra rings that represent the most recent pyroclastic eruptions from the chain. The Pumice Pit tephra ring and dome preceeded the tephra ring and dome of Panum crater, but the timing and nature of the several pyroclastic eruptions from these adjacent vents are complex in detail. Scattered stratigraphic sections of pyroclastics near the north end of the chain have not yet yielded a consistent story of the events that occurred here. Low sun-angle air photos (fig. 3d) show features suggesting that these eruptive centers lie at the intersection of a northeast-trending fracture zone with the northwest-trending extension of the Mono craters ring-fracture zone (Plate 1). The material that forms the hills south of the domes is composed of several block avalanche deposits. The older deposits may have been faulted prior to the deposition of the most recent block avalanche associated with the Panum Crater eruption, for it appears to be channelled in a low-lying triangular area with its apex at the low side of the Panum tephra ring. The low-lying 'Pumice Pit' dome appears to have intruded lacustrine sediment for the top of the dome contains chaotic blocks of green silt complexly mixed with the grey pumiceous glass of the dome. Exposures in the pumice pit show that the dome is overlain by 3 pyroclastic units probably from the adjacent Panum Crater (figure 3b). Hydration rinds from an obsidian spine of the 'Pumice Pit' dome range from 2.8 to 3.3 microns suggesting an age of 1550 to 2200 years. The Panum tephra ring partially overlies this dome and the block avalanche deposits. The most recent feature is Panum dome (dome no. 3) with reported hydration rinds of 2.5 ± 0.3 microns (Friedman, 1968) but which vary from 1.2 to 3.0 microns, suggesting an age between 300 and 1800 years (table 1). Panum dome, the Cratered dome of Smith (1973) (dome no. 5 on Plate 1), and the dome extruded upon the Northwest Coulee (dome no. 9) are not mantled by tephra and must be younger than a tephra erupted from the northern end of the chain with a well-established radiocarbon age of 1190 ± 80 years B.P.

Mono tephra

Lajoie (1968) studied the 17 rhyolite tephra layers in the lacustrine silts deposited during the late Wisconsin high stand of Mono Lake (fig. 6a, section WC). 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]). The 17 tephras have a relatively uniform and homogeneous trace-element chemistry characteristic of the Mono domes. These ash layers are generally quite thin over most of the basin. The thickest sequence, layers 9 through 14, rarely exceeds 30 cm in thickness, and most of the layers are a few cm. Lajoie (1968) observed that they are thicker and coarser east and northeast of the Mono craters in response to the prevailing winds. I am not able to make a one-for-one correspondence of these tephras with the domes. It is puzzling that more of the domes do not yield hydration-rind dates within the range 30,000 to 13,000 years B.P. Two large domes (nos. 11 and 24, Plate 1) yield estimated hydration rind ages of 24,000 ± 1500 and 23,000 ± 3000 yrs, respectively, which agree remarkably well with a radiocarbon date, 23,300 ± 300 years B.P., obtained by Lajoie (1968) on ostracodes associated with the thickest tephra layers in the lacustrine silt section. There are no matching domes for the other 11 tephra layers. One would conclude from relationships within the domes that all of the Mono tephras in the late Wisconsin silts would be porphyritic sanidine rhyolites. All such tephra examined in sections on the south shore of the lake are, indeed, porphyritic.

The next oldest section containing Mono tephra has been studied by Batchelder (1970) and is shown in figure 6b. This section of lacustrine silt from Black Lake 16 km east of the chain has no tephra in the interval containing radiocarbon dates of 11,350 ± 350, 8550 ± 210, and 5230 ± 110 B.P. Three tephra layers occur in the interval dated 5230 ± 110 to 4580 ± 130 B.P., and two tephra layers occur above sediment dated 2190 ± 90 B.P. Nearly identical stratigraphic sections (figure 6b) are found in Crooked and Sawmill Meadows on the north flank of Glass Mountain 16 and 32 km east of the chain and also in a spring deposit on Moho Mountain in the Excelsior Mountains, Nevada, 75 km northeast of the chain (R. Bucknam, written communication, 1975). Radiocarbon ages in these sections generally concur with those obtained by Batchelder (1970). In these sections are three layers of porphyritic pumice tephra between radiocarbon dates 3330 ± 200 and 4570 ± 200 and three layers of aphyric pumice tephra above a radiocarbon date of 1990 ± 200 B.P. These sections reflect the same relationship of aphyric rhyolite overlying porphyritic rhyolite observed in the Mono domes. The sections provide an independent radiocarbon determination of a date between 1990 ± 200 and 3330 ± 200 B.P. for the change in the nature of erupted magma. The estimated date for this change determined from hydration rinds is 2700 to 3700 yrs. It is indeed puzzling that there are no tephras between radiocarbon yrs 5230 and 11,350 in the Black Lake section. Ages estimated from hydration-rinds on the domes suggest considerable activity in this interval. One volcanic ash layer slightly younger than a radiocarbon date of 7705 ± 90 years B.P. (UGa-674), and with trace-element chemistry similar to that of the Mono Chain (Appendix II), is found in Beasore Meadow, 60 km southwest of the chain, on the west slope of the Sierra Nevada. It appears that while many domes extruded during this interval, there were few pyroclastic eruptions. Alternatively, the assumed hydration rate may not be correct, and most porphyritic domes are younger, or perhaps not enough sections have been found in the area about the craters to make a firm statement on the paucity of Mono tephra during the first half of the Holocene.

There appear to have been three major eruptions of aphyric pumice tephra (fig. 6a). Radiocarbon control on the age of the tephra is summarized in figure 6c. The oldest aphyric layer is dated 1990 ± 200 B.P. at Sawmill Meadow, although ages of 1695 ± 200 (W-3469) and 1520 ± 200 (W-3510) have been obtained on a basal aphyric layer in other sections (figs. 6a,b). This layer at Sawmill Meadow is characterized by a lapilli ratio of white pumice to black obsidian to grey rhyolite of about 4:3:3. A similar tephra mantles the Mono domes south of the South Coulee. The material erupted from the South Coulee Tephra Complex (fig. 3c) also has a similar lapilli makeup and is the most likely source. A similar tephra also occurs at the northern end of the chain, but radiocarbon dates obtained so far do not allow a simple correlation. The overlying two layers at Sawmill Meadow are of white aphyric ash. The middle one is a widely recognized volcanic ash in eastern California called tephra 2 by Wood (1977) and is well dated at 1185 ± 80 B.P. elsewhere. The uppermost layer at Sawmill and Crooked Meadow is thin and discontinuous but must represent a still younger eruption of aphyric ash in the Mono craters. In figure 6a, section PC, a radiocarbon age of 840 $\pm$ 250 years B.P. was obtained on a carbonized log within a layer of white aphyric pumice. It is not known whether this age is significantly different than 1185 years B.P. (M. Rubin, personal communication, 1976) and it will be reanalyzed using sufficient charcoal to make the distinction. Furthermore, the uppermost tephras of sections Z and PC are the same white aphyric pumice layer that mantles the area about Panum Crater. This tephra was tentatively correlated with the 1185 $\pm$ 80 B.P. tephra by Wood (1977), but recognition of a deeper layer of white aphyric pumice in the Z section makes this correlation suspect. Unfortunately, charcoal submitted for radiocarbon dating of this deeper tephra contained numerous rootlets and produced a modern age (200 yrs B.P.) that is not valid.

Mono tephras are encountered northeast of the Mono Basin by R. Bucknam (written communication, 1975, 1976, and U.S. Geological Survey, 1976). The stratigraphic sections, petrographic nature of the tephra, and radiocarbon control obtained by him are shown in figure 6b. All of these tephras are probably present in the Sawmill Meadow section but the exact correlation and areal extent of each tephra are yet to be worked out.

Average extrusion rates of Mono domes

Cumulative volume of extruded magma in the Mono Chain is plotted against time in figure 5. Volumes do not include pyroclastics other than those noted in table 1. The first extrusion of highly differentiated rhyolite magma characteristic of the Mono Chain occurred possibly 40,000 years ago (dome no. 6, Plate 1, and chemical analysis in Appendix I). Eruptions of domes and tephra occurred sporadically between 40,000 and 10,000 years ago and did not contribute significantly to the total volume of the chain. About 10,000 years ago, eruptive activity increased and lava was extruded at an average rate of 0.2 km^3/1000 years until about 3000 years ago. About 3000 years ago, the average rate of extrusion dramatically increased to 0.8 km^3/1000 years beginning with the eruption of the South Coulee and its associated tephra complex. The nature of magma also changed from sparsely porphyritic (3 to 10 per cent sanidine phenocrysts) to crystal-free (aphyric) rhyolite. All eruptions since 2000 radiocarbon yrs B.P. have produced magma that is aphyric but is of the same chemical composition as the earlier porphyritic magma. Volumes of porphyritic and aphyric extrusives, each of which includes volumes of lava and volumes of pumiceous pyroclastics reduced for porosity, are nearly equal and total about 4 km^3.

Projecting the recent rate of extrusion over the time since the last major eruption 1185 radiocarbon yrs ago suggests that a future eruption in the Mono chain could release as much as 1 km^3 of material. Judging from the proportion of lava to pyroclastics erupted from Panum Crater, at least half of this lava volume (or an equal volume of expanded tephra) could be ejected as pyroclastics in the form of base surges, tephra falls, and ash flows.

Examination of the eruption frequency in figure 5 suggests it has averaged 400 to 600 years and has not changed significantly with the change in extrusion rate and magma type. Twelve dome extrusions occurred in the interval 10,000 to 3,000 years, and extrusions occurred in the last 3000 years. Both radiocarbon-dated tephras and the hydration-rind data suggest periods of dormancy as long as 1500 years have occurred in the Holocene, but the two dating methods do not agree on the ages of the periods of abnormally long dormancy.

Chemical composition of Mono Chain magma does not appear to have changed through time (except for the one older rhyodacite dome) according to analysis by Carmichael (1967) and new analysis on the oldest dome (no. 6) and on one of the older domes with basalt inclusions (no. 18) presented in Appendix I. Therefore this change in the physical character of the magma must be caused by an event within a chamber of highly differentiated rhyolite magma. Understanding this change in the Mono craters magma system will not be complete until the mineralogy and petrochemistry of the various-aged rhyolite domes have been investigated in detail.

Discussion

The history of lava extrusions from the Mono magma chamber may contain useful information about the early evolution of shallow granitic magma bodies and associated rhyolite volcanism. A change with time from porphyritic to aphyric rhyolite is observed in the Mono Chain as well as in the Glass Mountain rhyolites, which preceded the eruption of the Bishop Tuff and formation of the Long Valley Caldera (Bailey and others, 1976, and Bailey in U.S. Geological Survey, 1976).

The porphyritic magma was probably more viscous than the aphyric magma by several orders of magnitude. Presence of 3 per cent phenocrysts may increase the viscosity by 10^2 (Shaw, 1965). Carmichael (1967) obtained iron-titanium-oxide quench temperatures for porphyritic rhyolite of the Punchbowl dome (Sample no. Cam 73 and 99) of 790° and 810°C. For very sparsely porphyritic rhyolite of the Northwest Coulee (Sample no. Cam 108) he obtained 915°C, and for aphyric rhyolite of the Pumice Pit dome (Sample no. Cam 110), he obtained 910°C. Such a temperature difference of 100°C may change the viscosity of near liquidus rhyolite magma by at least one order of magnitude (Friedman et al., 1963). Thus the increase in volume rate of extrusion with the change to aphyric magma seems attributable to the greater fluidity of the crystal-free magma.

The actual mechanism by which a change in magma type occurred 3000 years ago is a matter of speculation. One can imagine a sequence of events whereby rhyolite magma emplaced in the shallow crust begins to cool around the margin of the chamber. Regional tectonic strain or adjustments within the magma chamber intermittently open the ring fracture system sufficiently to allow extrusions. The first magma tapped would be the cooler outer layer of porphyritic magma. When this is exhausted in the vicinity of the ring fracture, the underlying aphyric magma wells up in a manner analogous to upward coning of water in an oil-producing well in a water-drive reservoir as illustrated in figure 7. The ring-fracture conduit thereafter produces only aphyric magma. Alternatively, Bailey (written communication, 1976) has suggested a convective change in the magma or a sudden rise of magma to a shallower depth could account for the change to the aphyric type.

Since the Mono Chain appears to have erupted rather continuously over the past 10,000 years, it is possible that pressurized magma erupts nearly as fast as it forms in the upper part of the magma chamber. This possibility suggests minimum rates of formation of pressurized magma equal to one of the eruption rates, or between 1×10^{-4} and 16×10^{-4} km^3 per year.

Geothermal Potential of the Mono Craters Area

The highly differentiated rhyolite magma of the arcuate Mono Chain and the concentric ring-fracture system suggested to Bailey et al. (1976) that a modern rhyolite magma chamber possibly 18 km in diameter lies beneath this area (U.S. Geological Survey, 1976). The Mono craters area lacks a near-surface heat-flow anomaly and evidence for a major hydrothermal convection system. Lachenbruch et al. (1976) obtained a shallow heat-flow value that can be interpreted as a typical Basin and Range value ($q = 2.18$ H.F.U. and $\Delta T/\Delta Z = 31^{\circ}C/km$) at Aeolian Buttes, 4 km west of the chain. A geothermal test on the south shore of Mono Lake 2 miles east of the trace of the ring-fracture zone encountered bottom-rock temperatures of $54^{\circ}C$ at 1.24 km depth in the granite basement (Axtell, 1972) or only $5^{\circ}C$ greater than that expected from projection of the geothermal gradient. During the driving of the L.A. aqueduct tunnel under

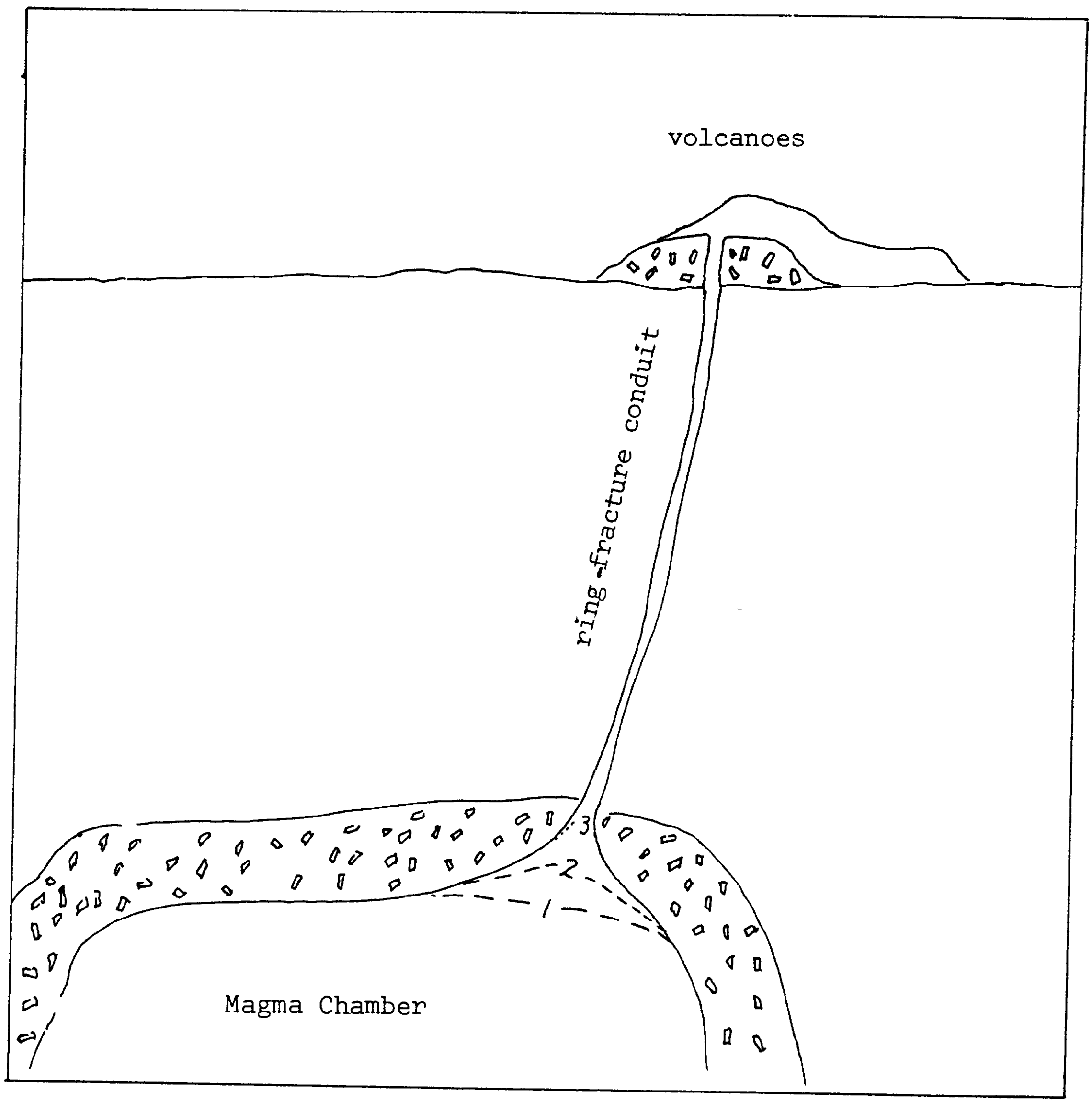


Figure 7. Illustration of the "coning" explanation for the time change of porphyritic to crystal-free lava as observed in the Mono Chain and in the Glass Mountain rhyolites: (1) is the pre-eruption lower boundary of the cooler and more viscous porphyritic layer, (2) shows the upward coning of the aphyric magma as extrusion proceeds, and (3) shows the aphyric magma breaking through and extruding on the surface.

the Mono Craters 38^{o}C waters were encountered beneath South Coulee (Gresswell, 1940), but this temperature is not excessive for this depth. No significant hot spring activity seems to be associated with the Mono Craters.

The estimated young age for the beginning of rhyolitic volcanism from the Mono magma chamber suggests that rhyolite magma may have been emplaced in the shallow crust as recently as 40,000 yrs. Calculation by Lachenbruch et al. (1976) indicate that a thermal disturbance of this age would have propagated upward by solid conduction only 4 km. It is possible that the magma chamber is deeper than 4 km and that the thermal front has not reached the porous basin sediments and evolved a hydrothermal system.

ago. Calculations by Lachenbruch et al.

WESTERN MONO BASIN AND THE ISLAND VOLCANOES

The Mono Basin is a shallow, elongate downwarp, 20 km wide and 40 km long, that plunges gently to the southwest. It is deepest on the west where it abuts the northwest trending eastern escarpment of the Sierra Nevada. Several lines of evidence suggested to Christensen et al. (1969) that the basin formed within the last 3 to 4 million years. Thickness of basin fill has been a matter of debate (Pakiser et al., 1960; Christensen et al., 1969), but recent revisions of geophysical interpretations indicate the basin sediments are no deeper than 2.5 km (Pakiser, 1976). Recent geothermal tests on the north and south flanks encountered granitic bedrock at 0.5 and 1.2 km, respectively (Axtell, 1972).

The pattern of recent faulting in the Mono Basin can be resolved into three groups: 1) the system of normal faults, trending N30°W, that parallel the frontal faults of the eastern Sierra escarpment, 2) a system of faults that trends about N60°E, and 3) the ring-fracture system concentric with the Mono crater arc (figure 1).

Frontal faults of the eastern Sierra escarpment form the west margin of Mono Basin. A recent fault of this system offsets Wisconsin-aged moraines in Lundy Canyon and is inferred to continue along the base of the steep escarpment to Lee Vining Canyon. Between Lee Vining Canyon and June Lake, the rangefront is set back to the west about 8 km, and no conspicuous faults cut moraines in the June Lake Loop area. This is the area that is outlined by Kistler's (1966) ring fracture and is presumably underlain by the Mono magma chamber (Bailey et al., 1976; and U.S. Geological Survey, 1976).

The group of northeast-trending faults includes the 25-m-high, up-to-the-north, bathymetric escarpment that runs for 15 km in a N60°E direction beneath Mono Lake (shown by the 6320-ft. contour, Plate 1). This escarpment can be extended to the recent small graben at the northwest end of Mono Valley shown by

Gilbert et al. (1968). This northeasterly trend also contains the westward shift of the "Nevada Seismic Zone" (Gumper and Scholtz, 1971) along 38^{O}N latitude. Ryall and Priestly (1975) observed that the composite focal mechanism of small earthquakes (M<4, 1970-1971) in this area has a remarkably good fit to oblique, left-lateral, up-to-the-north displacements on faults trending N49^{O}E and dipping 54^{O}NW. This fault-plane solution is in agreement with surface rupture observed by Callaghan and Gianella (1935) for the 1934 Excelsior Mountain Earthquake (M=6.3). Gilbert and others (1968) also recognized geologic evidence for a left lateral component of faulting in the northeast part of the basin.

Northwest trending, down-to-the-west scarps are mapped by Lajoie (1968) on the southeast side of Mono Lake (Simon Springs and the Warm Springs Faults). As one proceeds west along the south shore of Mono Lake, the orientation of fractures or faults, marked by spring lines and aligned tufa towers, show a systematic swing from a north-south strike to a northeasterly strike. At the north end of the Mono craters, this system is perpendicular to the Mono Crater arc. This system of faults implies recent down faulting of the western Mono Basin. The relation of the pattern of faulting to the ring-fracture system of the Mono craters is not evident. However, it seems more than a coincidence that volcanism forming the islands of Mono Lake and also the Mono craters should lie at the intersection of this northeast-striking fault and seismic zone with the frontal fault system of the eastern Sierra escarpment.

Bathymetry about Paoha Island (Scholl et al., 1967) shows that it is a broad domal feature about 100 m high and 6 km in diameter across the base. The island is interpreted as doming of lacustrine sediments by shallow intrusions of magma (Lajoie, 1968). An arcuate trough ("Putnam Basin") with numerous closed depressions forms the east base of the island, and is probably fissuring related to volcanism. On the south flank of the island is a feature resembling a small dome, 300 m in diameter and 10 m high within a closed depression. Hot springs discharge from the rhyolite dome on the south shore of the island at a rate of about 100 gal/min (378 ℓ/min) at 83°C. Warm potable water issues at a rate of about 30 gal/min (114 ℓ/min) from lacustrine sediment on the flank of an explosion pit on the west side of Hot Springs Cove.

The northwest part of Paoha Island is a complex mixture of large blocks and spires of grey pumiceous rhyolite with the lacustrine sediment. The northeast corner is overlain by a rhyodacite flow and a rhyodacite cinder core (Lajoie, 1968). The suspected young age of the Paoha Island volcanics (Lajoie, 1968) is supported by consistent hydration-rind thickness measurements of 2.0 to 2.2μ on rhyolite obsidian sampled from the cliffs on the northwest shore of the island. An age assignment based on hydration rinds is only an estimate until calibrated. Assuming a hydration rate of $5\mu^2$/1000 yrs (Friedman, 1968) yields an estimate of 800 to 900 yrs. Field relationships suggested to Lajoie (1968) that the rhyodacite flows and pyroclastics on Paoha are slightly younger than the rhyolites.

Negit Island is composed of two recent rhyodacite flows and a cinder cone, and a central saddle area of older tuffs mantled by a sequence of two surficial tephras. The lower of the two tephras is a rhyodacitic tephra with trace-element chemistry matching that of the Paoha Island rhyodacites and not that of the Negit Island rhyodacite (see section NI in Appendix II, p.64, and analysis by Lajoie (1968) published in Wood (1977). The rhyodacite tephra is overlain by a white aphyric rhyolite pumice ash and lapilli that must have come from eruptions in the Mono craters, and is probably 1185 ± 80 yrs B.P. or younger. Therefore, the pyroclastic rhyodacite eruptions on Paoha Island just precede the last pumice eruptions from the Mono craters. Paoha Island has not been searched for recent tephra sections, but there should presumably be Mono tephra mantling parts of Paoha Island if the age estimates and tephra correlations are correct.

On the northwest shore of Mono Lake just east of the Black Point basalt cone, an abandoned well discharges at least 90 gallons/min (6 liters/sec) of hot water at 67°C (table 3a). This is the Dechambeau Well (Pl. 1) drilled in 1911 as an oil test to a total depth of 940 ft (287 m). Details of this well, the drillers log, and also other hydrologic data and chemical analysis on Mono Basin thermal springs are reported by Lee (1968). Mariner et al. (1977) have attempted to compute geothermal temperatures on the Dechambeau Well waters and the Paoha Island hot springs. They found considerable contamination of the spring waters by Mono Lake waters which complicates interpretation of the water geochemistry. Nevertheless, their data suggest a hydrothermal system with geothermal potential may exist at depth. This area was drilled in 1972 to a depth of 2442 ft (745 m). Bottom hole temperatures were 58°C (Axtell, 1972), considerably less than 67°C water issuing from the 287-m-deep Dechambeau Well, 3 km north of this geothermal exploration well (Getty Oil Co., State PRC 4572.1, 23-1; see Pl. 1).

TEPHRA STRATIGRAPHY IN THE WESTERN LONG VALLEY CALDERA

The sequence of recent tephra layers found in the western Long Valley Caldera is discussed by Wood (1977) and illustrated in figure 8. Many sections containing older tephra are described in the Appendix II. Sections K, ML, and MM contain layers having distinctive trace-element chemistry, but their correlation with one another or with a particular vent cannot be made. Hopefully, chemical analysis in progress on volcanic rocks within the caldera by R. Bailey and R. Koeppen will identify possible sources for these tephra.

In roadcuts along U.S. Highway 395 between Mammoth Lakes Junction and the Deadman Recreation area turnoff (Section K) are several older pumice layers that are not the 720-yr. B.P. tephra 1 of Wood (1977). These older pumices may represent earlier eruptions from the Inyo domes area or they may be from Mammoth Mountain*. The thickest and uppermost pumice in these roadcuts is easily mis-

* Mammoth Mountain has had relatively recent activity. Pyroclastics in Sections ML and MM (Appendix II, p.63) are probably from Mammoth Mountain. Hydration rinds on tephra in Section MM are 9 to 12 microns (figure 4c), suggesting ages of 16,000-30,000 yrs. B.P. R. Bailey and R. Koeppen (written communication, 1976) have obtained a radiocarbon age of about 500 yrs. B.P. on a stump buried by explosion debris from an explosion pit on the north side of the mountain.

TABLE 3a.

KNOWN THERMAL WATERS IN MONO BASIN*

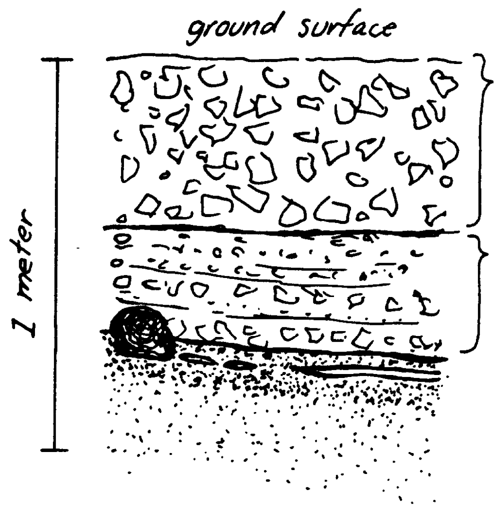
Location	Estimated Discharge (gallons per minute)	Temperature (°C)	Date of Measurement	Reference
Dechambeau Well (Total Depth 287 m) Sec 11,T2N,R26E	90	67°C	1 Jan.,1976	----
Paoha Island Hot Springs NE¼,NW¼,Sec 32,T2N,R27E	100 ∿100	80°C 83°C	∿1889 1 Oct.,1975	Russell(1889) ----
Paoha Island Springs SW¼,NW¼,Sec 32,T2N,R27E	∿ 30	27°C	1 Oct.,1975	----
Mono Basin Warm Spring Sec 17,T 2N, R 28 E.	10	33°C	∿1889	Russell(1889)

TABLE 3b.

RECORDS OF SUBSURFACE TEMPERATURES IN MONO BASIN*

Location	Depth (meters)	Temperature (°C)	Date of Measurement	Reference
L.A. Aqueduct Tunnel Sec 28,T1S,R27E	∿300	38°C	1938	Gresswell,1940
Geothermal Test Well Geothermal Resources,Inc. State PRC 4397.1 Sec 18,T1N,R27E (bottom hole temperature)	1236	54°C	1972	Axtell,1972
Geothermal Test Well Getty Oil Company State PRC 4572.1,23-1 Sec 14,T2N,R26E (bottom hole temperature)	745	58°C	1972	Axtell,1972
Heat Flow Measurement Sec 14,T1S,R26E (bottom hole temperature)	124	13.6°C	1974	Lachenbruch *et al.*, 1976

*More complete data can be found in Mariner and others (1977) and Lee (1968).



Tephra 1: 45 cm thick; Bombs and lapilli of white porphyritic pumice up to 8 cm diameter. Well-sorted massive unit.

Glass Creek tephra: 15 cm thick, contains 4 or more air-fall layers of white porphyritic pumice and grey rhyolite.

Loamy, ash-rich, soil: Tephra 2 is a discontinuous layer, about 1 cm thick, of white ash within the upper 4 cm of soil. Soil contains abundant charcoal and charred small logs.

Figure 8. Stratigraphy of tephra in the western Long Valley Caldera: Section is in the borrow pit at Mineret Summit on the Devils Postpile Road (SW¼ Sec. 25, T4S, R26E). Log is dated by M. Rubin, U.S. Geological Survey, for R. Bailey and R. Koeppen at 1040 ± 250 B.P. (W-2981). An age reported by Berger and Libby (1966) may have been from within the Glass Creek tephra, or possibly between Glass Creek tephra and tephra 1. This age is 920 ± 80 yrs. B.P. (UCLA-908).

taken for tephra 1, but it has a weathered, punky appearance and in places is covered by a meter of soil. XRF analysis (sample LV-1, Section K, Appendix II, p. 61) shows that it contains about 81 ppm Sr and not 200-225 ppm characteristic of tephra 1.

Also unresolved are two tephras, older than tephra 2 (1185±80 B.P.) that are found in meadows in the vicinity of Devils Post Pile and in the San Joaquin drainage (Wood, 1975). These layers are 15 to 20 cm thick and occur 1 m and 1.7 m deep, respectively, in meadow deposits of Cargyle Meadow, 15 km southwest of the Inyo Craters. They were not XRF analyzed in this study, but their distribution suggests they represent eruptions from the Inyo domes area or Mammoth Mtn. Their stratigraphic associations indicate an age older than 1200 yrs, but probably younger than 5000 yrs.

INYO DOMES AND ASSOCIATED PYROCLASTICS

Extrusions of the three, very recent, nearly treeless, rugged obsidian domes (nos. 32, 34, 36; Plate 1) of the Inyo Chain were each preceded by pyroclastic eruptions. Prominent tephra rings protrude from beneath the south dome on Deadman Creek and the south dome on Glass Creek. No conspicuous tephra ring protrudes from beneath the north dome on Glass Creek, but tephra stratigraphy discussed in the following section shows that formation of the dome was preceded by several pyroclastic eruptions.

Glass Creek Area

Recent events in the Glass Creek area are recorded in a stratigraphic section exposed by a borrow pit 2.5 km east of the vents (Section DS, fig. 6a and in Appendix II, p. 60). At 1.4 meters deep in this section near the top of a brown soil, is the conspicuous white ash of tephra 2 dated at 1185 years B.P. by Wood (1977). Tephra 2 is overlain by a few millimeters of the soil and 10 layers of air-fall tephra which I believe to be from eruptions in the Glass Creek area. The lower

5 layers are similar to a tephra set composed of up to 10 layers that is widespread in the west moat of the Long Valley Caldera and that also mantles parts of Mammoth Mountain. Preliminary XRF analysis shows that Sr, Zr, Rb, and Ba contents of pumice from one of these layers closely match contents of these elements in pumice from the tephra ring of the south Glass Creek Dome and contents found for the Glass Creek obsidian domes by Jack and Carmichael (1969). On the floor of the Long Valley Caldera and in the region south of the Glass Creek drainage, this tephra set is always overlain by the white porphyritic pumice tephra 1 (Wood 1977) or the ash-flow deposits erupted from the vent just south of Deadman Creek, 720 years B.P.

Here in the borrow pit section DS and in the Glass Creek area, the coarse pumice tephra and lithic fragments (0.3 to 1 m depth in section) do not resemble the Deadman Creek tephra 1. I believe these 2, or perhaps 3, layers of coarse pumice represent separate pumice eruptions from the Glass Creek vents, because 2 similar pumice layers occur in Glass Creek Canyon, west of the vents, and preliminary XRF analysis shows their Sr contents to be between 120 and 185 ppm.

The uppermost 2 layers of the borrow pit section are also believed to be from the Glass Creek vents. The second layer contains a conspicuous red scoria resembling the late Tertiary andesitic scoria and agglomerate that outcrops in the area adjacent to the west side of the north Glass Creek dome. Presumably phraetic explosions during emplacement of the north obsidian dome produced these uppermost 2 tephras composed mostly of obsidian fragments. This recent sequence at Glass Creek must be younger than 1185 yrs. B.P., and must have begun before 720 yrs. B.P. It could have continued intermittently to the last few hundred years for no minimum age has been established.

All of the older tephras (DS2 - DS6) shown in the borrow pit section are porphyritic Mono tephra according to XRF trace-element analysis. Of particular interest is the basal tephra, DS-2, for the surfaces of obsidian fragments are visibly hydrated and intact rinds are 30 to 50μ thick suggesting an age on the order of 100,000 years for the obsidian, or an unusually rapid hydration rate for buried tephra.

Lower Glass Creek has cut down through 20 to 30 meters of unconsolidated pyroclastic debris, much of which is waterlain. This pyroclastic debris at one time filled the bedrock gorge east of the volcanic vents. At the bottom of the gorge is a partly agglutinated 1.3-m-thick layer of a pyroclastic avalanche deposit. This slightly welded layer is composed of angular pumiceous and porphyritic rhyolite fragments 1 to 45 cm in diameter. The avalanche deposit appears to be down faulted to the east about 12 m. (Plate 1).

The overlying 20-30 meters of unconsolidated pyroclastics are not entirely exposed, and search for useful stratigraphic relationships in this thick section has thus far been disappointing. More detailed search of the gorge might reveal other earlier pyroclastic layers possibly interbedded with datable organic material. Several earlier eruptions must have occurred in the Glass Creek area, but only the recent sequence recorded in the borrow pit is well understood. Age of the uniformly gray, rhyolite, cratered dome (no. 33, Plate 1) is not known, but similar rhyolites occur as lithic fragments in several of the recent Glass Creek tephras. A chemical analysis of this dome is given in Appendix I.

Deadman Creek Area

Two recent domes lie on either side of Deadman Creek (no. 35 and 36, Plate 1). The northern dome (no. 35) is clearly the oldest, for it is thickly mantled by tephra. Hydration rinds on obsidian from this dome range from 7.0 to 11.6 microns in thickness (figure 4b) suggesting an age 10,000-27,000 yrs B.P. Chemical analysis of dome 35 (Appendix I) is similar to analysis on the late Moat Rhyolites [Bailey et al. (1976) and Bailey (personal communication, 1976)] and also to analysis on the Mono domes. The southern dome has extruded over the tephra ring

Figure 9. An active sinkhole in the pumice-mantled slope south of Glass Creek Canyon (SW¼,sec.29,T2S, R27E). The hole is 2.5 m wide and 1 m deep and is the freshest appearing of about 50 similar depressions distributed over an area of 300 m by 200 m. These depressions are associated with a system of fissures that extends south from this locality for 13 km to the north flank of Mammoth Mountain. This hole is probably forming by piping of the unconsolidated surficial material into an underlying bedrock fissure. The fissure system has been active within the last 720 years, but there is no clear evidence that the fissures are presently active.

of tephra 1 pumice dated at 720 yrs. B.P. (c.a. 1250 A.D.) by Wood (1977). An increment boring of the oldest living pine tree on the south dome indicates the tree is older than 1792 A.D. Thus the dome extruded some time between 1250 and 1792 A.D. It is now recognized that the eruption of tephra 1 was also accompanied by a hot ash flow which spread over a 5.7-km^2 area to the northeast of the south Deadman vent. Distribution of the ash-flow deposit is shown in Plate 1. No sections are known with both airfall tephra 1 and the ash-flow deposit in stratigraphic succession. This suggests that both may have been a result of the same eruption in which the airfall lapilli and ash were wind-blown strongly to the south, and the fluidized density flow of ash flowed to the northeast along the slope and the gradient of Deadman Creek. The ash appears to have flowed around obstacles and down drainage channels; it came to rest with a remarkably flat upper surface. Such features are typical of ash flows (Ross and Smith, 1961).

Faults and Fissures in the Inyo Domes Area

Several complex systems of north-striking fissures and small grabens run through the Inyo domes area (figure 1 and Plate 1). Some of the faulting and fissuring is very recent and post-dates the 720 ± 60-yr-B.P. tephra. Sinkholes have developed in the surficial pumice along this zone, and some are currently active (figure 9). These sinkholes are probably formed by piping of the surficial tephra into bedrock fissures at depth. The system of fissures and graben-faulting continues south of Deadman Creek and is being mapped by R. Koeppen and R. Bailey. The system includes the "Earthquake Fault" and another system that extends to Mammoth Mountain.

A LATE QUATERNARY RHYOLITE ERUPTION IN THE

TOOWA VOLCANIC FIELD, SOUTHERN SIERRA NEVADA

In the southern Sierra, 35 km northwest of the Coso geothermal area, is a recent tephra ring composed of porphyritic rhyolite pumice (figure 10). The rhyolite lies midway between the Monache and Templeton rhyodacite domes of supposed late Tertiary age. Crest to crest diameter is 0.8 km, and the total volume of rhyolite is less than 0.06 km^3. The rhyolite erupted within Long Canyon and actually diverted drainage to the north. It is an inconspicuous feature and was discovered by tracing pumice upslope from the canyon of the South Fork of the Kern River. The valley downstream from the vent has aggraded 5 to 10 m with fine ash and lapilli eroded from the tephra ring. Interbedded peat layers should provide a minimum radiocarbon age for the eruption. The feature has been modified by erosion about the same extent as early Wisconsin moraines in the area; therefore it may be as young as 30,000 to 100,000 yrs.

No far-flung tephra has been found in the surrounding area. The eruption was sufficiently powerful to hurl bombs 1 m in diameter to the top of the adjacent Kingfisher ridge (0.6 km).

Petrography of the pumiceous rhyolite is given in table 4. Chemical analysis given in Appendix I is similar to the analysis on a Coso rhyolite reported by Friedman and Long (1976), and XRF analysis shows it to be relatively low in Sr and Zr. Sanidine phenocrysts compose about 15% of the rock.

The occurrence of recent silicic volcanism within the Sierra block is unusual. It does not seem likely that it can be related to the Coso ring-fracture system reported by Duffield (1975). Instead it seems to be a separate area of silicic volcanism that was overlooked by Webb (1950) when he mapped the Toowa and Templeton volcanic centers. In view of the association of geothermal areas with silicic volcanism of late Cenozoic age, this area should be examined in more detail for it is doubtful if existing maps show all the volcanics and related structures.

* Note: See Bacon, C.R, and Duffield, W.A., 1981, Late Cenozoic Rhyolites from the Kern Plateau, Southern Sierra Nevada, California: American Jour. Science, v. 281, p. 1-34.

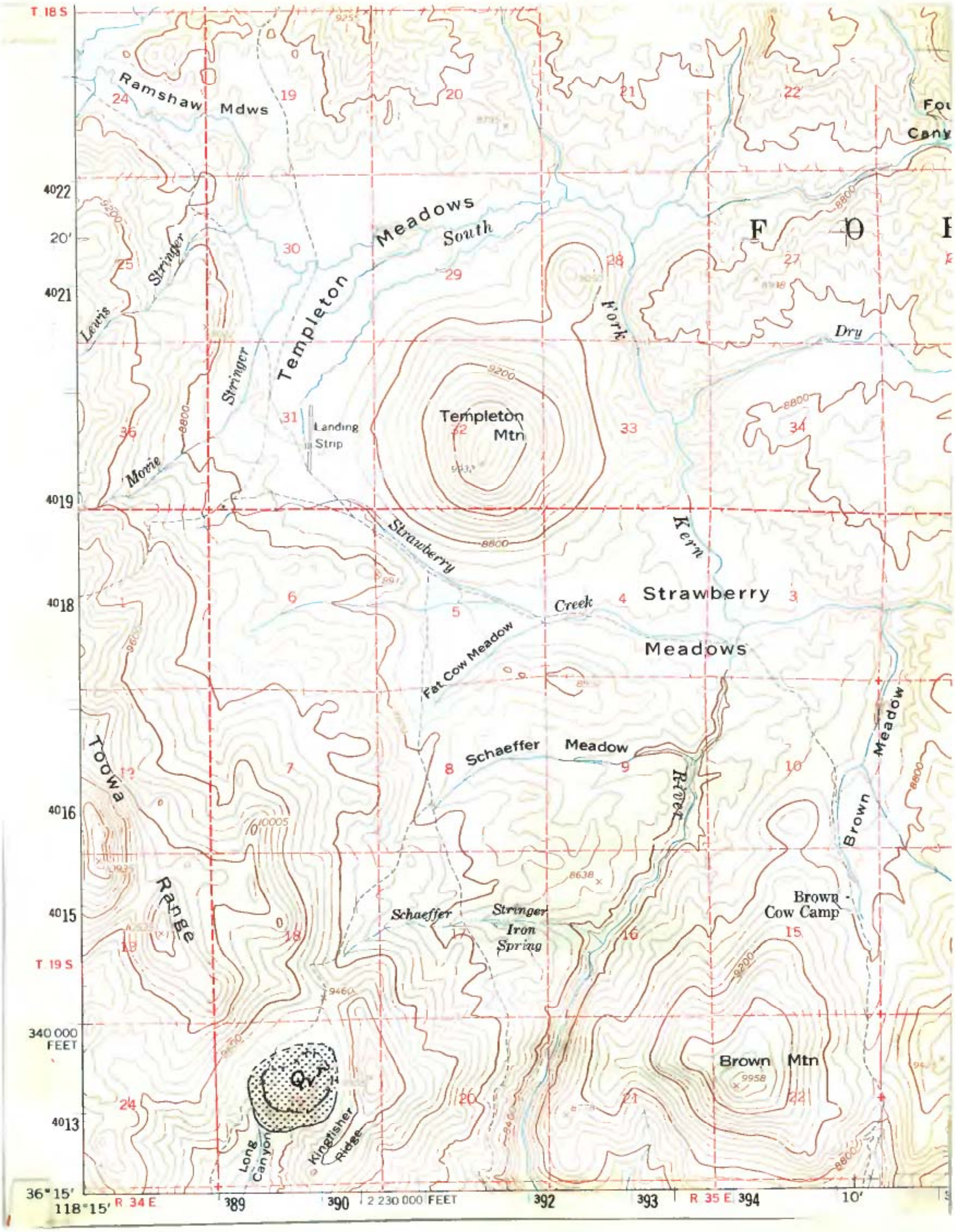


Figure 10. Map of rhyolitic pumice tephra ring in the Toowa Volcanic area of the Southern Sierra Nevada. Base map by U.S. Geological Survey, part of the Olancha 15-minute quadrangle.

TABLE 4.

PETROGRAPHY OF TOOWA RHYOLITE PUMICE

Component	Weight Percent*	Volume Percent*
Vesicles and other void space**	----	20 - 35%
Glass and Phenocrysts	100%	65 - 80%
Glass(R.I.=1.495-1.499±0.001)	75%	∿60%
Sanidine(2mm,euhedral)	15%	∿10%
Plagioclase(1mm,euhedral)	< 5%	∿ 4%
Quartz(2mm,euhedral)	tr.	tr.
Biotite(0.3mm,euhedral)	tr.	tr.

* Estimated in thin sections.

**Void spaces are 5-10% round to sub oval 0.5 mm vesicles, and about 10-25% irregular 1 to 2 mm voids created by rupturing the glassy matrix between vesicles.

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________ 1977, Distribution, correlation, and radiocarbon dating of late Holocene tephra, Mono and Inyo craters, eastern California: Geol. Soc. America Bull., v. 88, p. 89-95.

APPENDIX I: CHEMICAL ANALYSES OF VOLCANIC ROCKS

CHEMICAL ANALYSES OF VOLCANIC ROCKS FROM THE INYO DOMES AND THE TOOWA VOLCANIC FIELD

[Oxides in percent]

INYO DOME, NO. 35 (PLATE I) North Dome on Deadman Creek PUMICEOUS RHYOLITE SAMPLE NO. IC-3		INYO DOME NO. 33 Small Cratered Dome on Glass Creek Described by Mayo and others (1936) PUMICEOUS RHYOLITE SAMPLE NO. GCD		TEPHRA UNIT: 3.4 Meter Thick Airfall Unit Exposed in Road-cut, Highway U.S. 395 SW¼, Sec. 1, T3S, R27E (Sec. K) PORPHYRITIC PUMICE SAMPLE NO. LV-1		TEPHRA RING: Toowa-Templeton Volcanic Area, Southern Sierra Nevada Sec. 19, T19S, R35E PORPHYRITIC RHYOLITE PUMICE SAMPLE NO. KR-1	
SiO_2	73.26	SiO_2	72.08	SiO_2	67.28	SiO_2	73.04
TiO_2	0.13	TiO_2	0.16	TiO_2	0.35	TiO_2	0.00
Al_2O_3	13.41	Al_2O_3	14.02	Al_2O_3	15.29	Al_2O_3	13.35
MgO	0.03	MgO	0.00	MgO	0.22	MgO	0.04
Fe_2O_3	1.49	Fe_2O_3	1.83	Fe_2O_3	1.86	Fe_2O_3	0.62
MnO	0.06	MnO	0.06	MnO	0.13	MnO	0.12
CaO	0.73	CaO	0.81	CaO	0.77	CaO	0.61
Na_2O	3.94	Na_2O	4.20	Na_2O	4.71	Na_2O	4.08
K_2O	4.93	K_2O	5.06	K_2O	4.76	K_2O	4.12
P_2O_5	0.01	P_2O_5	0.01	P_2O_5	0.04	P_2O_5	0.00
LOSS	0.00	LOSS	0.00	LOSS	0.00	LOSS	0.00
TOTAL	97.93	TOTAL	98.20	TOTAL	95.41	TOTAL	95.91
Sr	22 ppm	Sr	40 ppm	Sr	81 ppm	Sr	12 ppm
Rb	151 ppm	Rb	152 ppm	Rb	104 ppm	Rb	274 ppm
Zr	143 ppm	Zr	185 ppm	Zr	290 ppm	Zr	52 ppm

Analysis by XRF except for Na_2O which is done by INAA.
All Fe is reported as Fe_2O_3. Iron present as FeO would diminish this percentage.
Water probably accounts for much of the missing component. Analysis by G. Cunningham, Center for Volcanology, University of Oregon

CHEMICAL ANALYSES OF VOLCANIC ROCKS FROM THE MONO CHAIN

[Values in percent]

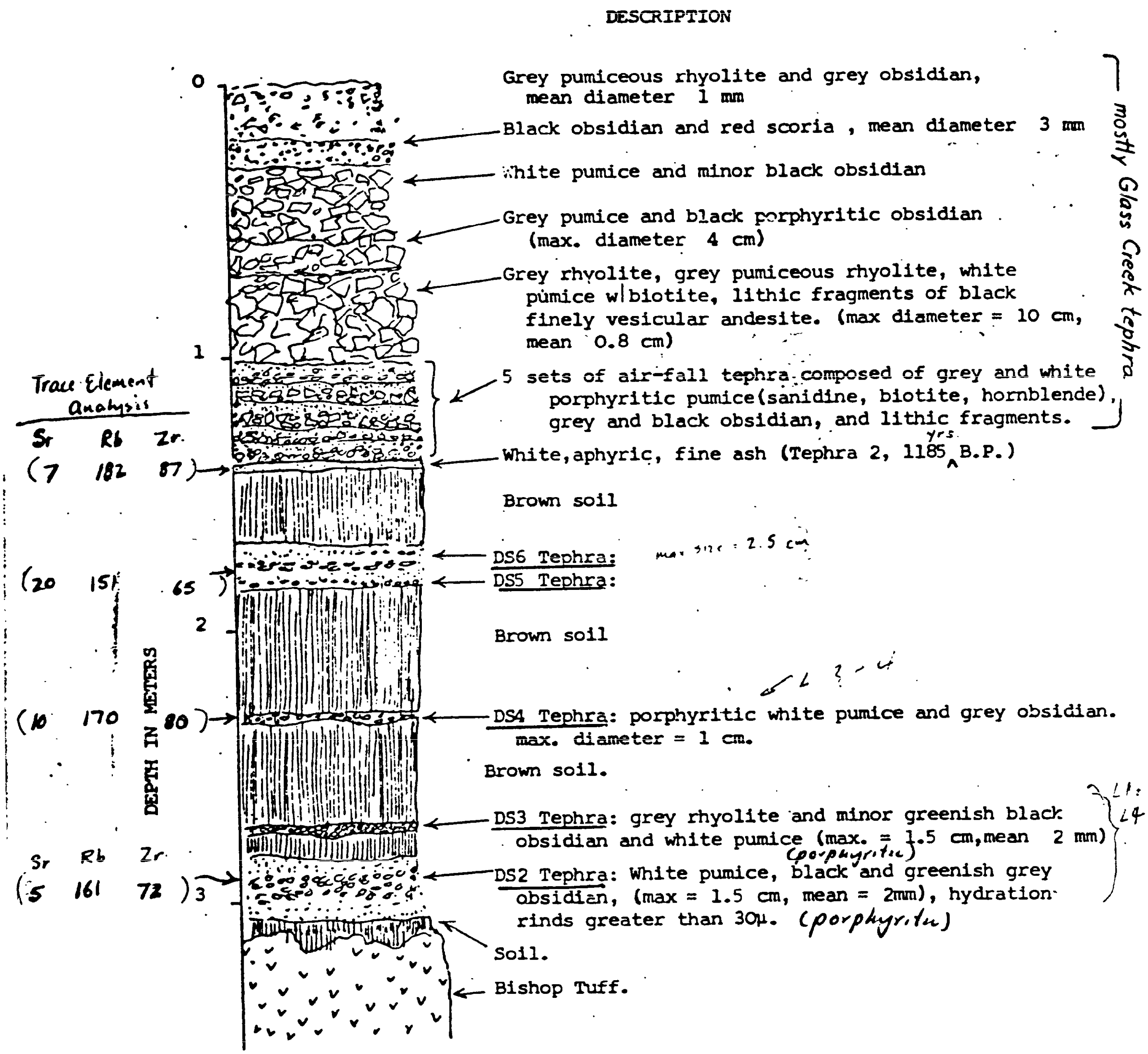
	Dome No. 6 porphyritic glassy rhyolite	Dome No. 18 porphyritic glassy rhyolite	Basalt inclusion from Dome No. 18
SiO_2	74.5	74.1	54.3
TiO_2	0.09	0.13	1.68
Al_2O_3	12.7	13.05	16.3
MgO	0.0	0.0	4.7
Fe_2O_3	1.2	1.5	9.7
MnO	0.05	0.06	0.16
CaO	0.59	0.78	7.18
Na_2O	3.8	4.15	3.81
K_2O	4.6	4.6	1.8
P_2O_5	0.0	0.01	0.36
Total	97.5	98.4	100.0

XRF analysis except for Na_2O which is done by INAA.

All Fe is reported as Fe_2O_3. Iron present as FeO would diminish this percentage. Water probably accounts for much of the missing component because other published analysis of porphyritic Mono rhyolites show water in amounts of 0.8 to 2 per cent., which is probably water of hydration. Analysis by G. Cunningham, Center for Volcanology, University of Oregon.

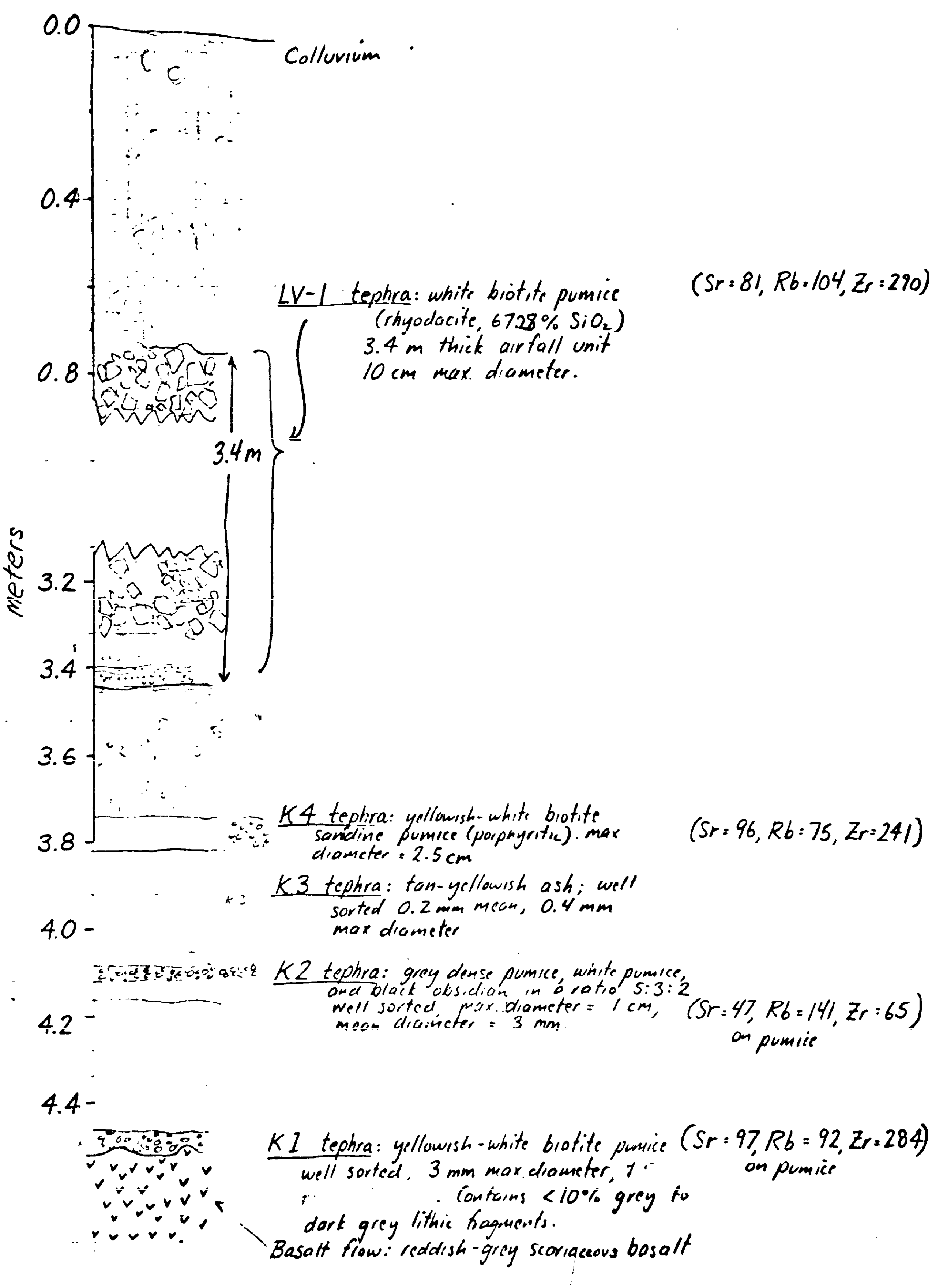
APPENDIX II: DESCRIPTIONS OF STRATIGRAPIC SECTIONS DS, K, L, ML, MM, AND NI (including XRF data on Rb, Sr, and Zr contents of tephra from these sections), U.S. Geological Survey radiocarbon dates for W-3469 to W-3473 from Section U and the Sawmill Meadows Section, and Requests for Radiocarbon Age Determination for sample W-3661 from Section PC and W-3665 from Section Z. Descriptions of Section U, the Sawmill Meadows Section, and Sections PC and Z are included with the requests.

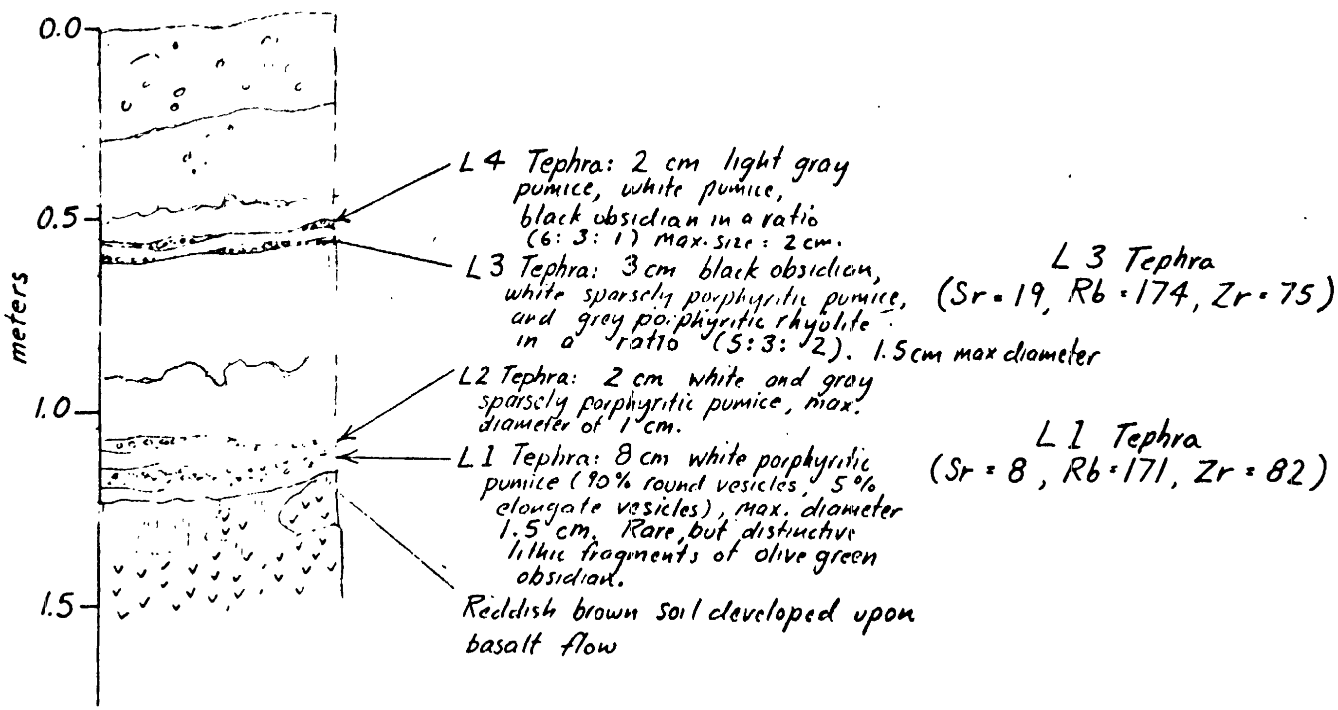
Trace elements contents are given in parts per million.



Section DS. Stratigraphic section in borrow pit just east of highway U.S. 395. Sec. 16, T 2 S, R 27 E.

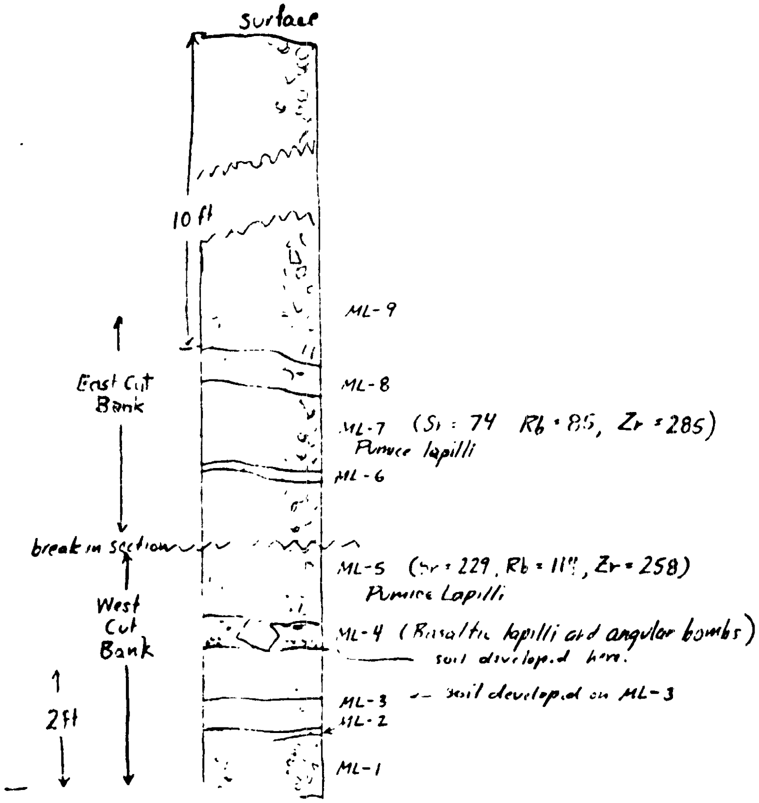
Section K in Highway 395 Roadcut, 1.6 km southwest of Lookout Mountain: SW¼ Sec. 1, T 3 S, R 27 E.



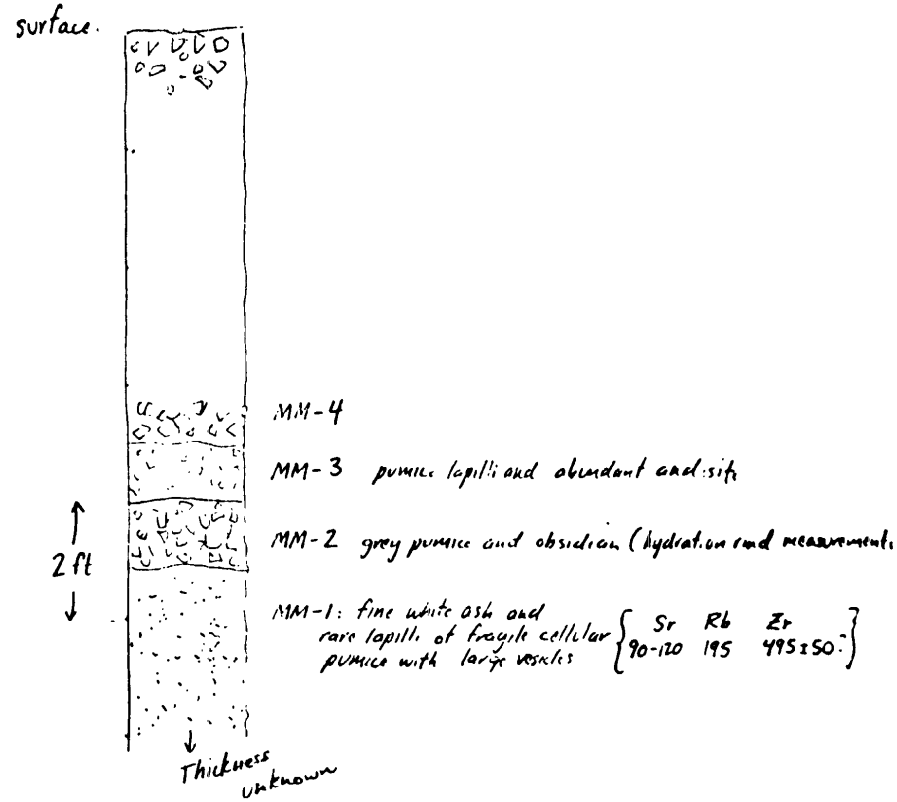


Section L.

Section in Hwy. U.S. 395 Roadcut at Deadman Recreation Area turnoff, NE 1/4, SE 1/4 Sec. 27, T2S, R27E. Southwest side of highway 395. XRF-analyses show L1 and L3 are Mono Crater tephra (Low Sr).

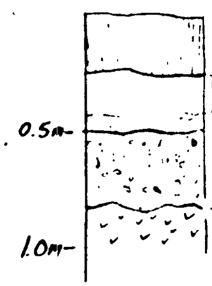


ML Section: In the town of Mammoth Lakes at intersection of Forest Trail and Lakeview. Basal 5 ft is now behind a retaining wall.



MM Section: Mineral Summit Road, roadcut by Lift 13 Terminal. Sec 32, 3S/27E

NI Section
Negit Island
NW¼ Sec 19, 2N/27E



Stratigraphy of surficial soil on flat area northeast of the prominent volcanic vent on Negit Island. NI-2 ash is most likely from Panum Crater (1185 ± 80 years B.P.) NI-1 tephra matches best the trace-element chemistry of the rhyodacites on the northeast side of Paoha Island which appear to be the only source of rhyodacite tephra in the Islands.

	Sr.	Rb	Zr
NI-1 tephra	483	79	258
Negit Is. rhyodacite	580	80	
rhyolite on shoals north of Negit Is.	380	100	
rhyodacite cinder cones on Paoha Is.	480	100	
rhyolite on Paoha Is.	115	180	

From Lajoie, 1968 (lower four rows)

9-011
(Rev. July 1962)

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

LABORATORY REPORT

Isotope Geology Branch

REPORT NO. WR-3469, 3470 **FOR** Spencer Wood **DATE** April 5, 1976

Occidental College: Los Angeles, Cal.

JOB NO. 3471 **PROJECT OR ORGANIZATION**

3472

LOT NO. 3473 **REFER TO OTHER REPORTS**

Radiocarbon Age Determination

Lab No.	Locality	Description	Age (Yrs. B.P.)
W-3469	395-2 (Section U)	Charred wood from Highway U.S. 395 Road cut 1.4 mile north of Wilson Butte, Mono County, California. 37° 47.72'N, 119° 02.30'W (NW1/4, NE 1/4 Sec.7, T.2S, R.27E.,Mono Craters Quad.). Collected by Spencer Wood on July 13, 1975.	1990 ± 200
W-3470	SM-1	Peat from meadow soil from walls of a 1-m deep gully at the lower end of Sawmill Meadow on the N.E. side of Glass Mt., Mono County, Cal. (37° 46.27'N, 118° 40.51'W) (NE 1/4, SW1/4, Sec.16, T.2S, R30E).Collected by Spencer Wood on August 13, 1975.	1170 ± 200
W-3471	SM-4	Silty organic soil from walls of a 1-m deep gully at lower end of Sawmill Meadow on the NE side of Glass Mt., Mono County, Cal. (37° 46.27'N, 118° 40.51'W) (NE 1/4, SW 1/4 Sec. 16,T2S, R30E). Collected by Spencer Wood on August 13, 1975.	3330 ± 200
W-3472	SMT	Wood from pine log buried 0.5 meters beneath surface,lower end of Sawmill Meadow on the NE side of Glass Mt., Mono County, Cal.(37° 46.27'N, 118° 40.51'W) (NE 1/4, SW 1/4 Sec. 16, T2S, R30E). Collected by Spencer Wood on August 13, 1975.	1990 ± 200
W-3473	SM-5	Peat from walls of a 1-m deep gully at lower end of Sawmill Meadow on the NE side of Glass Mt, Mono County, Cal.(37° 46.27'N,118° 40.51'W (NE1/4 SW1/4 Sec. 16,T2S, R30E) Collected by Wood on 8/13/75.	4570 ± 200

BY Meyer Rubin **APPROVED**

The Geol. Survey requires that radiocarbon age determinations quoted in any report or publication be identified by our lab. sample no., such as "W-185." Acknowledgment should be made that the measurement was done in the laboratory of the U.S.Geological Survey.

Meyer Rubin

U. S. 395-2 = W-3469
(U-2 tephra, See fig. 4d for additional data)

Request for Radiocarbon Age Determination

1. Field Project: Eruptive Chronology of Holocene Volcanism, Mono Basin and Long Valley, Eastern California.

3. Locality Name: Highway, U. S. 395 Road cut 1.4 mile north of Wilson Butte, Mono Co., California.
Sample No: U. S. 395-2.

4. Collector and Date: S. H. Wood, 13 July, 1975.

8. Geographic Location: 37°47.72'N, 119°02.30'W (NW¼, NE¼ Sec. 7, T.2S, R.27E., Mono Craters quadrangle).

11. Description of Sample: Charred heartwood from an 0.6-m-diameter pine log. Log is from tree with a longevity of 325 years based on a preliminary annual-ring count. Sample is from age 17 years to age 41 years. Log is embedded in an 0.8-m-thick pyroclastic unit (Unit 2 on ~~enclosed Section~~ and U-2 tephra in fig. 4d). Log is buried 1.5 meters beneath the ground surface that sloped about 10% to NE prior to roadcut.

12. Stratigraphic relationships: 4.5-m section exposed by roadcut and culvert excavation contains 5 distinguishable pyroclastic units described on the attached section. The log is embedded in the second unit from the top.

13. Geologic significance: Age of this log will be critical to calibration of the obsidian hydration-rind dating method in this area, as well as dating an explosive eruption of the Mono Craters. 7 preliminary hydration-rind measurements on Unit 2 (in which log is embedded) range from 4.1 to 5.7 μ suggesting an age on the order of 6500 years (using Friedman's [1968] assumed hydration rate of 5 μ^2 /1000 years).

Eight preliminary measurements on Unit 4 obsidian yield rind thicknesses of 7.5 to 10.9 μ (Avg. = 9.0 ± 0.7 μ) suggesting an age of the order 16,000 years.

US 395-2

15. Sampling and storage procedure: An entire 0.6-meter-diameter section of the log was excavated and removed. It was tightly wrapped in Al-foil. After 2 days foil was loosened, and the log air dried (75°F) in a lab for 2 weeks. Tree rings were counted and a section of carbonized wood carved out and trimmed with a clean knife. Parts and cracks with modern rootlets were trimmed off. Sample was oven dried at 110°C for 6 hours and then re-wrapped in Al-Foil on August 1st.

17. Send report to: S. H. Wood, Dept. of Geology, Occidental College, Los Angeles, CA 90041.

Stratigraphic Section U (see sketch)

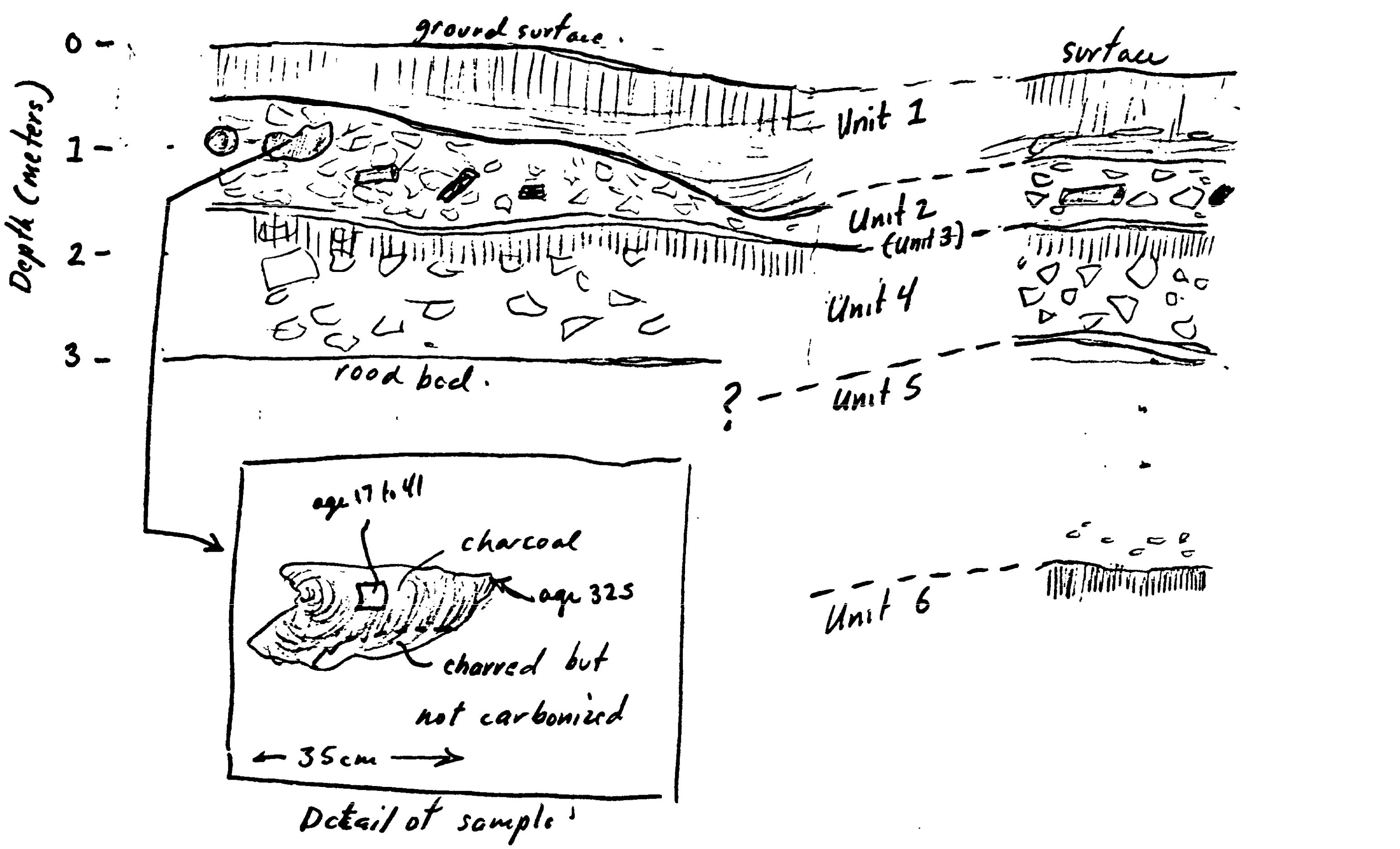
Unit 1: 0-0.5 m	Colluvial soil with partly mixed white volcanic ash bed which elsewhere in roadcut is a cross-bedded flow unit of ash and fine lapilli attaining a thickness of 1 m.
Unit 2: 0.5-1.6 m	Layer of angular pyroclastic debris and lithic fragments with abundant carbonized and charred logs and sticks. Grey pumiceous rhyolite and dense grey aphanitic, aphyric rhyolite predominate with minor white pumice, black obsidian, and lithic fragments of Wheeler-Crest-type quartz monzonite up to 15 or more cm in diameter. (Probably a near source airfall unit.)
Unit 3: 1.6-1.6 m	Thin (2 cm) layer of pinkish-white volcanic ash and elongate white pumice fragments (aligned in direction of flow) -- up to 7mm diameter -- layer is thinly stratified.
Unit 4: 1.6-3.1 m	1-m layer composed of 60% angular black prophyritic obsidian (blocks to 0.6m diameter) and lesser amounts of Wheeler-Crest-type quartz monzonite, grey and red banded porphyritic rhyolite. A soil had formed on the upper 0.3m of this unit.
Unit 5: 3.1+ m	0-7 cm discontinuous layer of white ash and obsidian and rhyolite fragments: (thinly bedded) underlain by 2m of loamy ashy soil w/o discernable stratification (not exposed at sample site).
Unit 6: not at sample site	Reddish Brown soil (loamy) without volcanic components.

U.S.395-2
W-3469

Stratigraphic Section (see description)

Sample Site

Culvert 0.2 km north.



See figure 4d.

W-3470 to W-3473

SM-1, SM-4, SM-5, SMT
Sawmill Meadow, Mono Co. CA

1. Field Project: Eruption chronology of Holocene volcanoes, Mono Basin and Long Valley, CA.

3. Locality Name: Sawmill Meadow on Glass Mountain, Mono County, CA.
   Sample Nos. SM-1, SM-4, SM-5, SMT

4. Collector and Date: S. H. Wood, 13 August, 1975

8. Geographic Location: From walls of a 1-m deep gully at the lower end of Sawmill Meadow on the N.E. side of Glass Mountain, Mono Co. CA (37° 46.27'N, 118° 40.51'W) (NE¼, SW¼ Sec. 16, T2S, R30E), Glass Mountain quadrangle.

9. References: Section probably correlates with one described by Batchelder, G. L., 1970, Postglacial ecology at Black Lake, Mono Co., CA (Ph.D dissert.): Tempe, Arizona State University, 180 p.

11. Description of Samples:

W-3470
SM-1: Fibrous meadow soil (the 3 cm immediately above ash layer 2 shown on enclosed section) Note: soil may contain up to 1% modern rootlets.

W-3471
SM-4: Silty organic soil (3 cm immediately above ash and lapilli layer 6 shown on enclosed section (probably free of modern roots).

W-3473
SM-5 Fibrous Peat (the 3 cm immediately beneath ash and lapilli layer 6). Free of modern rootlets.

W-3472
SMT: Wood from a log of Lodgepole pine buried 0.5 meters beneath surface within ash and lapilli of layer 3 on enclosed section. Log clearly fell just after deposition of ash and lapilli layer 3, and is covered by waterwashed ash 3. Log has 45 annual rings, age 21 to 44 submitted for analysis.

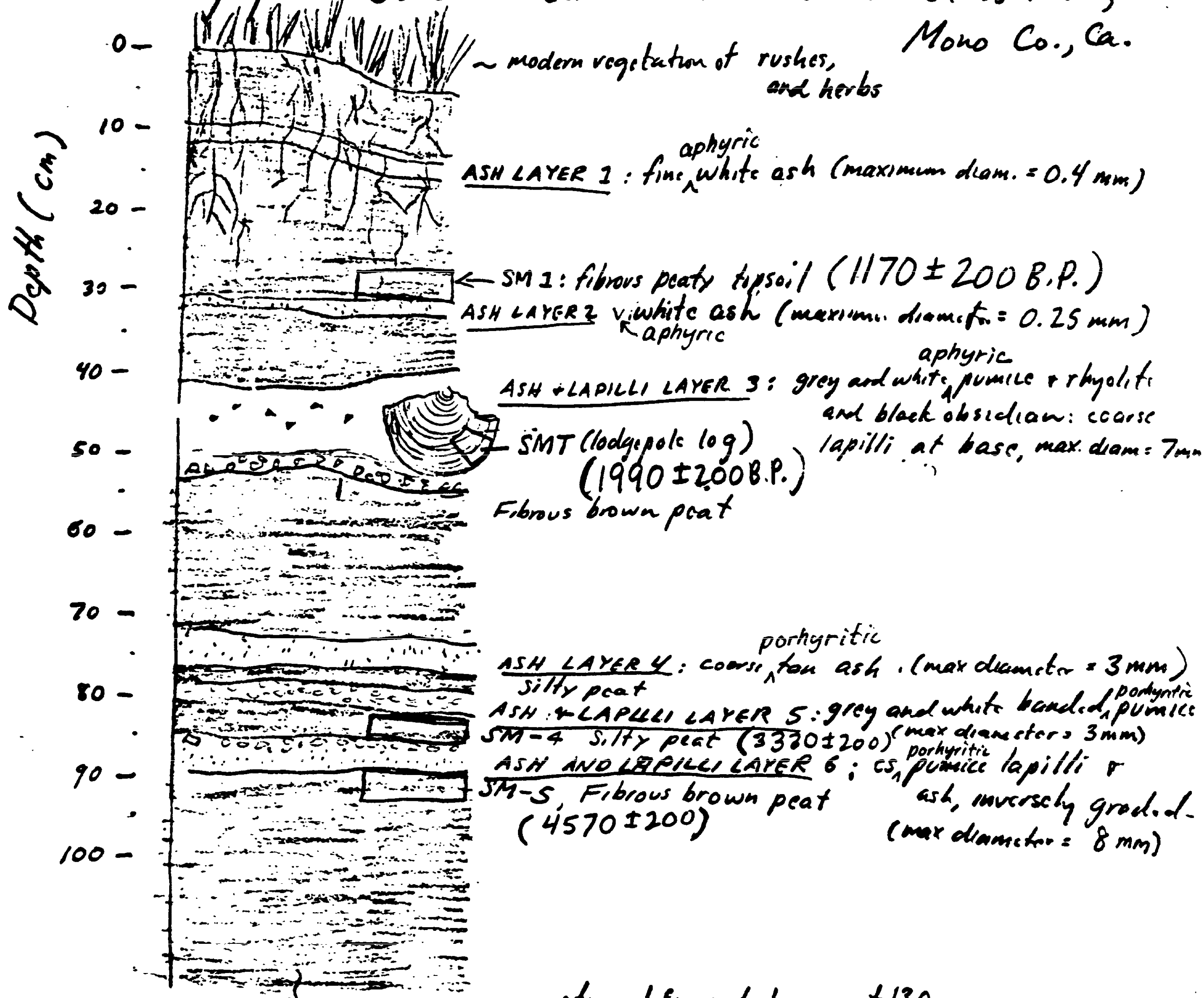
12. Stratigraphic relationships: 1.2-meter section of organic meadow soil exposed by gully, contains 6 layers of airfall rhyolitic ash and lapilli derived from the Mono Craters 29 km to the West-northwest. The stratigraphy is identical to a section observed in Crooked Meadows 8 km to the west -- thus eliminating the possibility that these layers are alluvium derived from the surrounding Glass Mtn. ash flows and obsidians.

15. Ages of these 4 samples will date eruptions of the Mono Craters and calibrate obsidian-hydration rate. Ash layers 3, 4, 5 and 6 have abundant obsidian for hydration-rind thicknesses. [See figure 4e where these layers are labelled SM-3, SM-4, and SM-5 tephra.]

18. Sampling and storage: Samples were cut from excavated clean exposure, removed with knife, and wrapped in Al-foil. Soil and peat have been stored in their original moist conditions. Wood sample was oven dried for 8 hours at 110°C.

19. Send report to S. H. Wood, Dept. of Geology, Occidental College, Los Angeles, CA 90041.

Stratigraphic Section: Sawmill Meadow on Glass Mtn., Mono Co., Ca.



Section SM ; NE 1/4, SW 1/4, Sec. 16, T2S, R30E
Glass Mtn. Mono Co., Ca.

REQUEST FOR RADIOCARBON AGE DETERMINATION

Sample no. PC-1
W-3661

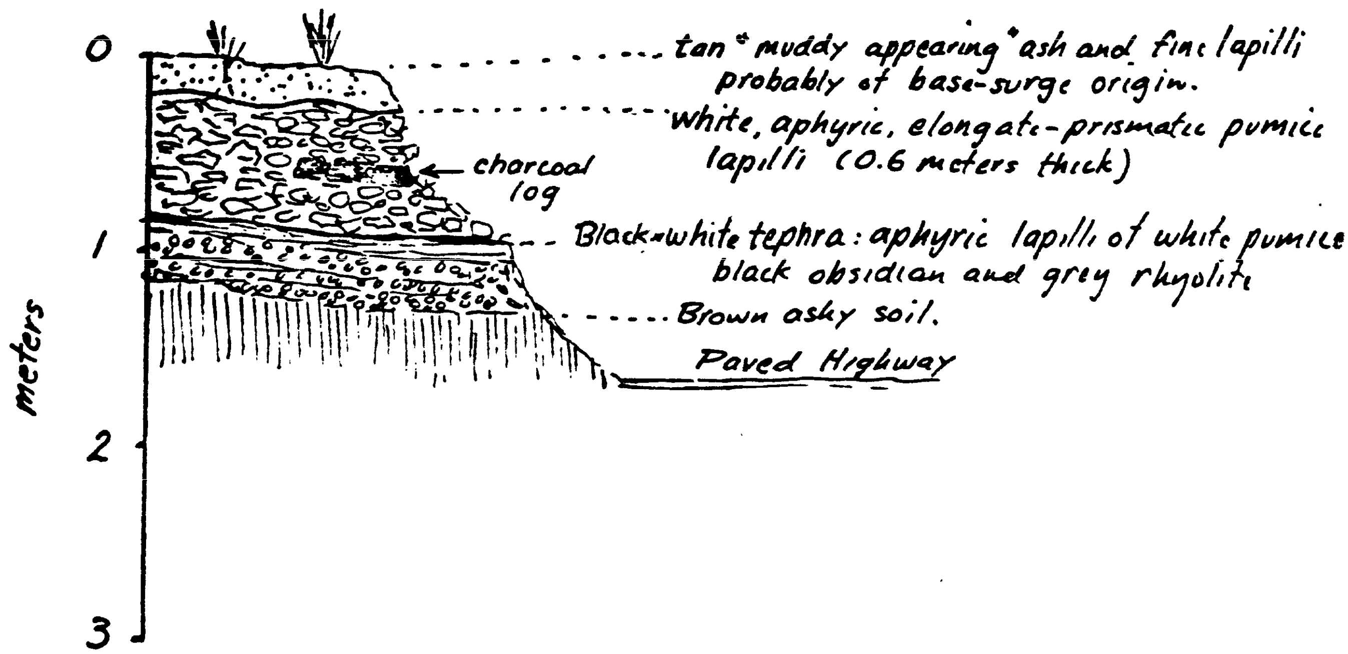
Field project: Holocene volcanics, Long Valley - Mono Basin geothermal areas, Eastern California.

Sample no. PC-1, Panum Crater, Mono Basin, Ca.

Collector: Spencer Wood
Dept. Geology
Occidental College
Los Angeles, Ca. 90041

Collected on 22 August, 1975
Submitted, April 19, 1976

Geographic Location: 119° 2.0' W, 37°55.4' N



Roadcut on north side of Benton Road (Calif. Highway no. 120), SE¼, SE¼, Sec. 19, T 1 N, R 27 E (Mono Craters Quad.). Charcoal log, 8 cm in diameter and 60 cm long, lies horizontally in a 0.6-meter layer of white pumice. Section was excavated to determine that the log was burned in place by the hot pumice after deposition. White pumice overlies the BW tephra and can be correlated to the surficial white pumice that surrounds the Panum Crater vent (Wood, S. H., 1976)

Geologic significance: This sample will date the last pyroclastic eruption from Panum Crater. There are two nearly identical white pumice layers erupted from the north end of the Mono Craters, but they are separated 2 meters of brown, wind-blown, soil in a section 1.9 km west of here. This sample (PC-1) will date the most recent white aphyric pumice, and the other sample (Z-3) from the latter section will date the older white aphyric pumice. One of these layers should match the

W-3661

the 1185 ± 80 year B.P. tephra 2 (Wood, 1975), and the other may match the 700 ± 200 B.P. age (W-629) age on an ash in the Bodie Hills, or it may a still a still older layer. The W-629 age has been difficult to explain in terms of stratigraphic relationships about the Mono Craters, and these two samples submitted for analyses will clarify the ages of the most recent Mono tephras.

Probable age of sample: Less than 2200 years

How Sampled: Sample was entirely excavated, and about 1/4 of it removed and wrapped in aluminum foil.

Environmental factors: Modern rootlets grew in cracks in the charred log. Rootlets have been cleaned off with tweezers, and contamination is estimated at less than 0.2 °/o, although humates may have filtered into the charcoal. Minor tree-ring consideration: 4-cm-radius log has about 64 annual rings; inner wood, age 39 to 64 submitted for analysis.

Send report to:

Spencer H. Wood
Dept. of Geology
Occidental College
Los Angeles, Ca. 90041

and also a copy to Robert C. Bucknam
U. S. Geological Survey
Seismic and Risk Analysis Branch
Federal Center
Denver Colo. 80225

Sample no. z-3
W-3665

REQUEST FOR RADIOCARBON AGE DETERMINATION

Field Project: Holocene volcanics, Mono Basin - Long Valley geothermal areas, eastern California.

Sample no. Z-3, Panum Crater, Mono Basin, Ca. W-3665

Collector: S. H. Wood
Dept. Geology
Occidental College
Los Angeles, Ca. 90041

Collected on August 30, 1975

Submitted on April 19, 1976

Geographic Location: From a 12-m stratigraphic section in a gully east of Rush Creek Canyon: SW ¼, SE¼ of Sec. 24, T 1 N, R 26 E, (37°55.5'N, 119°4.5'W)

Stratigraphic section and sample description (see attached illustration and note.)

Geologic significance: Provides an age on an early eruption of white aphyric pumice from the vicinity of Panum Crater.

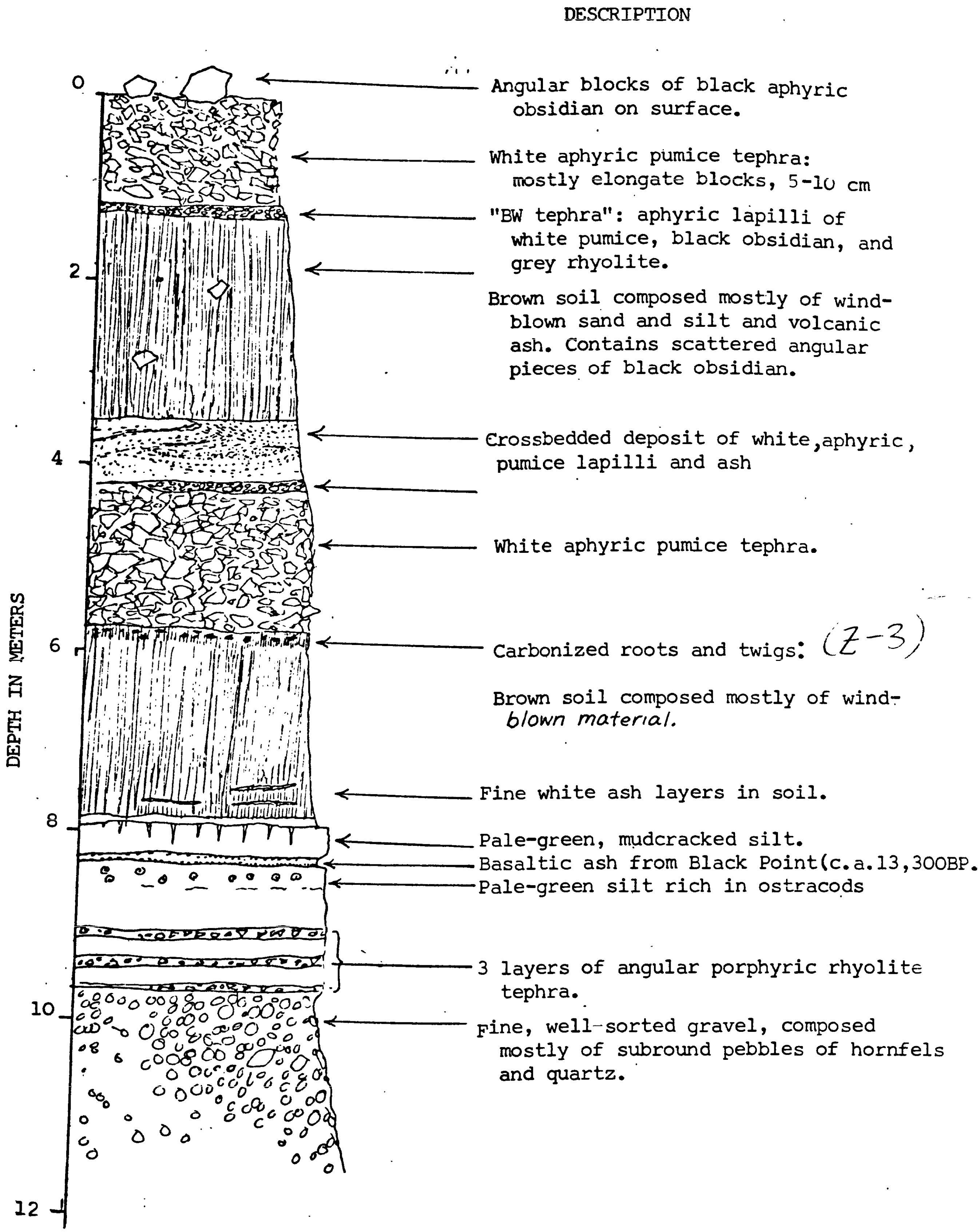
Estimated age: less than 2500 years

How sampled. Small pieces of carbonized twigs of brush were picked from a layer at the base of the pumice. These pieces of charcoal had numerous fine rootlets of modern plants. The rootlets were later picked out with tweezers from the larger pieces. 2.9 grams of pieces in which contamination must be less than 1 per cent are submitted for analyses, and the remainder of the bulk sample is included in a separate foil wrapping in case it is needed.

Send report to Spencer H. Wood
Dept of Geology
Occidental College
Los Angeles, Ca 90041

AND also a copy to
Robert C. Bucknam
U. S. Geol. Survey
Seismic and Risk analysis Branch
Federal Center
Denver, Colo. 80225

W-3665



Section Z. Stratigraphic section in gully east of Rush Creek Canyon, SE 1/4 Sec. 24, T 1 N, R26 E.

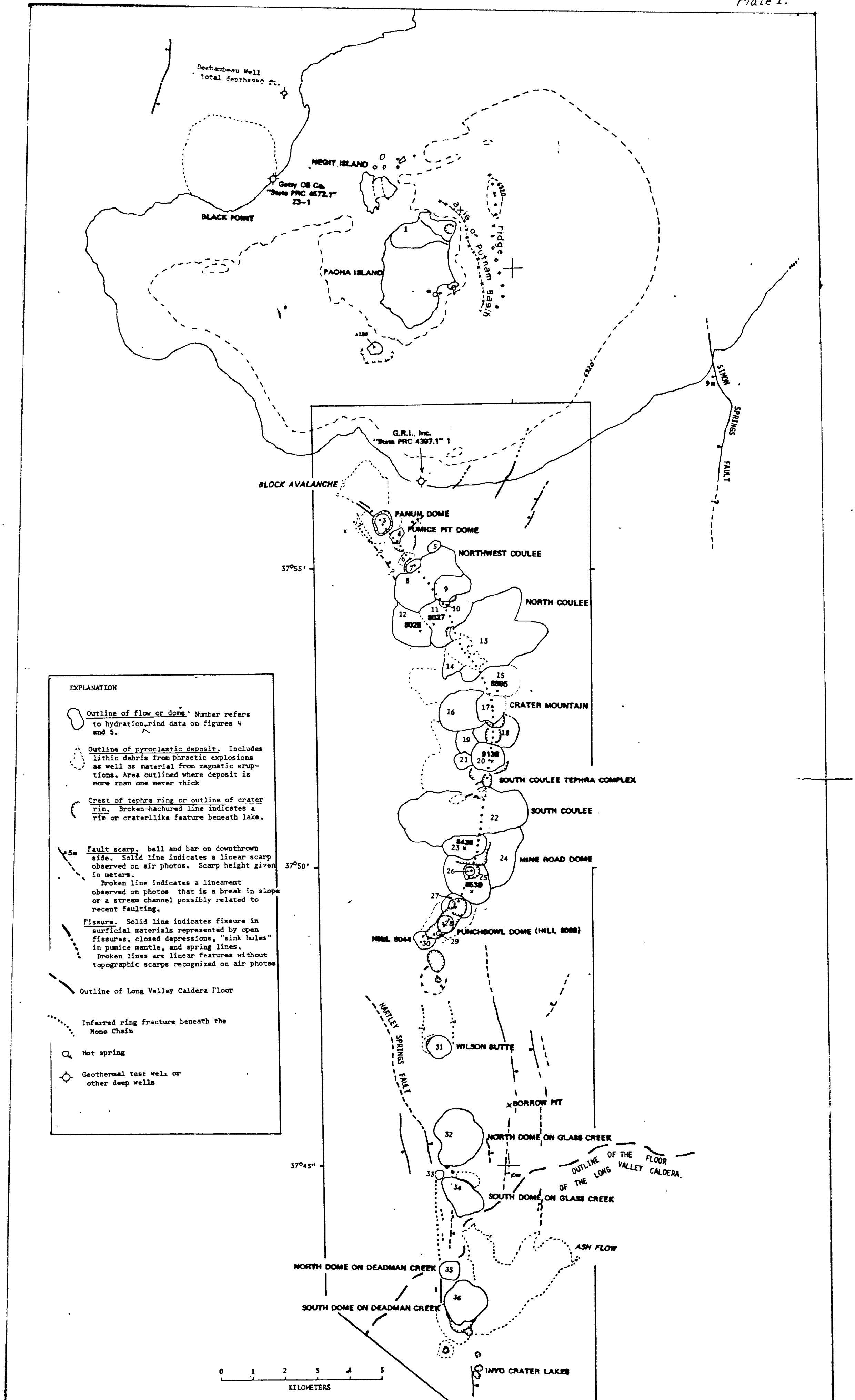


Plate 1. Map of the Mono Craters and Inyo domes showing numerical designation of domes.