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# *Introduction to* Paleoenvironments of Bear Lake, Utah and Idaho, and its catchment

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In 1996 a group led by the late Kerry Kelts (University of Minnesota) and Robert Thompson (U.S. Geological Survey) acquired three piston cores (BL96-1, -2, and -3) from Bear Lake. The coring arose from their recognition of Bear Lake as a potential repository of long records of paleoenvironmental change. They recognized that the lake is located in an area that is sensitive to changes in regional climate patterns (Dean et al., this volume), that the lake basin is long lived (see Colman, 2006; Kaufman et al., this volume), and that, unlike many lakes in the Great Basin, Bear Lake was never dry during warm dry periods.

Bear Lake lies in the northeastern Great Basin to the northeast of Great Salt Lake, just south of the Snake River drainage, and a short distance west of the Green River drainage that makes up part of the Upper Colorado River Basin (Fig. 1). Similarity among the historic Bear Lake and Great Salt Lake hydrographs and flows on the Green River indicates that the hydrology of Bear Lake reflects regional precipitation (Fig. 2). Therefore, paleorecords from Bear Lake are important to understanding past climate for a large region, including the Upper Colorado River Basin, the source of much of the water for the southwestern United States.

Initially, paleoenvironmental studies of Bear Lake sediments focused on cores BL96-1, -2, and -3. Additional coring was conducted to elucidate the spatial distribution of sedimentary units and to extend the record back in time. The study was also expanded to include extensive study of the catchment, including the properties of catchment materials and the processes that could potentially affect the delivery of catchment materials to the lake.

Cores BL96-1, -2, and -3 were taken with a Kullenburg piston corer along an east–west profile in roughly 50, 40, and 30 m of water, respectively (Table 1, Fig. 3). These three cores, each taken as a single 4- to 5-m-long segment, provide a nearly complete composite section from ca. 26 cal ka to the late Holocene. In 1998 a number of short gravity cores were taken from the uppermost water-rich sediments that were not sampled by the 1996 cores. During 2000, cores were taken with a percussion piston corer (manufactured by UWITEC) at three locations in and around Mud Lake and at two locations in the northern end of Bear Lake (Fig. 3). Cores acquired with the percussion corer comprise as many as three overlapping segments up to 2 m in length. In 2002, additional percussion piston cores and associated gravity cores of the uppermost sediments were acquired from five sites in the northern half of the lake. In conjunction with two of the cores collected in 2000, these cores form a north–south profile along a seismic line and span water depths from less than 10 m to ~40 m. Data from this profile provide much of the evidence for lake-level variations (Smoot and Rosenbaum, this volume). Finally, during 2000, two long cores, BL00-1D and -1E (collectively referred to here simply as BL00-1), were taken at a site near the depocenter during testing of the GLAD800 coring platform (Fig. 4; Dean et al., 2002). These cores provide a record back to ca. 220 ka.

Many of the studies in this volume utilize samples from these cores. To help constrain interpretations of core data, sediment traps were deployed (Dean, this volume), modern lake and stream sediments were sampled (Rosenbaum et al., this volume; Smoot, this volume), and numerous water samples were collected (Bright, Chapter 4, this volume).

Here we briefly review the various topics presented in detail in the chapters of this volume.

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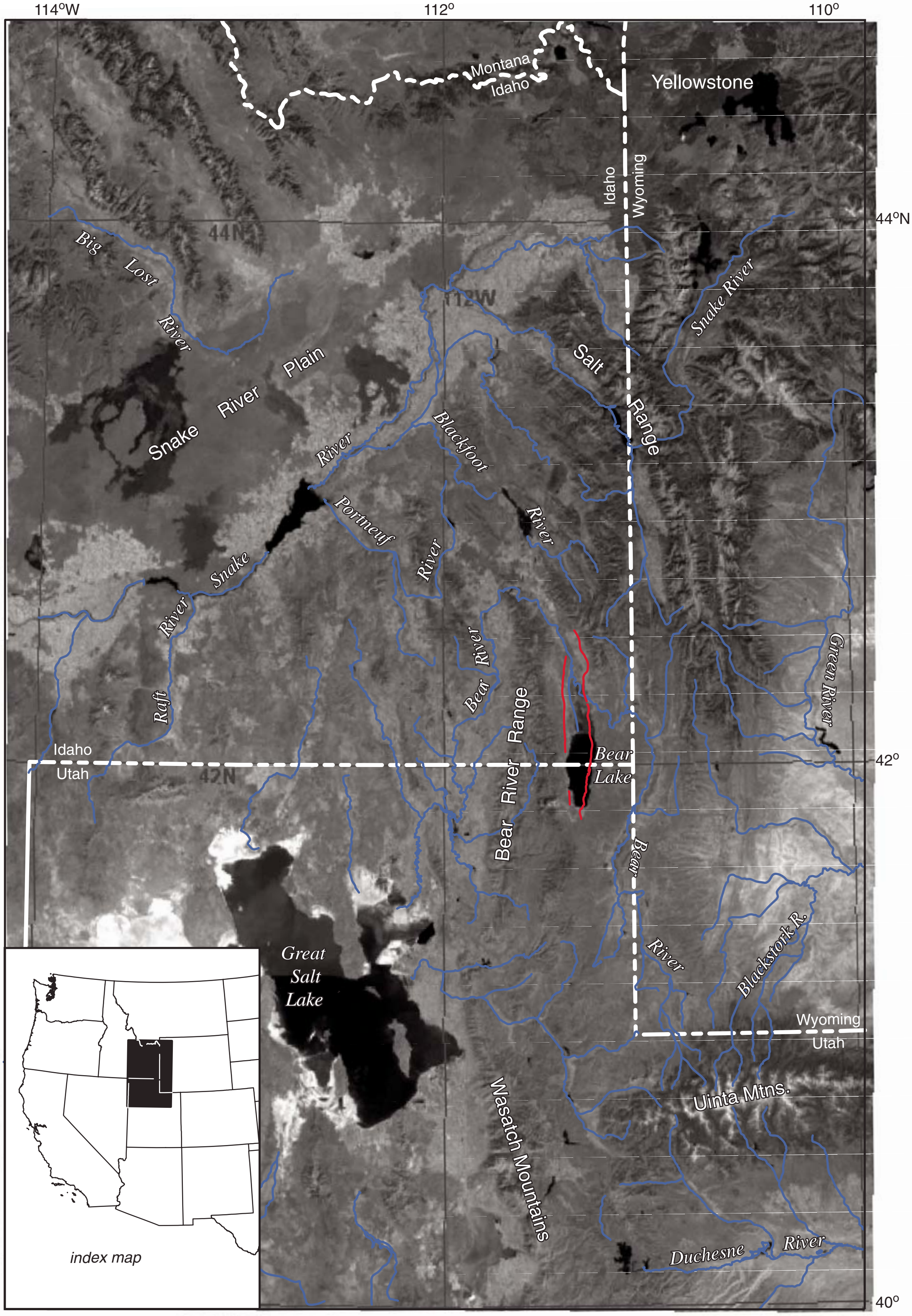

Figure 1. Location index map (inset) and regional setting, of Bear Lake, including drainages (blue) and principal faults bounding the Bear Lake Valley (red) (modified from Fig. 1 of Reheis et al., this volume).

## BEAR LAKE SETTING

### Geologic, Tectonic, and Geomorphic

As in other tectonically active basins in the Basin and Range Province, hundreds of meters of sediment have accumulated in Bear Lake Valley during the past several million years. Reheis et al. (this volume) describe the geology of Bear Lake Valley, including the bedrock units that underlie the adjacent uplands, and the faults that cut them. This geologic framework controls flow paths of groundwater discharged to Bear Lake (Bright, Chapter 4, this volume) and governs the types and quantities of sediment and solutes that accumulate in the lake. The modern Bear Lake Valley was shaped by faulting, particularly on the eastern valley margin. This faulting, which remains active, has southward-increasing slip rates and contributed to the migration of the Bear River both laterally, as evidenced by abandoned channels that mark the northern Bear Lake Valley, and vertically, as recorded by flights of fluvial terraces.

### Climatic, Hydrologic, Limnologic, and Biologic

Dean et al. (this volume) describe the large-scale pattern of modern atmospheric and oceanic circulation that influences Bear Lake. They present the instrumental record of climate and limnology, including long-term time series of climate variables, and of physical and chemical properties of the oligotrophic lake. Dean et al. (this volume) summarize the biological components of Bear Lake, including the endemic fish population. The endemic ostracode population is described by Bright (Chapter 8, this volume), who highlights the uniqueness of the Bear Lake microcrustaceans and speculates on their coevolution with the fish.

Bright (Chapter 8, this volume) suggests factors that have enabled Bear Lake to develop its diverse endemic ecosystem. One key factor is its long-lived, relatively stable, but not invariant, hydrologic setting. The lake has survived periods of major drought without becoming highly saline like Great Salt Lake. Groundwater that discharges in Bear River Range streams (Fig. 3) is an important part of the hydrologic budget of Bear Lake. In

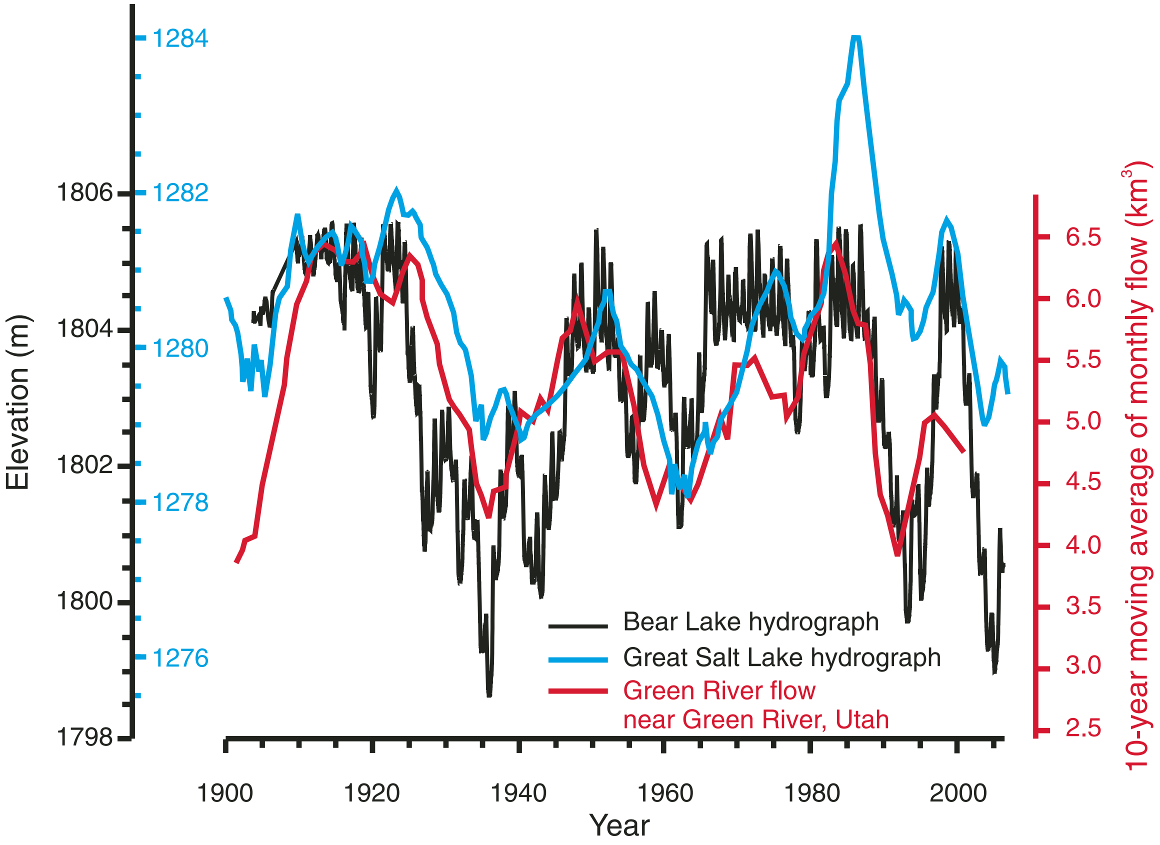

Figure 2. Elevations of Bear Lake and Great Salt Lake (in meters above sea level), and flow of the Green River near Green River, Utah. Elevation data for Bear Lake are from PacifiCorp, Salt Lake City, Utah. Note that the surface elevation of Bear Lake is limited to ~1805 m, at which point the lake spills. Elevation data for Great Salt Lake are from the U.S. Geological Survey. Green River flow is from Piechota et al. (2004).

addition to this west-side source, Bright (Chapter 4, this volume) used isotopic and major-ion compositions to identify three other major sources of groundwater in Bear Lake Valley.

During much of the Holocene, Bear Lake did not receive surface water from Bear River. Instead, inflow was dominated by streams fed by shallow groundwater in the fractured and karstic terrain of the Bear River Range west of the lake (Bright, Chapter 4, this volume). This water is charged with ions that, when concentrated by evaporation, yield alkaline lake water saturated with respect to carbonate minerals (Dean, this volume). The chemistry of Bear Lake changed after diversion of Bear River water into the lake ca. 1912. The history of this diversion and its influence on the lake and its biota are discussed by Dean et al. (this volume). The diversion produced pervasive shifts in the physical, chemical, and biological components of lake sediment, and these have been used by several authors of this volume to interpret analogous changes in the Quaternary sedimentary record.

## Surface Water and Sediment Input

By analyzing the composition of surface water and sediment in and around Bear Lake, downcore changes in the physical, chemical, and biological components of the sedimentary sequence of Bear Lake can be placed into a modern context. For example, the isotopic composition of spring and stream water (Bright, Chapter 4, this volume) provides the basis for interpreting changes in the isotope values of endogenic carbonates within the lake sediment (Dean, this volume; Kaufman et al., this volume). Similarly, the mineralogy, major-element composition, and mineral-magnetic properties of sediment carried by inflowing streams are used to infer changes in the sediment provenances through time (Dean, this volume; Kaufman et al., this volume; Rosenbaum et al., this volume). These studies show that the local streams that discharge to the lake from the east and west sides carry sediment with abundant carbonate minerals (calcite and dolomite) and high magnetic susceptibility. In contrast, sediments from the headwaters of

TABLE 1. CORE LOCATIONS AND DEPTHS

| Core name | Core type | Latitude (degrees N) | Longitude (degrees W) | Water depth relative to full lake level (m) | Depth to start of drive (m blf) | Depth to end of drive (m blf) |
|---|---|---|---|---|---|---|
| BL96-1 | K | 41.9527 | 111.3160 | 50 | 0.00 | 5.00 |
| BL96-2 | K | 41.9527 | 111.3333 | 43 | 0.00 | 3.92 |
| BL96-3 | K | 41.9532 | 111.3613 | 33 | 0.00 | 4.05 |
| BL98-4 | G | 41.9640 | 111.3750 | 31.4 | 0.00 | 0.20 |
| BL98-6 | G | 41.9640 | 111.3750 | 31.4 | 0.00 | 0.20 |
| BL98-9 | G | 41.9654 | 111.3384 | 44.4 | 0.00 | 0.33 |
| BL98-10 | G | 41.9654 | 111.3384 | 44.4 | 0.00 | 0.36 |
| BL98-12 | G | 42.0581 | 111.3116 | 31.4 | 0.00 | 0.38 |
| BLR-2K-1 (1) | U | 42.1877 | 111.2950 | 0* | 0.00 | 2.16 |
| (2) | U | | | | 2.16 | 3.55 |
| (3) | U | | | | 1.00 | 3.00 |
| BLR-2K-2 (1) | U | 42.1328 | 111.2974 | 0.8[†] | 0.00 | 1.80 |
| BLR-2K-3 (1) | U | 42.1559 | 111.3038 | 0.6[†] | 0.00 | 2.07 |
| BL2K-1 (1) | U | 42.1143 | 111.2983 | 6.1 | 0.00 | 1.10 |
| BL2K-2 (1) | U | 42.1063 | 111.2944 | 8.3 | 0.00 | 2.07 |
| (2) | U | | | | 1.50 | 3.57 |
| BL2K-3 (1) | U | 42.1142 | 111.2992 | 5.8 | 0.02 | 2.05 |
| BL2002-1 (1) | U | 42.1016 | 111.2912 | 9.5 | 0.00 | 1.40 |
| (2) | U | | | | 0.78 | 2.60 |
| BL2002-2 (1) | U | 42.0837 | 111.2975 | 18.0 | 0.00 | 1.37 |
| BL2002-3 | G | 42.0322 | 111.3191 | 42.9 | 0.00 | 0.15 |
| (1) | U | | | | 0.08 | 1.72 |
| (2) | U | | | | 1.18 | 2.83 |
| BL2002-4 | G | 42.0496 | 111.3106 | 34.5 | 0.00 | 0.39 |
| (1) | U | | | | 1.00 | 2.77 |
| (2) | U | | | | 2.37 | 4.14 |
| (3) | U | | | | 0.06 | 1.89 |
| BL2002-5 (1) | U | 42.0666 | 111.3046 | 26.8 | 0.10 | 1.91 |
| BL00-1 (D) | GLD | 41.9517 | 111.3083 | 54.8 | 0.00 | 100.47 |
| BL00-1 (E) | GLD | 41.9517 | 111.3083 | 54.8 | 0.00 | 120.65 |

*Note:* K—Kullenburg core; G—gravity core; U—UWITEC percussion core; GLD—GLAD800 drill core; blf—below lake floor.

*Core on dry land.

[†] Depth in Mud Lake.

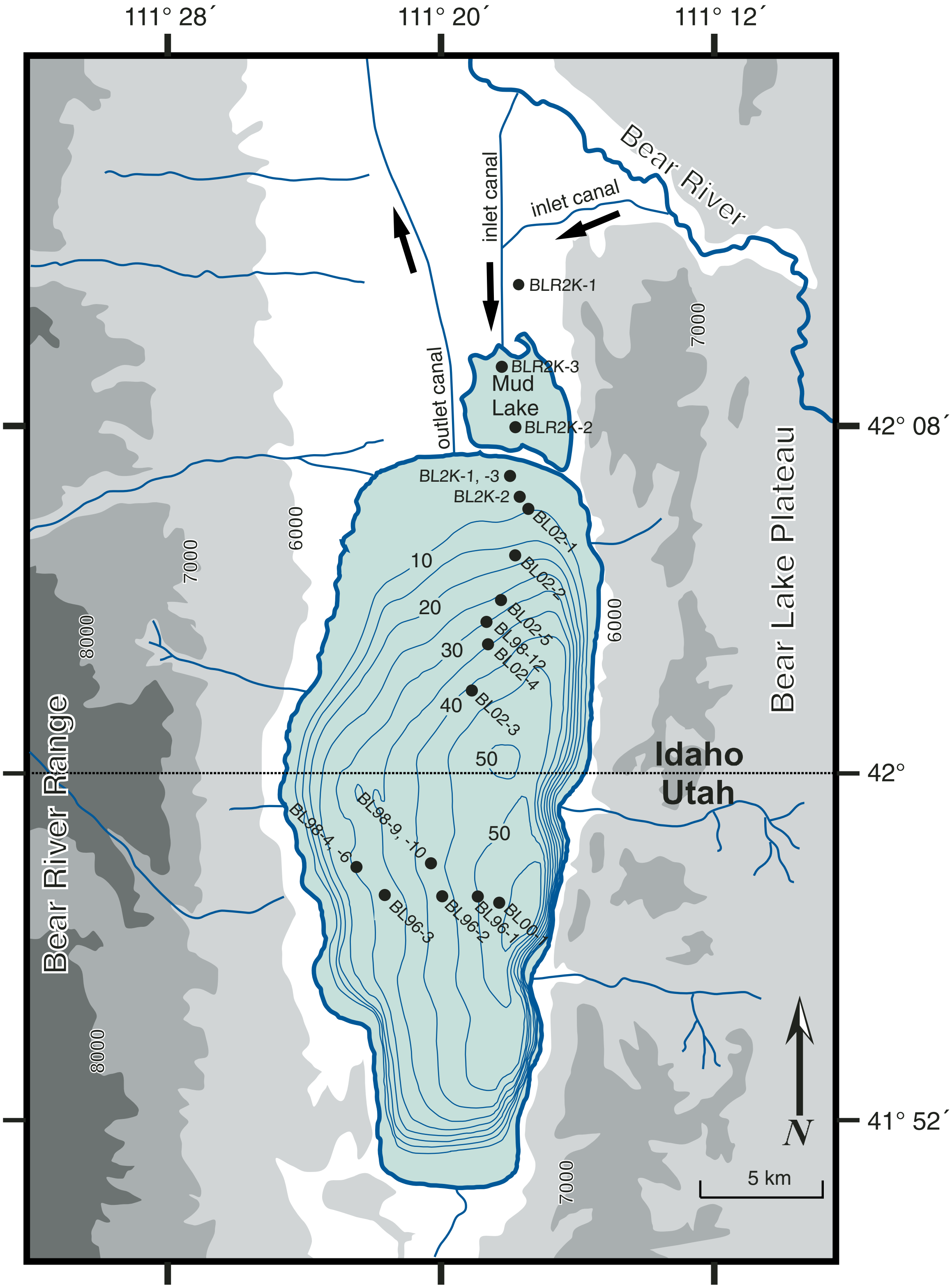

Figure 3. Core locations in and around Bear Lake. Topographic contours are in feet; bathymetric contours are in meters.

the Bear River in the Uinta Mountains lack carbonate minerals, have low susceptibility, but have high contents of hematite. Sediment traps deployed in Bear Lake record the production of high-magnesium carbonate and reveal the strong influence of sediment remobilization near the lake bottom (Dean, this volume).

## SEDIMENTARY RECORD OF BEAR LAKE

### Geochronology

Chronology for sediments deposited over the last 30 k.y. is based on the radiocarbon-dated stratigraphic framework developed by Colman et al. (this volume) from multiple cores. The geochronology of sediment beyond the range of radiocarbon dating is poorly constrained. A feature in the paleomagnetic data at 26.5 m depth in core BL00-1 may record the Laschamp excursion (Heil et al., this volume), and previously published data on U-series, amino acids, and tephra (Colman et al., 2006) are consistent with a relatively steady rate of sediment accumulation with an average for the last 220 k.y. of 0.54 mm $yr^{-1}$ near the depocenter (Kaufman et al., this volume).

### Allogenic and Endogenic Components

Sediment deposited in Bear Lake is strongly influenced by variable production of carbonate within the lake, by fluctuating input of fluvial and glacial-fluvial products, and by periodic retraction of the lake into a topographically closed basin. These changes are reflected in interpretations based on both allogenic lithic material (Rosenbaum et al., this volume) and endogenic carbonate (Dean, this volume) of the lake sediment. More specifically, the sediment has been studied for its paleomagnetism (Heil et al., this volume) and mineral magnetism (Heil et al., this volume; Rosenbaum and Heil, this volume; Rosenbaum et al., this volume); isotopic composition of endogenic carbonate (Dean, this volume; Kaufman et al., this volume); mineralogy and elemental geochemistry (Dean, this volume; Rosenbaum et al., this volume; Kaufman et al., this volume; Smoot, this volume); and sedimentary features (Smoot, this volume; Smoot and Rosenbaum, this volume).

Bear Lake sediment is primarily massive gray to greenish-gray calcareous silty clay, with quartz as the primary mineral in most of the sediment deposited during the last 220 k.y. (Dean, this volume; Kaufman et al., this volume). Carbonate-mineral content averaged ~30% over this entire interval and averaged 57% in six marl intervals. The endogenic component of Bear Lake sediment is the focus of the chapter by Dean, who investigated the limnological conditions that resulted in major variations in carbonate isotopic composition, geochemistry, and mineralogy on time scales ranging from seasons to millennia. These variations reflect climate changes in the region, which Dean (this volume) sets within a broader context of ocean and atmospheric circulation.

The 120 m section penetrated by core BL00-1 is only a fraction of the basin-fill sequence (Kaufman et al., this volume). The

Figure 4. The GLAD800 coring platform at the site of core BL00-1. View is to the east.

core comprises sediment that accumulated over the last two glacial-interglacial cycles (~220 k.y.), with essentially no hiatuses in deposition or breaks in core retrieval. We know of no other lake on the continent that has remained continuously inundated for this extended period. A large suite of analyses on the 120 m section penetrated by core BL00-1 is summarized by Kaufman et al. (this volume). Analyses have been completed at multi-centennial to millennial scales on sediment magnetic properties; oxygen, carbon, and strontium isotopes; organic- and inorganic-carbon content; palynology; mineralogy; ostracode taxonomy; and diatom assemblages. By combining evidence from multiple physical, chemical, and biological properties, the authors reconstructed the major paleoenvironmental changes during the last quarter-million years, and concluded that, although its influence has varied, the Bear River was connected to the lake for most of this period.

### Diagenesis and Reworking

Variable post-depositional destruction of detrital Fe-oxides and formation of Fe-sulfides (e.g., greigite and pyrite) indicates changing geochemical conditions (Heil et al., this volume), with good preservation of magnetite and hematite under only the freshest water conditions and pyrite formation under the most saline conditions. Ostracodes decrease in abundance in the lower half of the long core, probably because they were dissolved (Kaufman et al., this volume). Sediment traps installed near the lake bottom reveal extensive resuspension of older, aragonite-bearing lake sediment (Dean, this volume). Sediment cores contain unconformities, shell-rich gravel, rooting structures, and pedogenic features, indicating that lake level dropped as much as 40 m below present level during the past 18,000 years (Smoot, this volume; Smoot and Rosenbaum, this volume). Frequent migrations of the shoreline over tens of meters in elevation have reworked the sediment, particularly where the lake floor has low slope.

### Biological Components

Microfossils, including ostracodes, diatoms, and pollen, have been analyzed in sediment cores from Bear Lake. Changes in the abundance, preservation, and assemblages of diatoms reflect changes in hydrologic and climatic conditions over the past 19,000 years (Moser and Kimball, this volume), and the last two glacial-interglacial cycles at lower resolution (Kaufman et al., this volume). The absence of diatoms in sediment deposited during glacial periods (marine oxygen isotope stage [MIS] 6 and MIS 3/2) indicates low-light conditions associated with increased ice cover and turbidity. Diatom assemblages of interglacial periods (MIS 5 and 1) are dominated by small, benthic/tychoplanktic fragilarioid species indicative of reduced habitat availability associated with low lake levels and more saline conditions. The MIS 3 assemblage is distinct and suggests that lake level was higher during this period than during the full interglacials.

Changes in the ostracode assemblage are described for the latest Pleistocene and Holocene (Bright, Chapter 4, this volume), and over the length of core BL00-1 (Kaufman et al., this volume). With the exception of *Cytherissa lacustris*, all of the ostracode species in core BL00-1 and in water deeper than ~7 m are endemic. *C. lacustris* is generally absent from interglacial intervals, consistent with its preference for dilute lakes. It was discovered, however, in sediment that correlates with the interglacial MIS 7c. This is apparently the first documented occurrence of *C. lacustris* in the western contiguous United States during peak global interglacial conditions.

Core BL00-1 provides one of the most detailed and continuous records of Quaternary vegetation change in North America. Kaufman et al. (this volume) summarize the pollen spectra using a ratio of the "warm" (juniper and oak) plus "dry" (ragweed, saltbush, and greasewood) versus "cold" (including spruce) indicators. The pollen spectra from interglacial periods contain higher percentages of "warm" and "dry" indicators, with higher *Juniperus* percentages during the early part of each interglacial interval. Vegetation interpretations suggest that valley bottoms were occupied by salt-tolerant, high-desert shrubs, and that *Juniperus* woodlands expanded locally during interglaciations. Pollen spectra of glacial intervals generally have higher percentages of "cold" indicators, suggesting that forest or forest-woodland conditions prevailed. These assemblages are similar to those described by Doner (this volume), who analyzed a shorter core from the lake extending back 19 k.y.

## QUATERNARY CLIMATE CHANGE

### Glaciation

Quaternary climate change has caused glaciers to advance and retreat in the alpine headwaters of the Bear Lake drainage basin. The Bear River Range on the west side of Bear Lake supported glaciers that repeatedly advanced a few kilometers beyond their cirques, as mapped by Reheis et al. (this volume). The headwaters of the Bear River, in the northwestern Uinta Mountains, also supported glaciers that fluctuated with major glacial periods of the Pleistocene (Reheis et al., this volume). Meltwater charged with glacial flour from these valley glaciers left its mark on sediments of the last glacial maximum in Bear Lake. A red, siliciclastic unit recovered in several cores and dated to between 26 and 16 ka (Colman et al., this volume) is attributed to hematite-rich material derived from glacial-fluvial outwash of Uinta Mountain glaciers (Rosenbaum et al., this volume). Rosenbaum and Heil (this volume) present a continuous record of mountain-glacier extent within the upper Bear River Basin by using rock magnetic, mineralogic, and elemental composition of sediment from Bear Lake to infer the extent of glaciers in the headwaters. They conclude that glaciers began to form in the upper Bear River Basin ca. 26 cal ka; the glaciers reached their maximum extent around 20 ka, and receded by around 16 ka. Glaciers were probably extensive in the Uinta Mountains during MIS 6, but evidence of glacial flour has not been found in sediments of that age in Bear Lake. Magnetic property and mineralogic evidence may have been lost due to diagenetic alteration of these older sediments.

### Lake-Level Fluctuations and Bear River Migrations

Quaternary climate change exerted a major control on lake-level fluctuations at Bear Lake, although other geomorphic factors that influence the geometry of the outlet and the inlet of the lake also have undoubtedly played a role. As discussed by Reheis et al. (this volume), these include changes in threshold elevation caused by aggradation, downcutting, and faulting. The highest lake deposits are early Pleistocene in age and were formed ~25 m above the present lake, prior to progressive and episodic downcutting of the lake outlet. Lake level was also linked to the changing course of the Bear River. The lake basin interacts with the river in complex ways that are modulated by climatically induced lake-level changes, the distribution of active Quaternary faults, and by the migration of the river across its outwash fan north of the present lake. The various mechanisms that caused the Bear River to shift into and out of the lake are reviewed by Reheis et al. (this volume), and the resulting paleohydrogeographic reconstructions are illustrated by Kaufman et al. (this volume).

Fluctuations in lake level have been studied in auger holes and outcrops around the lake, as described by Reheis et al. (this volume), and unexpectedly low lake levels have been inferred from sedimentological features preserved in sediment cores (Smoot, this volume). Sediment grain size decreases with increasing water depth in the modern lake. Smoot and Rosenbaum (this volume) use this relation in conjunction with other sedimentary features to reconstruct a detailed history of lake-level changes since the latest Pleistocene. This record exhibits lake-level changes of tens of meters on millennial and shorter time scales. It indicates that, during the Holocene, lake level was generally lower than present.

On a longer time scale, the closed-basin configuration of the lake is restricted to the driest interglacial periods (Kaufman et al., this volume). Analyses of core BL00-1 indicate that Bear Lake retracted into a topographically closed basin only during portions of global interglaciations (MIS 7c, 7a, 5e, 5c, and 1). During these intervals, the lake generated abundant endogenic carbonate with aragonite and high values of $\delta^{18}O$ and $^{87}Sr/^{86}Sr$.

### Comparisons with Other Paleoclimate Records

The first-order fluctuations of all sediment properties analyzed in the long core from Bear Lake coincide with orbital cycles and global ice volume during the last two glacial-interglacial cycles (Dean, this volume; Kaufman et al., this volume). Millennial-scale fluctuations are pervasive throughout the last two glacial cycles and might correspond to stadial-interstadial cycles recognized in other well-known paleoclimate records, but uncertainties in age for core BL00-1 are too large to determine whether the cycles are synchronous. Millennial-scale variations in hematite content (Heil et al., this volume) and pollen assemblages (Kaufman et al., this volume) of Bear Lake sediment during the last glacial cycle resemble Dansgaard-Oeschger oscillations and Heinrich events, suggesting that the influence of millennial-scale climate oscillations influence the climate of the Great Basin. Although there are similarities in first-order trends, the timing of major lake-level changes at Bear Lake do not coincide in detail with those in the Bonneville Basin located ~100 km downstream of Bear Lake (Kaufman et al., this volume; Rosenbaum and Heil, this volume; Smoot and Rosenbaum, this volume). During the late glacial and Holocene, the lake-level history of Bear Lake is more similar to those in Pyramid Lake, Nevada, and Owens Lake, California, than to Lake Bonneville. For example, during the Younger Dryas, the level of Bear Lake seems to have lowered, whereas the level of Lake Bonneville rose (Smoot and Rosenbaum, this volume).

## POTENTIAL FUTURE STUDIES

This volume presents an extensive study of Bear Lake and its catchment. Nevertheless, there remain opportunities to improve and expand on the current studies. Such opportunities fall into several categories. First, understanding of the lake's hydrology can be improved. A conspicuous gap in knowledge is the contribution of sub-lacustrine springs to the hydrologic budget. Second, different techniques (e.g., biogeochemistry, different microfossils) could be employed to derive additional paleoenvironmental proxies. For instance, it would be particularly useful to separate the effects of temperature and precipitation on changes in lake level. Third, temporal resolution of the records can be improved by denser sampling. This is especially true for the record older than ca. 26 cal ka (i.e., that part of the record sampled only in the long cores from site BL00-1). However, the resolution of the Holocene section could be improved through dense sampling of core BL00-1, which has the highest deposition rate and most continuous section. Of particular interest would be a similarly high resolution study of the last interglaciation (continuous sequences are rare in North America) and a comparison with the Holocene. Fourth, and perhaps most importantly, an improved chronology for the record beyond the range of radiocarbon dating would increase the value of existing and future proxy records immensely.

## ACKNOWLEDGMENTS

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