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# *A 19,000-year record of hydrologic and climatic change inferred from diatoms from Bear Lake, Utah and Idaho*

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## ABSTRACT

**Changes in diatom fossil assemblages from lake sediment cores indicate variations in hydrologic and climatic conditions at Bear Lake (Utah-Idaho) during the late glacial and Holocene. From 19.1 to 13.8 cal ka there is an absence of well-preserved diatoms because prolonged ice cover and increased turbidity from glacier-fed Bear River reduced light and limited diatom growth. The first well-preserved diatoms appear at 13.8 cal ka. Results of principal components analysis (PCA) of the fossil diatom assemblages from 13.8 cal ka to the present track changes related to fluctuations of river inputs and variations of lake levels. Diatom abundance data indicate that the hydrologic balance between 13.8 and 7.6 cal ka is strongly tied to river inputs, whereas after 7.6 cal ka the hydrologic balance is more influenced by changes in lake evaporation. Wet conditions maintained high river inputs from 13.8 to 10.8 cal ka and from 9.2 to 7.6 cal ka, with a dry interval between 10.8 and 9.2 cal ka. After 9.2 cal ka until 2.9 cal ka lake levels were high except for two periods, one between 7.6 and 5.8 cal ka and one between 4.3 and 3.8 cal ka, as a result of decreased effective moisture. After 2.9 cal ka, fossil diatom assemblages suggest drier conditions until 1.6 cal ka to the present, when fragments of large, pennate diatoms appear, possibly the result of a rapid lake transgression. Although similarities exist between the Bear Lake records and other western hydrologic and climatic records, the covariations are not strong. Our data suggest that climatic regimes at Bear Lake have changed frequently over time, perhaps as a consequence of the position of several important climatic boundaries near Bear Lake.**

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## INTRODUCTION

Bear Lake is located on the border between Utah and Idaho, close to the eastern edge of Utah (Fig. 1). The lake is situated beneath the present-day mean winter position of the polar front and is just northwest of the region most strongly influenced by monsoonal precipitation (Mock, 1996; Adams and Comrie, 1997). As a result of its location, Bear Lake receives maximum precipitation during January and May (WRCC, 2007). The January peak results from Pacific airstreams flowing through the low-elevation gap of the Snake River Plain (Bryson and Hare, 1974), whereas the peak in May is due to meridional troughs and cutoff lows, which can draw moisture from the Gulf of Mexico and produce upslope precipitation (Hirschboeck, 1991). Owing to its position, Bear Lake is sensitive to climatic change, and small shifts in the atmospheric boundaries may result in significant changes to the hydrologic balance of Bear Lake. Tectonics, stream diversions, and changes in groundwater input could also affect the Bear Lake hydrologic balance.

Bear Lake, which is 32 km long and 6–13 km wide with an area of 280 km$^2$, contains sediments extending back hundreds of thousands and perhaps millions of years (Dean et al., 2006). The lake lies in a tectonically active half-graben underlain by Paleozoic and Mesozoic sedimentary rocks that include limestones, dolostones, shales, sandstones, and quartzites (Davidson, 1969). The maximum depth is 63 m, and the mean depth is 28 m (Birdsey, 1989). When full, the surface elevation is 1805 m above sea level (asl), but lake levels may have been as much as 11 m higher at times during the late Pleistocene (Laabs and Kaufman, 2003). Historically, Bear River bypassed the lake until it was diverted into the lake between 1911 and 1918, thereby transforming Bear Lake into a reservoir (Birdsey, 1989). The diversion increased the ratio of watershed area to lake area from 4.8 to 29.5 (Wurtsbaugh and Luecke, 1997). Prior to diversion, the lake was often topographically closed, overflowing intermittently. Since diversion, lake level has fluctuated, with minima in 1935 and 2004 ~5.5 m below full.

Bear Lake is an alkaline (pH = 8.4–8.6), oligotrophic system (Table 1; Birdsey, 1989; Wurtsbaugh and Hawkins, 1990). Although


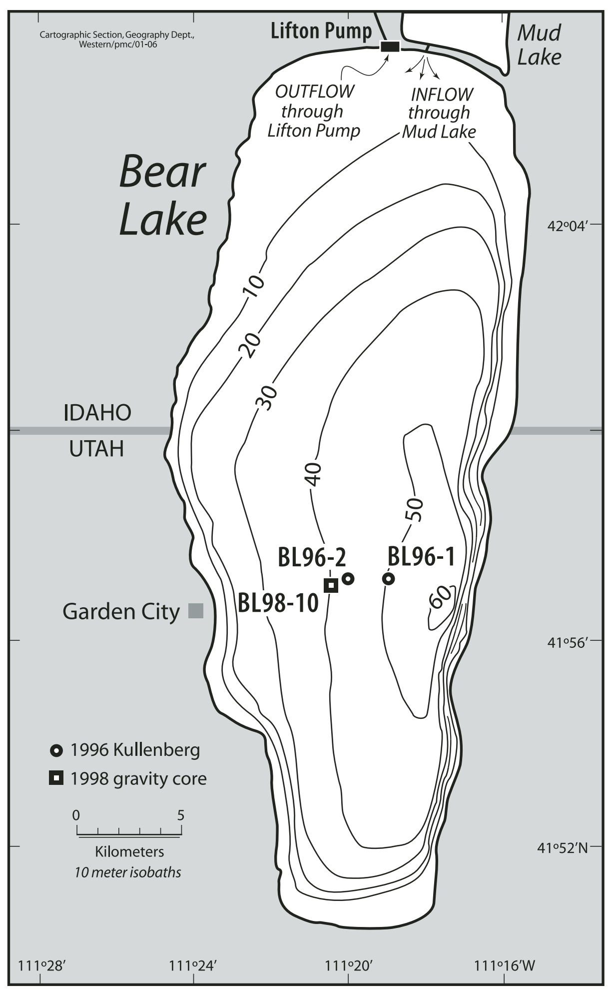


Figure 1. Location and bathymetry of Bear Lake. Kullenberg coring sites, BL96-1 and BL96-2, are depicted by open circles; gravity core site BL98-10 is shown by an open square. Today Bear River is diverted through Mud Lake at the north end of Bear Lake. Numerous small streams and springs flow into Bear Lake, but are not shown here. Water can be diverted out of Bear Lake through a series of canals at the north end of the lake.

TABLE 1. LIMNOLOGICAL VARIABLES OF BEAR LAKE PRE- AND POST-DIVERSION

| Limnological variable | 1912[a] | 1979[b] | 1980s | 1997–1998[g] |
|---|---|---|---|---|
| pH | N/A | 8.3–9.0[c] | 7.4–9.1[d] | 7.9–8.5 |
| Total alkalinity (mg $L^{-1}$) | 586 | 265 | 194–267[d] | N/A |
| Ca (mg $L^{-1}$) | 4.1 | 69 | 25–76[e] | N/A |
| Mg (mg $L^{-1}$) | 152 | 41 | 28–52[e] | N/A |
| Na (mg $L^{-1}$) | 66.3 | 39 | N/A | N/A |
| K (mg $L^{-1}$) | 10.5 | 3 | N/A | N/A |
| Cl (mg $L^{-1}$) | 78.5 | 46 | N/A | N/A |
| $SO_4$ (mg $L^{-1}$) | 96.8 | 16 | N/A | N/A |
| Secchi depth (m) | N/A | N/A | ~5[d] | 4.1–11.2 |
| Chlorophyll a (µg $L^{-1}$) | N/A | 0.25 | 0.25[d] | 0.60 |
| Total nitrogen (mg $L^{-1}$) | N/A | N/A | 0.25–1.1[f] | 0.25 |
| Total phosphorus (µg/$L^{-1}$) | N/A | N/A | <20, except in spring[d] | Max. = 14–25 |
| Total organic carbon | N/A | N/A | 4[f] | N/A |

*Note:* Data from Birdsey, 1989.
[a]Kemmerer et al.,1923;
[b]Werner, 1982;
[c]Lamarra et al., 1979;
[d]BLRC, 1986;
[e]Birdsey, 1982;
[f]Birdsey, 1985;
[g]Ecosystems Research Institute, 1998.

the lake does not freeze every year, it is dimictic (Wurtsbaugh and Hawkins, 1990). A deep chlorophyll maximum (20–30 m) can occur during the summer months (Birdsey, 1989). The diversion of Bear River into Bear Lake ca. 1912 markedly changed the chemistry of Bear Lake, increasing nutrient loading and decreasing alkalinity (Table 1; Birdsey, 1989; Dean et al., 2007).

Diatoms, single-celled algae that are characterized by cell walls composed of opaline silica, commonly record climatic (e.g., Smol and Cumming, 2000) and hydrologic (e.g., Wolin and Duthie, 1999) change. Diatoms have frequently been used to determine changes in lake level (Wolin and Duthie, 1999). For example, variations in lake depth result in changes in the relative areas of pelagic and littoral zones, and thus the ratio of planktic to benthic diatoms. It is, therefore, possible to infer past lake levels from the relative proportion of planktic to benthic diatoms (e.g., Bradbury, 1997). Lake-water salinity in closed basin lakes is also strongly linked to effective moisture (Fritz et al., 1991, 1999). In closed-basin lakes, decreases in effective moisture lead to ionic concentration (salinity), which results in changes in diatom community composition (Fritz et al., 1993, 1999). Diatoms have also been used to track changes in fluvial inputs (Ludlam et al., 1996).

In this research we use diatom fossil assemblages to interpret a 19,000-year record of environmental change. This record is compared with other paleolimnological evidence from Bear Lake in order to determine hydrologic and climatic change.

## METHODS

Diatom analyses were performed on three cores, BL96-1, BL96-2, and BL98-10, which are respectively 5.00, 3.92, and 0.36 m long (Rosenbaum and Kaufman, this volume). Radiocarbon dating indicates that BL96-1 and BL96-2 span the past 7.6 and 19.1 cal ka, respectively (Colman et al., this volume), and $^{210}$Pb dating indicates that BL98-10 spans the past few hundred years (Smoak and Swarzenski, 2004). The same cores that were used in Dean et al. (2006) are used in this manuscript; however, an improved chronological model is applied (Colman et al., this volume). In order to compare the data presented in Dean et al. (2006) with the data presented here, some of the data from the Dean et al. (2006) paper were re-plotted here using the new age model.

Preparation and analysis of 50 samples from BL96-1, 39 samples from BL96-2, and 11 samples from BL98-10 were made using standard procedures (Battarbee et al., 2001). First, a 10% HCl solution was used to remove carbonate minerals. After two or three washes of the slurry with deionized water, a mixture of concentrated nitric and sulfuric acid was applied to remove organic material. Residual acids were removed with a series of deionized water washes. Coverslips were prepared by evaporating a small aliquot of the resulting slurries, and were attached to glass slides using Naphrax® (refractive index > 1.74). Approximately 600 diatoms were identified and enumerated on each slide. Identification was done using oil immersion at 1000× on a Nikon Eclipse E600 microscope equipped with differential interface contrast optics. Diatom taxonomy was based mainly on Krammer and Lange-Bertalot (1986–1991) and Cummings et al. (1995).

A computer program for canonical community ordination (CANOCO; ter Braak and Šmilauer, 1999) was used to perform principal components analysis (PCA) to explore relationships among diatom taxa, and to compare diatom community composition changes with other paleolimnological proxies. For our analyses of the diatom data, we included only diatom taxa that occurred in at least two samples as well as in one sample in abundances greater than 1% (Table 2 lists these taxa and provides authority names).

TABLE 2. SPECIES NAMES AND CODES

| Species Number | Species | Authority |
|---|---|---|
| 1 | *Pseudostaurosira brevistriata* (total) | (Grunow in Van Heurck) D.M. Williams and Round |
| 2 | *P. brevistriata* | (Grunow in Van Heurck) D.M. Williams and Round |
| 3 | *P. brevistriata*/rhomboid | |
| 4 | *P. brevistriata*/oval | |
| 5 | *Staurosira elliptica* | (Schumann) D.M. Williams and Round |
| 6 | *Staurosirella pinnata* | (Ehrenberg) D.M. Williams and Round |
| 7 | *S. pinnata* var. *accumunata* | (A. Mayer) Regenbogen D.M. Williams and Round |
| 8 | *Staurosira construens* | (Ehrenberg) Grunow D.M. Williams and Round |
| 9 | *Staurosirella leptostauron* | (Ehrenberg) Hustedt D.M. Williams and Round |
| 10 | *Nitzschia fonticola* | Grunow |
| 11 | *N. gracilis* | Hantzsch |
| 12 | *N.* sp. | |
| 13 | *Achnanthes curtissima* | Carter |
| 14 | *A. lanceolata* | (Brébisson) Grunow |
| 15 | *A. saccula* | Carter |
| 16 | *Navicula rhyncocephala* | Kützing |
| 17 | *N. pupula* | Kützing |
| 18 | *N. capitata* var. *lueneburgensis* | (Grunow) Patrick |
| 19 | *N. oblonga* | Kützing |
| 20 | *N. tuscula* | (Ehrenberg) Grunow |
| 21 | *N. cryptotenella* | Lange-Bertalot |
| 22 | *N.* sp. | |
| 23 | *Stephanodiscus minutulus* | (Kützing) Cleve and Moller |
| 24 | *S. niagarae* | Ehrenberg |
| 25 | *S. medius* | Håkansson |
| 26 | *Cyclotella michiganiana* | Skvortzow |
| 27 | *C. rossii* | Håkansson |
| 28 | *C. meneghiniana* | Kützing |
| 29 | *C.* sp. | |
| 30 | *C. bodanica var. affinis* | (Grunow) Cleve-Euler |
| 31 | *C. ocellata* | Pantocsek |
| 32 | *Diploneis elliptica* | (Kützing) Cleve |
| 33 | *Cocconeis placentula* var. *lineata* | (Ehrenberg) Van Heurck |
| 34 | *Diatoma tenue* var. *elongatum* | Lyngbye |
| 35 | *Caloneis* sp. Bear Lake | |
| 36 | *C. schumanniana* | (Grunow) Cleve |
| 37 | *Amphora pediculus* | (Kützing) Grunow |
| 38 | *A. inariensis* | Krammer |
| 39 | *A. libyca* | Ehrenberg |
| 40 | *A. ovalis* | (Kützing) Kützing |
| 41 | *Cymbella mesiana* | Cholnoky |
| 42 | *C. aspera* | (Ehrenberg) Cleve |
| 43 | *Surirella minuta* | Brébisson in Kützing |
| 44 | *Surirella ovalis* | Brébisson |
| 45 | *Pinnularia viridis* | (Nitzsch) Ehrenberg |

## RESULTS

### Diatom Stratigraphy

The cored section was divided into five zones by visual inspection of the diatom stratigraphies (Figs. 2–4). Core BL96-2 includes zones 1, 2, 3, and 4, which were further divided into subzones 1a, 1b, 2a, 2b, 2c, 3a, 3b, and 3c. BL96-1 comprises zones 3 and 4, and BL98-10 contains zones 4 and 5. Diatom zone and subzone boundaries are sometimes coincident with the lithologic unit boundaries described by Dean et al. (2006) and Dean (this volume) (Figs. 2 and 3). The boundary between diatom zones 1a and 1b is roughly coincident with the boundary between lithologic unit 1, a red calcareous silty clay, and unit 2, a transitional red marl; the boundary between diatom zones 2a and 2b is approximately correlative with the boundary between unit 3, a green marl, and unit 4, a tan marl; the boundary between diatom zones 2c and 3a is coincident with the boundary between unit 5, a gray marl, and unit 6, a tan marl. Diatom zones 3 and 4, and therefore all of core BL96-1, are composed only of lithologic unit 6.

Comparison of results from cores BL96-1 and BL96-2 indicates good agreement (i.e., within 100 yr) in the ages of the onset of subzone 3b (Table 3). For more recent zone boundaries, however, there are greater differences in the ages between the two cores. The discrepancies are ~300 yr and 500 yr for the onset of zones 3c and 4, respectively. Also, distinct spikes in *Navicula oblonga*, which probably record the same event, occur at 1.9 cal ka and 1.6 cal ka in core BL96-2 and BL96-1, respectively. These discrepancies may be due to errors in the age models caused by small, unrecognized unconformities in the cored sections (Smoot and Rosenbaum, this volume). For the discussion below, ages of correlative boundaries in BL96-1 and BL96-2 have been averaged. The age of the boundary between zones 4 and 5, recorded

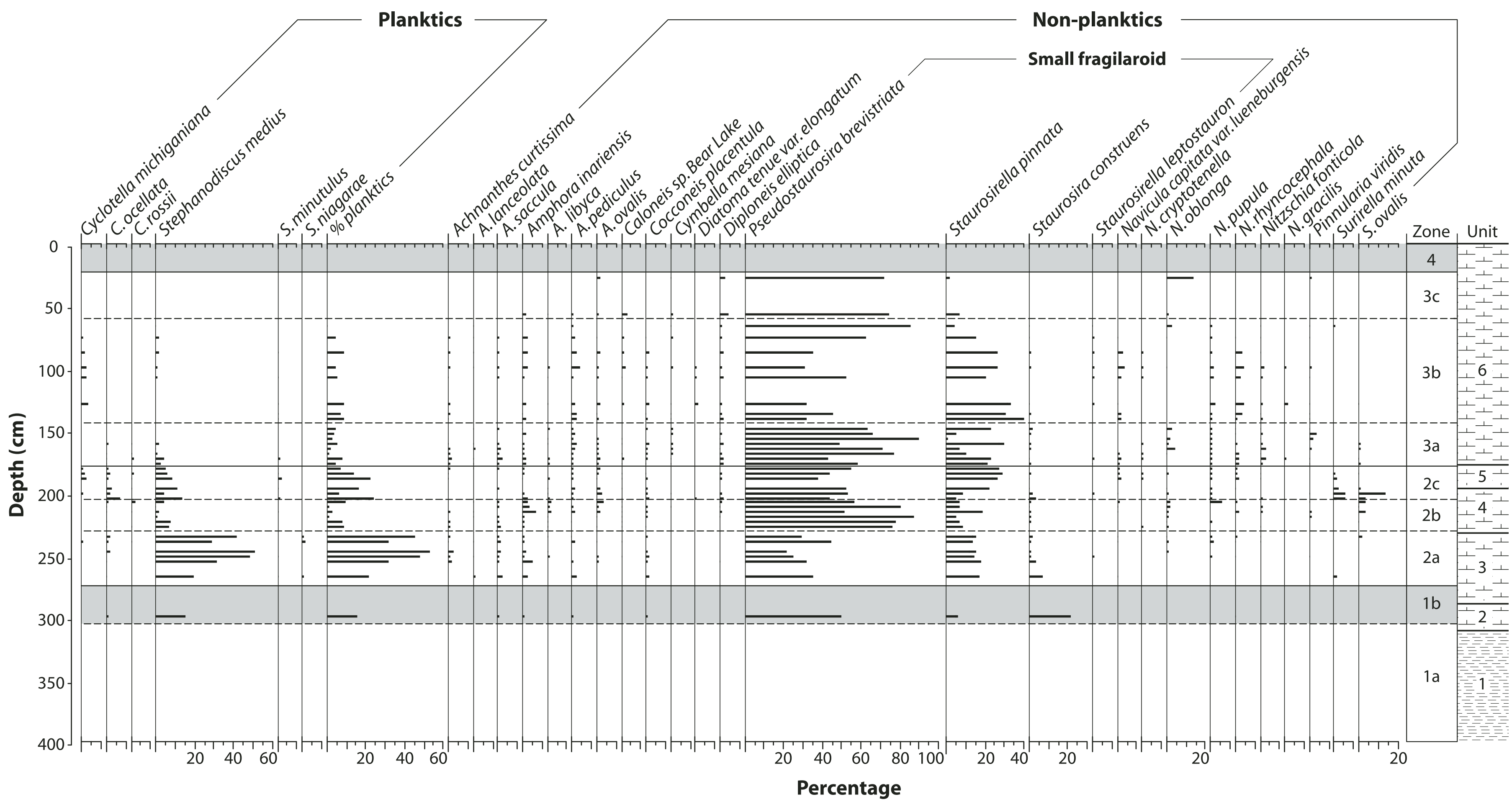


Figure 2. Diatom stratigraphy of BL96-2. Core BL96-2 extends to 19.1 cal ka and includes only the main diatom taxa. Zones depicted were determined by visual inspection and corroborated by principal components analysis (PCA). Zones 1 and 4 are distinguished from the other zones by the absence of well-preserved diatoms. Zone 1a contains no evidence of diatoms, whereas zones 1b and 4 contain dissolved and broken diatoms (shown by shading). PCA (Figs. 5–7) shows that zone 2 is distinct from zone 3 on the basis of diatom community composition, and this difference is attributed to changes in the hydrology of Bear Lake. During the deposition of zone 2, changes in river inputs affected the hydrology and chemistry of Bear Lake, whereas during zone 3, evaporation was more important in determining the hydrology and chemistry. Lithologic units are based on Dean et al. (2006) and are described in the text.

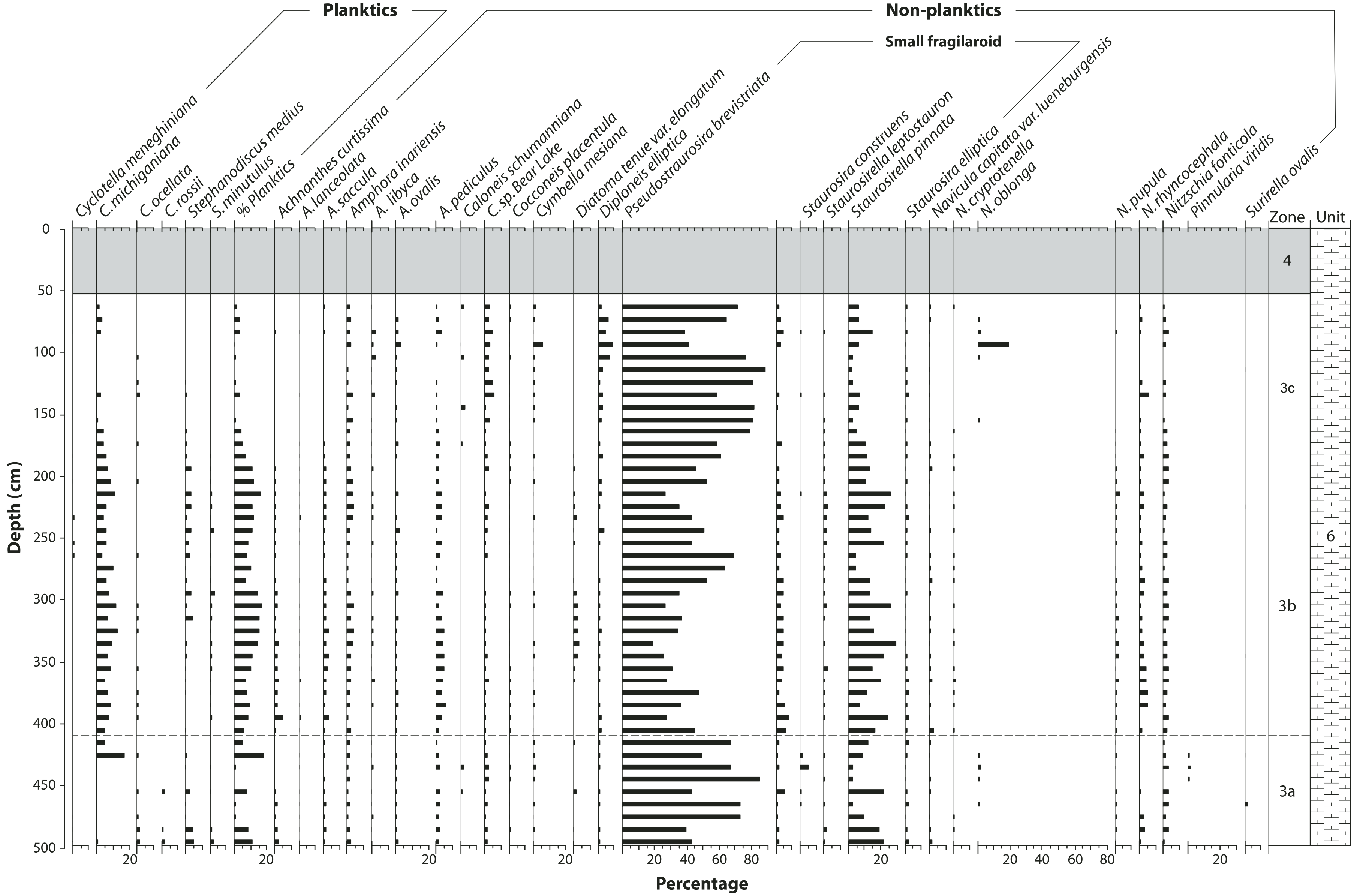


Figure 3. Diatom stratigraphy of BL96-1. Core BL96-1 spans the last 7.6 cal k.y. and includes only the main diatom taxa. Zones were determined by visual inspection and were corroborated by principal components analysis (PCA). The diatom community composition of these zones is virtually the same as in BL96-2.

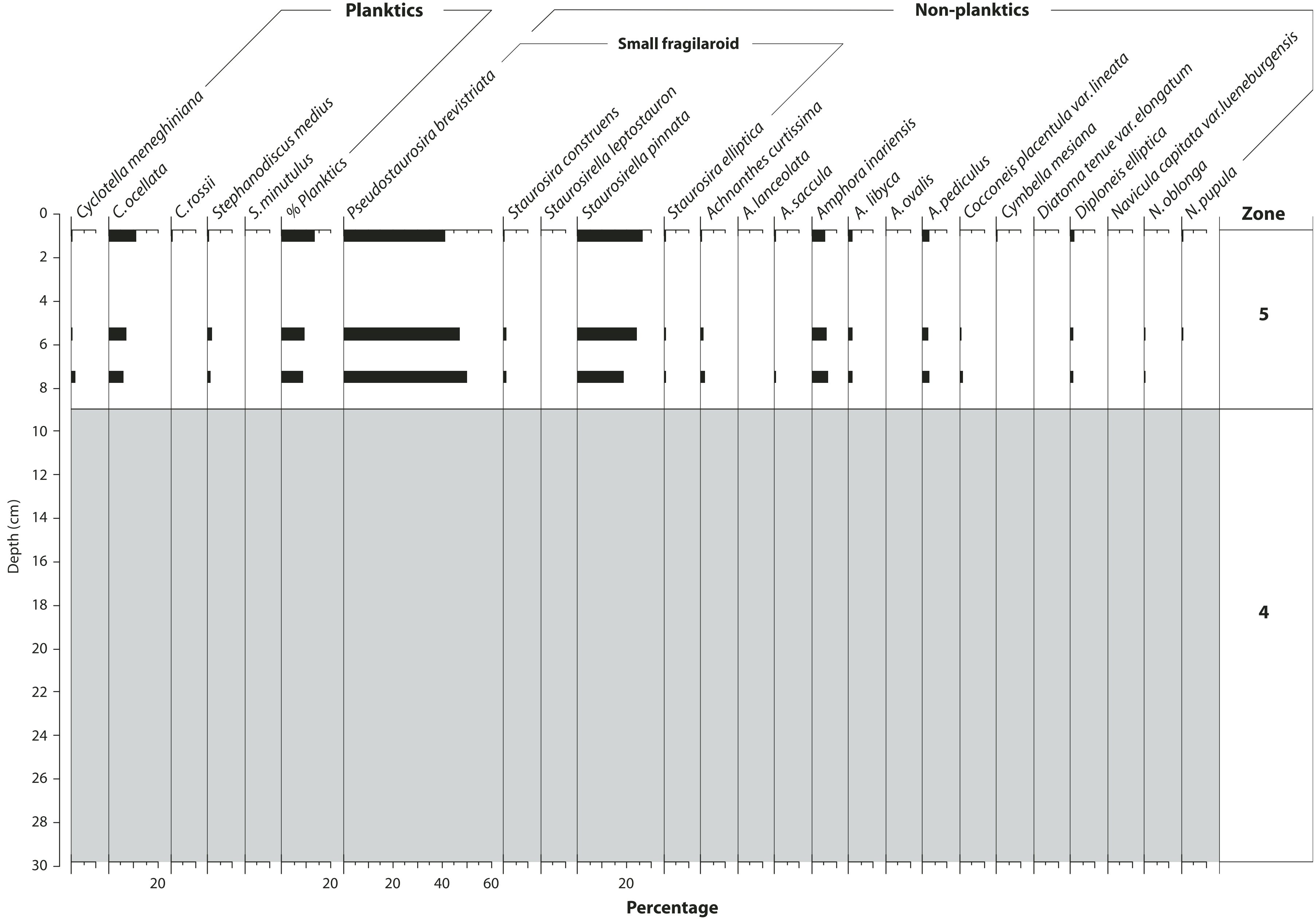


Figure 4. Diatom stratigraphy of BL98-10. The base of core BL98-10 is not dated, but the chronology for the upper part of the core is provided by $^{210}Pb$ (Smoak and Swarzenski, 2004). Only the main diatom taxa were included. BL98-10 contains zones 4 and 5, and $^{210}Pb$ indicates that the top of zone 4 is ca. A.D. 1936, although Dean et al. (2007) suggest that this age is too old. Zone 4 contains mainly diatom fragments, and zone 5 represents modern diatom assemblages of Bear Lake.

in core BL96-1 and BL98-10, is uncertain. Zone 4 comprises the top 50 cm of BL96-1, and the uppermost sediments have an age of 0.7 cal ka; however, the most recent sediments are missing (Colman et al., this volume). In core BL98-10 the top of zone 4 occurs between 8 and 9 cm, which is equivalent to ca. A.D. 1936 according to $^{210}$Pb ages (Smoak and Swarzenski, 2004); however, Dean (this volume) suggested that the $^{210}$Pb ages are too old. For this paper, we use the ca. A.D. 1936 date to refer to the top of zone 4, recognizing that this age is likely too old. All ages are in calendar years before 1950.

***Zone 1 (19.1–13.8 cal ka)***

Zone 1a (19.1–14.6 cal ka), which contains no evidence of diatoms, is distinguished from zone 1b (14.6–13.8 cal ka) by the appearance of broken and dissolved diatoms.

***Zone 2 (13.8–7.6 cal ka)***

Zone 2 marks the appearance of well-preserved diatoms. Relative to the overlying sediments, zone 2 contains abundant planktic diatoms, indicating large proportions of pelagic area relative to littoral area resulting from high lake levels (Wolin and Duthie, 1999). Zone 2a (13.8–10.8 cal ka) contains the greatest percentage of planktic species in the stratigraphy (an average of 38.4%). Of the planktic diatoms, *Stephanodiscus medius* is most common, and *Cyclotella ocellata* is common in lower percentages. *Stephanodiscus medius* is often associated with eutrophic conditions and is common during the transition from spring circulation to summer stratification (Kienel et al., 2005). The trophic status of *Cyclotella ocellata* is more ambiguous (Baier et al., 2004), but it has been found in the deep chlorophyll maximum (Stoermer et al., 1996) suggesting its presence may be indicative of deeper light penetration and/or strong stratification during late spring and early summer (Stoermer, 1993; Stoermer et al., 1996). The presence of these two diatoms in zone 2a suggests ameliorating conditions, with warmer temperatures and less turbidity than in zone 1, which would lead to thermal stratification.

The benthic diatom *Pseudostaurosira brevistriata*, which is the most common diatom throughout the core, is least abundant in zone 2a, whereas *Staurosirella pinnata* and *Staurosira construens* are relatively abundant. All three of these diatoms are epipelic and often found in association in alkaline waters. *Staurosirella pinnata* and *Staurosira construens* are indicative of mesotrophic waters, whereas *Pseudostaurosira brevistriata* are indicative of more oligotrophic waters (Cummings et al., 1995; Moser et al., 2004).

Zone 2b (10.8–9.2 cal ka) is distinguished from zone 2a by an abrupt decrease in the abundance of planktic species (average = 4.16%) and an increase in the abundance of the benthic species *Pseudostaurosira brevistriata.* The abundance of another benthic species, *Staurosirella pinnata,* declines.

Proportions of planktic taxa (average = 13% in BL96-2)—primarily *Stephanodiscus medius,* but also *Cyclotella ocellata* and *C. michiganiana*—in zone 2c (9.2–7.6 cal ka) are greater than in zone 2b, but less than in zone 2a. The abundance of *Pseudostaurosira brevistriata* declines relative to subzone 2b, whereas the abundance of *Staurosirella pinnata* increases. The base of subzone 2c is marked by a peak in *Surirella ovalis* and *Surirella minuta*. In samples from Bear Lake and inflowing streams, *Surirella ovalis* was only found in appreciable amounts (>1%) in Bear River sediments (Kimball, 2001). *Surirella minuta* is associated with fresh waters (Risberg et al., 1999) and has been found in eutrophic waters (Krammer and Lange-Bertalot, 1988).

TABLE 3. COMPARISON OF THE TIMING OF THE ONSET OF ZONES BETWEEN CORES

| Zone | BL96-2 | BL96-1 | BL98-10 |
|---|---|---|---|
| 1a | 19.1 | N/A | N/A |
| 1b | 14.6 | N/A | N/A |
| 2a | 13.8 | N/A | N/A |
| 2b | 10.8 | N/A | N/A |
| 2c | 9.2 | N/A | N/A |
| 3a | 7.6 | N/A | N/A |
| 3b | 5.8 | 5.9 | N/A |
| 3c | 3.0 | 2.7 | N/A |
| 4 | 1.8 | 1.3 | N/A |
| 5 | N/A | N/A | 1998–present |

Note: all ages are in cal ka years

***Zone 3 (7.6–1.8 cal ka)***

The boundary between zones 2 and 3 is defined by an abrupt decrease in the abundances of planktic diatoms (average = 3.1% in BL96-2 and 7.3% in BL96-1) and a substantial increase in the abundance of small, benthic/tychoplanktic fragilarioid taxa (average = 76.5% in BL96-2 and 69.2% in BL96-1). These shifts indicate a marked change in the hydrology of Bear Lake.

Zone 3a (7.6–5.9 cal ka) is delimited by the near disappearance of planktic species, a decrease of the abundance of the benthic diatom *Staurosirella pinnata,* and an increase of the abundance of *Pseudostaurosira brevistriata.*

Zone 3b (5.9–2.9 cal ka) is distinguished from zone 3a by an increase in the abundance of planktic species, mainly *Cyclotella michiganiana* and *Stephanodiscus medius.* The epiphytic species *Diatoma tenue* var. *elongatum*, which is a eutrophic diatom, reached its greatest abundance (1.6%) at Bear Lake in the middle of this zone. The benthic diatom *Pseudostaurosira brevistriata* shows an overall decline, whereas *Staurosirella pinnata* increases.

Zone 3c (2.9 to1.6 cal ka) is marked by an abrupt decrease in the abundance of planktic species and the benthic diatom *Staurosirella pinnata. Pseudostaurosira brevistriata* increases and *Caloneis* sp. Bear Lake reaches its greatest abundance in this zone. We were not able to identify *Caloneis* sp. Bear Lake as a previously described diatom, and recording the taxonomy is beyond the scope of this paper. This diatom has not been not observed in Bear Lake today (Kimball, 2001), so we have no ecological information for this taxon, although it is likely a epipelic diatom. A large spike in the abundance of *Navicula oblonga*, a epipelic, halophilous species, occurs in this zone.

### *Zone 4 (1.6 cal ka to ca. A.D. 1936)*

Zone 4 is characterized by broken and uncountable diatoms. Most of the diatom pieces observed were from large, pennate diatoms, including *Navicula oblonga*, *Diploneis elliptica*, *Pinnularia viridis*, and *Cymbella mesiana*, as well as the small, benthic/tychoplanktic fragilarioid taxa. *Pinnularia viridis* is well adapted to drying conditions; when conditions become dry this diatom moves deeper into the sediment (Evans, 1958, 1959). Diatom breakage and the presence of mainly littoral diatoms are suggestive of a shallow, high-energy environment (Flower, 1993), which would be consistent with reworking of littoral sediments during a lake transgression. Grazing can also result in broken diatoms, and it is possible that this zone represents a change in grazing intensity in the littoral zone at Bear Lake. However, the conditions that would result in a dramatic increase in grazing at Bear Lake during this time are unknown.

### *Zone 5 (ca. A.D. 1936–present)*

Zone 5 represents present-day conditions, with Bear River water flowing into Bear Lake. Although the $^{210}$Pb age, which indicates that the 1912 diversion is represented by sediments deposited at ~10.5 cm (Smoak and Swarzenski, 2004), may be correct, Dean (this volume) suggested that striking changes in the isotopic composition of bulk carbonate at 12.5 cm in BL98-10 mark the diversion. It is thus likely that there is a lag between the diversion and the change from diatom zone 4 to zone 5. Benthic diatoms, including *Pseudostaurosira brevistriata* and *Staurosirella pinnata* dominate this zone. A large pennate diatom, *Diploneis elliptica*, is also present. This shows that, despite the large size of Bear Lake, the littoral diatom community is well represented in the deep sediments. Planktic diatoms are relatively common and are dominated by *Cyclotella ocellata* and *Stephanodiscus medius*.

## Principal Components Analysis (PCA)

Principal components analysis (PCA) was used to summarize diatom data in BL96-2 and BL96-1 (Figs. 5–7). Prior to analyses, the diatom percentage data were square-root transformed to increase the importance of less abundant diatom taxa. In Figure 5, results from a standardized PCA (i.e., species scores were standardized to have a mean of 0 and a variance of 1) were scaled so that distances between samples approximated Euclidean distances. Therefore, species scores in Figure 5 are regression coefficients of the standardized species data onto the sample scores. The results presented in Table 4 were determined using a different scaling, so that the species scores are the correlation of the species to the ordination axis defined by the sample scores. Only taxa with a correlation of greater than the absolute value of 0.6 are included in the table.

Owing to the absence of fossil diatoms between 19.1 and 14.6 cal ka, samples from this interval were not included in the PCA. The top three samples of BL98-10 were the only samples that contained diatoms representing modern-day conditions. These samples were plotted passively (i.e., the samples did not influence the position of the axes) on the PCA biplots for comparison with BL96-2 and BL96-1 samples.

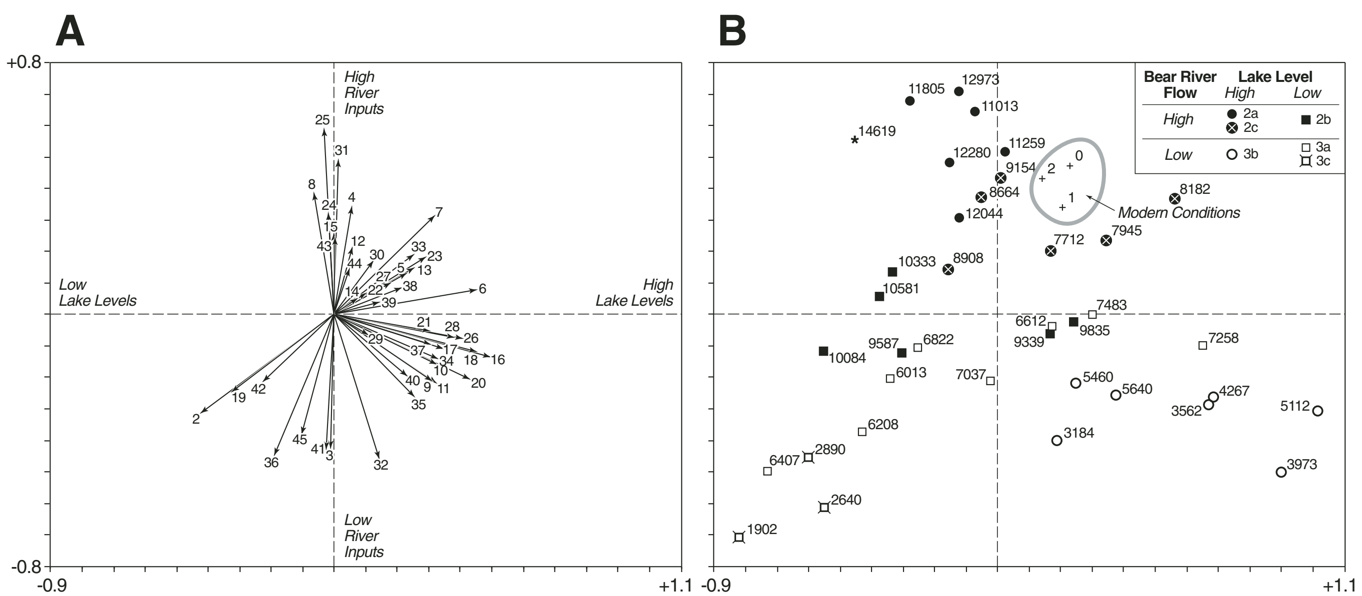


Figure 5. Principal components analysis biplot of diatom data from BL96-2. Eigenvalues are $\lambda_1 = 0.20$; $\lambda_2 = 0.14$. (A) Species are denoted by arrows, and the numbers refer to species names listed in Table 2. The position of the arrow is determined by the regression coefficients of the standardized species data onto the sample score. The interpretation of the axes is based on the ecology of diatom species that are most strongly correlated with the axes, and is explained in detail in the text. (B) Points represent different diatom samples, and the number assigned to a point represents the age of that sample. The closer two points are the more similar those samples are in terms of diatom community composition. Zone 1b is represented by a single sample, denoted by *. Zone 3 is depicted by open symbols and zone 2 is shown by black symbols.

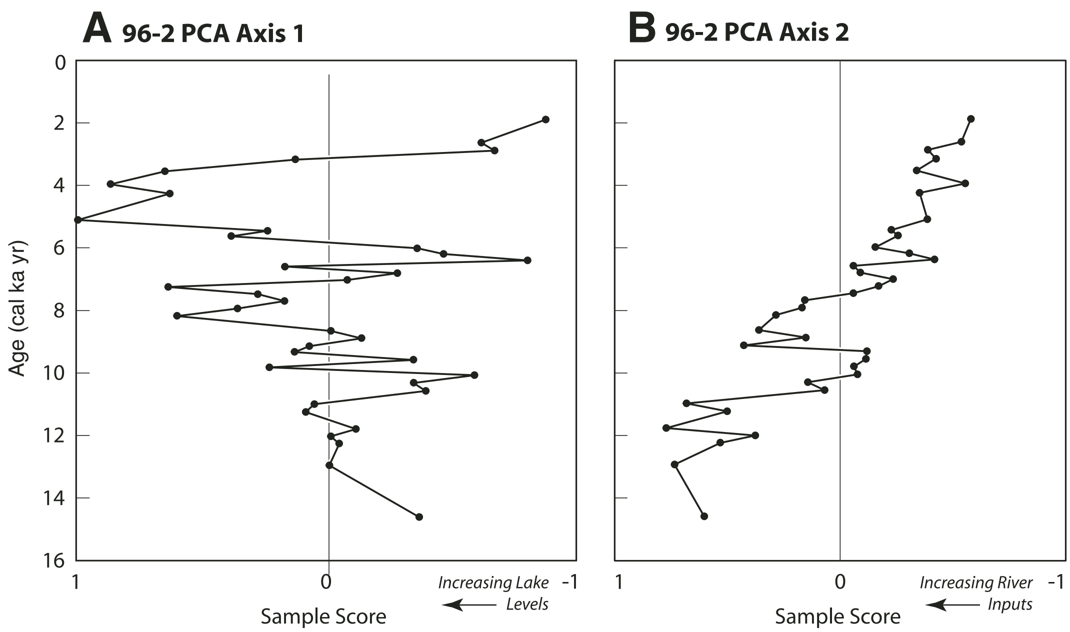


Figure 6. (A) Principal components analysis (PCA) axis 1 sample scores plotted against time for core BL96-2. (B) PCA axis 2 sample scores plotted against time for core BL96-2. The x-axis for both plots is reversed, so that wet conditions are to the left to be consistent with later plots. Note that prior to 7.6 cal ka river inputs and lake level change in the same direction, reflecting the importance of river and stream inflows in determining Bear River lake levels prior to this time. After 7.6 cal ka, lake levels change independently of river inputs, indicating the greater importance of other variables, such as evaporation, in determining lake levels.

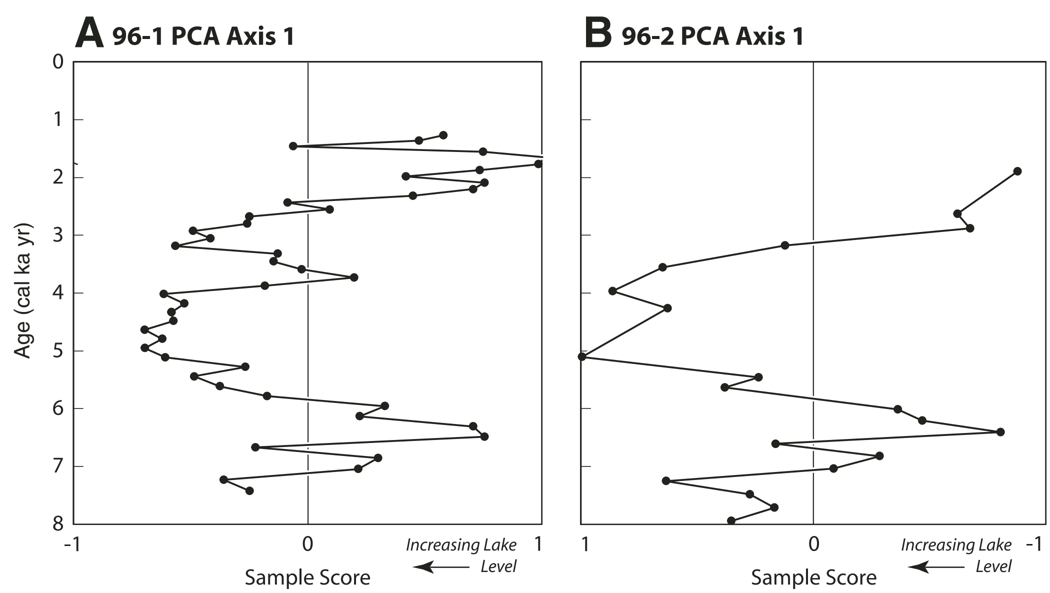


Figure 7. Principal components analysis (PCA) axis 1 sample scores plotted against age for core BL96-1 (A) and for core BL96-2 (B). Note that the BL96-1 axis 1 is reversed compared to the BL96-2 axis 1. When comparing two different PCA biplots, axes can be reversed, so that positive values in one biplot mean the same thing as negative values in the other plot. In this case increasing lake levels are shown to the left of both plots. Note the strong similarities between these two plots. The eigenvalue for BL96-1 for axis 1 is 0.26.

The eigenvalues (i.e., the dispersion of the species scores on the ordination axis) for the first two axes of the PCA of BL96-2 were $\lambda_1 = 0.20$ and $\lambda_2 = 0.14$, and of BL96-1 were $\lambda_1 = 0.26$ and $\lambda_2 = 0.08$. The total variance explained by the first four axes in the PCA of BL96-2 was 50%, and for BL96-1 was 46%. Because the eigenvalue for the second PCA axis of the BL96-1 analysis was low, it will not be considered further in this paper. Also, because the trends observed in the PCA biplot for BL96-1 and BL96-2 were similar, only the biplot for BL96-2 is depicted (Fig. 5).

### *PCA BL96-2 Biplots*

The ecology of the diatom taxa that determine the interpretation of the first axis of the PCA biplot for BL96-2 indicate that this axis represents lake-level changes at Bear Lake, with greater values indicating rising lake levels and lower values falling lake levels. Planktic taxa, including *Cyclotella michiganiana* (28) and *C. meneghiana* (21), and periphytic diatoms, including *Staurosirella pinnata* (6), *Navicula tuscula* (20), *N. rhyncocephala* (16), and *N. capitata var. lueneburgensis* (18), have high scores (>0.6) (Table 4) and are, therefore, positively correlated with axis 1 and important in interpreting axis 1. The high positive planktic diatom scores suggest that positive sample scores are indicative of times of increased lake level (Wolin and Duthie, 1999). This is supported by the ecology of the other diatom taxa that are strongly correlated with axis 1. According to Rühland et al. (2003) most of these taxa have large optimal values for dissolved organic carbon (DOC) and total nitrogen (TN) (Table 4). Allochthonous carbon is composed mainly of DOC, whereas autochthonous carbon is mainly particulate organic carbon (POC) (Wetzel, 2001). In Bear Lake today the ratio of allochthonous to autochthonous carbon is ~50:1, likely as a result of the large organic carbon loading from Bear River to Bear Lake (Birdsey, 1985, 1989). Although no measurements are available for Bear Lake, other research suggests that DOC inputs to Bear Lake would increase during wetter years (Schindler et al., 1997). Today nitrogen loading to Bear Lake is predominately from Bear River, and levels of nitrogen increase during wetter years (Birdsey, 1989). In addition, rising lake levels during wet years would flood shores of the lake and release DOC and nitrogen from these areas to the lake.

*Pseudostaurosira brevistriata* (2) has a large absolute score (>0.60) and is negatively correlated with PCA axis 1 (Table 4, Fig. 5). *P. brevistriata* has low TN and DOC optima (Table 4; Rühland et al., 2003). *Navicula oblonga* (19), which is also negatively correlated with axis 1 (species score = –0.36), is a halophilous species (Risberg et al., 1999) and *Cymbella aspera* (42) (axis 1 species score = –0.31) has been described as aerophilous (Zong, 1998). The ecology of these diatoms is consistent with drier conditions causing reduced TN and DOC, and with falling lake levels, which would expose shorelines and increase concentrations of ions. As well, no planktic diatoms are negatively correlated with axis 1 and have large absolute scores, suggesting that negative values indicate shallower waters.

Three lines of evidence indicate that the second PCA axis of the BL96-2 analysis represents river inputs, with positive values indicating increased fluvial inputs and negative values decreased inputs. First, taxa strongly correlated with axis 1, *Stephanodiscus medius* (25) and *Cyclotella ocellata* (31), are planktic and eutrophic, whereas all taxa strongly negatively correlated with axis 2 are periphytic (Table 4).

Second, post-diversion BL98-10 samples, which represent a time when Bear River water flowed into Bear Lake, have relatively high and positive scores on the second axis. The present nutrient budget to Bear Lake is largely composed of inputs from Bear River. In fact, Birdsey (1989) estimated that 60%–80% of post-diversion phosphorus delivery to Bear Lake is from Bear River. Moreover, nutrients increased significantly to Bear Lake when Bear River was connected to Bear Lake (Table 1; Birdsey, 1989). Although nutrient loading to Bear River is probably greater in historical times than it would have been prior to agriculture and other human activities, greater catchment size would

TABLE 4. DIATOM ECOLOGICAL INFORMATION

| Species Number | Species | Species Score on Axis 1 of 96-2 | Species Scores on Axis 2 of 96-2 | DOC Optimum ug/L | TN Optimum mg/L |
|---|---|---|---|---|---|
| **Positively Correlated to Axis 1** | | | | | |
| 16 | *Navicula rhyncocephala* | 0.87 | | N/A | N/A |
| 6 | *Staurosirella pinnata* | 0.79 | | 13.30 | 473.20 |
| 18 | *N. capitata* var. *lueneburgensis* | 0.79 | | N/A | N/A |
| 20 | *N. tuscula* | 0.75 | | N/A | N/A |
| 26 | *Cyclotella michiganiana* | 0.7 | | 23.50 | 882.10 |
| 28 | *C. meneghiniana* | 0.66 | | N/A | N/A |
| **Mean Value of Optima** | | | | 18.40 | 677.65 |
| **Negatively Correalted to Axis 1** | | | | | |
| 2 | *Pseudostaurosira brevistriata* | –0.74 | | 8.50 | 344.10 |
| **Mean Value of Optima** | | | | 8.50 | 344.10 |
| **Positively Correlated to Axis 2** | | | | | |
| 25 | *Stephanodiscus medius* | | 0.88 | N/A | N/A |
| 31 | *Cyclotella ocellata* | | 0.73 | 10.50 | 268.80 |
| **Mean Value of Optima** | | | | 10.50 | 268.80 |
| **Negatively Correlated to Axis 2** | | | | | |
| 32 | *Diploneis elliptica* | | –0.68 | N/A | N/A |
| 36 | *Caloneis schumannii* | | –0.66 | N/A | N/A |
| 3 | *Pseudostaurosira brevistriata* form rhomboid | | –0.63 | N/A | N/A |
| 41 | *Cymbella mesiana* | | –0.62 | N/A | N/A |

*Note:* DOC—dissolved organic carbon; TN—total nitrogen.

have increased terrestrial inputs and hence nutrient delivery (Schindler, 1971; Prairie and Kalff, 1986).

Third, several species found only in modern samples collected from rivers and streams flowing into Bear Lake today, including *Cocconeis placentula* (33), *Amphora inariensis* (38), *Surirella ovalis* (44), *Achnanthes curtissima* (13), and *Achnanthes lanceolata*, have positive scores on the second PCA axis (Kimball, 2001).

### *PCA Sample Scores*

Prior to 7.6 cal ka the direction of change shown in the plot of PCA axis 1 sample scores is similar to the direction of change shown in the plot of PCA axis 2, although the values of the scores and magnitude of change between scores are different (Fig. 6). Assuming that axis 1 represents lake levels and axis 2 river inputs, prior to 7.6 cal ka lake level was strongly linked to Bear River inflows, but after this time lake level was more strongly controlled by other factors, probably evaporation. Increases in saline and aerophilic diatoms after 7.6 cal ka suggest that effective moisture is an important driver of lake-level fluctuations.

From 13.8 to 10.8 cal ka inferred lake levels were moderate and relatively stable, whereas inferred river inputs were high. At 10.8 cal ka, lake levels fell rapidly in response to decreased river and stream inputs. River inputs remained low until 9.2 cal ka, and although lake levels fluctuated between 10.8 and 9.2 cal ka, they also remained generally low. Beginning ca. 9.2 cal ka, river inputs increased rapidly and remained high until 7.6 cal ka.

Beginning ca. 9.2 cal ka, river inputs increased rapidly. Lake levels began to rise ca. 8.5 cal ka and remained high until 7 cal ka. As river inputs slowly declined following 7.6 ka, however, lake levels fluctuated rapidly, likely in response to changes in evaporation.

Sample scores for BL96-2 on axis 1 show similar trends for BL96-1 on axis 1 (Fig. 7), and the diatom species that most influence the position of axis 1 are similar in analyses of the two cores. Because BL96-1 has better temporal resolution, we will focus on it to examine lake-level fluctuations. Lake levels were low from 7.6 to 5.9 cal ka, but increased rapidly at 5.9 cal ka and remained high until 2.9 cal ka. This generally wet period was interrupted by a dry period between 4.3 and 3.8 cal ka. Lake levels dropped rapidly at 2.9 cal ka and remained low until 1.6 cal ka.

## Discussion

### *Late Pleistocene (19.1–13.8 cal ka): Poor Diatom Preservation*

The absence of diatoms from 19.1 to 14.6 cal ka in zone 1a is probably related to the harsh conditions at Bear Lake during the last glacial interval (24–15 cal ka) (Dean et al., 2006). Cold temperatures during this time would have increased ice cover, which would have decreased transmission of light. Turbidity would have been high as a result of increased sediment load in Bear River originating from the Uinta Mountains (Dean et al., 2006; Rosenbaum and Kaufman, this volume), which would have further reduced light and limited diatom growth (Bradshaw et al., 2000). Detrital quartz dominated sediment deposition until ca. 18 cal ka, when it decreased rapidly and was replaced with endogenic calcite (Dean, this volume). By ca. 15 cal ka, approximately the same time that diatoms first appear, low-Mg calcite dominated sediments deposited at Bear Lake. Diatoms deposited between 14.6–13.8 cal ka are poorly preserved as a result of dissolution. Dissolution of diatoms is affected by pH (Lewin, 1961; Iler, 1979), major-ion composition and concentration (Flower 1993; Barker et al., 1994), temperature (Marshall, 1980), and silica saturation levels (Flower, 1993; van Cappellen and Qiu, 1997). It is unlikely that poor diatom preservation between 14.6 and 13.8 cal ka occurred as a result of changes in pH or major-ion composition or concentration because (1) the diatom community composition suggests that Bear Lake has always been alkaline, (2) endogenic calcite dominated sediment deposition, and (3) Mg:Ca ratios remained relatively unchanged between 16 and 11 cal ka (Dean et al., 2006). More likely, diatom dissolution during this period was related to continued cold temperatures and limited silica. Increasing temperatures increase silica dissolution (Marshall, 1980), and as a result increase silica concentrations in streams. Temperatures in the Great Basin during the last glacial maximum are estimated to have been 10 °C lower than present (Thompson, 1988). Such low temperatures would decrease weathering rates, and thereby reduce silica concentrations in inflowing streams (Vesley et al., 2005). Reduced temperatures would also reduce thermal stratification and productivity (Sorvari et al., 2002), and might decrease internal lake cycling of silica, although silica cycling in lakes is complicated and affected by many processes (Wetzel, 2001).

### *Latest Pleistocene to Middle Holocene (13.8–7.6 cal ka): Bear River Influence on Bear Lake*

The appearance of well-preserved diatoms and the presence of *Stephanodiscus medius* and *Cyclotella ocellata* in zone 2 are indicative of warmer temperatures and reduced turbidity relative to zone 1. These changes would have led to increased thermal stratification and increased nutrient cycling (Interlandi et al., 1999). The pollen record, which records a switch from conifers and cold-tolerant trees and herbs to sage-steppe plants, also indicates warmer temperatures (Doner, this volume). Warmer temperatures in the Great Basin at this time are attributed to greater-than-present summer insolation as a result of orbital variations (Thompson et al., 1993).

The presence of mesotrophic and eutrophic diatoms indicates high nutrient availability, which would result from increased runoff. PCA indicates that river inputs were high during deposition of zone 2a (13.8–10.8 cal ka), but that lake levels were moderate (Fig. 6). Increased values of isotope ratios for Sr, C, and O after ca. 12 ka suggest that Bear River was not connected to Bear Lake after this time (Fig. 8; Dean et al., 2006). The difference in the timing of the Bear River disconnection suggested by the diatom evidence compared to the isotope and carbonate chemistry may be related to the greater sensitivity of the latter variables to Bear

River inflows. The geochemical signature of Bear River is distinct from that of Bear Lake and other streams flowing into Bear Lake (Dean et al., 2007; Dean, this volume); however, although the Bear River diatom assemblage is distinct from Bear Lake diatoms, it is not distinct from that of other streams entering the lake (Kimball, 2001). Taken together, the evidence suggests that Bear River disconnected by 12 cal ka, but that other fluvial inputs continued to be relatively high until 10.8 cal ka. Between 13.8 and 10.8 cal ka, PCA of diatom data indicates that, despite continued high river inputs, Bear Lake levels were moderate, perhaps reflecting increasing evaporation during the summer (Fig. 6). High inflows from rivers accompanied by relatively high evaporation suggest that winters were wet and summers were warm and dry.

Increasingly arid conditions are reported for the Bonneville Basin beginning ca. 13.9–13.3 cal ka (Godsey et al., 2005; Madsen et al., 2001), which is earlier than what is inferred for Bear Lake. The delay in the onset of arid conditions at Bear Lake could be because Bear Lake's hydrologic balance was more influenced by glaciers, which may have persisted in the Uinta Mountains until 10 cal ka (Munroe, 2003), or could indicate a different climatic control for Bear Lake and the Bonneville Basin at this time. More humid conditions existed between 13.6 and 10.7 cal ka on the Great Plains than during the middle Holocene (Valero-Garcés et al., 1997), suggesting a common climatic control between this region and Bear Lake that may be related to the position of the jet stream and to storms tracking eastward from the Pacific (Thompson et al., 1993).

Planktic diatoms decrease rapidly at 10.8 cal ka and remain low until 9.2 cal ka, indicating either a decrease in nutrients due to reduced river inputs or a decrease in lake levels (Figs. 2 and 6). The period between 10.8 and 9.2 cal ka is also marked by a switch from calcite-rich to aragonite-rich sediments (Fig. 8; Dean et al., 2006). Although aragonite deposition in a cold, oligotrophic lake is unusual, it likely was in response to increasing temperatures and salinity (Dean et al., 2006; Dean, this volume). Records from the northern Great Plains similarly indicate slowly and then rapidly increasing aridity beginning ca. 10.5 cal ka and 7.9 cal ka, respectively (e.g., Laird et al., 1996; Valero-Garcés et al., 1997).

In contrast to the northern Great Plains, evidence suggests that conditions at Bear Lake became wetter between 9.2 and 7.6 cal ka. Planktic diatoms increase in tandem with a decrease of oxygen isotope values and a switch from aragonite to calcite deposition (Fig. 8). Stable isotope evidence, including O, C, and Sr, indicates that this period was a time of increased lake levels as a result of reconnection of Bear River to Bear Lake (Dean et al., 2006). Peaks in *Surirella ovalis* and *S. minuta*, found by Kimball (2001) to occur mainly in Bear River today, suggest greater river input (Fig. 2). PCA of the diatom data similarly point to greater river inputs as well as higher lake levels (Fig. 6), thereby corroborating Dean et al.'s (2006) interpretation. According to Smoot and Rosenbaum (this volume), lake levels increased ~10 m above modern limit, and the timing of this shift is roughly coincident with the Willis Ranch shoreline, which is at ~1814 m asl (8 m above modern lake levels) (Laabs and Kaufman, 2003).

The lack of correlation between the Bear Lake record and records from the northern Great Plains and much of the western United States (Fritz et al., 2001) between 9 and 7.5 cal ka

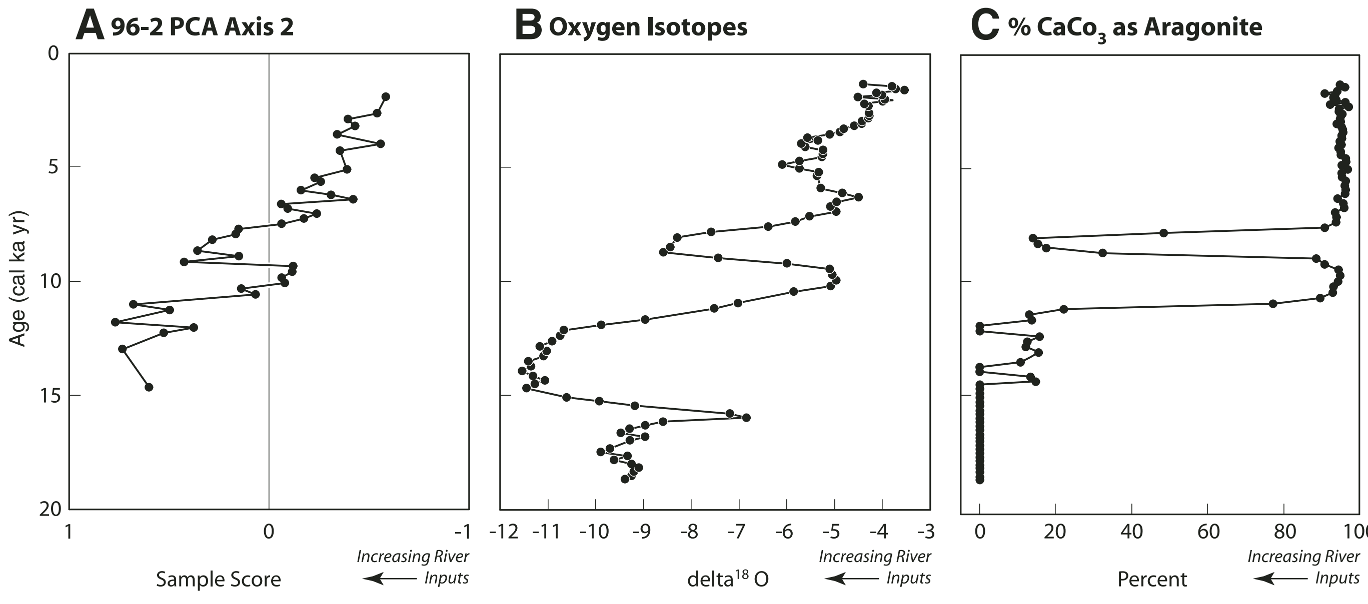


Figure 8. (A) Principal components analysis (PCA) axis 2 scores plotted against age for core BL96-2. (B) $\delta^{18}O$ in bulk carbonate versus age in BL96-2 (after Dean et al., 2006). (C) Percent $CaCO_3$ as aragonite in BL96-2 (after Dean et al., 2006). The x-axis for the diatom PCA score plot has been reversed to match the direction of inferred river inputs in the plots of oxygen isotopes and % $CaCO_3$ as aragonite. For all three plots, scores to the right of the figure represent lower river inputs.

implies that either these two regions were affected by two different climatic regimes or that non-climatic factors were controlling Bear Lake's hydrologic balance. It is possible that the reconnection between Bear River and Bear Lake was the result of tectonic or geomorphic processes, although no evidence has been found to support this. However, it is also difficult to explain this event climatically.

Wetter conditions at Bear Lake are consistent with pollen evidence from adjacent regions, which indicates greater summer precipitation during the early Holocene than today (Whitlock and Bartlein, 1993). Wetter conditions could be linked to intensified monsoonal circulation during the middle Holocene. Bear Lake climate during this time is similar to those described for regions in the southwest, which were wetter and warmer between 9 and 4 cal ka (Betancourt et al., 1993; Poore et al., 2005). Several researchers have hypothesized that wetter conditions in the southwest beginning 9 cal ka were the result of intensified monsoonal circulation as a result of greater seasonal differences in insolation. However, as will be discussed below, the timing of increased monsoonal circulation is contentious (Barron et al., 2005).

***Middle to Late Holocene (7.6 cal ka to ca. A.D. 1918): Recording Lake-Level Variations***

Changes in diatom community composition, which are reflected in the PCA, indicate reduced river inflow to Bear Lake following 7.6 cal ka. This is supported by a switch from calcite to aragonite deposition and increasing Sr isotope values, which point to a final disconnection between Bear River and Bear Lake at this time (Fig. 8) (Dean et al., 2006). PCA also shows that there is reduced correlation between river inputs and lake-level variation following 7.6 cal ka, indicating that after this time Bear Lake levels were more influenced by changes in factors other than stream flow, most likely summer precipitation and evaporation.

PCA suggests lower lake levels, and increased isotope values indicate greater evaporation, between 7.6 and 5.9 cal ka, most likely due to increased aridity at this time. Beginning ca. 5.9 cal ka until 2.9 cal ka, PCA suggests that lake levels increased rapidly and isotope values suggest decreased evaporation, which together indicate a wetter climate. Following 2.9 cal ka, diatom data show falling lake levels and increasing isotope values record increasing evaporation, indicating that conditions became drier again (Fig. 9). A brief dry period occurred between 4.3 and 3.8 cal ka. A lake-level model applied to other Bear Lake cores indicates lake-level changes similar to those inferred from diatoms, although the timing of correlative lake-level highs and lows between cores is not exact (Fig. 8; Smoot and Rosenbaum, this volume). For example, Smoot and Rosenbaum (this volume) found that lake level remained low until 3.5 cal ka.

From the inferred lake-level changes, the Bear Lake record could be interpreted as a generally wet period extending from 9.2 to 2.9 cal ka that is interrupted by two dry intervals, 7.6–5.9 cal ka and 4.3–3.8 cal ka. Many records from the southwest United States indicate that conditions were wetter during the middle Holocene (post 9–7 cal ka) as a result of intensified monsoonal flow (e.g., Spaulding, 1991; Ely et al., 1993; Waters and Haynes, 2001). Today most precipitation at Bear Lake occurs during January; however, years with increased monsoonal circulation result in greater August precipitation in the area of Bear

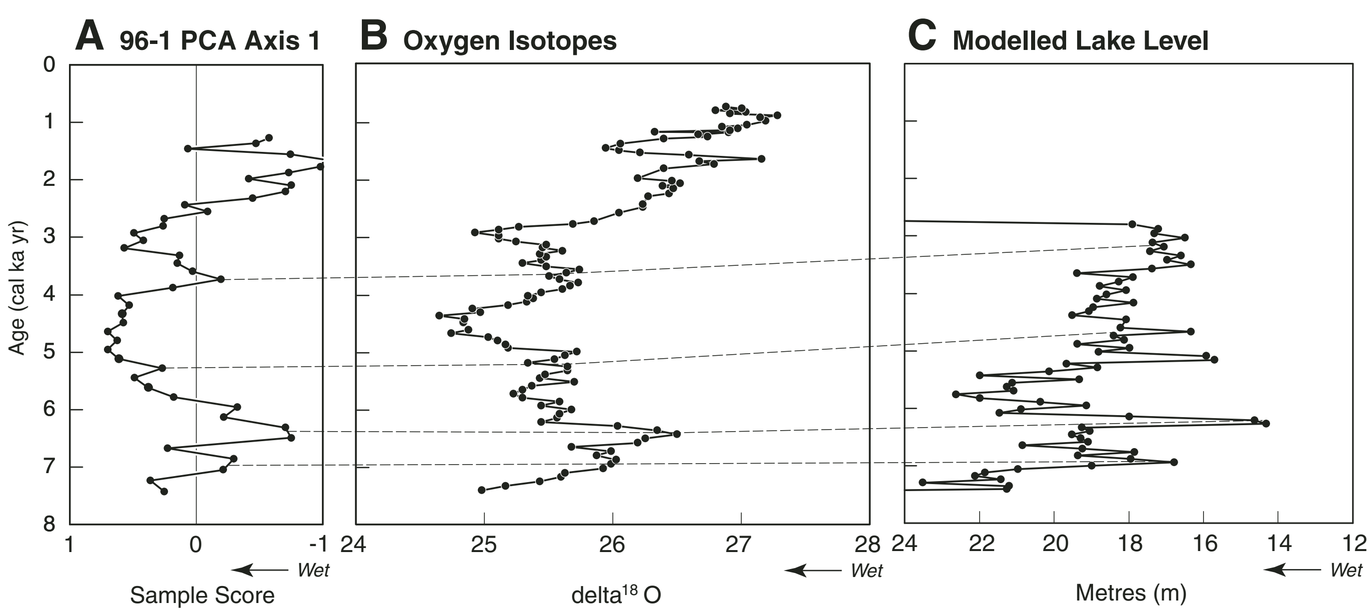


Figure 9. (A) Principal components analysis (PCA) axis 1 sample scores plotted against age for core BL96-1. (B) $\delta^{18}O$ in bulk carbonate versus age in BL96-1 (Dean, this volume). (C) Modeled lake level based on grain-size analysis (Smoot and Rosenbaum, this volume). Lake levels are plotted in reverse (i.e., from highest to lowest) on the x-axis so that in all plots, points on the right-hand side of the figure represent drier conditions. Dotted lines connect what are believed to be times of similar high or low lake levels.

Lake (Mock and Brunelle-Daines, 1999). Increased monsoonal flow during the middle Holocene has been attributed to altered latitudinal and seasonal distribution of insolation caused by variations in Earth's orbital parameters at that time (Thompson et al., 1993; Mock and Brunelle-Daines, 1999). An increase in monsoonal moisture in the southwest United States should occur in tandem with higher sea-surface temperature (SST) records from the Gulf of California and Gulf of Mexico, but SST in the Gulf of California began to increase at 6 cal ka (Barron et al., 2005), and SSTs in the Gulf of Mexico are highest between 7.0 and 4.7 cal ka (Poore et al., 2003, 2005). Moreover, modeling has suggested that orbital variations alone cannot explain regional-scale moisture patterns (Diffenbaugh and Sloan, 2004), and that ocean-atmosphere feedbacks are important forcing mechanisms for determining mid-Holocene moisture balance in the western United States (Vettoretti et al., 1998; Harrison et al., 2003).

On the Great Plains conditions were dry from 10 to 4.5 cal ka, with maximum aridity between 7.5 and 5.5 cal ka (Fritz et al., 2001). This pattern of a wet Southwest and dry Midcontinent is similar to present-day patterns of moisture/aridity resulting from the formation of a crescent-shaped region of enhanced subsidence bordering the area of the enhanced monsoon (Higgins et al. 1997, 1998; Higgins and Shi, 2000). Modeling has also demonstrated that mid-Holocene aridity in North America is dynamically linked to an orbitally induced enhancement of the summer monsoon in the American Southwest (Harrison et al., 2003). These experiments indicate that Bear Lake is on the border between increased moisture due to enhanced monsoonal flow versus increased aridity due to associated subsidence (Harrison et al., 2003). We hypothesize that subtle changes in monsoonal strength and related subsidence result in shifts in moisture at Bear Lake during the Holocene. Therefore, the dry periods at Bear Lake ca. 7.6–5.9 cal ka and 4.3–3.8 cal ka may indicate monsoon core shifts when Bear Lake fell within the area of subsidence (aridity). These periods of increased aridity at Bear Lake also coincide with dry conditions in other parts of the Great Basin including (1) the driest conditions of the Holocene at Pyramid Lake between 7.6 and 6.3 cal ka (Mensing et al., 2004), (2) dry conditions at Mono Lake between 7.4 and 4.5 cal ka (Davis, 1999), (3) desiccation of Walker Lake at 5 cal ka (Benson et al., 1991), and (4) persistent drought at Owens Lake from 6.5 to 3.8 cal ka (Benson et al., 2002).

The timing of the second dry event could also be related to a widespread drought that occurred between 4.3 and 4.1 cal ka in mid-continental North America (Booth et al., 2005). This event may have been global; however, the forcing mechanism remains uncertain (Booth et al., 2005).

The period from 2.9 to 1.6 cal ka is characterized by decreasing lake levels and increased evaporation. This zone is capped by an interval of broken pennate diatoms, which may be indicative of reworking of littoral sediments during the past 700 years as lake levels increased. The decreasing lake levels beginning at 2.9 cal ka may be related to reduced monsoonal circulation. Marine records from the Gulf of Mexico showing a decrease in the planktic foraminifera, *Globigerinoides sacculifera* following 3 cal ka (Poore et al., 2005) indicate decreased monsoonal circulation, and Barron et al. (2004, 2005) report a decrease in upwelling in the Gulf of California, which they attribute to reduced monsoonal circulation beginning at 2.8 cal ka.

Many paleoenvironmental records from the United States indicate that at 2.8 cal ka modern conditions were established. For example, lake sediment records from the continental United States indicate more humid and less variable conditions beginning ca. 2.8 cal ka (Clark et al., 2002), and in the Sierra Nevada, wetter but more variable conditions were recorded (Brunelle and Anderson, 2003; Bloom, 2006). Records from the Great Basin are in general agreement with these records suggesting that the period following 3 cal ka was wetter than the middle Holocene (Benson et al., 2002).

## CONCLUSIONS

Diatoms at Bear Lake record changes in hydrologic and climatic condition for the last 19.1 cal ka.

- From 19.1 to 14.6 cal ka the complete absence of diatoms indicates that Bear Lake was characterized by cold, turbid, and silica-poor conditions. The presence of diatoms between 14.6 and 13.8 cal ka is linked to increased light due to decreased turbidity as the glaciers disappeared from the Uinta Mountains and the sediment load of inflowing streams was reduced. The poor preservation of the frustules during this time, however, suggests that conditions continued to be relatively cold.
- Between 13.8 and 7.6 cal ka, the PCA of the diatom data generally indicates greater river inputs than following 7.6 cal ka. The period between 10.8 and 9.2 cal ka, however, was characterized by diatoms indicative of low river inputs and low lake levels. Other geochemical evidence suggests that Bear River was not flowing into Bear Lake at this time. After 7.6 cal ka diatoms indicate low river inputs until ca. A.D. 1912, when the Bear River was diverted by humans into Bear Lake.
- In general, between 9.2 and 2.9 cal ka, diatom community composition and stable isotope ratios suggest that lake levels were generally high and evaporation low, but that at least two prolonged periods of lower lake levels and greater evaporation occurred: 7.6–5.9 cal ka and 4.3–3.8 cal ka. Increased monsoonal circulation could have increased summer precipitation and reduced evaporation at Bear Lake following 9.2 cal ka. The two prolonged dry periods recorded at Bear Lake during this time may indicate subtle changes in monsoonal strength although other climatic mechanisms remain to be considered.
- Following 2.9 cal ka, Bear Lake shows marked changes that are characterized by falling lake levels, indicative of drier conditions linked to reduced monsoonal circulation as recorded in marine sediment from the Gulf of Mexico and the Gulf of California.

• Because the location of Bear Lake is at the junction of several major climatic boundaries in the western United States (Mock, 1996), it is expected that climatic, and therefore hydrologic, conditions would change frequently as the boundaries shift in response to large-scale climatic forcings. We suggest, therefore, that the shifts from periods when effective moisture at Bear Lake was similar to the Great Plains and Great Basin to periods when effective moisture at Bear Lake was similar to the monsoon-dominated Southwest track changes in the relative mean positions of important air-mass boundaries.

## ACKNOWLEDGMENTS

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## ARCHIVED DATA

Archived data for this chapter can be obtained from the NOAA World Data Center for Paleoclimatology at http://www.ncdc.noaa.gov/paleo/pubs/gsa2009bearlake/.

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## A 19,000-year record of hydrologic and climatic change inferred from diatoms from Bear Lake, Utah and Idaho


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