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Age model for a continuous, ca 250-ka Quaternary lacustrine record from Bear Lake, Utah–Idaho

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Abstract

The Quaternary sediments sampled by continuous 120-m-long drill cores from Bear Lake (Utah-Idaho) comprise one of the longest lacustrine sequences recovered from an extant lake. The cores serve as a good case study for the construction of an age model for sequences that extend beyond the range of radiocarbon dating. From a variety of potential age indicators, we selected a combination of radiocarbon ages, one magnetic excursion (correlated to a standard sequence), and a single Uranium-series age to develop an initial data set. The reliability of the excursion and U-series data require consideration of their position with respect to sediments of inferred interglacial character, but not direct correlation with other paleoclimate records. Data omitted from the age model include amino acid age estimates, which have a large amount of scatter, and tephrochronology correlations, which have relatively large uncertainties.

Because the initial data set was restricted to the upper half of the BL00-1 core, we inferred additional ages by direct correlation to the independently dated paleoclimate record from Devils Hole. We developed an age model for the entire core using statistical methods that consider both the uncertainties of the original data and that of the curve-fitting process, with a combination of our initial data set and the climate correlations as control points. This age model represents our best estimate of the chronology of deposition in Bear Lake. Because the age model contains assumptions about the correlation of Bear Lake to other climate records, the model cannot be used to address some paleoclimate questions, such as phase relationships with other areas.

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1. Introduction

Age models for sedimentary successions are fundamental components of paleoenvironmental reconstructions. For such reconstructions, age models are arguably just as important as interpretation of the environmental proxies themselves. In the most highly resolved Quaternary records (ice cores, tree rings, and varved lake sediments), annual layers can be counted. Such records are commonly younger than 10 ka, but exceptional records extend to 30–40 ka (e.g., Kitagawa and van der Plicht, 1998; Meese et al., 1997). Other records are based on uniform precipitates that are ideally suited for certain dating methods—the best examples are Uranium-series-dated cave stalagmites (e.g., Wang et al., 2001) and groundwater calcite veins (e.g., Ludwig et al., 1992; Winograd et al., 1992). In contrast, virtually all marine and continental paleoclimate records that extend to more than about 50 ka come from complex, fine-grained accumulations of terrigenous and biogenic sediment.

Long continental sedimentary records form in a variety of depositional environments, but for reasons related to resolution and continuity, sedimentary sequences from

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lakes are especially valuable (Colman, 1996). Recent lake drilling projects, such as those in Lake Baikal (Kuzmin et al., 2000; Williams et al., 2001) and Lake Titicaca (Baker et al., 2001; Fritz et al., 2004), have yielded long records of paleoenvironmental changes, and the first results from Bear Lake are reported in a companion paper (Bright et al., this issue). The extent to which these records can be compared with those from other regions depends on the accuracy of the chronological control.

Constructing age models for long lacustrine sequences is difficult because the data are typically imperfect. Reliability varies greatly and different age estimates commonly conflict. Age estimates beyond the range of radiocarbon methods are commonly based on experimental methods whose assumptions are not fully explored and whose accuracy is poorly known. Difficulties are accentuated for sediment sequences younger than 780 ka, for which paleomagnetic-reversal stratigraphy is not applicable. Correlations of local paleoenvironmental proxies with well-established climatic events, such as those known from ice-core and marine-sediment records, are commonly helpful, but relying on an a priori assumption of globally synchronous climate change limits the climatic questions that can be validly addressed, especially those related to geographic and temporal variability. Detailed comparisons of local versus global climate events and their phasing can become circular reasoning if climate correlations are used in the age models. The sedimentary record from Bear Lake affords a good case study of these issues, and this paper represents our attempts to deal with them.

As part of an international effort to develop long continental paleoclimate records (Colman, 1996), the GLAD800 (Global Lake Drilling to 800 m) drilling system (http://www.dosecc.org/html/glad800.html) was developed (Dean et al., 2002). During the initial testing of this system, two holes were drilled and continuously cored, with nearly 100% recovery, in Bear Lake, Utah–Idaho (Fig. 1; Dean et al., 2002). Sediments at the drill site (41 ° 57′ 06″ N, 111′ 18′ 30″ W, 51.12 m water depth) consist of alternating marl and relatively low-carbonate mud deposited in an active half-graben basin. Two long drill cores were obtained a few meters apart, BL00-1D (100 m) and BL00-1E (120 m). The two holes were drilled so that their core breaks were vertically offset to provide a continuous record. Their magnetic susceptibility records correlate precisely and the composite record (hereafter, “BL00-1”) is discussed here on the depth scale of BL00-1E.

2. Approach

Building an age model from imperfect chronological data is, of necessity, an iterative operation. However, the goal is to minimize, to the extent possible, the arbitrary selection of data, and to avoid circular reasoning about correlations. Construction of the age model also should be as simple, clear, and as reproducible as possible. Finally, one should clearly separate (but not necessarily eliminate) inferences based on climatic correlations.

We first examine all relevant chronological data, regardless of reliability. We then develop an initial data set, eliminating ages that are conflicting or have large uncertainties. If possible, we would then construct an age model with data that do not require direct correlation to other climatic time series. As discussed in the following sections, this was not possible for core BL00-1, so we have included a simple set of correlations to another well-dated climate record. We then calculated an age-depth model using newly developed statistical techniques for specific age-depth curves (Birks and Heegaard, 2003; Heegaard et al., 2005). These techniques weight data according to their uncertainty and produce confidence limits for the age model that account for both analytical uncertainty and regression as sources of error.

The Bear Lake age model provides age estimates for a variety of events, such as the deposition of tephra layers. The models also can be used for proxy climate indicators that have been analyzed from BL00-1, as in the companion paper for stable isotopes and mineralogy (Bright et al., this issue). However, because the available independent age data were insufficient to produce an age model for the entire core, we resorted to direct correlation of the BL00-1 to other independently dated climate records. In doing so, we are restricted in the ways in which the age model can be used to address paleoclimate questions. Those that require complete independence of age control, such as the phasing of climate events between different areas, are beyond the utility of our age model.

3. Data and methods

3.1. Radiocarbon ages

Although no radiocarbon ages are available from core BL00-1, we performed extensive radiocarbon dating on samples from nearby piston cores from Bear Lake (Colman et al., 2005). These piston-core ages were obtained from samples of total organic carbon (TOC), biogenic carbonate (ostracode shells), and samples that were pre-treated using standard pollen preparation techniques to concentrate a pollen-rich fraction (“pollen + ”). Comparisons among the different kinds of samples at the same horizons indicated that the ages of the TOC and carbonate samples were several hundred years older than the pollen + samples, presumably due to allochthonous carbon and reservoir effects, respectively. No corrections were applied to the pollen + samples, and only those samples are used here. All radiocarbon ages were converted to calibrated ages using Calib 5.0 (Stuiver et al., 1998).

Pollen + samples younger than the last glacial maximum (<17 cal ka) consist mainly of pollen, but also include small amounts of other refractory organic matter. Radiocarbon ages for samples older than 17 cal ka, which contain little pollen, may be somewhat older than the true age of

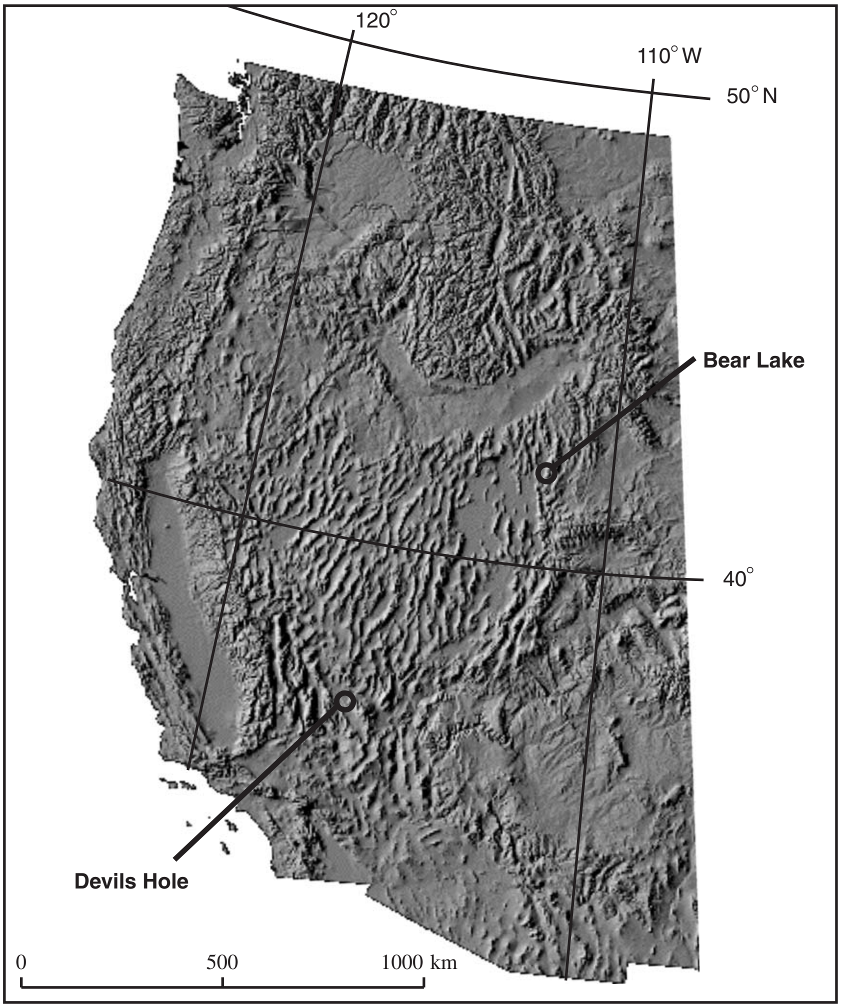

Fig. 1. Map of the western United States showing the location of Bear Lake and Devils Hole.

the sediment, because of the dominance of detrital organic matter (Colman et al., 2005).

Sediments below the uppermost marl in all piston and drill cores have distinctive magnetic susceptibility profiles that can be readily correlated from core to core (Fig. 2). On the basis of these correlations and correlative horizons within the Holocene section, radiocarbon ages from piston cores BL96-2 and BL96-3 (pollen+ samples only) were transferred to the depth scale of drill core BL00-1 (Fig. 2). In general, these ages form a smooth progression with depth.

3.2. *Magnetic excursions*

We took u-channel samples from the entire length of core BL00-1D and from most of core BL00-1E including the bottom 20 m, which comprise a complete 120-m record. After stepwise alternating-field (AF) demagnetization up to 80 mT, we measured magnetic directions and properties on the u-channel samples using a 2–G® Enterprises small-access cryogenic magnetometer every 2 cm. The sediments carry a strong, stable remanence, which closely approximates the geocentric axial dipole (GAD) inclination values.

As many as 14 excursions have been identified in marine sediment based on GAD analysis (Lund et al., 2001). These excursions provide excellent age constraints when present in the sediment record. The paleomagnetic-field orientations in core BL00-1 exhibit several rapid shifts, but detailed analysis and measurements indicated that all but one of these was from sediment that had been subjected to deformation in the coring process. Such deformation is common phenomenon that is not always readily apparent (Rosenbaum et al., 2000). We thus include only the excursion at 26.5 m, correlated with the 3β (Laschamp) event of Lund et al. (2001). An age of 41 ± 3 ka is taken from the excursion timescale of Lund et al. (2001) and the associated error is estimated from that record and consideration of sedimentation rates.

3.3. *Uranium-series age*

Several samples exhibiting elevated carbonate contents were selected from BL00-1 for testing the suitability for

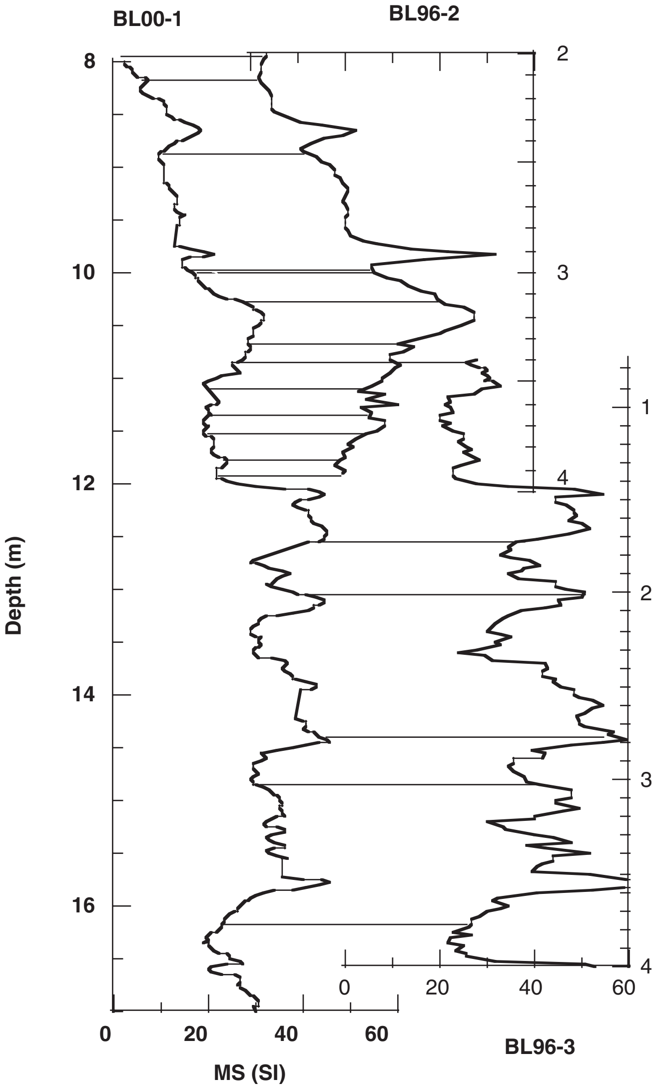

Fig. 2. Magnetic susceptibility profiles for correlative parts of cores BL96-2, BL96-3, and BL00-1. Values for BL00-1 are from a pass-through sensor and are volume susceptibilities (SI); those for the two 1996 cores are from discrete samples and are mass susceptibilities (m^3/kg). Depth scales (in m) have been linearly adjusted to show the correlations among the cores. Radiocarbon ages from cores BL96-2 and BL96-3 (Colman et al., 2005) were transferred to core BL00-1 at the horizons indicated.

U-series dating by thermal ionization mass spectrometry. Only one sample, BL00-1D-22A at 67.0 m, with the highest carbonate content of the group (66.4 wt%, mostly aragonite) was found viable on the basis of isotopic composition. This sample (USGS lab number 01-129) exhibited an unusually high content of uranium of 16.3 ± 0.2 ppm, a $^{234}U/^{238}U$ activity ratio of 1.24 ± 0.024, a $^{230}Th/^{232}Th$ ratio of 2.0, and a $^{230}Th/^{234}U$ ratio of 0.713 ± 0.01. With the requisite closed-system assumption, these results produce a nominal (uncorrected) age of 127.7 ± 3.9 ka. The $^{230}Th/^{232}Th$ ratio of 2.0, however, indicates the sample contains a significant level of non-radiogenic ^{232}Th, presumably accompanied by some (non-quantifiable) amount of ^{230}Th, upon which the age is calculated. At one extreme, a correction to the calculated age can be made assuming that the extraneous ^{232}Th represents average crustal detritus. Using the computer program Isoplot (Ludwig, 2000), we obtained a corrected age of 112.3 ± 4.2 ka. It is entirely likely, however, that extraneous ^{232}Th in lake systems is accompanied by significantly less ^{230}Th than in average crustal detritus, this based on studies at Owens Lake, California (Bischoff and Cummins, 2001) and Lake Banyolas, Spain (Julià and Bischoff, 1991).

Because of the uncertainties related to detrital Th, the nominal U-series age probably cannot stand on its own. However, the age corresponds to Termination II, the beginning of Oxygen-Isotope Stage 5e, which is consistent with its location at the maximum pre-Holocene level of carbonate and aragonite content in the core. By analogy with the Holocene, high carbonate and aragonite contents are inferred to represent interglacial conditions (Dean et al., 2006). Thus the nominal age of 127.7 ± 3.9 ka may be close to the true age and is used here.

3.4. Amino acid (aspartic acid) age estimates

Ostracodes are well preserved in the upper half of core BL00-01. We determined the extent of amino acid racemization (AAR) in *Candona* spp. from 10 levels of the core. An average of eight subsamples, each comprising a single valve, were analyzed from each level. In addition, we analyzed 26 samples from piston cores BL96-1 and BL96-2, each sample comprising an average of 12 subsamples, and projected these results onto BL00-1 by correlating magnetic susceptibility. Ostracodes were prepared and analyzed according to procedures presented by Kaufman (2000). We focus on aspartic acid because of its relatively high rate of racemization in cold-water conditions and its abundance in ostracode valves. We used two independent approaches to interpret the extent of AAR in terms of sample age. The first approach relied on the kinetic model developed using laboratory heating experiments, which relates the extent of racemization to time and temperature (Kaufman, 2000). For this "uncalibrated" approach, we assumed an effective diagenetic temperature of 4 °C, which is reasonable for the bottom of deep lakes at temperate latitudes. The second approach relied on the rate of racemization determined for ostracodes analyzed from the Burmester core in the Great Salt Lake basin (Oviatt et al., 1999). This "calibrated" approach is based on the empirical parabolic relation between the extent of racemization in ostracodes whose ages were determined independently in the core. In addition, the effective diagenetic temperature for the Bonneville basin (averaged over the last 150 ka) has been estimated at 4.1 ± 1.3 °C (Kaufman, 2003), which suggests that AAR correlation between Bear Lake and Burmester is reasonable. The AAR age estimates derived from the two approaches generally overlap, although the "calibrated" ages tend to be older than the "uncalibrated" ages for samples between about 60 and 100 ka. This divergence probably reflects differences in the temperature histories between the sediment of the Burmester and Bear Lake cores.

3.5. Tephrochronology

Four regionally important tephras are recognized in the Bear Lake core. These tephras are the Arco-1 and Hebgen Narrows tephras of Izett (1981) and the Summer Lake JJ and NN tephras of Davis (1985). They were sampled at depths of 50.24, 77.00, 100.31, and 117.56 m below lake floor, respectively. The tephras were identified by major-element analyses of tephra glass shards and comparison of these analyses with those in the database of western US tephra maintained at the Department of Geology and Geophysics, University of Utah (Appendix A). None of the Bear Lake tephras, nor their correlatives from reference sections, have yet been dated directly by isotopic methods. However, we have estimated their ages based on linear interpolation and on the position of each tephra relative to dated horizons above and below the tephras at their reference localities. These interpolation ages (Appendix A) are based on published and unpublished information from core and surface sections near Arco, Idaho (S. Olig, URSCorp; pers. comm. 1997, 2004); Bonneville basin, Utah (Williams, 1994); Butte Valley, California (Sarna-Wojcicki et al., 2001); Summer Lake, Oregon (Davis, 1985; Sarna-Wojcicki et al., 2001); and Tulelake, California (Rieck et al., 1992). The interpolation ages and age control horizons for the tephras are given below. Errors are estimated at one sigma (Appendix A).

- Arco-1—75 ± 10 ka. Bracketed by a single luminescence age of 50 ka (no reported precision) for eolian sand above the type tephra and a pair of luminescence ages of 77 ± 8 and 87 ± 7 ka from eolian sand 30 cm below the tephra.
- Hebgen Narrows—146 ± 18 ka. Weighted average bracketed by the surface (20 ± 5 ka) and the Lava Creek B tephra (640 ± 2 ka, Lanphere et al., 2002) in the Burmester and S28 cores of the Bonneville basin.
- Summer Lake JJ—202 ± 20 ka. Weighted average bracketed by the Hebgen Narrows and Lava Creek B tephras in the Burmester core and surface (20 ± 5 ka) and Lava Creek B tephra in the Wendover core. This age is younger than the age of an Ar-Ar dated tephra correlated to one (GG) from higher in the Summer Lake section by Herrero–Bervera et al. (1994).
- Summer Lake NN—261 ± 19 ka. Bracketed by the Summer Lake JJ and the Dibekulewe tephras in the Ana River C section and core. The age of the Dibekulewe tephra is 617 ± 6 ka, based on a weighted average of upward extrapolations from underlying Lava Creek B and Brunhes/Matuyama paleomagnetic boundary.

As discussed below, these age estimates are in general agreement with other age estimates from the Bear Lake core. Thus, the validities of the tephra correlations are supported by both the compositional correlations and the age estimates.

3.6. Climatic correlations

Several long, previously published climate records can be correlated with the sediment record from Bear Lake. Of these, we focus on the Devils Hole Oxygen-isotope record (Ludwig et al., 1992; Winograd et al., 1992) for two reasons: (1) its upwind proximity, ca 700 km southwest of Bear Lake (Fig. 1), and (2) its high-quality independent dating. The Devils Hole Oxygen-isotope record is interpreted as a paleo-temperature record—specifically winter–spring temperatures in the Great Basin (Winograd et al., 1992). It may represent a more regional signal compared to the Marine Oxygen-isotope record (Herbert et al., 2001), but this is appropriate considering the setting of Bear Lake. We made similar correlations between the Bear Lake record and the marine Oxygen-isotope record (Martinson et al., 1987), but the effects on the final age model were negligible.

We identified specific climate-related events in the stable-isotope (Bright et al., this issue), carbonate content, and aragonite occurrence data from Bear Lake and correlated them to the Devils Hole Oxygen-isotope record (Ludwig et al., 1992; Winograd et al., 1992) (Fig. 3). We focused on the maxima and minima of the records rather than the stage boundaries because they are more easily defined. In the Bear Lake record, we refer to the ages of these events as climate-correlation ages. For convenience, we have labeled these events by their stage names in the marine Oxygen-isotope record (SPECMAP; Martinson et al., 1987), although the SPECMAP and Devils Hole time scales differ in the interval between 100 and 200 ka. We used one additional control point, that for the last glacial maximum (LGM), identified by a maximum in glacial flour inferred from magnetic properties (Rosenbaum, 2005). We assigned this maximum an age of 21 ka based on previously determined ages for the Pinedale glacial maximum dated in the Wind River Range (21–23 ka, summarized by Pierce, 2004). Uncertainties in the ages of the peaks of these events were estimated from the uncertainties in U-series ages for the correlative time in the Devils Hole record (Ludwig et al., 1992), and approximately doubled to account for uncertainty in correlation (Table 1).

Of the Bear Lake climate proxies, the interpretation of the carbonate data[1] is the most straightforward, and is supported by the stable-isotope data, which were analyzed at a coarser sample interval (Bright et al., this volume). The present interglaciation at Bear Lake is dominated by marl deposition in which the carbonate is predominantly

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[1] These critical data, generated by WED, are first presented here and in the companion paper by Bright et al. (this volume). The interpretation of high carbonate contents and aragonite occurrence as indications of Holocene-like interglacial conditions is from Dean et al. (2006).

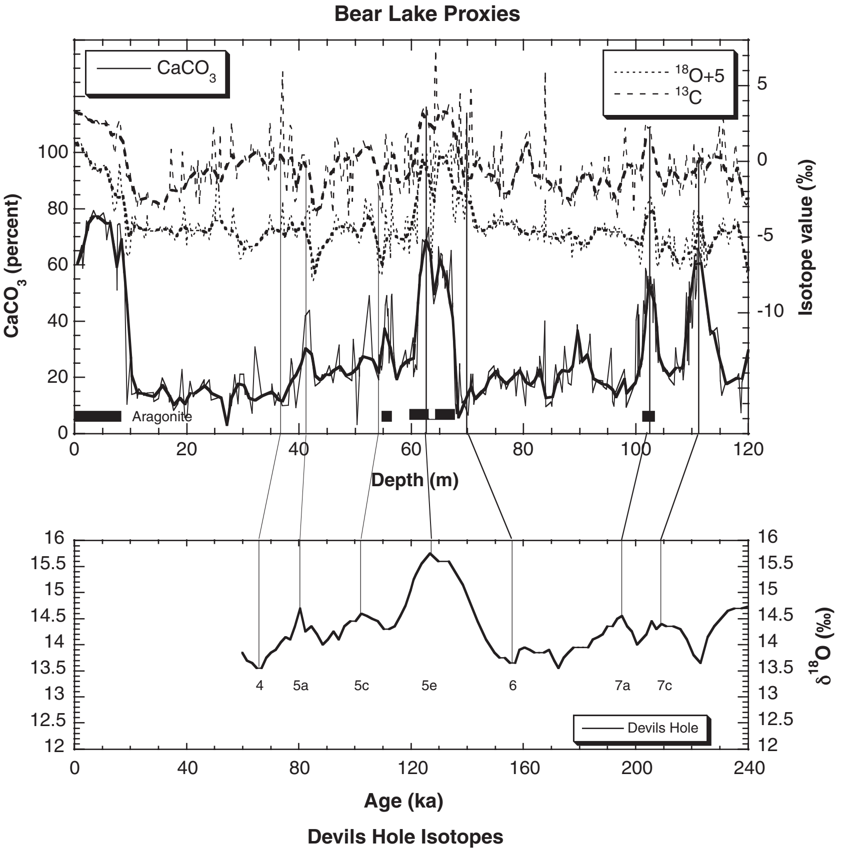

Fig. 3. Bear Lake stable isotope records (Bright et al., this volume), carbonate content, and aragonite occurrence, correlated to the Devils Hole Oxygen-isotope record (Winograd et al., 1992). For the Bear Lake data, light line represents all of the data and heavy line a 3% weighted smoothing; $^{18}O+5$ indicates that 5‰ were added to Oxygen Isotope values for scaling purposes. Labeled peaks in the Devils Hole data are the corresponding marine Oxygen-isotope stages. Vertical lines indicate correlations listed in Table 1.

Table 1
Climate events used for correlation between Bear Lake and Devils Hole

Climate event (Marine Oxygen-Isotope stage)	Depth (m) in BL00-1	Age (ka) in Devils Hole record	Uncertainty (ka)
2 (LGM)	10.8	—[a]	3
4	37.6	65.7	2
5a	41.7	80.2	2
5c	54.0	101.9	2
5e	62.9	126.4	2
6	70.0	155.9	4
7a	101.9	194.9	6
7c	111.4	208.8	8

[a] LGM based on glacial-flour maximum inferred from magnetic properties and assigned an age of 21 ± 3 ka.

aragonite. By analogy, we infer that previous intervals with high carbonate contents represent interglaciations. Aragonite is present in these high-carbonate intervals, but low-Mg calcite is the dominant mineral in some of the older intervals, probably derived from recrystallization of metastable aragonite. The ages inferred by correlation of the Bear Lake record with the Devils Hole climate record compare well with other age data (Fig. 4).

3.7. *Age model construction*

Age-depth functions can be fitted to sediment-chronology data in a variety of ways, ranging from simple linear interpolation between data points to complex least-squares fits of polynomial functions. However, with these methods, it is commonly difficult to deal with uncertainty, both in the fit process and in the age estimates themselves. Here, we construct smooth age models and confidence limits using newly developed statistical methods that weight data by their uncertainty and include the uncertainty introduced by the regression procedure (Birks and Heegaard, 2003; Heegaard et al., 2005). These methods use weighted, non-parametric regression in a framework of generalized additive models. Smooth functions are fitted to the data using multiple spline functions; the degree of smoothing is determined by the number of spline functions (K). The methods also produce confidence limits for the age model. We found that using a value for K equal to about half the number of control points yielded a good balance between smoothness and precision of fit. This balance follows the recommendation to use "the simplest parsimonious model," i.e., the "simplest statistically significant solution that uses the fewest terms in the model and the fewest numbers of degrees of freedom in the fitted smoother"

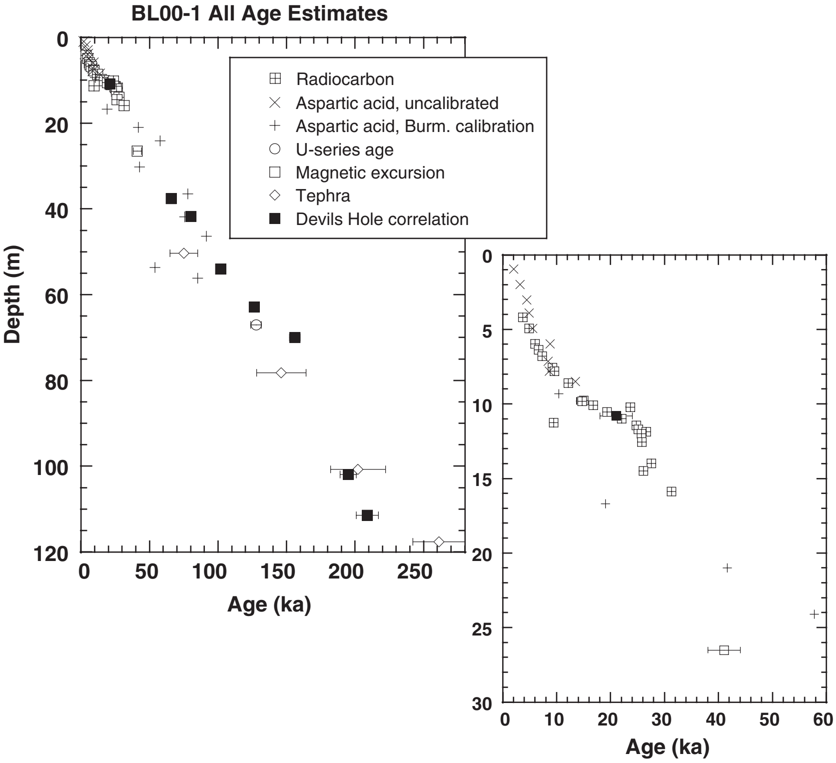

Fig. 4. All available age estimates for the Bear Lake drill core BL00-1. See text for explanation of individual methods.

(Birks and Heegaard, 2003). Although these methods were developed specifically for Holocene radiocarbon chronologies, they are equally applicable to longer-term records with other types of age control. Of necessity, these methods assume that the age estimates used for control are accurate within their stated uncertainties.

In our initial data set, we use only those data judged most reliable and independent. These data include the radiocarbon ages transferred from piston cores BL96-2 and BL96-3, the single magnetic-excursion correlation, and the single U-series age. As discussed earlier, we judge the U-series age and the age derived from the magnetic excursion to be reliable, but only with additional consideration of their position with respect to zones thought to represent Holocene-like interglaciations. Data omitted from this initial set are the amino acid and tephra age estimates and the climate correlations.

Given other age control for the core, along with the relatively large uncertainties associated with the independent tephra ages, the ages of the tephras are likely to be better defined from the Bear Lake age model than from their independent estimates. Thus, to avoid circularity, the tephra ages were not used in the construction of the age model.

Independent amino acid ages from piston cores BL96-2 and BL96-3 are compatible with radiocarbon ages from these cores (Colman et al., 2005) and are shown in Fig. 4, transferred to BL00-1 in the same way as the radiocarbon ages. For the Holocene samples, the amino acid age estimates derived from both the "calibrated" and "uncalibrated" approaches overlap with the radiocarbon ages transferred by correlation of magnetic susceptibility profiles. For older samples taken directly from BL00-1, amino acid age estimates also generally overlap with ages from other techniques, but exhibit considerable scatter. Because of the scatter in the older ages, and because the amino acid ages from cores BL96-2 and BL96-3 overlap with the radiocarbon ages for the Holocene section, the amino acid data were not used in constructing the age models.

Although our goal was to create an age model independent of direct climate correlations, it was not possible to do so because the initial data set contained ages only for the upper half of the core. We therefore combined the initial data set with the set of climate correlations to the Devils Hole record, discussed earlier. The age model (Fig. 5) was then constructed from this combined data set using the statistical methods described earlier (Birks and Heegaard, 2003; Heegaard et al., 2005). This age model is our best estimate of the true age–depth relationships for drill core BL00-1. This age model can serve a variety of uses (see Discussion section), but because it is not independent of climate correlations, detailed climate history questions, such as geographical differences and phase relationships, cannot be validly addressed using this model.

4. Discussion

Our analyses suggest that the Bear Lake drill cores contain a continuous sedimentary record that extends to

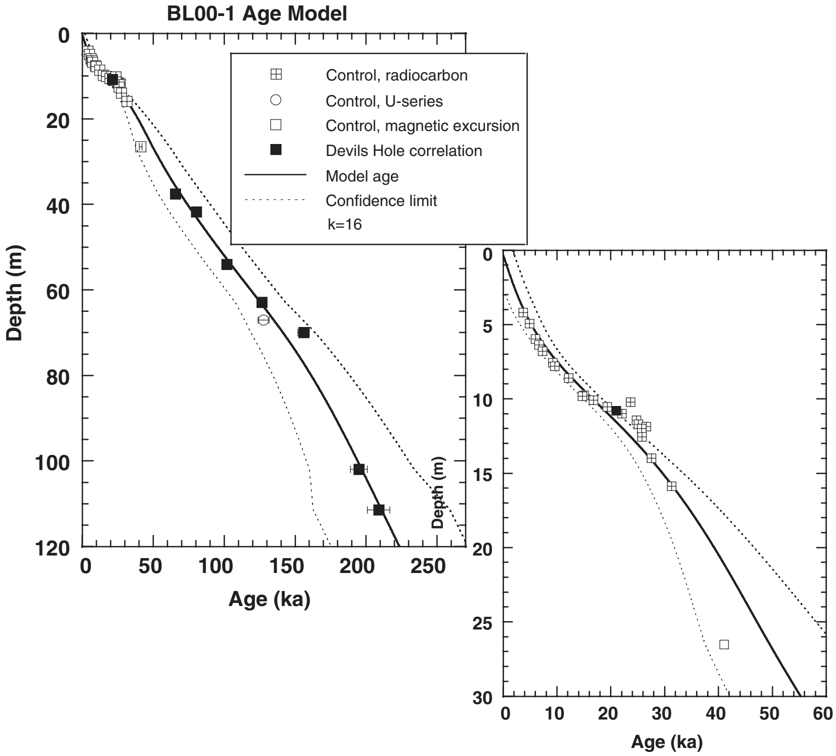

Fig. 5. The age model and 95% confidence limits for core BL00-1, constructed using the methods discussed in the text. The age model was constructed using the radiocarbon, magnetic excursion, and Uranium-series age estimates, as well as the climate correlations from Fig. 3. *K* is the number of spline functions used in the fit, which controls the degree of smoothness (see text).

about 225 ka, covering most of the last two glacial–interglacial cycles. As such, it joins a relatively short list of well-studied, continuous records of this length from North America. In addition to Devils Hole, others include Owens Lake (Smith et al., 1997), Searles Lake (Smith et al., 1983), near Tulelake (Rieck et al., 1992), Summer Lake (Negrini et al., 2000), and, to a lesser extent, Great Salt Lake (Kowalewska and Cohen, 1998; Balch et al., 2005). Unlike many of the other long lake records from the continent, the sediments from Bear Lake contain no recognized gap in deposition. The Bear Lake age model is intended to be the backbone of ongoing paleoenvironmental reconstructions using a variety of geochemical and biological proxies.

One example of the application of our age model relates to the age of the volcanic tephras found in core BL00-1. Although these tephras have independently estimated ages (Fig. 4), those age estimates have relatively large uncertainties and are based on an assumption of linear sedimentation rates and stratigraphic position in their type and reference sections. Using our age model, we derive the following age estimates for the tephras (Table 2).

The age model also can be used to define a long-term record of sediment-accumulation rates in the lake, in terms of both thickness and mass (Fig. 6). The overall pattern of sediment accumulation is similar regardless of whether sedimentation is calculated as thickness or mass. Compaction of the sediment appears to be significant only in the uppermost few meters.

Table 2
Age estimates for tephras estimated from independent and from the BL00-1 age model

Tephra	Depth (m)	Age ± confidence intervals (ka)[a]	
		Independent estimate	Bear Lake age model
Arco-1	50.24	75 ± 10	96.1 ± 8.6
Hebgen Narrows	77.0	146 ± 18	155.7 ± 13.2
Summer L.—JJ	100.31	202 ± 20	194.4 ± 18.5
Summer L.—NN	117.56	261 ± 19	219.9 ± 24.6

[a] See text for independent age estimates; confidence intervals are one sigma for independent age estimates and 95% for Bear Lake age model.

No obvious relation to large-scale climate fluctuations is apparent in the Bear Lake sediment-accumulation data. In fact, some of the relations are surprising at first glance. For example, Holocene sediment accumulation rates are higher than latest Pleistocene rates, presumably due to the precipitation of authigenic carbonate (Dean et al., 2006). The single most prominent feature in the accumulation-rate record is a peak in sediment accumulation centered on about 40–50 ka (Fig. 6). Prior to that time, sediment accumulation rates show less variation, with modestly high mass accumulation rates centered on about 100 and 180 ka.

Sediment accumulation rates in Bear Lake have been influenced by a variety of factors other than the direct

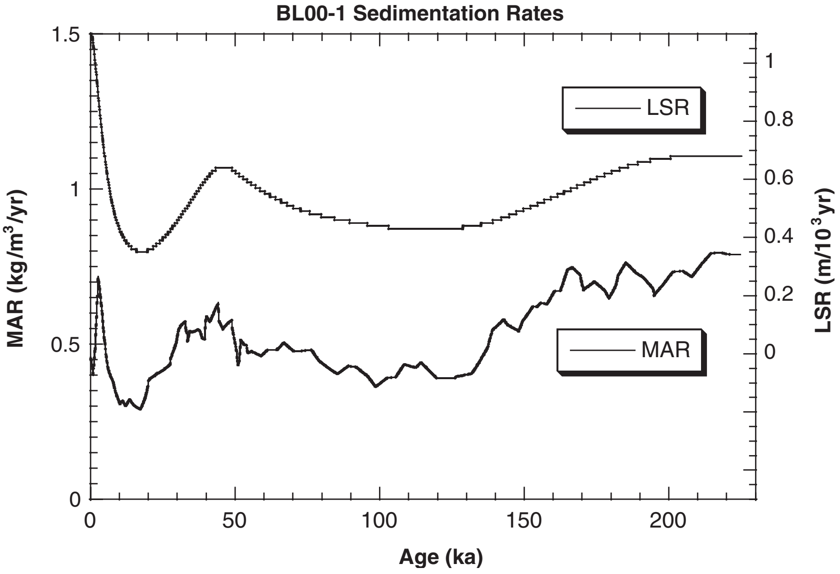

Fig. 6. Sedimentation rates for BL00-1 calculated from the age model (Fig. 5). Sediment accumulation rates are expressed as both linear sedimentation rates (LSR, m/10^3 yr) and mass accumulation rates (MAR, g/cm^2/yr). The latter were calculated using measured dry bulk densities in the cores.

effects of climate. Climate indirectly affects sedimentation by inducing carbonate precipitation, which is added to detrital accumulation, during warm intervals (Dean et al., 2006). In addition, the Bear River, which heads in the glaciated Uinta Range, appears to have alternated between episodically flowing into Bear Lake and by-passing it (Dean et al., 2002; Laabs and Kaufman, 2003). This alternation probably was controlled primarily by the level of Bear Lake. Whether the Bear River enters Bear Lake impacts both the clastic sediment load to the lake as well as the lake geochemistry, which in turn affects the rate of endogenic carbonate production. Finally, in a tectonically active basin such as that of Bear Lake, changes in the rate of subsidence of the basin or the rate of displacement on the east-side master fault of the half graben potentially could affect sediment accumulation rates.

5. Conclusions

Assembling our most reliable data from piston and drill cores suggests that the Bear Lake sedimentary record is continuous to at least 130 ka, and by extrapolation, to about 225 ka. These data include radiocarbon ages, one magnetic excursion (correlated to a standard sequence), and a single U-series age. Some of the data are not entirely independent of climate inferences, however, because in order to judge the reliability of the magnetic-excursion and U-series ages, we had to consider the location of these data with respect to high-carbonate, Holocene-like interglacial intervals. We did not use amino acid age estimates (which have a large amount of scatter) or tephra correlations (which have large age uncertainties) in our initial data set. Independent ages comprising the initial data set are available for only the upper half of the core.

Paleoclimate proxy data, including carbonate content, mineralogy, and stable-isotope composition, suggest that Bear Lake sediments responded to major glacial–interglacial events. Comparisons of the climate-proxy data with other independently dated paleoclimate records (i.e., Devils Hole), along with the assumption that peak climate conditions occurred simultaneously at Devils Hole and Bear Lake, allow basic correlations that provide additional age estimates for the Bear Lake core. Using a combination of our independent ages and the correlations with Devils Hole, we developed an age model for the BL00-1 core using statistical methods that consider both the uncertainties of the original data and that of the curve-fitting process. This age model represents our best estimate of the chronology of deposition in Bear Lake.

Our age model can be used in a variety of ways, but the model must be applied to paleoclimate questions with care, because it contains prior assumptions about climatic correlations. The age model provides new age estimates for the four tephras in the Bear Lake cores with uncertainties less than those associated with previous estimates. Finally, the age model yields a record of sediment-accumulation rates in the lake for the past ca. 250 ka, which are complex. Evidently, deposition has been affected by both the direct and indirect influences of climate and by active tectonics and drainage changes.

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Appendix A. Tephrochronologic data and methods

A total of 13–22 glass shards were analyzed for each of the Bear Lake tephra samples on a Cameca SX50 electron microprobe. Correlation of the Bear Lake tephras follows methods described by (Perkins et al., 1995, 1998). The analyses of the Bear Lake core tephras and other relevant tephras are listed in Table A.1.

Comparison of tephras is based on "statistical distance" between a sample pair, essentially a chi-square test. The basic calculation of statistical distance is:

$$D^2 = S[(C_{1i} - C_{2i})^2/(2_{\underline{s}i}^2)], \qquad (1)$$

where C_{1i} and C_{2i} are measured concentrations for the ith element in samples 1 and 2, , and s_i^2 is the variance for the mean of a typical 20 shard analysis on the University of Utah's Cameca SX50 electron microprobe. If the number of analyzed shards varies significantly from standard 20-shard analysis the following expression for variance is used:

$$s_1^2 = (20/n_1 + 20/n_2)\underline{s}_i^2, \qquad (2)$$

where n_1 is the number of analyses in sample 1 and n_2 the number for sample 2. If n_1 and n_2 are both 20 then variance reduces to the form $2s_i^2$ used in [1]. For comparing compositionally similar samples the elements Ti, Fe, Mn, Mg, Ca, and Cl are most useful in highlighting potential compositional differences between two such samples and *D* values listed in Table A.1 are based on these six elements. Ideally, we anticipate $D < \mathrm{v}C^2(0.05,\ 6) = \mathrm{v}12.59 = 3.55$, where $C^2()$ is the Chi-square distribution. So with $D < {\sim}3.6$

Table A.1
Analyses of glass shards

Tephra/Sample	*n*[a]	Si	Ti	Al	Fe[g]	Mn	Mg	Ca	Ba	K	Na	Cl	F	O	−O	H_2O	Total	D_0	D_1
Arco-1		[.570][b]	[.007]	[.058]	[.013]	[.004]	[.003]	[.020]	[.006]	[.084]	[.100]	[.004]	[.040]	–	–	–	–	–	–
F95-IM4	25	34.23	.154	7.15	1.25	.044	.189	1.049	.014	2.06	2.78	.164	.071	51.95	0.07	4.57	101.60	–	1.3
BL-1E-18E-1	19	33.82	.155	7.07	1.23	.043	.185	1.081	.022	2.05	3.05	.161	.088	51.28	0.07	4.34	100.72	2.5	1.3
Avg	44	34.02	.154	7.11	1.24	.043	.187	1.065	.018	2.05	2.92	.163	.079	51.62	0.07	4.45	101.16	–	0
tco92-24[c]	18	33.57	.073	7.02	1.19	.038	.139	1.002	.031	2.16	1.87	.095	.004	52.69	0.02	6.83	100.65	26.0	36.0
Heben Narrows		[.574]	[.006]	[.054]	[.012]	[.003]	[.001]	[.011]	[.005]	[.104]	[.094]	[.003]	[.060]	–	–	–	–	–	–
hn92-01	31	34.78	.085	6.13	0.97	.028	.028	.330	.010	4.33	2.24	.101	.161	50.48	0.09	3.59	100.08	–	2.2
BL-1E-28E-2	22	34.58	.086	6.16	1.00	.022	.029	.331	.008	4.26	2.24	.109	.205	51.31	0.11	4.80	100.87	3.8	2.1
Bur-50.6	23	34.87	.087	6.16	1.02	.033	.029	.341	.003	4.35	2.25	.109	.207	50.20	0.11	3.11	100.00	5.0	3.2
s28-112.9	22	34.45	.088	6.08	0.97	.027	.027	.332	.010	4.27	2.23	.105	.094	50.85	0.06	4.48	100.04	1.5	1.8
Avg	98	34.67	.087	6.13	0.99	.028	.028	.333	.008	4.30	2.24	.106	.167	50.71	0.09	3.99	100.24	–	0
brg 630[d]	21	34.77	.083	6.11	0.97	.020	.034	.320	.009	4.44	2.21	.103	.255	51.37	0.13	4.67	101.21	4.9	5.1
Summer Lake JJ		[.561]	[.006]	[.058]	[.014]	[.004]	[.002]	[.016]	[.011]	[.089]	[.104]	[.004]	[.055]	–	–	–	–	–	–
Sml01-1149	19	33.20	.113	7.14	1.62	.057	.096	.704	.046	2.61	3.14	.135	.133	51.67	0.09	5.42	101.26	–	1.0
BL-1E-38E-2	19	33.31	.106	7.34	1.65	.053	.091	.689	.068	2.52	3.37	.135	.119	51.04	0.08	4.30	100.96	3.2	2.5
Bur-76.10	25	33.51	.119	7.29	1.60	.054	.096	.709	.051	2.54	3.35	.135	.110	50.15	0.08	3.09	100.06	1.8	2.0
Avg	43	33.34	.113	7.25	1.62	.055	.094	.701	.055	2.56	3.29	.135	.121	50.95	0.08	4.27	100.76	–	0
del94-725[e]	23	33.86	.090	7.41	1.61	.042	.054	.746	.036	3.00	2.47	.050	.182	51.44	0.09	4.26	101.47	29.7	29.2
Summer Lake NN		[.551]	[.006]	[.060]	[.025]	[.004]	[.005]	[.024]	[.001]	[.087]	[.105]	[.003]	[.061]	–	–	–	–	–	–
Sml01-1148	18	31.99	.388	7.68	2.74	.077	.407	1.641	.000	2.36	3.19	.091	.163	49.98	0.09	3.17	101.06	–	2.3
BL-1E-46E-1	13	31.45	.373	7.69	2.82	.072	.405	1.600	.002	2.37	3.21	.091	.135	49.95	0.08	3.79	100.59	4.6	2.3
Avg	31	31.72	.380	7.69	2.78	.075	.406	1.620	.001	2.37	3.20	.091	.149	49.96	0.08	3.48	100.82	–	0
tco92-26[f]	5	31.47	.329	7.41	2.86	.072	.353	1.632	.059	2.13	2.27	.134	.004	50.47	0.03	5.03	99.75	20.9	19.9

[Data include: (1) an analysis of the "type" tephra from the database of western US tephras maintained at the Department of Geology and Geophysics, University of Utah: (2) an analysis of the correlative sample in the Bear Lake core; (3) if available, analyses of other correlative tephras in the database; (4) an average analysis of all correlative samples for each tephra layer; and (5), an analysis of a sample of a non-correlative tephra that is closest in composition to the average of the correlative tephra].

[a] Number of analyzed shards.

[b] Values in brackets are estimates of analytical precision (1 s) for each tephra based on model of analytical variance for the Univ. of Utah Cameca SX50 microprobe. Model is of the form $s^2 = aC^b + s_d^2$ for each element. C is the concentration, a and b are empirically estimated constants, and s_d^2 is the variance of run to run drift for the element. For some elements, such as Fe, analytical precision is dominated by this run to run drift. Values shown are for the 1 s variation of the average of a 20 shard analysis.

[c] 15 Ma tephra from southeastern Oregon.

[d] 340 ka tephra sampled in cuttings of Amoco Bridge well, Great Salt Lake, Utah. See Davis and Moutoux (1998).

[e] Late Oligocene to early Miocene tephra in the Valley Springs Fm. of the Sierra Nevada Foothills, California.

[f] 15 Ma tephra from southeastern Oregon.

[g] Calculated on basis of stoichiometry with Fe as Fe^2O^3.

the composition of the two samples are statistically identical at the 95% confidence level

Two measurements of D, D_0 and D_1, are important and are listed in Table A.1. D_0 is for the comparison of the type sample, the first sample in each tephra group in Table A.1, with the other samples in the group. D_1 is for the comparison of all samples in the group with the average of the correlative samples in the group. For all four tephras the two basic requirements for a convincing compositional correlation (Perkins et al., 1998) are met: (1) the composition of the correlative tephras are all statistically identical at the 95% confidence level; and (2) the correlative tephras are compositionally distinct from the non-correlative tephra that is closest in composition, as measured by **D**, to the correlative tephra.

Tephra ages for sections other than Bear Lake were estimated by linear interpolation. Assuming sediment accumulation is a linear stochastic process errors are estimated by

$$\sigma_t^2 = \sigma_{t_1}^2[(1-c)^2+\sigma_c^2]+\sigma_t^2 = \sigma_{t2}^2[c^2+\sigma_c^2]+\sigma_c^2(t_1-t_2)^2,$$

$$\sigma_c^2 \approx s^2\frac{|c||1-c|}{(t_1-t_2)},$$

where t_1 and t_2 are the age of the lower and upper control horizons used in interpolation/extrapolation age estimate; s_{t1} and s_{t2} are the 1s errors for these ages; $c=(z-z_1)/(z_2-z_1)$ where z is the stratigraphic position of the tephra and z_1 and z_2 are the stratigraphic positions of the lower and upper control horizons, respectively; s_c is deviation of c from values expected for a strictly linear sedimentation rate. $s^2\approx 6.25$ is the average measured value for the cores/sections used in this study with time in units of ka.

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