Late Cenozoic tephrostratigraphy of deep sediment cores from the Bonneville Basin, northwest Utah

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ABSTRACT

Five deep sediment cores from the Bonneville Basin contain a rich tephra record encompassing the past 3.3 m.y. Twenty-two chemically distinct tephra layers were found, 15 of which correlate with previously described tephra from the western United States. Two of the remaining seven tephra layers are in the Glenns Ferry Formation of southwestern Idaho. The tephrostratigraphic framework of the Bonneville Basin provides a spatial and temporal framework for the sediments in this basin. Age-depth curves allow calculation of sediment accumulation rates (range: 8.9–27 cm/k.y.) and age estimates of the previously undescribed tephra layers. The Burmester core, which contains the longest and most complete record, has rates of sediment accumulation ranging from 1.7 to 20.9 cm/k.y.

INTRODUCTION

Although the eastern Great Basin contains numerous exposures of tuffaceous deposits of Miocene to Holocene age, little work has been done on the tephrostratigraphy of the sediments buried within the Bonneville Basin. Most tephra studies have focused on the western margin of the Great Basin and along the west coast of the United States, but Davis (1978) did extensive tephrostratigraphic work on surficial deposits within the Lahontan Basin in western Nevada. The U.S. Geological Survey has undertaken numerous studies of tephra deposits in the western United States (Sarna-Wojcicki, 1976; Sarna-Wojcicki and others, 1979, 1980, 1983, 1984, 1991; Izett, 1981; Izett and others, 1988), and has recently completed a tephrochronologic study on a core from Tulelake in northern California (Rieck and others, 1992).

The Bonneville Basin, in the northeastern part of the Great Basin, is relatively far removed from large Pliocene to Holocene volcanic centers of the western United States such as the Yellowstone area of Wyoming (Christiansen, 1979), Long Valley–Glass Mountain area of California (Hildreth, 1979; Izett and others, 1988), Valles Caldera of New Mexico (Izett and others, 1981), and the Cascade Range of Washington and Oregon (Borchardt and others, 1971; Kittleman, 1973; Mullineaux and others, 1975). Few rhyolitic volcanoes have erupted within the basin for the past 5 m.y., with the exception of those near the Mineral Mountains in central Utah (Evans, 1978; Crecraft and others, 1981). Therefore, tephra in the basinal sediments should be products of distant (>200 km distant) Plinian eruptions.

This tephrostratigraphic and tephrochronologic study deals with distal air-fall tephra deposits and their significance to the history of the Bonneville Basin. Sarna-Wojcicki and Davis (1991) showed that volcanic glass is the most useful component of a tephra layer to analyze for correlation between distant localities, an approach followed here. Glass is usually ubiquitous throughout the distributional area of a tephra layer and is the most chemically homogeneous and abundant phase. Glass in each widespread tephra layer is usually compositionally distinct from other tephra layers; thus, discrete correlation is possible (Sarna-Wojcicki and others, 1991). Many other workers have used the composition of volcanic glass for correlating upper Tertiary and Quaternary sediments in the western United States and elsewhere (for example, Eastwood, 1969; Jack and Carmichael, 1969; Sarna-Wojcicki, 1976; Davis, 1978; Izett, 1981; Perkins and others, 1992; Cerling and Brown, 1982; Haileab, 1988).

Exposed late Quaternary sediments of the Bonneville Basin have been thoroughly investigated by Morrison (1965, 1966), Eardley (1966, 1967), Eardley and others (1973), Currey and others (1984), Spencer and others (1984), and Benson and others (1990) in their studies of Lake Bonneville and precursor lakes. Spencer and others (1984), Oviatt and Nash (1989), and Oviatt (1991) studied and correlated upper Quaternary tephra deposits found in exposures around the Bonneville Basin.

Adamson and others (1955), Jones and Marsell (1955), and Slentz (1955) recorded tephra in Miocene and lower Pliocene strata of the Salt Lake Group of northern Utah. Later, Smith (1975), Smith and Nash (1976), and Perkins and others (1992) determined the composition of many tephra in the Salt Lake Group, showing that some tephra could be correlated throughout the northeastern Basin and Range Province.

Despite substantial interest in the latest lake cycle of the Bonneville Basin, little work has focused on Pliocene-Pleistocene strata, perhaps because strata of this age are poorly exposed. From 1956 to 1970, a program of deep-sediment coring in the Bonneville Basin was undertaken by Armand Eardley (University of Utah). Five boreholes were drilled along an east-west transect across the northern Bonneville Basin, from Salt Lake City to Wendover (Fig. 1). Only the Burmester and Saltair cores have been previously studied in detail (Eardley and Gvosdetsky, 1960; Eardley and others, 1973; Lister, 1975), but little work was done on the tephra.

The earlier work focused on determining lacustrine versus nonlacustrine facies in the Burmester and Saltair cores, as revealed by the sedimentology, paleontology, and presence of soils. This was done in an attempt to correlate surficial outcrops with the subsurface record (Eardley, 1967). On the basis of chemical analyses, Eardley and others (1973) identified two tephra layers as the Lava Creek B ash bed (formerly the Pearlette O ash) and the Bishop ash bed. Two other tephra layers were noted in the Burmester core but were not identified by Eardley and coworkers.

This study establishes the tephrostratigraphy of the cores and, through magnetostratigraphy and correlation with tephra dated elsewhere, provides a chronologic framework for sediments in the Bonneville

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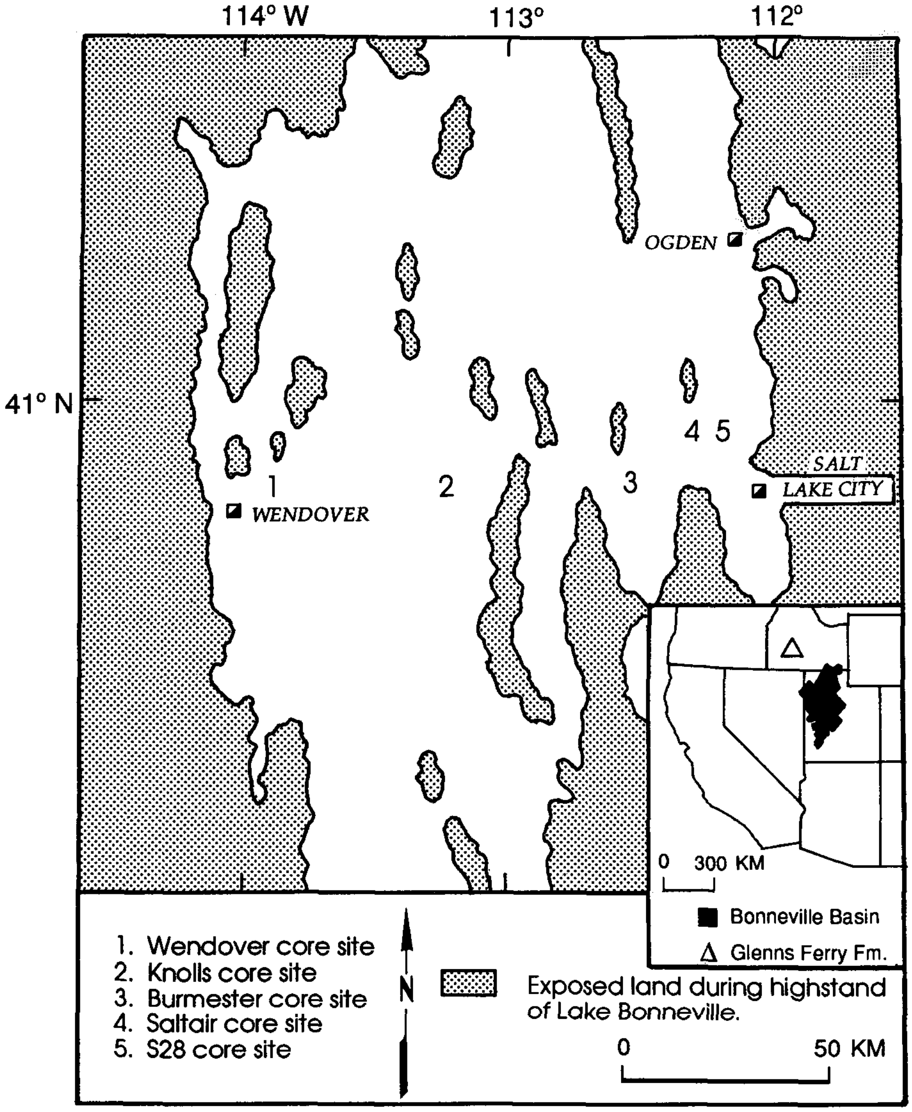

Figure 1. Generalized map of the Bonneville Basin study area, northwestern Utah. Also shown is the location of the Glenns Ferry Formation. Core sites are labeled as follows: core name; location; elevation; and depth. Wendover core; SE¼ sec. 15, T. 1 S., R. 18 W.; 1285.3 m; 171 m. Knolls core; SW¼ sec. 15, T. 1 S., R. 13 W.; 1289.3 m; 152 m. Burmester core; SE¼ sec. 7, T. 2 S., R. 5 W.; 1285.0 m; 306.3 m. Saltair core; SE¼ sec. 25, T. 1 N., R. 3 W.; 1281.7 m; 200 m. S28 core; SE¼ sec. 28, T. 1 N., R. 2 W.; 1285.6 m; 236 m.

Basin for the past 3.3 m.y. In addition to published tephra data, Bonneville Basin tephra were compared to tephra of comparable age in the Glenns Ferry Formation in southwestern Idaho (Fig. 1). Emphasis is on the Burmester core because it contains the most detailed tephrochronologic record. Periods of slow deposition, nondeposition, or erosion, along with periods of higher sediment accumulation rates, are apparent from age-depth curves of individual cores. The accumulation rates enable estimation of ages of previously undated tephra layers within the Bonneville Basin.

METHODS

Because glass shards are commonly mixed with epiclastic sediment in the cores, tephra layers are not always readily discernible. Therefore, at intervals of $\sim$5 cm, a spot sample was removed and immersed in clove oil for examination under a petrographic microscope. When glass shards were seen, scratch samples were taken at closer intervals to locate the highest concentration of glass. Where a satisfactory concentration of glass shards was located, generally when glass shards represented >30% of total particles, a 2 cm section of core was removed for cleaning and glass separation. Samples were numbered with a three-letter code indicating the core, and a number indicating depth from the surface (for example, BUR-317.2 = Burmester core, depth 317 feet, 2 inches from the surface). English units were used for depth because the original core log and previous publications refer to relevant datums in these units. Sample preparation for electron microprobe and X-ray fluorescence analysis is discussed in detail in Williams (1993).

Samples of glass were analyzed by both electron microprobe and X-ray fluorescence at the University of Utah. The microprobe analyses were performed on a Cameca SX50 electron microprobe with the following instrument conditions: high voltage of 15 keV, beam current of 25 nA, spot size of 15 μm. An ARL 8410 wavelength dispersive X-ray fluorescence spectrometer was used for the X-ray fluorescence analyses.

Raw data from the microprobe are reported as elemental weight percent for each element analyzed. From these, cationic elemental concentrations were recalculated to weight percent oxide. In this recalculation, iron was calculated as Fe_2O_3 for consistency. The oxides were then normalized to 100% on a water-free basis for comparison with published data for western United States tephra. The oxide totals range from 90% to 98%. The low totals result from the presence of water in the glass either as primary (magmatic) water, or water added by hydration after burial. The original oxide total is reported so that the original concentrations may be back-calculated.

Iron, calcium, titanium, and magnesium concentrations, obtained from electron microprobe analyses, proved most useful in correlating tephra from the cores with previously analyzed tephra. Because silicon and aluminum are abundant and uniform between tephra layers, neither is a good discriminator, except in distinguishing between rhyolitic, rhyodacitic, and dacitic tephra. Sodium was not used because of its mobility under the electron beam and its potential for exchange while buried. Ten to 20 shards were analyzed in each sample, and analyses of individual tephra layers were checked for homogeneity. Many tephra layers contain shards of more than one composition. In such cases, averages were calculated for each mode, and an overall average was computed using all of the analyses of the sample.

X-ray fluorescence data were obtained for those tephra layers containing sufficient glass (2.0 g) and purity (>99.5%). The minor- and trace-element data were used to confirm the correlations based on microprobe analysis.

Mineralogy, chemistry, petrography, and other physical properties have all been used to correlate tephra layers (Sarna-Wojcicki, 1976; Sarna-Wojcicki and others, 1979, 1983, 1991; Izett, 1981; Izett and others, 1988). Sarna-Wojcicki and Davis (1991) warn that these characteristics may change with distance from source, depositional environment, and age. Moreover, because tephra layers are prone to reworking, Sarna-Wojcicki and Davis (1991) suggested the stratigraphic context and homogeneity of each tephra layer be carefully studied. Many tephra layers in the Bonneville cores are composed of glass shards that could be separated into several distinct chemical populations. Without a distinct dominant chemical composition, these tephra layers could not be definitely correlated, and therefore such layers were not used for correlation. Because many stratigraphic intervals in the Bonneville cores are tuffaceous clays, silts, or sands rather than tephra layers, associated minerals could not be used for correlation because of the possibility of detrital contamination.

Terminology used here follows that suggested by Sarna-Wojcicki and Davis (1991). As all particle sizes encountered in this study are much less than 2 mm in diameter, the term *tephra layer* is used to describe deposits that contain >70% glass shards, and *tuffaceous* refers to deposits containing between 40% and 70% glass. The term *ash bed* is used in some instances to avoid confusion with previous nomenclature (Izett, 1981; Sarna-Wojcicki and others, 1991).

In this study, glass-shard chemistry and stratigraphic relations were used to correlate tephra layers and tuffaceous deposits found in the Bonneville cores. Electron microprobe data were compared with published and unpublished analyses of other tephra layers from the western United States. Similarity coefficients (SC) (Borchardt and others, 1972; Sarna-Wojcicki and others, 1984) were calculated for each tephra layer found in this study. Although they are useful in discriminating between tephra layers, they alone cannot be used to correlate tephra layers, because tephra layers from the same or different source, separated by 1 m.y., can have similarity coefficients of 0.93 or higher. Other statistical programs developed by M. E. Perkins (University of Utah) were also used to evaluate the chemical data for correlation. Different standardizations, analytical techniques, and data reduction routines give slightly different results; thus, matches with other published and unpublished data are not exact. When a possible compositional match was found, the stratigraphic and chronologic context of the two candidate tephra layers were compared to determine the practicability of their correlation.

PREVIOUS WORK ON CORES

Because the five cores were drilled in different parts of the Bonneville Basin (Fig. 1), differences in their depositional and tectonic history can be deciphered once they are correlated. The sedimentology and paleontology of the cores were not studied in detail here, but were discussed by Eardley and Gvosdetsky (1960), Shuey (1971), Eardley and others (1973), and Lister (1975).

Wendover Core

Shuey (1971) described this core as consisting solely of claystone, with gypsum layers throughout. He observed no soils, and only one tephra layer, which was correlated with the Bishop ash bed (Eardley and others, 1973) on the basis of glass composition. Four additional tephra layers are present within this core, two above and two below the Bishop ash bed. Recovery for the Wendover core was <50% in the upper 122 m and only ~15% in the lower 49 m (Shuey, 1971). Some tephra layers that exist at this site were probably not recovered.

Knolls Core

Shuey (1971) described this core as consisting only of claystone, with numerous tuffaceous layers between 90 and 152 m depth. Although the core consists dominantly of white and gray claystone, it also contains thin layers of sandstone, siltstone, and fine carbonate layers. Soil horizons were noted by Shuey (1971) in the upper 30 m. Several compositionally heterogeneous tuffaceous intervals are found in this core that could not be correlated with tephra elsewhere; thus, these are not included in the discussion below. Both the compositional heterogeneity and the disseminated nature of the shards suggest that these intervals may have formed by reworking of older tephra deposited in the Knolls area.

Burmester Core

The upper 100 m of the Burmester core was studied in detail by Eardley and others (1973). Sediments in the Burmester core range in size from clay to cobble. Recovery was ~90%. Paleomagnetic studies on the core suggest that the sediments at the bottom of the core were deposited during the Mammoth Reversed Subchron, according to Eardley and others (1973). Although these authors recognized only two tephra layers within the Burmester core, detailed reexamination of the core in this study disclosed 54 tephra-rich intervals, 18 of which are compositionally homogeneous. Some of the remaining intervals contain glass with chemical similarities to Miocene tephra.

Saltair Core

The Saltair core has been well studied by previous workers (Shuey, 1971; Eardley and Gvosdetsky, 1960); therefore, no detailed tephrostratigraphic study was carried out during this investigation, but samples of two previously identified tephra layers were examined. Eardley and others (1973) identified these tephra layers as the Lava Creek B and Bishop ash beds on the basis of glass-shard chemistry, identifications confirmed here.

S28 Core

Core S28 contains several tephra layers. Sandstone is the dominant rock type; recovery was only 40%. The interval from 41 to 62 m was not recovered, nor was the lowest 12 m. Eardley and others (1973) identified the Bishop ash bed on the basis of glass-shard chemistry at a depth of 175 m.

A paleomagnetic study was undertaken by Shuey for Eardley on the Burmester core. All paleomagnetic data used in this study are from this earlier work. Eardley and others (1973) reported on the methods used. Cubes were removed from the entire core at 80 cm intervals, and the natural remanent magnetism was measured. The mean inclination of the normally magnetized segments is 61°, whereas it is −41° for the reversely magnetized segments. Paleomagnetic sampling was done for the other cores (Shuey, 1971), but the results were inconclusive, although the Brunhes-Matuyama boundary was identified in the

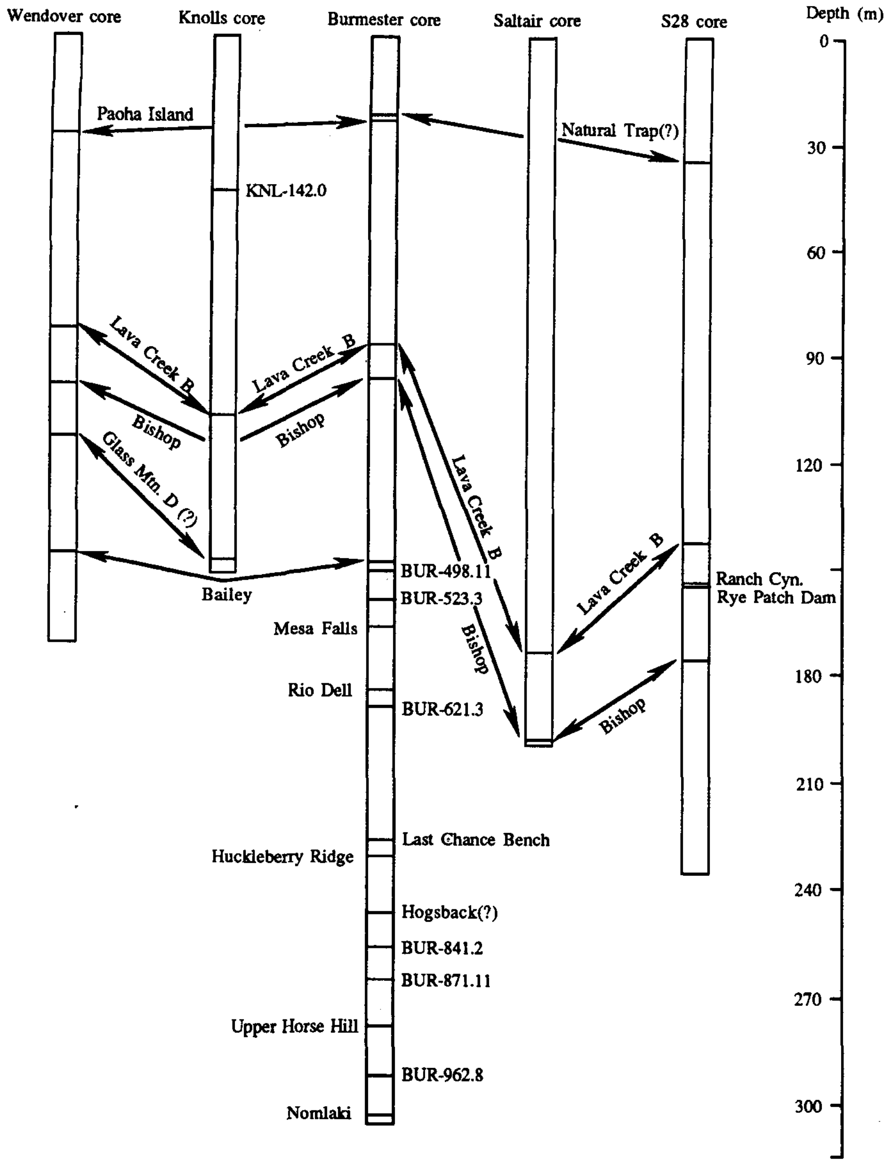

Figure 2. Tephrostratigraphy of the Bonneville Basin. Arrows indicate correlations of tephra layers in the cores. Note that the Bishop ash was not found in the Knolls core.

Wendover, Knolls, and S28 cores. The Saltair core ended at the Bishop ash bed and therefore did not reach the Brunhes-Matuyama boundary.

TEPHROSTRATIGRAPHY AND CHRONOLOGY OF THE BONNEVILLE BASIN CORES

Twenty-two distinct tephra layers have been identified from the cores. Of these, 15 correlate with previously described tephra layers from the western United States. Seven tephra layers are chemically distinct, two of which correlate with tephra of the Glenns Ferry Formation, but the remaining five have not yet been correlated with known tephra layers. These seven are referred to here by their sample numbers.

In addition to the overall tephrostratigraphy of the Bonneville Basin cores (Fig. 2), a detailed chronology was developed for the Burmester core. Of the five cores, the Burmester contains the oldest and most complete magnetic and tephra record (Fig. 3) and is the only core that extends beyond the middle Pleistocene.

Correlation and identification of tephra layers in the Bonneville Basin cores are described below from youngest to oldest. The correlation is queried (?) if it is tentative.

Natural Trap(?) Ash Bed

A tephra layer in the Burmester core (BUR-50.6) is correlated with a tephra layer in the S28 core (S28-112.9). The tephra layer is light gray to white, medium to fine sand sized, and composed dominantly of elongately ridged and platy shards. The only difference between these two tephra layers is the slightly lower iron content of BUR-50.6 (Table 1). The glass is compositionally unimodal and similar to the Lava Creek B ash bed, but it contains more titanium and less chlorine. This tephra layer is tentatively correlated with the Natural Trap ash bed (SC = 0.92), which is believed to have erupted from the Yellowstone area because it is chemically similar to the Lava Creek, Mesa Falls, and Huckleberry Ridge ash beds (Izett, 1981). The Hebgen Narrows ash bed is also compositionally similar to BUR-50.6 and S28-112.9 (SC = 0.98), but based on published age data for the Hebgen Narrows it cannot correlate with either of the samples from the cores (see below).

Paoha Island Tephra Layer

This tephra layer has been identified at a depth of 23.4 m in the Burmester core and at 27 m in the Wendover core. It correlates with the next-to-uppermost Paoha Island tephra layer from Mono Lake, California (Tables 1 and 2; Sarna-Wojcicki, 1992, personal commun.). The light brownish-gray glass shards are dominantly pumiceous or elongately ridged. Although tephra layers BUR-76.10 and WDR-88.6 are similar in major element composition to the next-to-uppermost Paoha Island tephra layer (SC = 0.92 and 0.95, respectively), they differ slightly in the iron and potassium content. In the Burmester core, this tephra layer lies 3.7 m below the base of the Blake Subchron.

Tephra Layer KNL-142.0

At a depth of 43.3 m in the Knolls core, there is a 3-cm-thick tephra layer in a gray claystone. It is light brownish gray, medium sand sized, and dominated by elongately ridged shards with a few platy and elongated pumiceous shards. KNL-142.0 is chemically distinct (Tables 1 and 2) but has not yet been correlated with any previously described tephra. This ash has the highest iron content (3.82 wt% Fe_2O_3) of any ash in the Bonne-

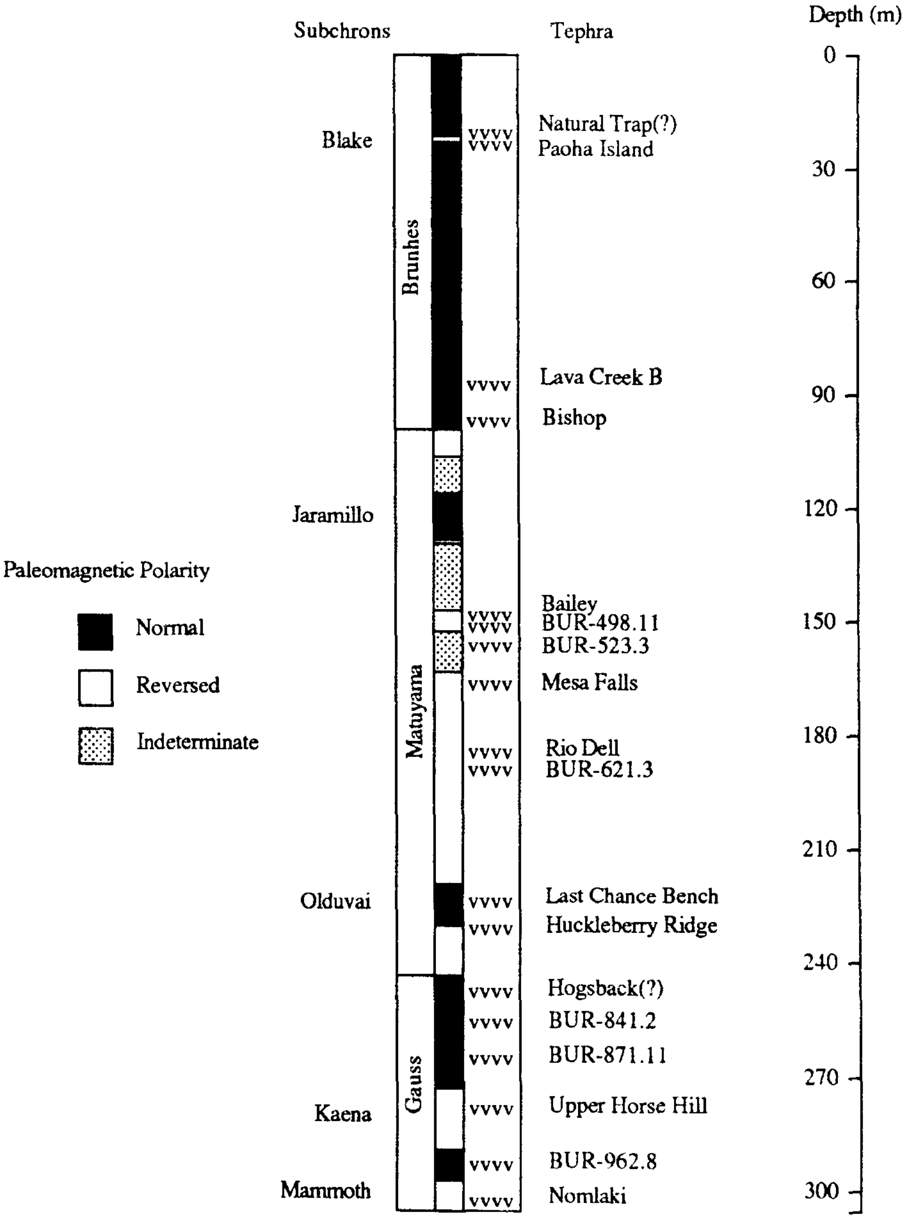

Figure 3. Tephrostratigraphy and magnetostratigraphy of the Burmester core. Paleomagnetic data are from Eardley and others (1973) and University of Utah (unpubl. data).

ville Basin cores. Based on its color and chemical composition, it is probably derived from the Cascade Range.

Lava Creek B Ash Bed

The Lava Creek B ash bed was identified in the Saltair core (SLT-547.6) by Eardley and Gvosdetsky (1960), and in the Burmester core (BUR-281.9, BUR-283.1, and BUR-285.2) and the Knolls core (KNL-346.0 and KNL-350.6) by Eardley and others (1973). In the Wendover core, this ash bed lies at a depth of 82.9 m (WDR-271.8 and WDR-272.8), and 142.6 m in the S28 core (S28-467.9). The Lava Creek B ash bed was erupted from the Yellowstone area 0.62 Ma (Christiansen, 1979) and is widely distributed around the western United States.

Microprobe analyses of glass shards from the Lava Creek B ash bed show two distinct compositional modes (Williams, 1992). Boellstorff (in Westgate and others, 1977) also noted two distinct compositional modes and separated them into two units, the Pearlette ash (restricted) and the Hartford ash. The two modes (Table 3) differ in iron, calcium, and titanium content (Fig. 4). One population of shards has ~1.43% Fe_2O_3, 0.10% TiO_2, and 0.49% CaO, whereas the other contains 1.76% Fe_2O_3, 0.14% TiO_2, and 0.55% CaO. Samples taken from the base, middle, and top of the ash bed in the cores indicate the two modes are equally dispersed throughout the stratigraphic thickness of the ash bed. This bimodality is found in samples from many other localities throughout the United States (W. P. Nash, 1992, personal commun.).

X-ray fluorescence analyses (Table 3) confirm the correlation between the Lava Creek B ash bed in the cores and at other localities in the western United States.

Ranch Canyon Ash Bed

The S28 core contains a white, medium-sand-sized ash bed (S28-505.4) dominated by pumiceous glass shards similar to the Ranch Canyon ash bed (SC = 0.95) erupted from the Mineral Mountains, Utah (Table 2). Like other young rhyolitic rocks in the Mineral Mountains, S28-505.4 is high in fluorine (Evans, 1978). The presence of the Ranch Canyon ash bed (or a related ash bed from the same source, see below) in the S28 core indicates a component of wind from the south at the time of the eruption.

Rye Patch Dam Ash Bed

Sample S28-505.8, from a depth of 154.1 m in the S28 core, correlates (SC = 0.95) with the Rye Patch Dam ash bed of Davis (1978) (Tables 1 and 2). This ash bed is 0.5 cm thick, light brownish gray, fine sand sized, and has equal amounts of platy and elongately ridged shards. Rieck and others (1992) identified the Rye Patch Dam ash bed in the Tulelake core and tentatively correlated it with the Desert Spring ash flow near Bend, Oregon. In the S28 core, the Rye Patch Dam ash bed is a distinct ash 10 cm below the Ranch Canyon ash bed. It underlies the Lava Creek B ash bed and overlies the Bishop ash bed. The presence of this tephra layer in the S28 core extends the known areal distribution 440 km east of its type locality near Oreana, Nevada.

Bishop Ash Bed

The Bishop ash bed, erupted from Long Valley caldera, California (Izett and others, 1970), is found in surficial deposits around the Bonneville Basin and in all of the cores

TABLE 1. ELECTRON MICROPROBE ANALYSES OF THE GLASS PHASE FROM TEPHRA WITHIN CORES OF THE BONNEVILE BASIN EXCLUSIVE OF THE LAVA CREEK B, BISHOP, AND BISHOP-LIKE ASHES

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Cl	F	Total	SC1	SC2
Natural Trap ash(?) ash bed														
BUR-050.6	77.72	12.34	1.36	0.05	0.04	0.48	0.15	2.39	5.22	0.11	0.14	95.80	0.91	0.98
S28-112.9	78.13	12.34	1.50	0.05	0.04	0.48	0.15	2.17	5.15	0.11	0.15	96.83	0.92	0.98
WY092-08[*]	77.15	11.95	1.50	0.05	0.03	0.45	0.11	3.14	5.36	0.11	0.17	96.28	1.00	0.92
HBN92-01[†]	76.97	12.00	1.44	0.05	0.04	0.48	0.15	3.18	5.41	0.10	0.17	96.45	0.92	1.00
Paoha Island tephra layer														
BUR-076.10	76.40	13.67	2.54	0.19	0.07	1.02	0.17	2.78	3.12	n.d.	n.d.	92.67	0.92	
WDR-088.0	74.77	15.00	2.46	0.18	0.07	1.03	0.19	3.00	3.31	n.d.	n.d.	93.87	0.95	
PAOH-1, T12-11[§]	72.87	14.91	2.28	0.15	0.07	1.00	0.19	5.56	2.97	n.d.	n.d.	n.d.	1.00	
Tephra layer KNL-142.0														
KNL-142.0	72.12	14.70	3.82	0.30	0.13	1.48	0.37	4.37	2.57	0.15	n.d.	95.98		
Ranch Canyon ash bed														
S28-505.4	77.33	13.13	0.56	0.03	0.09	0.36	0.07	2.98	4.85	0.10	0.50	90.53	0.93	0.95
Ranch Canyon ash[#]	77.72	12.74	0.62	0.03	0.07	0.43	0.07	3.58	4.62	0.11	n.d.	95.10	1.00	0.98
Pumice Hole Mine[**]	77.57	12.97	0.62	0.03	0.08	0.43	0.07	3.15	4.62	0.03	0.34	96.07	0.98	1.00
Rye Patch Dam ash bed														
S28-505.8	72.20	14.55	3.40	0.35	0.09	1.46	0.44	3.70	3.68	0.13	n.d.	95.15	0.95	
RPD91-01[#]	72.61	15.31	3.42	0.39	0.07	1.43	0.44	2.51	3.66	0.14	0.04	93.40	1.00	
Tephra layer BUR-498.11														
BUR-498.11	72.12	15.36	2.40	0.51	0.09	1.81	0.40	3.99	3.11	0.13	0.06	95.10		
Tephra layer BUR-523.3														
BUR-523.3	76.74	14.06	1.36	0.18	0.06	0.89	0.18	2.63	3.75	0.13	0.02	95.02		
Mesa Falls ash bed														
BUR-547.8	77.73	12.22	1.43	0.04	0.04	0.53	0.09	2.49	5.42	n.d.	n.d.	93.29	0.93	
Mesa Falls[#]	76.79	12.24	1.49	0.04	0.03	0.58	0.11	3.21	5.41	0.11	n.d.	94.14	1.00	
Rio Dell ash bed														
BUR-605.0	74.86	14.90	1.92	0.37	0.08	1.37	0.29	3.26	2.89	n.d.	n.d.	94.84	0.91	
Rio Dell[††]	74.11	14.59	1.91	0.28	0.07	1.34	0.27	5.08	2.35	n.d.	n.d.	93.30	1.00	
Tephra layer BUR-621.3														
BUR-621.3	77.84	13.05	1.26	0.17	0.04	1.01	0.14	3.69	2.71	n.d.	n.d.	95.18		
Huckleberry Ridge ash bed														
BUR-756.1	76.36	12.19	1.75	0.03	0.04	0.56	0.14	3.09	5.69	n.d.	n.d.	96.21	0.93	
BUR-760.8	76.35	12.26	1.80	0.02	0.05	0.56	0.12	3.32	5.36	n.d.	n.d.	96.07	0.95	
Huckleberry Ridge[††]	76.45	12.33	1.76	0.02	0.04	0.61	0.13	3.49	5.16	n.d.	n.d.	95.55	1.00	
Hogsback(?) ash bed														
BUR-812.6	76.67	12.75	1.11	0.05	0.06	0.70	0.07	2.27	6.24	n.d.	n.d.	95.76	0.75	
BEV92-06[#]	76.25	13.28	1.11	0.00	0.07	0.73	0.03	3.44	4.92	0.16	n.d.	94.76	1.00	
Tephra layer BUR-841.2														
BUR-840.4	76.70	12.61	2.45	0.01	0.07	0.43	0.13	3.15	4.38	0.13	0.05	95.94	0.82	0.91
BUR-841.2	76.74	12.62	2.49	0.02	0.06	0.44	0.13	2.97	4.48	0.14	0.03	96.10	0.83	1.00
CAES#1 648.6[§]	76.10	12.28	2.35	0.00	0.05	0.42	0.13	4.51	4.17	n.d.	n.d.	n.d.	1.00	0.83
Tephra layer BUR-871.11														
BUR-871.11	71.95	15.21	3.53	0.60	0.10	1.91	0.49	3.19	2.97	n.d.	n.d.	95.71		
Upper Horse Hill ash bed														
BUR-914.2	73.51	14.70	2.87	0.29	0.11	0.88	0.30	3.47	3.88	n.d.	n.d.	91.88	0.96	0.97
BUR-915.0	72.90	14.10	2.74	0.25	0.10	0.86	0.32	4.51	4.00	0.14	0.07	97.07	0.94	0.95
C-83-6A[§]	72.50	14.47	2.73	0.27	0.11	0.89	0.29	5.39	3.36	n.d.	n.d.	n.d.	1.00	0.98
SFC92-18[#]	73.55	14.30	2.78	0.27	0.11	0.86	0.30	4.15	3.48	0.17	0.04	96.53	0.98	1.00
Tephra layer BUR-962.8														
BUR-960.2	72.46	14.31	3.29	0.24	0.11	0.90	0.31	4.93	3.23	n.d.	n.d.	96.61	0.97	
BUR-962.8	73.68	14.42	3.43	0.23	0.13	0.94	0.35	3.61	3.21	n.d.	n.d.	93.55	0.97	
SFC92-16[#]	73.67	14.21	3.33	0.23	0.12	0.92	0.32	3.94	3.09	0.15	0.02	96.00	1.00	
Nomlaki ash bed														
BUR-989.4	78.21	12.44	1.03	0.17	0.05	0.88	0.20	3.27	3.75	n.d.	n.d.	94.79	0.95	0.94
BUR-996.0	78.39	12.46	1.02	0.19	0.05	0.88	0.19	3.17	3.66	n.d.	n.d.	94.47	0.96	0.94
NT91-01[#]	77.78	12.88	1.11	0.19	0.05	0.98	0.21	3.18	3.72	0.01	0.12	96.30	1.00	0.90
T-4-86K[§]	78.12	12.47	1.01	0.16	0.04	0.86	0.17	3.49	3.68	n.d.	n.d.	n.d.	0.90	1.00
Standard														
MM3[§§]	77.03	12.39	0.74	0.07	0.05	0.55	0.13	3.56	5.29	0.07	0.13	99.159		
(±σ)	0.67	0.12	0.08	0.04	0.02	0.06	0.03	0.15	0.09	0.01	0.05	1.33		

Note: Data given as wt%. Data normalized to 100% for comparison with published data. Total iron reported as Fe_2O_3. Total reported for core samples is original oxide total.

[*] Sample from Tensleep Canyon, Wyoming (Bed 2 of Izett, 1981).

[†] Sample from type locality at Hebgen Narrows (Bed 1 of Izett, 1981).

[§] Data from A. M. Sarna-Wojcicki and C. E. Meyer (personal commun., 1992).

[#] Data from correlative samples. BEV92-06, SW1/4 sec. 30, R. 7 W., T. 28 S., Beaver, Utah; Mesa Falls, E1/2 sec. 12, R. 42 E., T. 9 N., Ashton, Idaho; NT91-01, NW1/4 sec. 12, R. 6 W., T. 24 N., Flourney, California; Ranch Canyon Ash, S1/2 sec. 34, R. 9 W., T. 27 S., Bearskin Mountain, Utah; RPD91-01, NE1/4 sec. 18, R. 33 E., T. 30 N., Oreana, Nevada; SFC92-16, and SFC92-18, SE1/4 sec. 6, R. 3 E., T. 7 S., Perjue Canyon, Idaho.

[**] Data from W. P. Nash (personal commun., 1993).

[††] Data from Sarna-Wojcicki and others (1987).

[§§] Mineral Mountain obsidian standard.

SC1 = Similarity coefficient computed using Si, Al, Fe, Mg, Mn, Ca, Ti, and K.

SC2 = Similarity coefficient computed using Al, Fe, Mg, Ca, Ti, and K.

n.d. = not determined.

TALBE 2. X-RAY FLUORESCENCE DATA FOR ASHES WITHIN THE BONNEVILLE BASIN CORES AND CORRELATIVE ASHES

Sample	Fe_2O_3	CaO	K_2O	Ba	Mn	Nb	Rb	Sr	Ti	Y	Zn	Zr	La	Nd	Th	Ce	SC
Paoha Island tephra layer																	
BUR-76.10	2.17	0.98	3.11	765	488	12	73	88	1079	19	50	288	35	28	8	60	
Tephra layer KNL-142.0																	
KNL-142.0	3.44	1.94	2.35	743	865	10	46	116	2002	14	67	223	24	33	12	53	
Lava Creek B ash bed																	
BUR-281.9	1.43	0.49	5.58	141	238	61	188	13	687	78	70	207	79	61	25	156	0.90
BUR-283.1	1.49	0.48	5.49	135	248	61	183	6	692	76	72	222	81	63	26	170	1.00
KNL-350.6	1.55	0.50	4.95	161	248	61	180	7	726	75	77	234	83	69	25	172	0.94
SLT-547.6	1.50	0.50	4.95	128	248	62	189	5	698	80	74	221	81	66	26	172	0.96
Rye Patch Dam ash bed																	
S28-505.8	3.10	1.50	3.74	771	566	15	86	111	2397	27	51	344	37	36	12	70	0.96
RPD91-01*	3.18	1.55	3.43	758	572	16	84	119	2469	28	52	346	29	34	9	84	
Bishop ash bed																	
BUR-317.2	0.64	0.37	4.93	<1	253	25	176	2	385	32	37	71	26	22	19	45	0.83
SLT-646.0	0.67	0.40	4.54	14	227	23	166	8	441	28	42	77	26	27	21	51	1.00
WDR-323	0.69	0.43	5.27	52	199	19	142	14	503	22	22	77	26	26	18	69	0.85
CFT91-01*	0.68	0.38	4.83	<1	225	24	188	7	161	30	35	70	14	20	21	50	0.87
Tephra layer BUR-498.11																	
BUR-498.11	2.20	1.83	3.08	705	563	9	78	235	2186	13	43	188	19	24	11	56	
Mesa Falls ash bed																	
BUR-547.8	1.18	0.47	5.39	21	201	54	246	3	543	94	48	137	70	50	32	127	
Tephra layer BUR-621.3																	
BUR-621.3	1.14	1.04	2.92	578	263	8	41	163	792	0	21	125	17	21	8	45	
Huckeberry Ridge ash bed																	
BUR-760.8	1.52	0.53	5.48	224	245	55	181	10	663	78	85	221	81	69	26	172	0.94
BEV91-01*	1.61	0.54	5.14	288	258	54	177	10	723	75	85	240	90	72	26	179	1.00
($\pm\sigma$)	0.04	0.02	0.16	25	5	1	2	1	12	1	1	5	4	2	1	13	
Tephra layer BUR-841.2																	
BUR-840.4	2.10	0.42	5.25	558	361	18	119	20	828	53	95	433	34	43	12	88	0.95
BUR-841.2	2.14	0.40	5.31	551	359	17	116	15	838	53	98	433	31	42	13	86	1.00
Tephra layer BUR-871.11																	
BUR-871.11	3.18	1.90	2.98	915	634	10	50	148	2639	11	53	228	26	32	18	67	0.93
SFC92-27*	3.20	1.90	3.43	914	636	12	55	180	2684	21	53	297	32	36	9	72	1.00
Upper Horse Hill ash bed																	
BUR-914.2	2.38	0.88	4.18	853	668	18	70	67	1700	31	66	373	33	42	11	84	0.92
BUR-915	2.43	0.87	4.02	851	689	16	63	60	1706	30	66	372	36	42	9	85	0.95
ORE92-10*	2.51	0.87	4.61	875	727	17	59	59	1760	30	68	388	33	43	9	72	1.00
Tephra layer BUR-962.8																	
BUR-962.8	2.93	0.95	3.75	880	76	17	60	61	1850	32	75	386	29	39	7	81	0.96
SFC92-16*	2.92	0.93	4.39	847	769	16	55	60	1834	34	76	382	33	44	6	70	1.00
Nomlaki ash bed																	
BUR-993.0	1.06	0.96	4.34	835	315	11	103	111	1155	14	25	148	21	23	12	48	0.95
HHL92-05*	0.97	0.94	4.08	938	278	7	93	112	1154	9	18	139	26	21	13	46	0.96
NT91-01†	1.04	0.97	3.64	966	290	8	94	114	1200	11	38	150	17	20	12	49	1.00
($\pm\sigma$)	0.04	0.04	0.05	10	8	1	1	2	31	1	8	5	2	2	1	8	

Note: data given in ppm except for Fe_2O_3, CaO, and K_2O, which are wt% oxide.

*Data from correlative samples. CFT91-01, SW1/4 sec. 31, R. 6 W., T. 25 S., Cove Fort, Utah; RPD91-01, NE1/4 sec. 18, R. 33 E., T. 30 N., Oreana, Nevada; BEV91-01, SE1/4 sec. 19, R. 7 W., T. 28 S., Beaver, Utah; ORE92-10, NE1/4 sec. 7, R. 1 E., T. 5 S., Oreana, Idaho; SFC92-16 and SFC92-27, SE1/4 sec. 6, R. 3 E., T. 7 S., Perjue Canyon, Idaho; HHL92-05, NE1/4 sec. 31, R. 6 E., T. 7 S., Sugar Valley, Idaho; NT91-01, NW1/4 sec. 12, R. 6 W., T. 24 N., Flourney, California.

†Average of 3 samples.

SC = similarity coefficient.

except Knolls (S28-574.6, BUR-313.4, BUR-314.5, BUR-317.2, WDR-323.0, and SLT-646.0). The Bishop ash bed was identified in preliminary studies of the cores by Eardley and others (1973). Sarna-Wojcicki and Pringle (1992) reported an age of 0.759 ± 0.002 Ma for the Bishop ash bed based on single-crystal laser-fusion $^{40}Ar/^{39}Ar$ methods.

The Bishop ash bed is white, composed dominantly of pumiceous shards with some blocky and platy shards, and ranges from 0.2 to 1.2 m in thickness in the cores. The Bishop ash bed from each of the cores is compositionally similar to the Bishop ash bed elsewhere (SC = 0.92–0.96) (Table 4). Samples from the top, middle, and bottom of the Bishop ash bed in the Burmester core reveal no significant vertical variation in chemical composition.

Glass Mountain D(?) Ash Bed

Electron microprobe analyses (Table 4) suggest that tephra layers WDR-372.7 and KNL-486.10 correlate with the Glass Mountain–Long Valley family of tephra. Identification of individual ash beds in the Glass Mountain–Long Valley family is difficult because the ash beds are similar to the Bishop ash bed and to each other (Sarna-Wojcicki and others, 1984; Izett and others, 1988). Based on stratigraphic position and glass chemistry, WDR-372.7 and KNL-486.10 are tentatively correlated with the Glass Mountain D ash bed (SC = 0.94), which, based on K-Ar dating, is 1.06 ± 0.01 Ma (Izett, 1981).

Bailey Ash Bed

The tephra layer identified as the Bailey ash bed in the Burmester core (BUR-488.1) was deposited in a white claystone that contains ostracodes. WDR-497.4 and BUR-488.1 are compositionally similar and are tentatively correlated with the Bailey ash bed (SC = 0.89) (Table 4). The Bailey ash bed has previously been identified in the Ventura Basin and South Mountain–Bal-

TABLE 3. ELECTRON MICROPROBE ANALYSES OF LAVA CREEK B ASH FROM BONNEVILLE BASIN CORES

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Cl	F	Total	SC1	SC2
Lava Creek B data divided into two distinct chemical populations														
BUR-281.9	77.07	12.18	1.59	0.02	0.04	0.52	0.10	2.95	5.53	n.d.	n.d.	93.19	0.99	0.98
BUR-283.1	77.23	12.20	1.56	0.02	0.04	0.53	0.12	2.92	5.37	n.d.	n.d.	92.60	0.97	0.98
BUR-285.2	76.82	12.38	1.58	0.02	0.04	0.53	0.10	3.05	5.48	n.d.	n.d.	91.94	1.00	0.98
KNL-346.0	76.80	12.14	1.58	0.03	0.04	0.52	0.09	3.05	5.37	0.17	0.21	93.09	0.94	0.93
KNL-350.6	76.80	12.24	1.50	0.02	0.02	0.51	0.11	3.05	5.35	0.19	0.21	93.05	0.91	0.93
S28-467.9	76.86	12.03	1.47	0.02	0.04	0.50	0.09	3.63	4.92	0.17	0.27	94.84	0.96	0.95
SLT-547.6	77.01	12.33	1.55	0.03	0.05	0.52	0.11	3.03	5.38	n.d.	n.d.	93.66	0.91	0.93
WDR-271.8	77.05	12.68	1.58	0.02	0.04	0.53	0.10	2.59	4.51	n.d.	n.d.	93.56	1.00	0.98
WDR-272.8	77.15	12.69	1.54	0.02	0.04	0.52	0.11	2.57	5.36	n.d.	n.d.	93.30	0.98	1.00
BUR-281.9	76.57	12.10	1.99	0.02	0.05	0.59	0.17	2.79	5.72	n.d.	n.d.	92.65	0.94	
BUR-283.1	76.64	12.21	1.93	0.02	0.04	0.58	0.14	2.89	5.55	n.d.	n.d.	91.96	1.00	
BUR-285.2	76.53	12.23	1.96	0.03	0.05	0.59	0.19	2.88	5.53	n.d.	n.d.	91.63	0.90	
KNL-346.0	76.51	12.07	2.00	0.02	0.04	0.60	0.18	2.84	5.49	0.12	0.13	93.01	0.96	
KNL-350.6	76.50	12.16	1.96	0.06	0.03	0.60	0.14	2.79	5.55	0.13	0.10	92.53	0.88	
S28-467.9	76.49	12.07	1.87	0.02	0.04	0.59	0.14	2.88	4.95	0.12	0.20	94.24	0.98	
SLT-547.6	77.28	12.29	1.99	0.02	0.04	0.61	0.14	2.41	5.22	n.d.	n.d.	91.25	0.98	
WDR-271.8	76.69	12.59	1.98	0.03	0.04	0.60	0.15	2.40	5.52	n.d.	n.d.	93.63	0.94	
WDR-272.8	76.69	12.64	1.90	0.04	0.03	0.60	0.15	2.50	5.44	n.d.	n.d.	93.74	0.88	
Average values of the combined populations														
BUR-281.9	76.92	12.16	1.71	0.02	0.04	0.54	0.12	2.90	5.59	n.d.	n.d.	93.03	0.94	0.99
BUR-285.2	76.71	12.32	1.72	0.03	0.04	0.55	0.13	2.99	5.50	n.d.	n.d.	91.83	1.00	0.94
BUR-283.1	77.11	12.20	1.64	0.02	0.04	0.54	0.12	2.91	5.40	n.d.	n.d.	92.47	0.94	1.00
KNL-346.0	76.72	12.12	1.71	0.03	0.04	0.54	0.11	2.99	5.41	0.19	0.16	93.07	0.97	0.94
KNL-350.6	76.61	12.19	1.79	0.04	0.02	0.57	0.13	2.89	5.47	0.14	0.15	92.72	0.89	0.85
S28-467.9	75.03	11.77	1.56	0.02	0.04	0.52	0.10	3.30	4.82	0.15	0.24	97.01	0.89	0.95
SLT-547.6	77.15	12.31	1.79	0.02	0.05	0.57	0.13	2.70	5.29	n.d.	n.d.	92.34	0.92	0.94
WDR-271.8	76.79	12.62	1.87	0.02	0.04	0.58	0.13	2.46	5.48	n.d.	n.d.	93.65	0.94	0.96
WDR-272.8	77.00	12.68	1.66	0.03	0.03	0.55	0.13	2.55	2.39	n.d.	n.d.	93.52	0.96	0.91

Note: Data given as wt%. Data normalized to 100% for comparison with published data. Total iron reported as Fe_2O_3. Total reported for core samples is original oxide total.
SC1 = Similarity coefficient computed using Si, Al, Fe, Mg, Mn, Ca, Ti, and K.
SC2 = Similarity coefficient computed using Al, Fe, Mg, Ca, Ti, and K.
n.d. = not determined.

com Canyon areas of southwestern California (Sarna-Wojcicki and others, 1984, 1991). The glass shards are compositionally quite similar to tephra erupted from the Glass Mountain–Long Valley area, the likely source area for this ash bed.

In the Burmester core, this ash bed is found 18 m above the Mesa Falls ash bed and lies in a reversed magnetozone below the Jaramillo Subchron. This tephra layer could correlate equally well with a thin white tephra layer of about the same age that overlies the Bailey ash bed by ~4.6 m in Ventura, California, rather than with the Bailey ash bed itself (Sarna-Wojcicki, 1991, personal commun.).

Tephra Layer BUR-498.11

BUR-498.11 is characterized by light tan, elongately ridged shards having a high calcium and iron content (Tables 1 and 2). The shard chemistry is similar to many tephra from the Cascade Range, but there is no apparent correlation with any previously described tephra layer.

Tephra Layer BUR-523.3

BUR-523.3 is another distinctive tephra layer (Table 1) that could not be correlated with any previously described ash from western North America. This ash is white, fine sand sized, and has dominantly elongately ridged and pumiceous shards, with minor amounts of platy shards.

Mesa Falls Ash Bed

A tuffaceous claystone layer, at a depth of 166.9 m in the Burmester core (BUR-547.8), correlates with the Mesa Falls ash bed. The Mesa Falls ash bed was erupted from the Yellowstone area and has been K-Ar dated at 1.27 Ma (Izett, 1981). This ash bed is white, fine sand sized, and composed of elongately ridged shards. It contains less iron than the younger Lava Creek B and older Huckleberry Ridge ash beds and is in sediments with reversed paleomagnetic polarity. Analyses of this ash bed compare well with published data for the Mesa Falls ash bed (SC = 0.93) (Sarna-Wojcicki and others, 1984) in all elements except sodium (Table 1). This correlation extends the distribution of the Mesa Falls ash bed as shown by Izett and Wilcox (1982) southward by 300 km.

Rio Dell Ash Bed

The Rio Dell ash bed of Sarna-Wojcicki and others (1987) is called the Centerville Beach ash bed by Izett (1981). It correlates with a grayish white, fine-sand-sized, elongately ridged and pumiceous ash bed (SC = 0.91) in the Burmester core at a depth of 184.4 m (BUR-605.0). The Rio Dell ash bed is also found in deep-sea cores off the coast of California, outcrops in California and Oregon, and at a depth of 139 m in the Tulelake core in northern California (Sarna-Wojcicki and others, 1991; Rieck and others, 1992). Identification of the Rio Dell ash bed in the Burmester core significantly extends its eastern limit. The Rio Dell ash bed is distinctively high in iron and calcium (Table 2). Although the source of the Rio Dell has not been identified, Sarna-Wojcicki and others (1991) suggested that it probably erupted from the Cascade Range.

The Rio Dell ash bed lies below the Jaramillo Subchron boundary and above the Olduvai Normal Subchron, within a reversely magnetized section of the Burmester core. This stratigraphic position is in accord with Izett's (1981) placement. Izett (1981) gives a fission track age of 1.48 ± 0.56 Ma for the Centerville Beach ash bed, and an age of 1.50 Ma is suggested by Sarna-Wojcicki and others (1987) based on its position in Deep Sea Drilling Project core 173.

Tephra Layer BUR-621.3

This tephra layer is white, fine to medium sand sized, and composed of elongately ridged and pumiceous shards. It lies 5 m below the Rio Dell ash bed at 189.3 m depth.

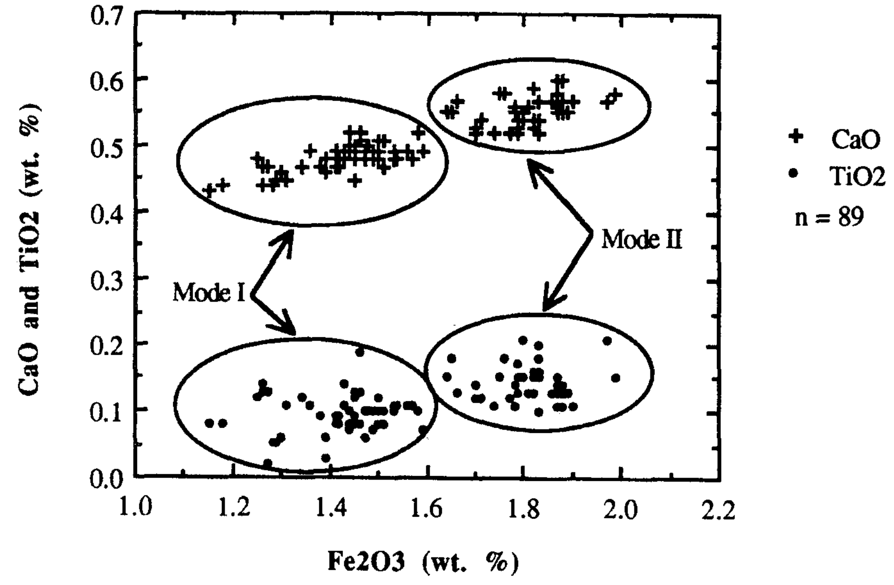

Figure 4. Electron microprobe data of individual glass shards showing Fe_2O_3 versus CaO and TiO_2 for the Lava Creek B ash bed. Two distinct modes are present: I is low Fe_2O_3, CaO, and TiO_2, while II contains greater amounts of Fe_2O_3, CaO, and TiO_2.

Although BUR-621.3 is homogeneous and has a distinctive glass chemistry (Tables 1 and 2), it does not correlate with any known tephra in the western United States. This tephra layer has high calcium and low potassium for a white tephra, and it was probably erupted from the Cascade Range.

Last Chance Bench Ash Bed

At a depth of 226.9 m in the Burmester core lies a light gray, medium- to fine-sand-sized ash bed (BUR-744.4) composed of pumiceous and elongately ridged shards. Like the Bishop ash bed, it is compositionally similar to ash beds derived from the Long Valley area (Table 4). Based on its stratigraphic position ~5 m above the Huckleberry Ridge ash bed, and its chemical composition, this tephra layer is correlated with the Last Chance Bench ash bed (SC = 0.82). The correlation is tentative because potassium and calcium contents do not agree well (Table 4). The Last Chance Bench ash bed was described from Pliocene sediments near Beaver, Utah, where it overlies the Huckleberry Ridge ash bed by ~30 m (Izett, 1981; Machette, 1982). Izett and others (1988) estimated its age at 1.8–1.9 Ma because of its proximity to the underlying Huckleberry Ridge ash bed. This age is consistent with paleomagnetic evidence from the Burmester core in which it lies 3.35 m above the base of the Olduvai Subchron (1.97 Ma). The Last Chance Bench ash bed may correlate to the "late" tuff of Taylor Canyon, which has an age of 1.917 ± 0.020 Ma (Sarna-Wojcicki and Pringle, 1992).

Huckleberry Ridge Ash Bed

The Huckleberry Ridge ash bed is identified in the Burmester core (BUR-756.1 and BUR-760.8) from a 1-m-thick silty ash bed lying at 231.9 m depth, just below the normal-polarity interval identified as the Olduvai Normal Subchron, and above a layer of gravel. This ash bed is gray, coarse sand sized, and made up of platy and elongately ridged shards. Average electron mi-

TABLE 4. ELECTRON MICROPROBE ANALYSES OF BISHOP AND BISHOP-LIKE ASH BED SAMPLES FROM THE BONNEVILLE BASIN CORES

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Cl	F	Total	SC1	SC2
Bishop ash														
BUR-313.4	78.21	12.57	0.72	0.04	0.04	0.44	0.05	3.18	4.76	n.d.	n.d.	90.13	0.93	0.94
BUR-314.5	77.91	12.58	0.80	0.04	0.03	0.46	0.07	3.02	5.10	n.d.	n.d.	91.93	0.90	0.96
BUR-317.2	78.16	12.52	0.77	0.03	0.03	0.43	0.05	3.16	4.85	n.d.	n.d.	92.73	0.93	0.93
S28-574.6	78.20	12.78	0.76	0.05	0.03	0.45	0.07	2.74	4.82	0.07	0.03	96.30	0.88	0.95
SLT-646.0	78.10	12.61	0.74	0.04	0.05	0.45	0.08	3.16	4.70	0.09	n.d.	93.23	0.90	0.92
WDR-323.0	77.46	12.61	0.78	0.05	0.03	0.46	0.07	3.21	5.18	0.14	n.d.	97.02	0.88	0.94
Bishop av.*	77.55	12.56	0.75	0.03	0.04	0.46	0.06	4.03	4.49	0.06	n.d.	92.20	1.00	0.92
Bishop av.†	77.55	12.64	0.74	0.04	0.03	0.45	0.06	3.70	4.78	n.d.	n.d.	94.02	0.92	1.00
Bailey ash														
BUR-488.1	77.80	12.83	0.70	0.02	0.06	0.42	0.05	2.30	5.64	0.07	0.09	95.98	0.86	0.89
WDR-479.4	77.95	12.89	0.73	0.04	0.06	0.52	0.08	2.69	5.02	n.d.	n.d.	93.45	0.90	0.89
PICO-4§	77.36	12.33	0.80	0.03	0.05	0.51	0.06	3.83	5.03	n.d.	n.d.	100.00	1.00	0.93
PICO-5§	77.43	12.56	0.70	0.03	0.07	0.45	0.06	3.74	4.96	n.d.	n.d.	100.00	0.93	1.00
Glass Mountain D ash														
KNL-486.10	77.93	12.72	0.79	0.04	0.03	0.43	0.08	2.72	5.26	n.d.	n.d.	97.37	0.91	
WDR-372.7	78.03	12.65	0.79	0.04	0.04	0.43	0.08	2.77	5.16	0.05	n.d.	97.23	0.94	
PICO-23§	77.28	12.87	0.77	0.04	0.05	0.42	0.07	3.89	4.61	n.d.	n.d.	100.00	1.00	
Last Chance Bench ash														
BUR-744.4	77.53	12.73	0.74	0.03	0.08	0.31	0.08	2.24	6.07	0.08	0.09	97.73	0.82	
BEV92-07#	77.78	12.75	0.75	0.04	0.04	0.46	0.09	3.09	4.88	0.07	n.d.	94.22	1.00	

Note: Data given as wt%. Data normalized to 100% for comparison with published data. Total iron reported as Fe_2O_3. Total reported for core samples is original oxide total.
*Data from Sarna-Wojcicki et al. (1984).
†Data from Sarna-Wojcicki et al. (1987).
§Data from A. M. Sarna-Wojcicki and C. E. Meyer (personal commun).
#Sample from type locality near Beaver, Utah (Machette, 1982).
SC1 = Similarity coefficient computed using Si, Al, Fe, Mg, Mn, Ca, Ti, and K.
SC2 = Similarity coefficient computed using Al, Fe, Mg, Ca, Ti, and K.
n.d. = not determined.

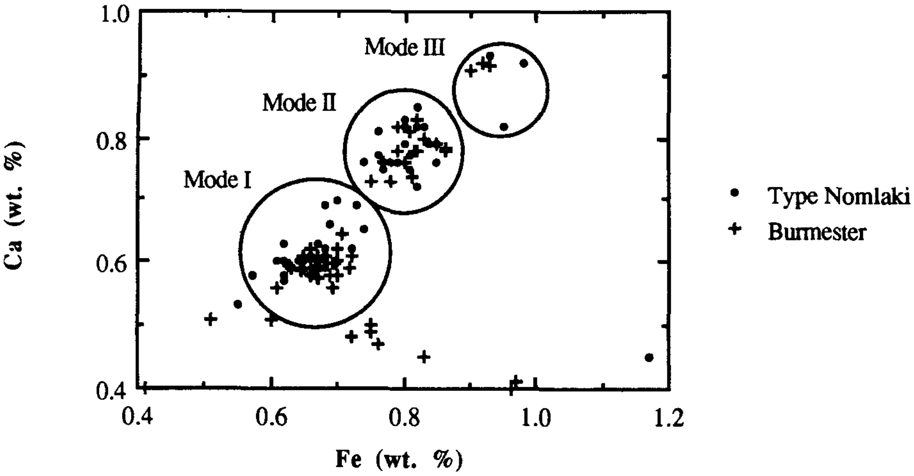

Figure 5. Electron microprobe data of individual glass shards showing iron versus calcium for the Nomlaki ash. Three distinct modes are present: I and II are dominant, while III is minor. The scattering of low calcium values in the Burmester core probably represents another tephra reworked into the Nomlaki at this locality.

croprobe analyses (Table 1) and X-ray fluorescence analyses (Table 2) show good correlation with similarity coefficients of 0.93–0.95.

The Huckleberry Ridge ash bed was produced by one of the largest eruptions from the Yellowstone area in late Tertiary time with an estimated volume of 2500 km^3 (Christiansen, 1979). Sarna-Wojcicki and Pringle (1992) reported an age of 2.057 ± 0.008 Ma for the Huckleberry Ridge ash, based on single-crystal laser-fusion ^{40}Ar/^{39}Ar.

Hogsback(?) Ash Bed

BUR-812.6 has a distinctive chemical composition similar to tephra layers derived from the Mineral Mountains area of Utah. It is light gray, medium sand sized, with extremely pitted, platy and elongately ridged shards, and lies at a depth of 247.7 m.

Glass of this tephra layer is similar in composition to that of the Hogsback ash bed (SC = 0.75), but it contains more magnesium, titanium and potassium (Table 1). The Hogsback ash bed is known only from the Beaver, Utah, area. Machette (1982) suggested that its source lies northwest of the Mineral Mountains based on chemical similarities with rhyolite outcrops at Cudahy Mine and South Twin Peak.

Tephra Layer BUR-841.2

A tephra layer known from two samples in the Burmester core (BUR-840.4 and BUR-841.2) correlates with an unnamed tephra layer (SC = 0.83–0.91) from cores near Broadwell Lake, California (Sarna-Wojcicki, 1992, personal commun.) (Table 2). In these cores, the tephra layer underlies the tuff of Taylor Canyon (2.17 ± 0.009 Ma; Sarna-Wojcicki and Pringle, 1992) and overlies the Upper Horse Hill ash. The tephra layer is light gray, medium to fine sand sized, and has platy and elongately ridged shards. It is similar to Cascade Range tephra, although the magnesium content is lower than that of most tephra from that region (Sarna-Wojcicki, 1992, personal commun.).

Tephra Layer BUR-871.11

BUR-871.11 is a distinctive tephra layer with unimodal, brownish-gray, fine-sand-sized pumiceous and platy shards. Its composition and color are similar to dacitic tephra derived from the Cascade Range. This tephra layer has one of the highest iron and calcium contents of any tephra layer from the cores (Tables 1 and 2), but it does not correlate with any tephra in the western United States for which data have been published, although a compositionally similar tephra layer is present near the base of the Glenns Ferry Formation in southwestern Idaho near Grandview.

Upper Horse Hill Ash Bed

BUR-914.2 and BUR-915.0 are correlated with an undated ash bed (C-83-6A) in the Kettleman Hills, southern California, and near Tulelake, northern California (Sarna-Wojcicki and others, 1991). It is medium gray, with coarse- to medium-sand-sized platy shards and minor amounts of bubble junction shards. This ash bed is informally named the La Salida ash bed (Sarna-Wojcicki, 1991, personal commun.), but a correlative ash bed in the Glenns Ferry Formation was identified as the Upper Horse Hill ash bed by Swirydczuk (1977). Although the published compositional data for this ash bed (Swirydczuk and others, 1982) differ from the data from the Burmester core, analysis of a sample of the Upper Horse Hill ash bed from its type locality (Tables 1 and 2) shows the chemical composition of the ash beds is very similar (SC = 0.94–0.97).

Tephra Layer BUR-962.8

Burmester samples BUR-960.2 and BUR-962.8 are chemically indistinguishable from one another (Table 1) and constitute another distinct dacitic tephra. This tephra layer is medium dark gray with medium-sand-sized elongately ridged and platy shards. The samples were taken from two distinct zones of glass shards, separated by 30 cm of silty claystone with no glass present. A correlative, based on microprobe (SC = 0.97) (Table 1) and X-ray fluorescence analyses (SC = 0.97) (Table 2), does exist in the Glenns Ferry Formation where it underlies the two tephra layers correlated with BUR-871.11 and the Upper Horse Hill ash bed, and overlies a tephra layer correlated with the Nomlaki Tuff.

Nomlaki Tuff

BUR-989.4, BUR-993.0, and BUR-996.0 represent samples from a 6.1 m silty claystone interval containing light gray, coarse-sand-sized, pumiceous, blocky, and elongately ridged glass shards. These samples are compositionally similar to the Nomlaki Tuff (SC = 0.94–0.96) from northern California, although electron microprobe (Table 1) and X-ray fluorescence analyses (Table 2) give somewhat conflicting results. Electron microprobe data (Fig. 5) show that each sample has two dominant compositional modes (I and II) and a minor compositional mode (III). Because X-ray fluorescence uses a bulk sample and the microprobe is grain-discrete, the two analytical methods may not give corresponding results on polymodal samples. Electron microprobe analyses of the Nomlaki Tuff from the type locality in

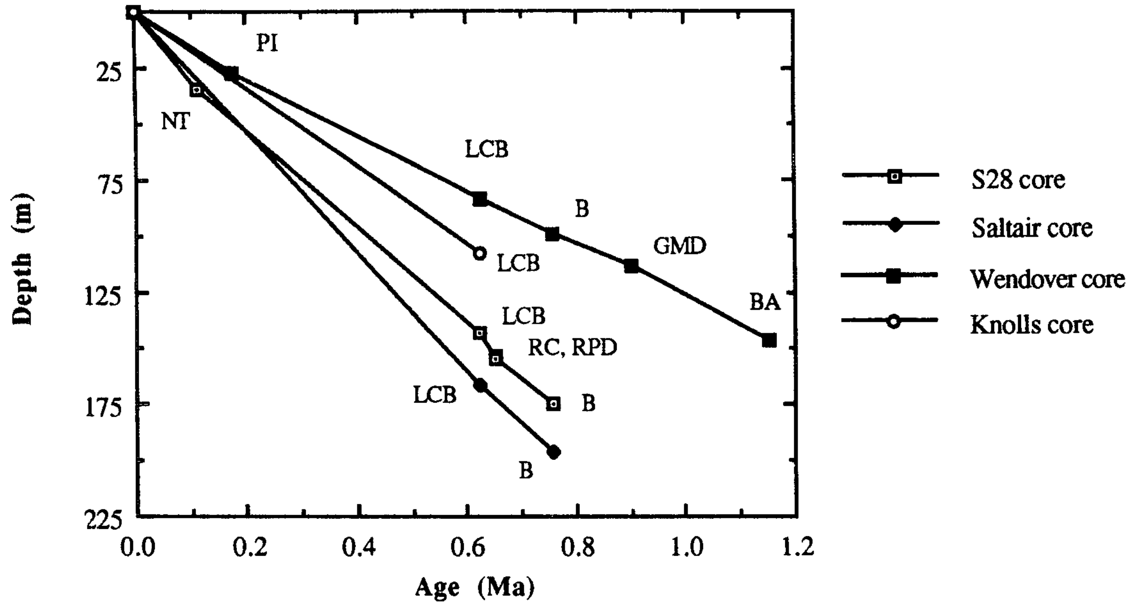

Figure 6. Age-depth curves for the S28, Saltair, Wendover, and Knolls cores using ash beds as datums. PI = Paoha Island tephra layer; NT = Natural Trap ash bed; LCB = Lava Creek B ash bed; B = Bishop ash bed; RC = Ranch Canyon ash bed; RPD = Rye Patch Dam ash bed; GMD = Glass Mountain D ash bed; BA = Bailey ash bed

northern California show that it contains shards of several different compositions, similar to the modes of the Burmester samples (Fig. 5). The Burmester samples also contain shards with chemical compositions different from the Nomlaki Tuff, which may indicate that another tephra has been mixed with the Nomlaki in the Burmester core.

SEDIMENTATION RATES IN BONNEVILLE BASIN

Time-depth curves were constructed for each core using correlations with tephra layers dated in other sections and, for the Burmester core, both published and unpublished paleomagnetic data. Because the Wendover (five tephra layers), Knolls (one tephra layer), Saltair (two tephra layers), and S28 (three tephra layers) cores contain few dated ash layers, and the paleomagnetic results are inconclusive, accumulation curves for these cores (Fig. 6) are less detailed than for the Burmester core, which contains 14 datums of known age (Fig. 7). Accumulation rates for the Wendover core are relatively low (8.9–15.3 cm/k.y.). For the Knolls core, the Lava Creek B ash bed is the only securely dated marker, and the calculated sedimentation rate is 17.2 cm/k.y., 10%–50% higher than in the Wendover core. Five separate tephra layers were identified in the S28 core, but only the Lava Creek and Bishop ash beds have been isotopically dated. Accumulation rates are rea-

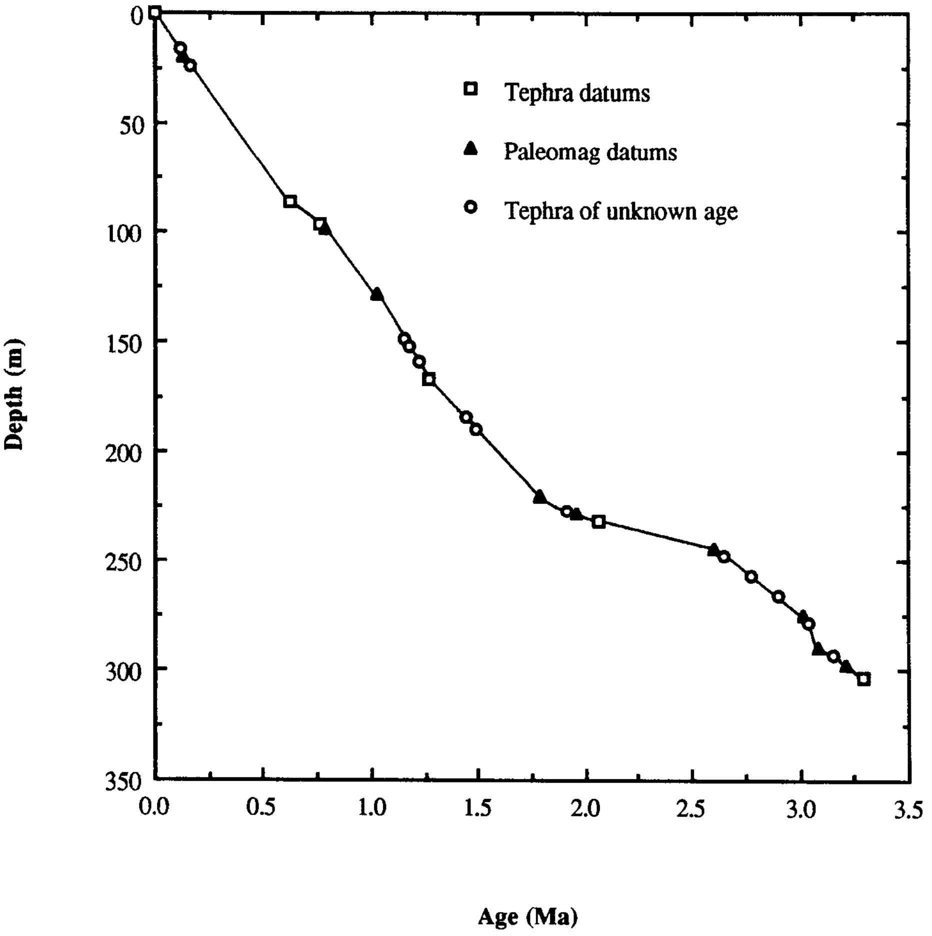

Figure 7. Age versus depth curve for the Burmester core. Approximate ages for previously undated tephra layers can be estimated from this curve.

TABLE 5. RATES OF SEDIMENT ACCUMULATION FOR BURMESTER CORE

Datum	Depth (m)	Age (Ma)	Rate	
			(cm/ka)*	(cm/ka)†
Blake	15.2	0.128	15.48	13.63
Lava Creek B	86.9	0.62	14.01	7.02
Bishop	96.6	0.759	12.73	10.16
Brunhes-Matuyama	99.1	0.783	12.65	12.89
Jaramillo (base)	128.3	1.01	12.71	14.77
Mesa Falls	166.7	1.27	13.13	10.34
Olduvai (top)	219.5	1.79	12.26	5.61
Olduvai (base)	230.1	1.97	11.68	1.69
Huckleberry Ridge	231.7	2.06	11.25	22.6
Matuyama-Gauss	243.9	2.60	9.38	7.40
Kaena (top)	275.0	3.02	9.10	20.90
Kaena (base)	289.6	3.09	9.37	6.86
Mammoth (top)	297.8	3.21	9.28	7.24
Nomlaki	303.6	3.29	9.23	
Average			12.99	12.51

*Average rate between datum and top of the core.
†Average rate between datum and datum directly below.

sonably constant in the S28 core (23.4–26.6 cm/k.y.) but are more than twice that of the Wendover core. Sediment accumulation rates for the Saltair core (25–27.4 cm/k.y.) are also fairly constant and similar to those in the S28 core.

The age-depth curve for the Burmester core can be subdivided into three segments. From 3.3 to 2.5 Ma, the rate of sedimentation is fairly constant at 8.7 cm/k.y. Between 2.5 and 2.0 Ma, either nondeposition, very intermittent rapid sedimentation separated by periods of nondeposition, or erosion occurred. This 11 m interval is composed of sand and gravel across which the accumulation rate is only 2.2 cm/k.y. This 0.5 m.y. period includes the Réunion Subchrons, which were apparently not recorded in the gravel. Thereafter, between 2.0 Ma and the present, the sediment accumulation rate is approximately constant at 11.7 cm/k.y. Accumulation rates between each of the Burmester datums are given in Table 5.

AGE ESTIMATES FOR UNDATED TEPHRA LAYERS

Sediment accumulation rates interpolated between the well-dated horizons in the Burmester core allow the ages of previously undescribed tephra layers to be estimated (Table 6). These ages should be considered approximations because they are based on the accuracy of independently dated horizons and the assumption of constant sedimentation throughout the stratigraphic interval between the dated horizons. The assumption of constant sedimentation is not strictly valid as independent evidence (gravels and soils) indicate fluctuating lake levels and periods of nondeposition. Nonetheless, when compared with other age estimates for the same tephra layers, the ages interpolated here are in close agreement. Tephra layers that were previously dated but differ in age interpolated from the age-depth curves are discussed below.

Natural Trap(?) Ash Bed

In the Burmester core, this tephra layer lies at the top of a reversely magnetized interval identified as the Blake Subchron (Eardley and others, 1973). The Blake Subchron has been dated at 0.128 ± 0.033 Ma (Champion and others, 1988). The compositionally similar Hebgen Narrows ash bed is assigned an age of ca. 0.11 Ma based on its stratigraphic position below till of Bull Lake age at the type locality of the Hebgen Narrows ash bed by Izett (1981). However, Richmond (1986) reported a K-Ar age of 0.485 ± 0.005 Ma for the Hebgen Narrows ash bed. If correct, then the Hebgen Narrows cannot correlate with either of the core samples because of their close stratigraphic position to the Blake Subchron.

Paoha Island Tephra Layer

Several tephra layers bear the name Paoha Island tephra layer (Sarna-Wojcicki, 1992, personal commun.), with ages of 0.15, 0.16, and 0.175 Ma. The age estimated for the Paoha Island in the Bonneville Basin is 0.16 Ma, which compares favorably with the age of 0.16 Ma for the next-to-uppermost Paoha Island tephra layer (Sarna-Wojcicki, 1992, personal commun.).

Ranch Canyon Ash Bed

Sanidine from the Ranch Canyon ash bed was K-Ar dated at 0.55 ± 0.01 Ma (Izett, 1981). Its stratigraphic position between the Lava Creek B ash bed (0.62 Ma) and Bishop ash bed (0.76 Ma) in core S28 would suggest the age to be nearer 0.67 Ma. Therefore, S28-505.4 may not be the Ranch Canyon ash bed *per se*, but instead the product of an earlier eruption from the Mineral Mountains. Lipman and others (1978) reported a K-Ar age of 0.70 ± 0.04 Ma for an ash-flow tuff in Ranch Canyon, and Evans (1978) reported a K-Ar date on an obsidian from an ash flow unit in Ranch Canyon of 0.68 ± 0.04 Ma, making the foregoing supposition possible. Alternatively, it is possible that the age of 0.55 Ma is incorrect for the Ranch Canyon ash bed.

Hogsback(?) Ash Bed

The Hogsback ash bed lies stratigraphically below an ash bed correlated with the tuff of Taylor Canyon-C (2.1 ± 0.02 Ma) in the Beaver Basin (Machette, 1982). From the suspected source of the Hogsback ash bed, Lipman and others (1978) reported a K-Ar age of 2.38 ± 0.15 Ma for a rhyolite flow at the Cudahy Mine, the suggested source of the Hogsback ash bed, whereas

TABLE 6. AGE ESTIMATES FOR UNDATED BURMESTER CORE TEPHRA LAYERS BASED ON STRATIGRAPHIC POSITION BETWEEN DATED MARKERS

Datum	Depth (m)	Age of tephra (Ma)	Age of paleomag. (Ma)	Estimated age in Burmester core (Ma)	Age reference
Blake	15.2		0.128		Champion and others (1988)
Natural Trap	15.4			0.11	
Paoha Island	23.5			0.16	
Lava Creek B	86.9	0.62			Christiansen and Blank (1972)
Bishop	96.6	0.759			Sarna-Wojcicki and Pringle (1992)
Brunhes-Matuyama	99.1		0.78		Spell and others (1992)
Jaramillo (base)	128.3		1.02		Spell and others (1992)
Bailey	148.8			1.15	
BUR-498.11	152.1			1.17	
BUR-523.3	159.5			1.22	
Mesa Falls	166.7	1.27			Izett (1981)
Rio Dell	184.4			1.44	
BUR-621.3	189.4			1.49	
Olduvai (top)	219.5		1.78		McDougall and others (1992)
Last Chance Bench	226.8			1.91	
Olduvai (base)	230.1		1.96		McDougall and others (1992)
Huckleberry Ridge	231.7	2.06			Sarna-Wojcicki and Pringle (1992)
Matuyama-Gauss	243.9		2.60		McDougall and others (1992)
Hogsback	247.7			2.65	
BUR-841.2	256.4			2.77	
BUR-871.8	265.8			2.90	
Kaena (top)	275.0		3.02		McDougall and others (1992)
Upper Horse Hill	278.9			3.04	
Kaena (base)	289.6		3.09		McDougall and others (1992)
BUR-962.8	293.5			3.15	
Mammoth (top)	297.8		3.21		McDougall and others (1992)
Nomlaki	303.6			3.29	

Crecraft and others (1981) reported a K-Ar age of 2.63 ± 0.10 Ma on obsidian from the same unit. In the Burmester core, this tephra layer lies 3.5 m below the Matuyama-Gauss Chron boundary, from which its age is estimated at ca. 2.65 Ma in agreement with the age of the suspected source.

Tephra Layer BUR-871.11

A fission-track age of 2.4 ± 0.2 Ma was obtained on glass (Kimmel, 1979) for a tephra layer at approximately the same stratigraphic level as BUR-871.11 in the Glenns Ferry Formation. This would imply an age of ca. 2.4 Ma for BUR-871.11, whereas an age of 2.90 Ma is estimated for this ash from the depth-age curve for the Burmester core. This indicates the base of the Glenns Ferry Formation near Grandview is older than hitherto suspected.

Upper Horse Hill Ash Bed

Sarna-Wojcicki and others (1991) suggested an age of ca. 2.2 Ma for the correlative ash bed based on its stratigraphic position at the base of the Tulare Formation, Kettleman Hills, California. Magnetostratigraphic information from the Burmester core, however, suggests that this age might be too young. An age of ca. 3.04 Ma is calculated from the age-depth curve from the Burmester core for the Upper Horse Hill ash bed.

Nomlaki Tuff

The age of the Nomlaki Tuff is 3.4 ± 0.3 Ma (Evernden and others, 1964; Sarna-Wojcicki and others, 1991). This is consistent with the age of samples from the Burmester core, where the Nomlaki Tuff is found in a paleomagnetically reversed interval interpreted as the Mammoth Subchron (3.21–3.29 Ma; McDougall and others, 1992), suggesting that the Nomlaki Tuff cannot be older than 3.29 Ma.

DISCUSSION AND CONCLUSIONS

In a sense, the Bonneville Basin has acted as a low-pass filter for volcanic eruptions in the western United States. For an eruption to have been recorded, it must have been large enough for tephra to reach the upper levels of the atmosphere and entrained by the prevailing winds or jet stream. Small-scale eruptions would not have the necessary eruptive force to reach the upper levels of the atmosphere and therefore could not reach the Bonneville Basin unless they were nearby. Since the Bonneville Basin is far removed from the major volcanic centers, the presence of tephra in the basinal sediments suggests that its generating eruption was large.

Qualitatively, paleowind directions for the past 3.3 m.y. do not appear to have been much different from those today. The presence of four Yellowstone tephra layers suggests a wind direction (or at least a wind component) from the north. Many of the other tephra layers are derived from sources to the west and northwest and could have been transported to the basin by atmospheric flow similar to that of the present. Only two tephra, the Hogsback and the Ranch Canyon, indicate a wind component from the south during their eruptions, and these are from more proximal sources. Even today, strong winds from the south occur as storms approach northern Utah from the northwest.

Several tephra layers are present in only one or two cores, indicating that depositional conditions were not uniform over the entire Bonneville Basin. For different tephra to have been deposited in different cores, sedimentation must have been active at some sites, while there was no deposition at others. Alternatively, the absence of tephra layers in some cases may simply reflect incomplete recovery.

The period of decreased deposition in the Burmester core from 2 to 2.5 Ma is consistent with other regional evidence of slow deposition in the Great Basin. Rieck and others (1992) noted a break in sedimentation in the Tulelake core at roughly the same period. In core KM-3 from Searles Lake, southern California, Smith and others (1983) found a long, dry period from 2.04 to 2.56 Ma. They suggested deposition on a playa during a period of markedly decreased precipitation in the Sierra Nevada and decreased streamflow of the ancestral Owens River. Thus, three independent basins indicate a regional decline in effective precipitation in the western United States between ca. 2.5 and 2.0 Ma.

Of 22 compositionally distinct tephra layers in the Bonneville Basin cores, 15 can be correlated with known tephra layers. Approximate ages are estimated from sediment accumulation rates for the remaining seven tephra layers. Sarna-Wojcicki and others (1991) and Izett (1981) developed a regional tephrostratigraphy for the western United States, and the addition of the new tephrochronologic markers reported here will help to determine and refine the chronology at other sites in the western United States. Also, the areal extents of many known ash beds—for example, Natural Trap(?), Paoha Island, Ranch Canyon, Rye Patch Dam, Glass Mountain D(?), Bailey, Mesa Falls, Rio Dell, Last Chance Bench, Hogsback(?), Upper Horse Hill, and Nomlaki—have been significantly expanded as a result of this study.

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