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The glacial/deglacial history of sedimentation in Bear Lake, Utah and Idaho

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ABSTRACT

Bear Lake, in northeastern Utah and southern Idaho, lies in a large valley formed by an active half-graben. Bear River, the largest river in the Great Basin, enters Bear Lake Valley ~15 km north of the lake. Two 4-m-long cores provide a lake sediment record extending back ~26 cal k.y. The penetrated section can be divided into a lower unit composed of quartz-rich clastic sediments and an upper unit composed largely of endogenic carbonate. Data from modern fluvial sediments provide the basis for interpreting changes in provenance of detrital material in the lake cores. Sediments from small streams draining elevated topography on the east and west sides of the lake are characterized by abundant dolomite, high magnetic susceptibility (MS) related to eolian magnetite, and low values of hard isothermal remanent magnetization (HIRM, indicative of hematite content). In contrast, sediments from the headwaters of the Bear River in the Uinta Mountains lack carbonate and have high HIRM and low MS. Sediments from lower reaches of the Bear River contain calcite but little dolomite and have low values of MS and HIRM. These contrasts in catchment properties allow interpretation of the following sequence from variations in properties of the lake sediment: (1) ca. 26 cal ka—onset of glaciation; (2) ca. 26–20 cal ka—quasi-cyclical, millennial-scale variations in the concentrations of hematite-rich glacial flour derived from the Uinta Mountains, and dolomite- and magnetite-rich material derived from the local Bear Lake catchment (reflecting variations in glacial extent); (3) ca. 20–19 cal ka—maximum content of glacial flour; (4) ca. 19–17 cal ka—constant content of Bear River sediment but declining content of glacial flour from the Uinta Mountains; (5) ca. 17–15.5 cal ka—decline in Bear River sediment and increase in content of sediment from the local catchment; and (6) ca. 15.5–14.5 cal ka—increase in content of endogenic calcite at the expense of detrital material. The onset of glaciation indicated in the Bear Lake record postdates the initial rise of Lake Bonneville and roughly corresponds to the Stansbury shoreline. The lake record indicates that maximum glaciation occurred as Lake Bonneville reached its maximum extent ca. 20 cal ka and that deglaciation was under way while Lake Bonneville remained at its

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peak. The transition from siliciclastic to carbonate sedimentation probably indicates increasingly evaporative conditions and may coincide with the climatically driven fall of Lake Bonneville from the Provo shoreline. Although lake levels fluctuated during the Younger Dryas, the Bear Lake record for this period is more consistent with drier conditions, rather than cooler, moister conditions interpreted from many studies from western North America.

INTRODUCTION

Bear Lake is a large, long-lived lake that lies in the southern end of a fault-bounded valley astride the Utah-Idaho border (Fig. 1), and contains a thick sequence of Quaternary sediments (Colman, 2006). The upper 120 m of these sediments, which were penetrated near the depocenter by core BL00-1 during testing of the GLAD800 coring platform (Dean et al., 2002), provide a record of at least the last two glacial–interglacial cycles (Kaufman et al., this volume).

The Bear River arises in glaciated terrain in the Uinta Mountains, flows generally northward, and then crosses an outwash fan north of the lake as it enters the Bear Lake Valley (Reheis et al., this volume). During historic times and throughout much of the Holocene the river continued to the north (Fig. 1) without entering the lake, exiting the valley before bending to the south on its way to Great Salt Lake. At times in the past, however, the river flowed into the lake (Kaufman et al., this volume). Many factors may influence the relation between the river and the lake, including surficial processes such as migration of the river on the outwash fan, active tectonism that may have changed the river's course, and changes in climatic conditions that caused the lake to rise or fall, thereby capturing or abandoning the river (Reheis et al., this volume).

The endogenic and allogenic materials in Bear Lake provide a complex record of past environmental conditions. Endogenic minerals (Dean et al., 2006; Dean, this volume) and biologic materials yield a record of changing hydrologic conditions, whereas allogenic materials provide information about erosional processes and fluvial transport within the catchment areas. The presence or absence of the Bear River has a large influence on both the endogenic and allogenic components. When the Bear River did not enter Bear Lake, the lake was fed by short local streams and sublacustrine springs and was probably topographically closed or intermittently overflowing. During such times, the lake precipitated abundant carbonate minerals; lake level (Smoot and Rosenbaum, this

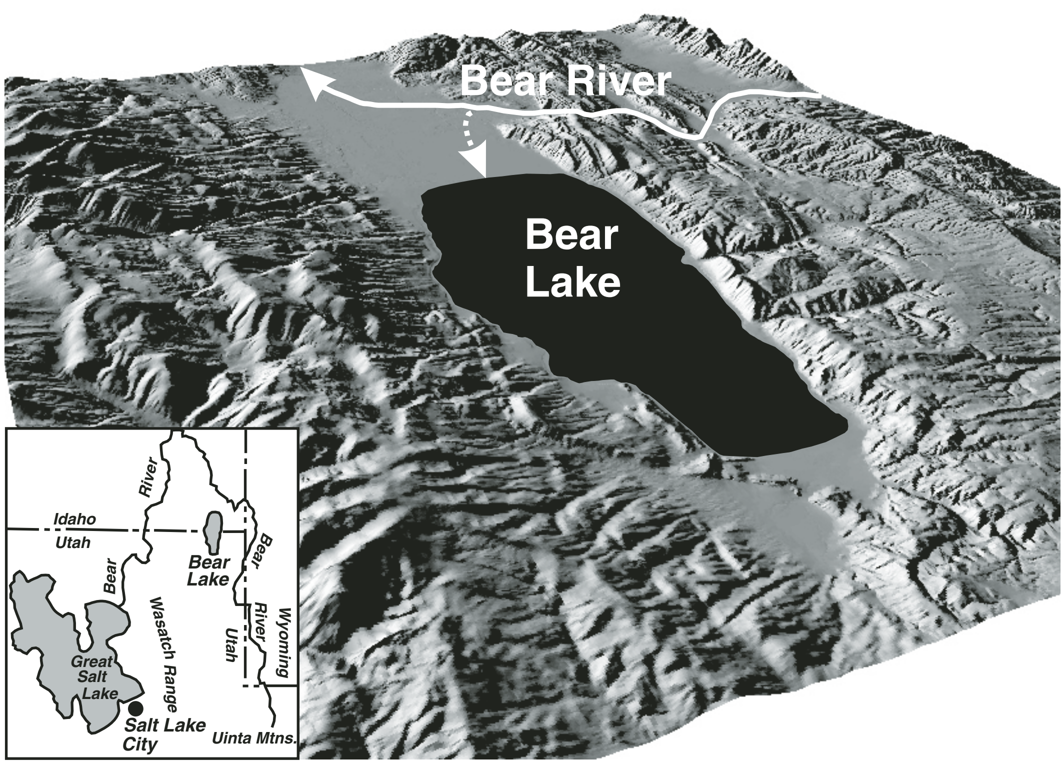

Figure 1. Shaded relief digital elevation model of Bear Lake area (view to the northeast) and location of Bear Lake and the Bear River. The dashed arrow indicates the approximate path of the river when it entered the lake.

volume), mineralogy, and stable isotopes (Dean, this volume) were sensitive to evaporative conditions; and all fluvial sediment was derived from the local catchment. When the Bear River flowed into Bear Lake, the lake was more likely to be fresh and overflowing. At such times the lake precipitated little if any carbonate minerals and fluvial sediments were derived from the Bear River above Bear Lake Valley as well as from the local catchment.

In this paper we interpret the paleoenvironmental record from the onset of the last period of extensive local glaciation to the beginning of the Holocene. The analysis is based on multi-proxy data sets from two 4-m-long cores, BL96-2 and BL96-3, located in ~40 m and 30 m of water respectively (Fig. 2). Core BL96-2 contains ~3 m of carbonate-rich sediment overlying ~1 m of siliciclastic material (Dean et al., 2006). Core BL96-3

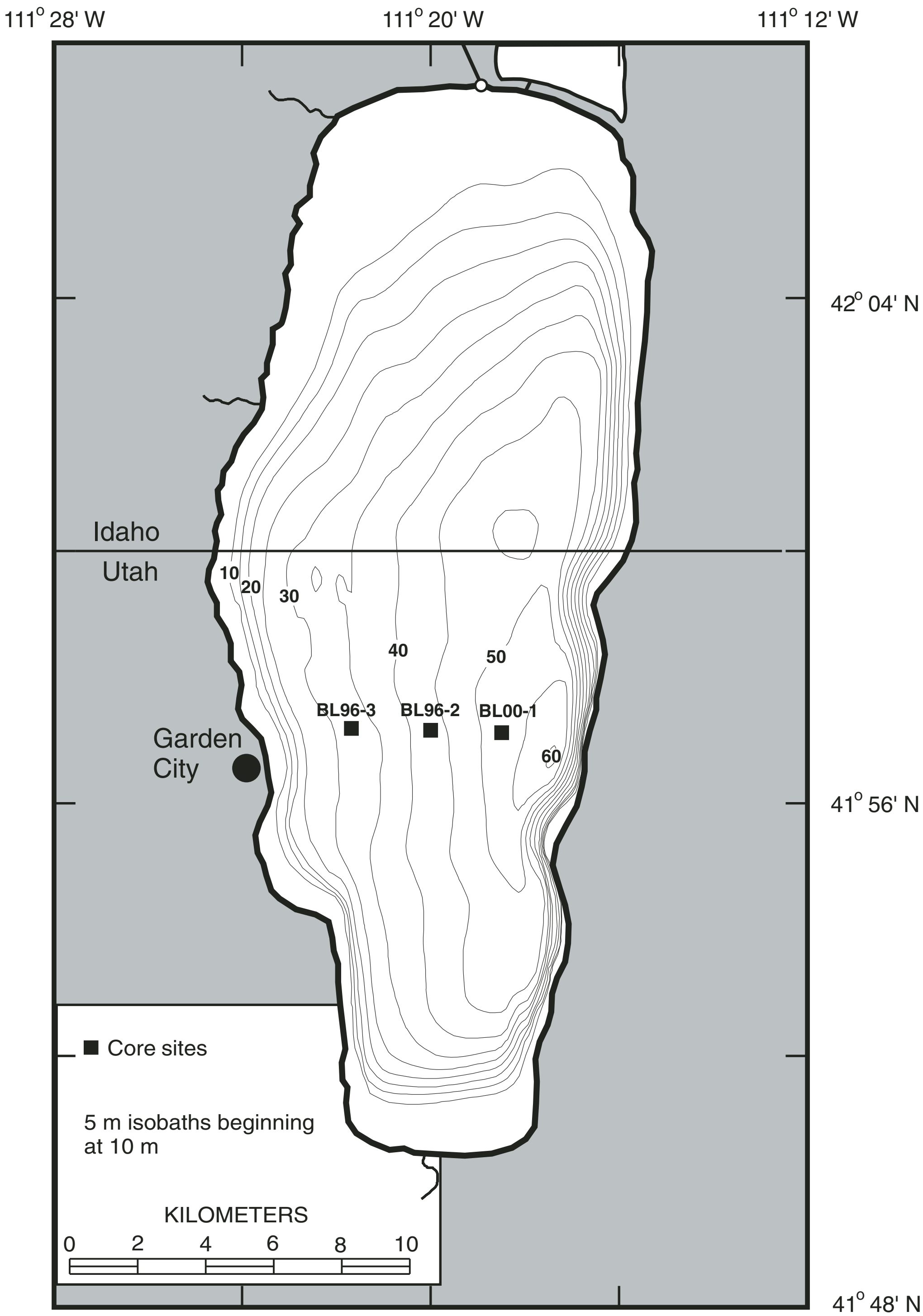

Figure 2. Coring locations BL96-2, BL96-3, and BL00-1. Bathymetry was mapped in 2002 by Denny and Colman (2003).

contains a highly attenuated, incomplete section of the carbonate-rich sediment overlying more than 3.5 m of the older siliciclastic unit. Several distinct horizons (e.g., changes in mineralogy and magnetic properties) allow the sections penetrated by these and other cores to be precisely correlated (Colman et al., this volume; Dean, this volume; Rosenbaum et al., this volume). Together the two cores provide a nearly complete composite record extending from ca. 26 cal ka to the late Holocene. Chronology is provided by age models based on radiocarbon ages obtained mostly from pollen concentrates (Colman et al., this volume). These concentrates contain pollen and other refractory organic material (e.g., charcoal) that survived dissolution of carbonate and silicate minerals during standard pollen preparation procedures. For the carbonate-rich sediment in core BL96-2, the age model is based on 17 radiocarbon ages. Because of the discontinuous nature of the record, no age model was created for the attenuated carbonate-rich section in core BL96-3. Earlier studies (Colman et al., 2005; Dean et al., 2006; Laabs et al., 2007) accepted ages from sediments interpreted herein to contain glacial flour, but Colman et al. (this volume) determined that all such ages are thousands of years too old. Therefore, for glacial flour-rich sediments, an age model using ages from above and below the glacial flour-bearing sediments was constructed for core BL00-1 (Fig. 2). Interpolated ages for distinct horizons were then transferred to cores BL96-2 and BL96-3. Six such horizons were used to provide age control for core BL96-2 and ten were used for BL96-3 (Colman et al., this volume). The radiocarbon analyses provide an apparently reliable chronology, although potential systematic errors of a few hundred years from possible reworking of sediment (Smoot and Rosenbaum, this volume) and storage in the catchment cannot be fully evaluated. Although actual dating uncertainty is probably several hundred years, we give calibrated ages to the nearest 100 years provided by the cubic spline models of Colman et al. (this volume) for the purpose of describing variations in proxy data and environmental change with age.

The record of environmental change derived from the siliciclastic sediments provides an interpreted glacial history. This record is largely based on changes in provenance of detrital material in the Bear Lake sediments. Therefore, we first describe some properties of fluvial sediments from the Bear River and from streams entering the lake that allow us to infer such changes.

PROPERTIES OF FLUVIAL SEDIMENTS

As shown by Rosenbaum et al. (this volume), there are significant differences in the mineralogy, elemental composition, and magnetic properties of fluvial sediments among the various areas that have supplied detrital material to Bear Lake. In part, these differences reflect differences in bedrock geology (Fig. 3), but, in the case of some magnetic properties, differences reflect variable concentrations of dust in the fluvial material (Reynolds and Rosenbaum, 2005). Although the ferrimagnetic Fe-oxide grains in dust are mostly not derived from the local bedrock, Rosenbaum et al. (this volume) demonstrate that such grains are delivered to the lake largely through fluvial input and therefore provide a powerful tool to assess changes in provenance for the Bear Lake sediments. For the purpose of understanding the provenance of detrital material, the catchment was divided into three areas: (1) the local Bear Lake catchment (i.e., stream sampling sites 1 and 7–17 on Fig. 3), (2) the lower Bear River (sites 19–45), and (3) the headwaters of the Bear River in the Uinta Mountains (sites 47–53).

Although there are significant differences among the properties of the different size fractions of the alluvial sediment, only data from the finest-sized fraction (<63 μm) from the local catchment and the lower Bear River are considered here because Bear Lake sediments contain little detrital material coarser than silt, except in very shallow water (Rosenbaum et al., this volume). For the headwaters of the Bear River, data for both the <63 μm fraction and the coarse-sand-sized fraction are considered, because late Pleistocene glaciers in that area would have generated fine-grained material from lithologies now largely represented in the coarser fractions of the river sediments. There is little difference among the magnetic properties of the fine-sand, coarse-sand, and pebble fractions, and mineralogical and chemical data were acquired from only the <63 μm and coarse-sand-sized fractions (Rosenbaum et al., this volume).

Local Bear Lake Catchment

On average, samples of <63 μm fluvial material from the local catchment contain more dolomite and more ferrimagnetic minerals than other potential sediment sources (Fig. 4). Outcrops on the west side of Bear Lake are largely lower Paleozoic formations containing large amounts of dolomite, quartzite, and limestone. The west-side exposures contain lesser amounts of Precambrian quartzite and shale, and fluvial clastic rocks of the Tertiary Wasatch Formation (Fig. 3). In contrast, rocks on the east side of the lake consist of Mesozoic limestone and clastic sedimentary rocks (with little dolomite) as well as widespread Wasatch Formation (Oriel and Platt, 1980; Dover, 1995). The widespread dolomitic rocks on the west side of the lake are reflected in the mineralogy and elemental chemistry of fluvial sediments in the area (Table 1). The average dolomite and Mg contents of the local catchment samples are much higher than averages from other potential sediment sources (Fig. 4). Differences in bedrock between east-side and west-side sources contribute to the high dispersion of dolomite, calcite, and Mg contents.

The average magnetic susceptibility of samples from the local catchment is more than 2.5 times greater than that from either of the other areas (Table 1, Figs. 4 and 5). Samples from both the east and west sides of the lake have similar magnetic properties despite differences in bedrock. The stream sediments, both from the local catchment and from along the Bear River, contain a wide variety of silt-sized Fe-oxide mineral grains (including magnetite, titanomagnetite, and ilmenohematite), most of which must have been derived from lithologies not present in the watersheds and are therefore interpreted to be a component of dust (Reynolds and Rosenbaum, 2005). The high susceptibilities of stream

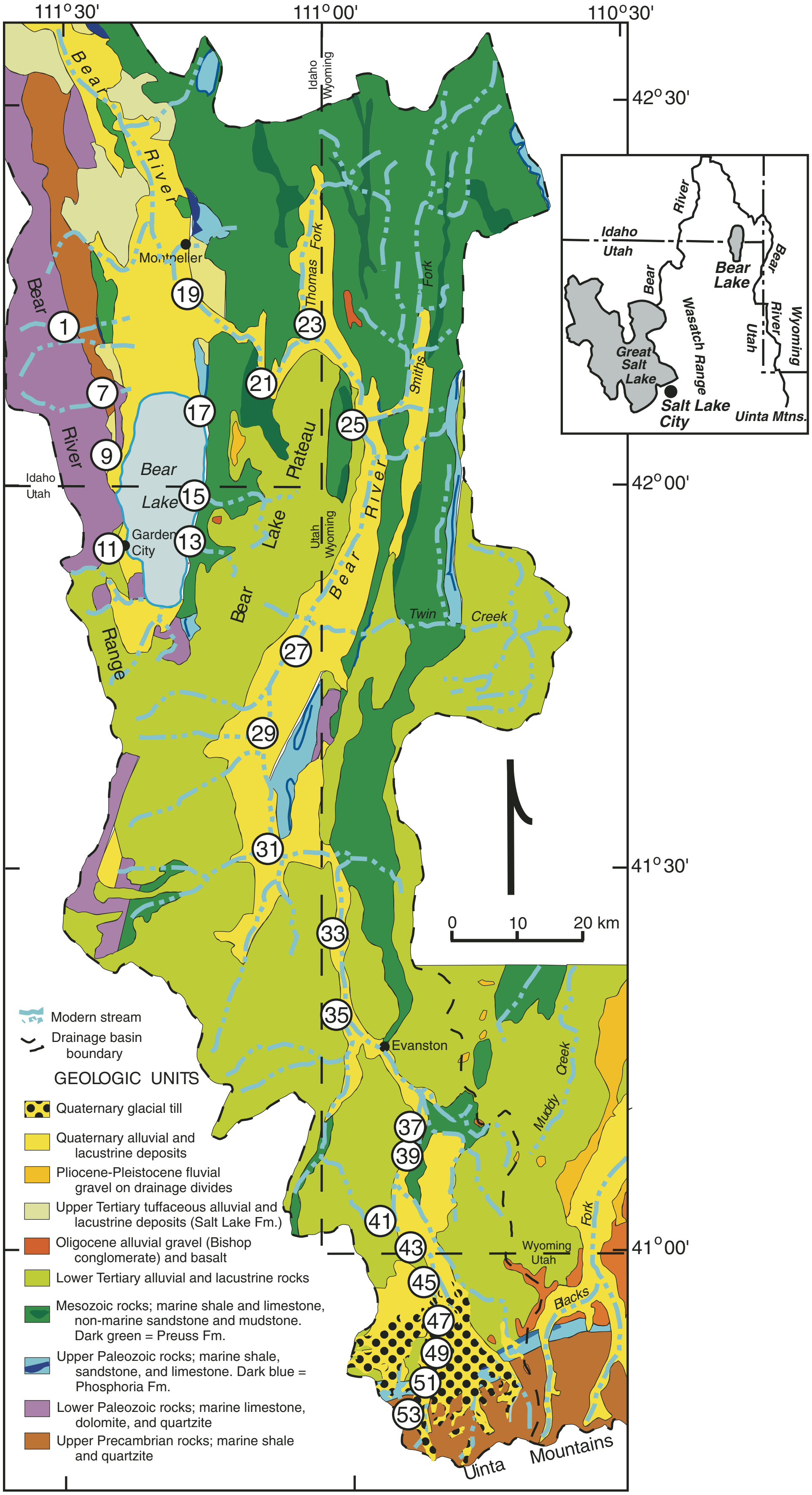

Figure 3. Generalized geologic map of the Bear Lake area and the Bear River drainage above Bear Lake Valley (modified from Reheis et al., this volume). Numbered circles are stream sample locations. Odd-numbered samples were collected from stream bottoms. Even-numbered samples (not shown) were collected from bank or over-bank deposits near locations of the odd-numbered samples.

samples from the local catchment as compared to susceptibilities from along the Bear River reflect either greater amounts of dust deposition or less dilution by locally derived rock material.

Headwaters of the Bear River

The mineralogy and elemental chemistry of samples from the headwaters of the Bear River differ markedly from those of the local Bear Lake catchment (Fig. 4). The headwaters of the Bear River contain Precambrian quartzites and shales of the Uinta Mountain Group (Bryant, 1992), which commonly contain abundant hematite cement (Ashby et al., 2005). The Bear River sediments in this area contain little calcite and no dolomite and, as a consequence, have low contents of Ca and Mg (Table 1). Al and Ti contents of the <63 μm and coarse-sand fractions differ greatly. Values for the finer fraction are slightly higher than those from the local Bear Lake catchment and lower reaches of the Bear River, whereas values for the coarser fraction are significantly lower than from either of these areas. In comparison to these other source areas, values of Al/Ti from the headwaters of the Bear River are significantly higher, with the fine-fraction yielding values ~1.5 times those from these other areas and the coarse fraction values ~3 times as high (Table 1).

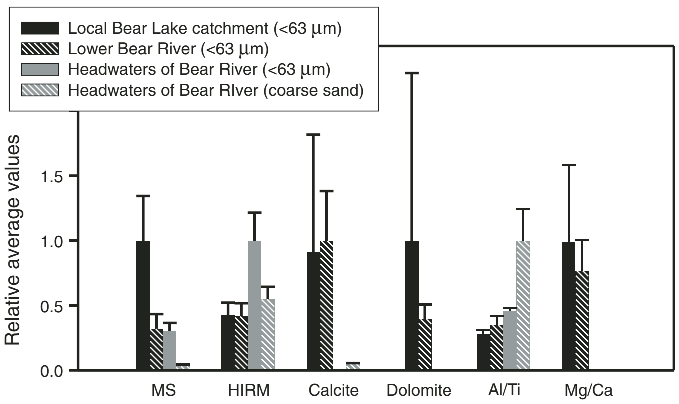

Figure 4. Relative average values and standard deviations of magnetic susceptibility (MS), hard isothermal remanent magnetization (HIRM), minerals, and elemental ratios for fluvial sediments. Mg/Ca values are not shown for samples from the headwaters because these samples contain very small quantities of carbonate minerals, and for these samples Mg and Ca reflect silicate minerals. In the lower reaches of the Bear River and in the Bear Lake catchment Mg and Ca probably reflect dolomite and calcite.

Magnetic properties of the headwater samples are also distinct from other areas. The hematite content (as measured by hard isothermal remanent magnetization [HIRM]) of the coarse-sand fraction is greater than the contents from the other source areas by a factor of ~1.3 and the content of the <63 μm fraction is greater by a factor of ~2.4 (Table 1, Fig. 4). Magnetic susceptibility (MS) values for the two size fractions also differ greatly. Both indicate that the content of ferrimagnetic minerals is much lower than in samples from the local Bear Lake catchment. MS of the finer fraction is about the same as for samples from the lower reaches of the Bear River, whereas MS for the coarser fraction is an order of magnitude lower. For the two size fractions of the headwater samples, differences in hematite content and in elemental concentrations probably reflect differences in the lithologies contained in the fractions. Differences in MS, however, are probably due

TABLE 1. MEAN VALUES AND STANDARD DEVIATIONS FOR MAGNETIC, MINERALOGICAL, AND ELEMENTAL DATA FROM STREAM SAMPLES IN DIFFERENT CATCHMENT AREAS

	Local Bear Lake Catchment <63 μm	Lower Bear River <63 μm	Upper Bear River <63 μm	Upper Bear River coarse sand
MS x 10^{-7} (m^3kg^{-1})	5.63 ± 1.96 (14)	1.82 ± 0.64 (28)	1.71 ± 0.37 (8)	0.21 ± 0.07 (8)
HIRM x 10^{-4} (Am^2kg^{-1})	3.47 ± 0.81 (13)	3.38 ± 0.84 (26)	8.12 ± 1.76 (8)	4.46 ± 0.78 (8)
Quartz (%)	69 ± 14 (13) 71 ± 10 east 67 ± 17 west	77 ± 6 (20)	82 (2)	90 ± 1 (4)
Calcite (%)	11 ± 11 (13) 20 ± 11 east 4 ± 4 west	12 ± 5 (20)	0 (2)	<1 (4)
Dolomite (%)	12 ± 17 (13) 3 ± 1 east 21 ± 19 west	5 ± 1 (20)	0 (2)	0 (4)
Ca (%)	6.03 ± 2.28 (8)	5.38 ± 1.15 (14)	0.81 ± 0.14 (4)	0.05 ± 0.01 (4)
Mg (%)	1.80 ± 1.39 (8)	1.21 ± 0.29 (14)	0.91 ± 0.14 (4)	0.11 ± 0.03 (4)
Mg/Ca	0.30 ± 0.17 (8)	0.23 ± 0.07 (14)	1.15 ± 0.031 (4)	2.25 ± 0.18 (4)
Al (%)	3.72 ± 0.68 (8)	4.64 ± 1.32 (14)	7.31 ± 1.20 (4)	2.44 ± 0.17 (4)
Ti (%)	0.21 ± 0.04 (8)	0.21 ± 0.03 (14)	0.25 ± 0.03 (4)	0.04 ± 0.01 (4)
Al/Ti	18 ± 2 (8)	22 ± 5 (14)	30 ± 2 (4)	65 ± 16 (4)

Note: Number of measurements given in parentheses. Values for quartz, calcite, and dolomite in the local Bear Lake catchment are given for all 13 samples from around the lake and for samples subdivided into those from the east side (6 samples) and those from the west side (7 samples). MS—magnetic susceptibility; HIRM—hard isothermal remanent magnetization.

in large part to origin of most of the ferrimagnetic Fe-oxides as a component of dust. The silt-sized dust particles are highly concentrated in the <63 µm fraction of the alluvial sediment.

Lower Bear River

Properties of alluvial sediments from the lower reaches of the Bear River are similar to those of sediments from the local Bear Lake catchment, but differ in several important ways. Sediments from the two areas have similar contents of calcite, Al, Ti, and Ca, and nearly identical values of HIRM (Table 1, Fig. 4). The content of dolomite in the lower Bear River sediment is about the same as in the streams on the east side of Bear Lake and much lower than in streams on the west side (Table 1), so that overall the Bear River sediments have less dolomite (and therefore less Mg) than average sediment from streams in the local catchment. In addition, MS values are much lower for the Bear River sediments than for those from the local catchment, indicating that the Bear River sediment contains lower concentrations of dust.

In contrast to samples from the headwaters, the lower Bear River sediments have lower values of Al/Ti and HIRM as well as higher concentrations of carbonate minerals (Table 1). Importantly, sediments derived from the small catchment area in the Uinta Mountains are quickly diluted by material from other parts of the catchment so that under present (interglacial) conditions Precambrian Uinta Mountain Group material is a minor component of Bear River sediment (see HIRM in Fig. 5).

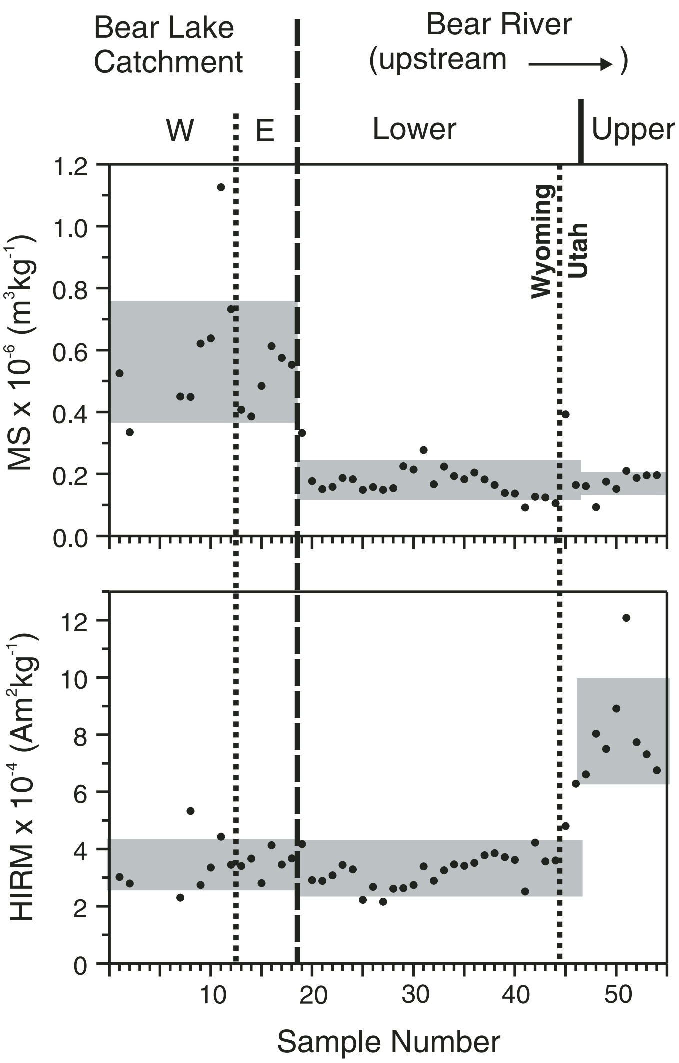

Figure 5. Magnetic susceptibility (MS) and hard isothermal remanent magnetization (HIRM) of catchment samples. Sample locations are shown on Figure 3. Shaded boxes indicate one standard deviation about the mean.

PROPERTIES OF LAKE SEDIMENTS

Stratigraphic Zones

The composite section sampled by cores BL96-2 and BL96-3 was divided into seven zones based on changes in carbonate and quartz contents, magnetic properties (MS and HIRM), and elemental ratios (Fig. 6). Zones 1a–1d are characterized by high quartz content, low carbonate content, and intermediate to high values of MS and HIRM relative to the full range of values observed in the section. Zone 1a extends from the base of core BL96-3 to the top of a sharp decrease in MS and coincident increase in HIRM. This zone is distinguished by well-defined variations in MS, HIRM, Mg/Ca, and Al/Ti. Within zone 1a, MS is negatively correlated with HIRM and positively correlated with Mg/Ca (Fig. 6 and 7). In addition, Al/Ti varies with HIRM. As noted by Rosenbaum et al. (this volume), these relations begin to change in zone 1b (equivalent to their zone I). The top of zone 1b occurs at maxima in HIRM and Al/Ti (Fig. 6). Within this zone, variations in MS are unmatched by variations in Mg/Ca, which remains essentially constant (Fig. 7). Values of Mg/Ca are consistently higher than those predicted by the relation between Mg/Ca and MS in zone 1a. Zone 1c extends from the top of zone 1b to an upward increase in Mg/Ca. Values of Mg/Ca in zone 1c are similar to those in zone 1b and do not vary with MS. Relative to zones 1a and 1b, MS in zone 1c varies less with HIRM. The upper boundary of zone 1d is defined by the beginning of a decrease in quartz content and concomitant increase in carbonate content. Within this zone, Mg/Ca varies with MS and HIRM varies inversely with MS, but with trends that are offset from those in zone 1a (Fig. 7). Zone 2a marks a major transition in sedimentation. Within this zone, the sediment becomes progressively enriched in endogenic carbonate at the expense of detrital material (e.g., quartz). MS, HIRM, and Mg/Ca decrease upward across zone 2a. The lower boundary of zone 2b is the beginning of an interval of nearly constant calcite content (~40%). The calcite content increases abruptly in the upper part of zone 2b. MS and HIRM continue to decrease across this zone (although there are two spikes in MS of unknown origin) and Mg/Ca is uniformly low. The boundary between zones 2b and 2c is defined by a sharp increase in aragonite content. MS, HIRM, and Mg/Ca are low throughout zone 2c.

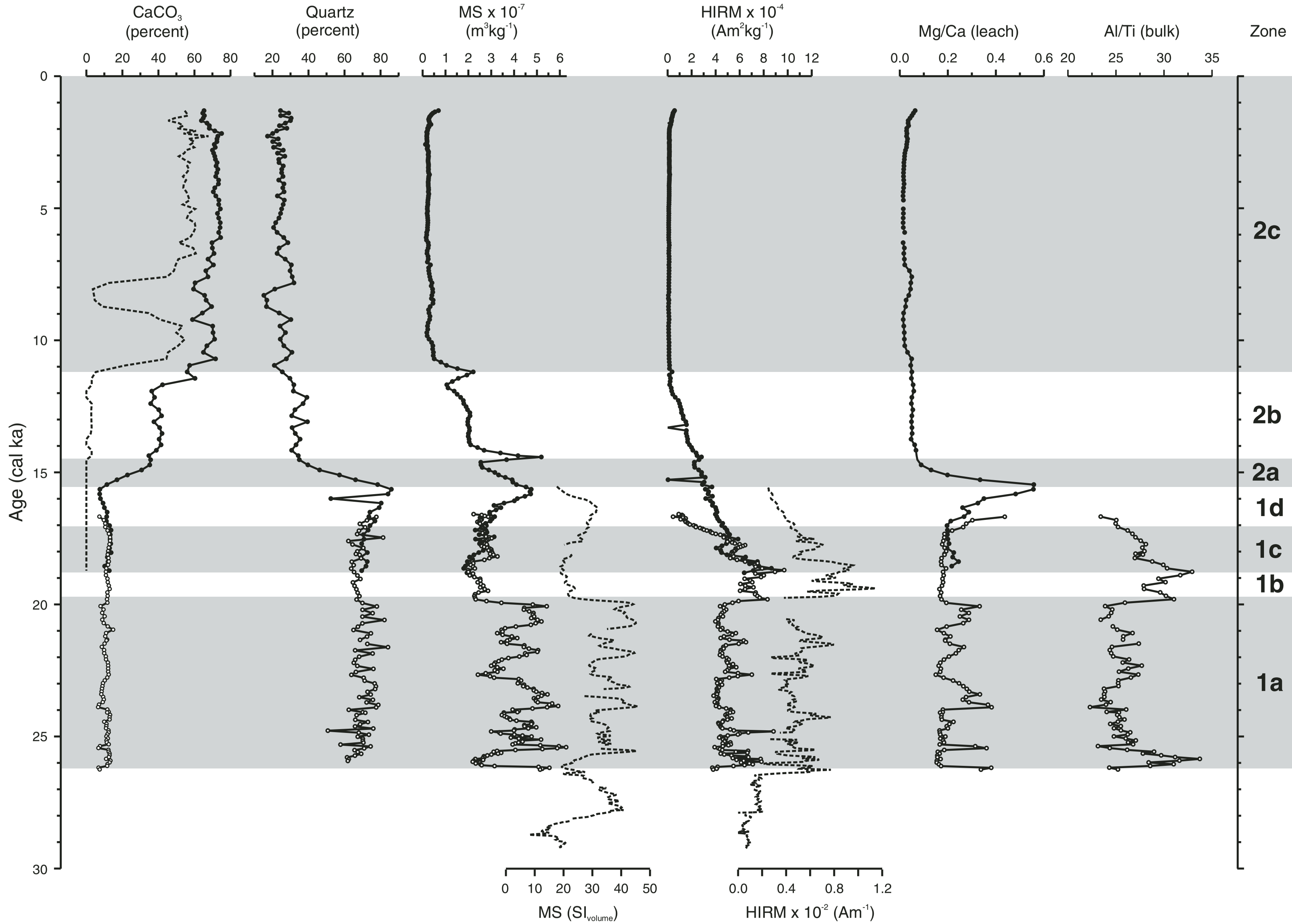

Figure 6. Contents of $CaCO_3$ and quartz (Dean, this volume), magnetic susceptibility (MS), hard isothermal remanent magnetization (HIRM; Rosenbaum et al., this volume), and elemental ratios versus age for cores BL96-2 (solid circles) and BL96-3 (open circles). Ages are from cubic spline models of Colman et al. (this volume). Data from the uppermost 40 cm of core BL96-3 are not plotted because the age control for that part of the core is limited. The dashed line on the carbonate plot shows the content of aragonite. Dashed curves for MS and HIRM are from core BL00-1 (Heil et al., this volume). Mg/Ca values were determined from acid-leached samples (Bischoff et al., 2005); Al/Ti values were determined for bulk samples (Rosenbaum et al., this volume). Stratigraphic zones are described in the text.

Changes in Provenance

Between 26 and 15.5 cal ka, zones 1a–1d, the sediments contain little, if any, endogenic carbonate. These sediments consist largely of quartz with lesser amounts of calcite, dolomite, and small quantities of other minerals (Dean et al., 2006). The quartz and carbonate-mineral contents remain relatively constant (Fig. 6), and detrital Fe-oxide minerals appear largely unaffected by post-depositional alteration (Reynolds and Rosenbaum, 2005; Rosenbaum et al., this volume). Within this interval, the properties of stream sediments, described above, provide a qualitative basis for interpreting changes in sources of the lithogenic material (Table 2).

The quasi-cyclical variations in magnetic properties and elemental ratios in zone 1a (Fig. 6) are interpreted to reflect variations in the concentrations of detrital material derived from Uinta Mountain Group rocks and of that derived from local Bear Lake catchment. HIRM and Al/Ti are highly correlated (Fig. 7) and high values of these parameters indicate high concentrations of sediment derived from headwaters of the Bear River. Similarly, MS and Mg/Ca are highly correlated and high values of these parameters indicate elevated concentration of sediment from the local Bear Lake catchment, with high values of MS indicating high input of dust from surficial material, and high values of Mg/Ca indicating high input from dolomitic bedrock. The strong

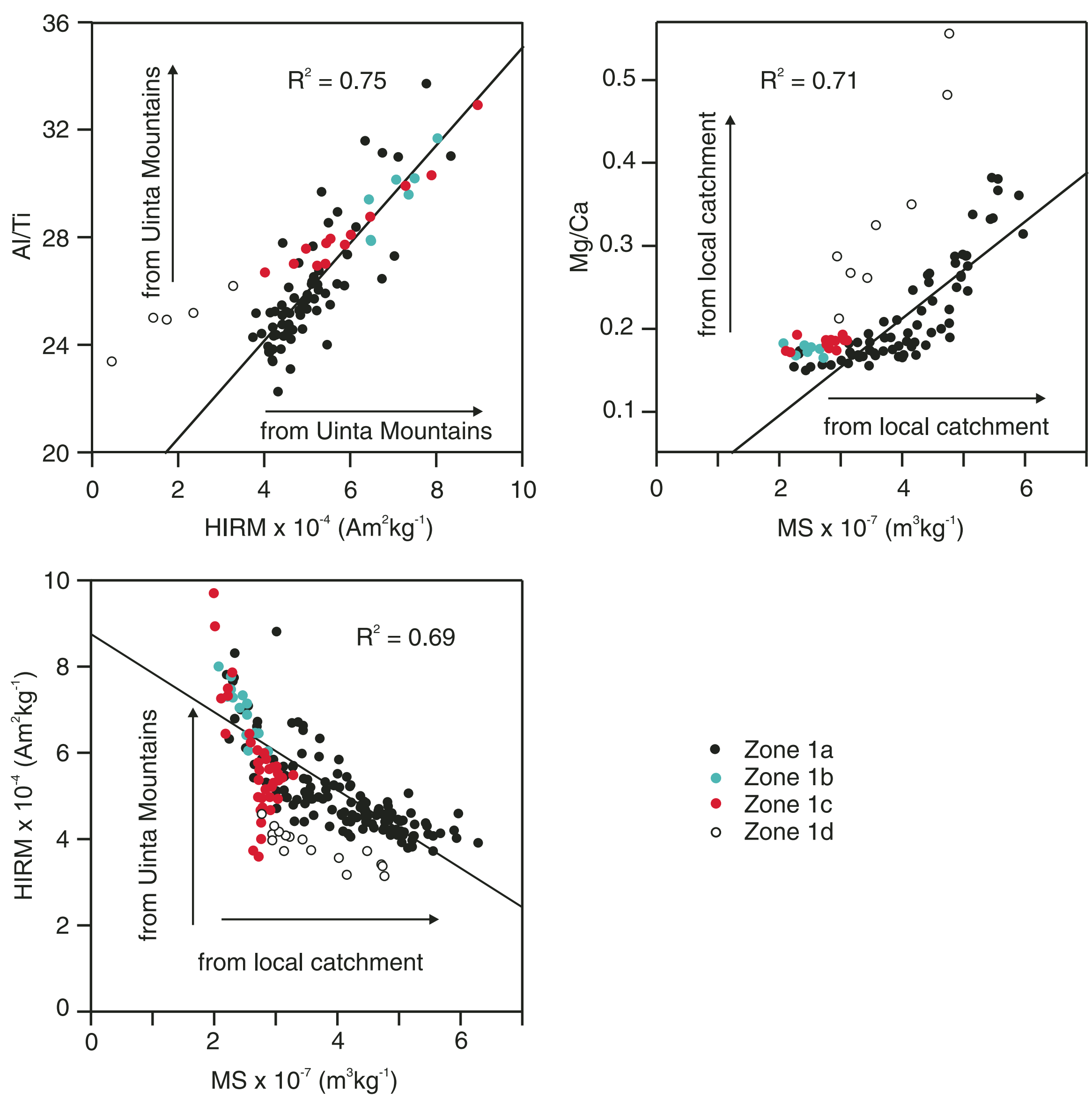

Figure 7. Plots of magnetic properties and elemental ratios for samples from zones 1a–1d, showing: (1) the positive relations between HIRM and Al/Ti (indicative of material from the Uinta Mountains), and MS and Mg/Ca (indicative of the local Bear Lake catchment), and (2) the negative relation between MS and HIRM. For Al/Ti versus HIRM, linear fit is for zones 1a, 1b, and 1c. For HIRM versus MS, linear fit is for zones 1a and 1b. For Mg/Ca versus MS, linear fit is for zone 1a.

TABLE 2. QUALITATIVE CHARACTERISTICS OF SEDIMENT SOURCE AREAS

	Local Bear Lake catchment <63 µm	Lower Bear River <63 µm	Upper Bear River <63 µm	Upper Bear River coarse-sand
Dolomite/Calcite (leachable Mg/Ca)	High	Low	None*	None*
Al/Ti	Low	Low	Intermediate	High
MS	High	Intermediate	Intermediate	Low
HIRM	Low	Low	High	Intermediate

Note: MS—magnetic susceptibility; HIRM—hard isothermal remanent magnetization.
*Because Upper Bear River rocks contain very little carbonate and no dolomite, Mg in these sediments is not acid leachable.

negative relation between concentrations of material from the Bear Lake catchment and from the Uinta Mountains (Fig. 7) suggests that the variations are driven by the same mechanism. As discussed below, the Uinta Mountain detritus is thought to be largely glacial flour. As the supply of glacial flour changed in response to waxing and waning of glaciers, the flux of Uinta Mountain-derived material into Bear Lake varied and variably diluted the locally derived sediment.

In zone 1b, high values of HIRM and Al/Ti and low values of MS and Mg/Ca indicate high concentrations of material from the headwaters of the Bear River and low concentrations of material from the local catchment. However, the relation between dust-derived material and bedrock from the local catchment differs from that in zone 1a. In zone 1b, Mg/Ca values do not vary with MS and, as noted previously, are high with respect to MS (Fig. 7). This relation suggests that, in comparison to zone 1a, material from the local catchment is enriched in detritus from the local bedrock relative to that from surficial material.

Decreasing values of HIRM and Al/Ti across zone 1c indicate decreasing concentration of sediment from the Uinta Mountain Group rocks (Fig. 6). This decrease is not offset by an increase in MS comparable to the relation in the underlying zones (Fig. 7). The concentration of dolomitic detritus is similar to that in zone 1b. These relations indicate that the decrease in content of Uinta Mountain Group material is not fully offset by an increase in content of material from the local catchment and, therefore, must be increasingly replaced by material derived from lower reaches of the Bear River.

The content of detritus from the Uinta Mountain Group (i.e., HIRM and Al/Ti) continues to decrease upward across zone 1d. In this zone, the content of sediment derived from the local Bear Lake catchment increases. Both MS and Mg/Ca increase, although the relation of these components to each other and of MS to HIRM differ from that in zone 1a (Fig. 7). These changes could be produced by changes in input from the local catchment or by changes in the input from the Bear River, or both.

Zone 2a represents the transition from sediment dominated by detrital material to sediment dominated by endogenic carbonate; within this zone and zones 2b and 2c, the magnetic properties and elemental data provide little information about the sources of detrital material. Decreases in HIRM and MS across zone 2a are consistent with dilution of detrital material by increasing amounts of endogenic carbonate, whereas decreasing values of Mg/Ca reflect large increases in the content of Ca due to calcite precipitation rather than changes in the proportions of detrital dolomite and calcite. HIRM and MS continue to decline through zone 2b and remain at very low values through zone 2c. Carbonate content (which is nearly constant across zone 2b and increases from ~40% to 70% from the top of zone 2b to the base of zone 2c) is not high enough to fully account for the low values of HIRM and MS by dilution. Therefore, increasing post-depositional destruction of detrital Fe-oxide minerals is thought to produce the low values of HIRM and MS within these zones.

INTERPRETATIONS OF ENVIRONMENTAL CHANGE

Glacial History

Glacially derived material in lake sediments has been used to infer variations in glacial extent (Leonard, 1985; Karlén and Matthews, 1992; Bischoff and Cummins, 2001; Rosenbaum and Reynolds, 2004). Although there is considerable uncertainty about the timing of sediment discharge and its relation to subglacial storage and subsequent flushing (Hicks et al., 1990; Harbor and Warburton, 1993; Hallet et al., 1996), Leonard (1997) argues that glacial flour output largely reflects glacial extent when averaged over periods of several tens to hundreds of years or longer. This position is supported by a study of glacial flour in sediments of Upper Klamath Lake, Oregon (Rosenbaum and Reynolds, 2004).

The interpretations of glacial history from Bear Lake sediments presented below is much more detailed than those presented by Dean et al. (2006) and Laabs et al. (2007). In addition, because of revisions to the Bear Lake chronology (Colman et al., this volume), the timing of the onset of glaciation, maximum glaciation, and subsequent glacial retreat differs significantly from that presented in the earlier studies.

ΔHIRM as Rock Flour Proxy

Magnetic properties and geochemical data indicate that sediments in zones 1a–1c contain large quantities of material derived from Uinta Mountain Group rocks. This material is interpreted to be largely glacial rock flour for several reasons. (1) The age of the sediments coincides with a period in which glaciers were widespread in the Rocky Mountains including the Uinta Mountains (Pierce, 2004; Laabs et al., 2007). (2) The glaciated area in the headwaters of the Bear River makes up a small fraction of the drainage basin above Bear Lake (Fig. 3) so that in the absence of enhanced erosion, such as that provided by glaciers, detritus from the Uinta Mountains would be expected to be a minor component of Bear Lake sediment. This expectation is corroborated by the observation that HIRM values for modern stream sediments are elevated within the glacial limits in the Bear River Valley (Fig. 3) but abruptly decrease downstream due to dilution (Fig. 5). (3) In general, the proxy indicators of Uinta Mountain Group-derived material (i.e., HIRM and Al/Ti) in zones 1a–1c covary with content of fine-silt- and clay-sized siliciclastic material (Fig. 8). This relation is similar to that observed for Upper Klamath Lake where glacially derived rock flour in the lake sediment is finer than other detrital rock material (Reynolds et al., 2004; Rosenbaum and Reynolds, 2004).

Variations in glacial-flour content could reflect (1) changes in the location of the Bear River and its delta, (2) changes in the course of the Bear River that caused the river to alternately enter and bypass the lake, or (3) changes in the flux of glacial flour that reflect changes in the extent of glaciation. As discussed by Rosenbaum et al. (this volume), changes in the location of the river and its delta are probably insignificant because such changes would alter the distribution of sediment within the lake and, therefore, cannot account for the nearly identical variations observed in cores BL96-3 and BL00-1 (Fig. 6), which are separated by 4.5 km (Fig. 2). In the absence of the Bear River, Bear Lake produces large amounts of endogenic carbonate minerals (Dean et al., 2006). The low uniform content of calcite within zones 1a–1d indicates that the Bear River was connected to the lake throughout this interval. We therefore interpret variations in glacial flour to reflect changes in the extent of glaciation in the headwaters of the Bear River.

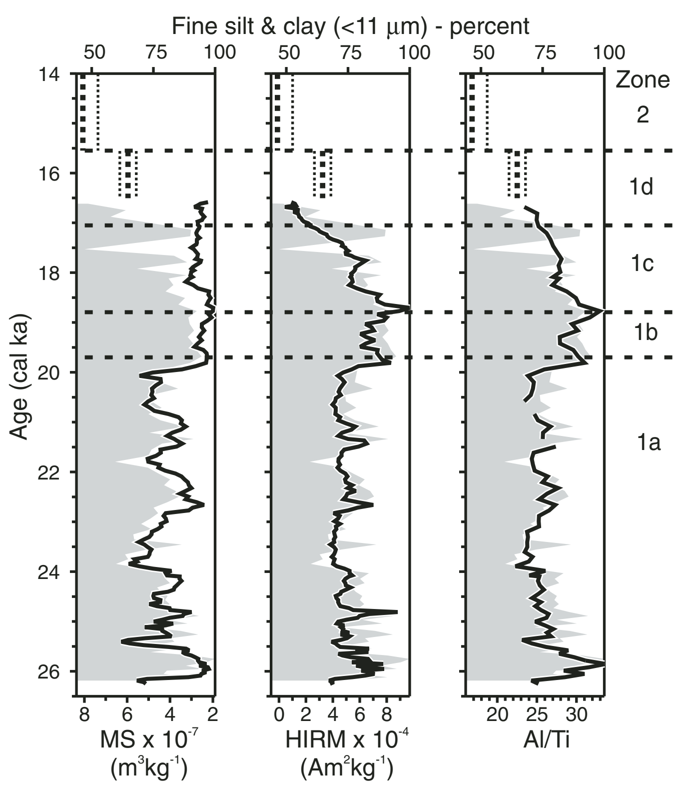

Figure 8. Content of <11 µm material (shaded curve) in core BL96-3 plotted with MS, HIRM, and Al/Ti. Stratigraphic zones are described in the text. Vertical dashed lines show means and standard deviations of <11 µm material for groups of samples outside the range of the age model for the core.

High concentrations of hematite (i.e., high values of HIRM) indicate high concentrations of glacial flour derived from the Uinta Mountain Group, but not all hematite is derived from these rocks. The initial precipitation of endogenic carbonate at the base of zone 2a, following the increasing dominance of sediment derived from the local catchment, suggests that at this point little if any sediment was being delivered by the Bear River. The value of HIRM at this point (~3.3×10^{-4} Am^2 kg^{-1}) is close to the average value of HIRM for stream samples from the local catchment (Table 1). Fortuitously, the average HIRM value for the lower Bear River samples is close to that of the local catchment. Therefore, 3.3×10^{-4} Am^2 kg^{-1} is taken as an estimate of HIRM for siliciclastic sediment lacking hematite-rich detritus from the Uinta Mountains.

In core BL96-3, magnetic properties were determined for ~190 samples spanning the ~10,500 yr interval of zones 1a–1d, an average of ~55 yr per sample. Within these zones, we interpret variations of HIRM that are defined by three or more values (Fig. 6) to reflect changes in glacial extent. ΔHIRM (i.e., HIRM - 3.3×10^{-4} Am^2 kg^{-1}) is therefore a measure of the content of glacial flour derived from the Uinta Mountain Group. Values of ΔHIRM are >0 through all but the uppermost part of zones 1a–1d, indicating significant glaciation during most of the period. This proxy record of late Wisconsin glaciation of the Uinta Mountains (derived from the Bear Lake sediments) and a similar record for the southern Cascade Range (derived from Upper Klamath Lake) both identify a number of millennial-scale variations in glacial extent prior to the maximum advance of ice (Fig. 9).

Glacial flour derived from rocks other than those of the Uinta Mountain Group will not contribute to ΔHIRM. Such glacial flour would have been produced by portions of glaciers extending down the Bear River Valley beyond the extent of Precambrian rocks of the Uinta Mountain Group (Fig. 3). In addition, small glaciers along the crest of the Bear River Range west of Bear Lake (Reheis et al., this volume) would have contributed hematite-poor dolomitic glacial flour to the lake.

Onset of Glaciation

The lowest content of glacial flour in zone 1a occurs at the base of core BL96-3. Magnetic properties from a longer record in core BL00-1 (Heil et al., this volume) are precisely correlated to the BL96-3 data and demonstrate that core BL96-3 captures the entire interval of elevated hematite content (Fig. 6). Therefore, the onset of extensive glaciation in the northwestern Uinta Mountains (e.g., the headwaters of the Bear River) apparently occurred ca. 26 cal ka, similar to the timing of the 1965 radiocarbon-based model of glacial extent for the Rocky Mountains presented by Porter et al. (1983), which is shown in Figure 9. There is no evidence in the Bear Lake record for extensive glaciation prior to ca. 26 cal ka, like that shown in the 1983 model. Changes in vegetation within the Bonneville Basin ca. 32 cal ka indicate that a cold dry climatic regime that had existed for ~10,000 years began to give way to moister but still cool conditions (Madsen et al., 2001). The onset of glaciation indicated in the Bear Lake record postdates this vegetation change and the initial growth of Lake Bonneville by ~6000 years (Fig. 10), and apparently coincides with formation of the Stansbury shoreline.

Maximum Glaciation

The Bear Lake record indicates that maximum content of glacial flour derived from the Uinta Mountain Group, interpreted from ΔHIRM (Fig. 9), was attained ca. 19.7 cal ka and persisted for ~800 years (i.e., zone 1b). During the last glacial interval, the maximum ice extent in the Bear River Valley extended well beyond outcrops of Precambrian Uinta Mountain Group rocks (Fig. 3). The distal portions of glaciers would have produced glacial flour largely from Tertiary sedimentary rocks and would not have contributed to high values of ΔHIRM. Therefore, ΔHIRM probably underestimates the maximum content of glacial flour from the Uinta Mountains. Although, it is possible that hematite-poor glacial flour diluted hematite-rich glacial flour to such an extent that peak glacial-flour content occurred after the maximum in ΔHIRM, the peak could not have been more than a few hundred years later given the cosmogenic ages, 18.1–18.7 cal ka, from terminal moraines in the Bear River Valley (Fig. 9; Laabs et al., 2007). Lacking a definitive proxy for glacial flour derived from Tertiary sedimentary rocks and recognizing the above uncertainty, we nevertheless interpret ΔHIRM to represent the extent of glaciation in the Bear River drainage.

During the period of maximum glaciation, zone 1b, the content of material from dolomitic bedrock (i.e., Mg/Ca) no longer varied with material derived from surficial deposits (i.e., MS) in the same manner as in zone 1a (Fig. 7). In comparison to zone 1a, the content of dolomitic material in zone 1b is consistently high with respect to surficial material. We suggest that this relative enrichment of dolomitic material reflects glacial flour produced by small glaciers on the crest of the Bear River Range (Reheis et al., this volume).

The timing of maximum glacial extent derived from the Bear Lake record coincides with the maximum glacial extent in the southern Cascade Range derived from Upper Klamath Lake, Oregon (Rosenbaum and Reynolds, 2004). The timing also coincides with the late stages of widespread glaciation according to radiocarbon-based age models for the Rocky Mountains (Porter

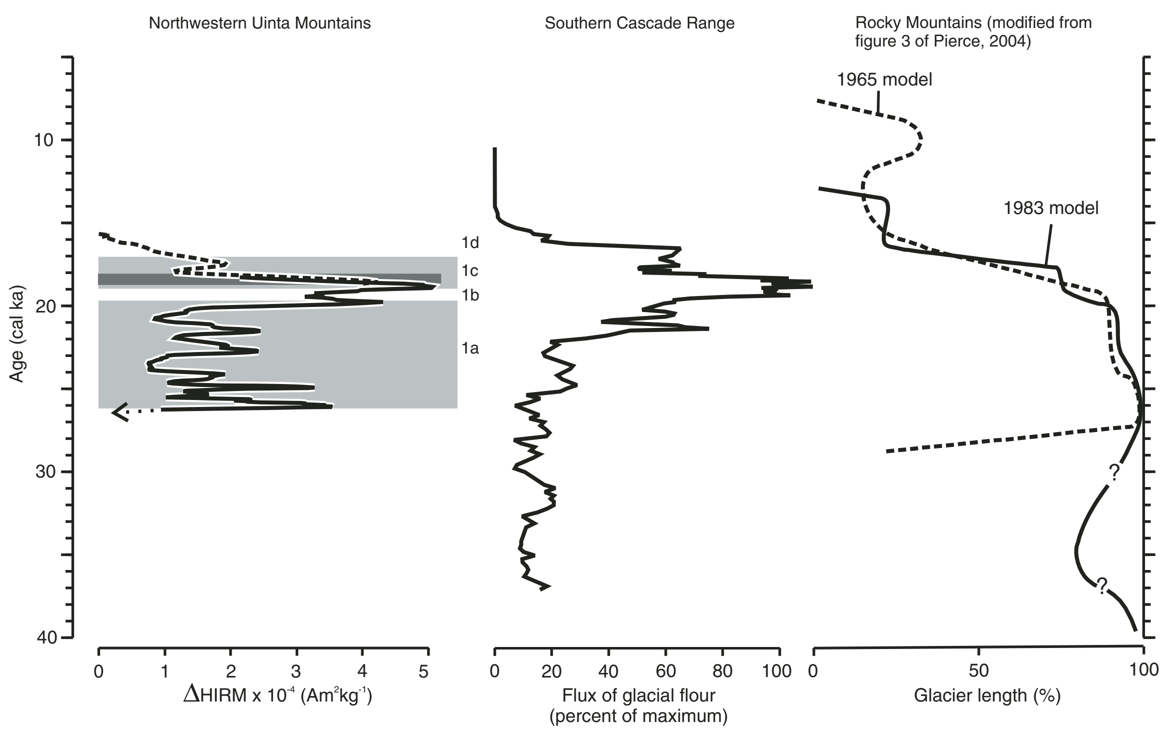

Figure 9. Comparison of the Bear Lake glacial record for the northwestern Uinta Mountains with a record from the southern Cascades derived from glacial flour in Upper Klamath Lake (Rosenbaum and Reynolds, 2004), and with models of glacial length for the Rocky Mountains (Porter et al., 1983). Zones 1a–1d are as shown in Figure 6. For the Bear Lake record, the solid (dashed) line is the portion of the record from core BL96-3 (BL96-2). The dark horizontal band in the Bear Lake record indicates the range of cosmogenic ages (18.1–18.7 ka) from terminal moraines in the Bear River Valley (Laabs et al., 2007).

et al., 1983; Pierce, 2004). An age for the maximum extent of glaciation of 19.7–18.9 cal ka, as indicated by the Bear Lake record, implies that glaciers attained their greatest size as Lake Bonneville grew to its maximum depth (Fig. 10; Oviatt et al., 1992; Oviatt, 1997).

Glacial Recession

In zone 1c, glacial extent in the headwaters of the Bear River decreased abruptly at 18.9 cal ka (Fig. 9). The initial recession was followed by a short re-advance that culminated shortly before 17.5 cal ka. Within this interval, the content of fine silt and clay remained high (Fig. 8), and the relation between the content of dolomitic material and surficial material was like that in zone 1b, indicating probable continued input of glacially derived material from the Bear River Range. Glacial extent then decreased continuously in the top of zone 1c and through zone 1d. No glacial input from the Bear River Range is apparent in zone 1d and glacial flour from the Uinta Mountains became undetectable at 15.7 cal ka.

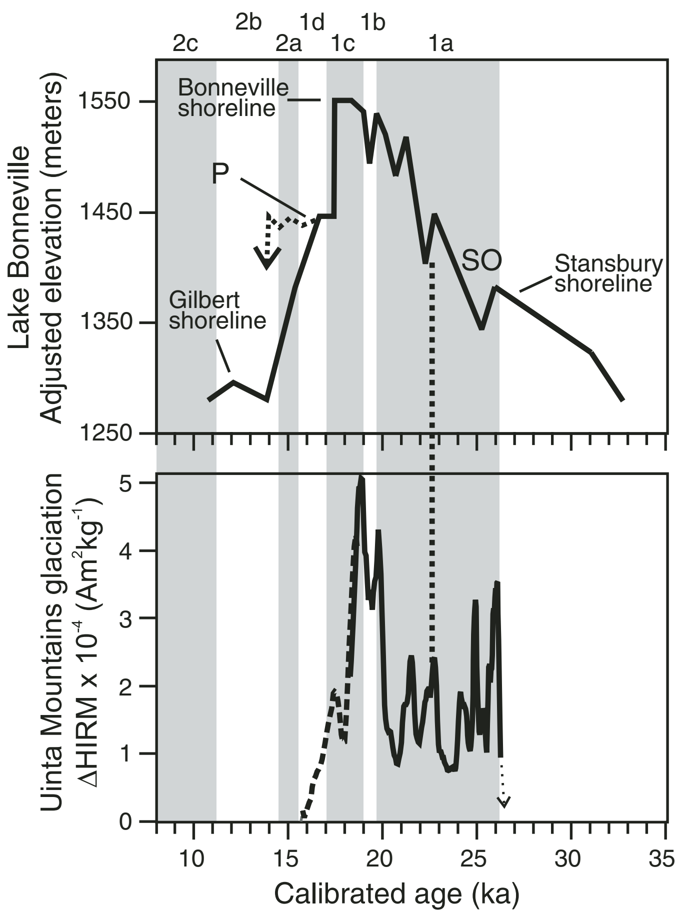

Figure 10. Comparison of the Bear Lake glacial flour record with the Lake Bonneville hydrograph (modified from Oviatt, 1997). The dashed arrow indicates an alternative interpretation of the timing of regression following formation of the Provo shoreline (Godsey et al., 2005). SO indicates the Stansbury oscillation. Zones 1a–2c are those shown in Figure 6.

These features closely match variations in the record from Upper Klamath Lake (Fig. 9). The initial rapid recession following the glacial maximum occurred during the highstand of Lake Bonneville, and the beginning of the final retreat apparently occurred during or after formation of the Provo shoreline (Fig. 10).

Post-Glacial Record

Although glaciers persisted at high elevations in the Uinta Mountains until ca. 10 cal ka (Munroe, 2003), Bear Lake received little glacial flour after ca. 15.7 cal ka. Increasing content of endogenic calcite beginning ca. 15.5 cal ka (zone 2a) indicates increased salinity of the lake and probable abandonment of the lake by the Bear River (Dean et al., 2006). The period of increasing carbonate content occurs within the period in which Oviatt (1997) interpreted climatic conditions to produce the major regression of Lake Bonneville from the Provo shoreline (Fig. 10). Godsey et al. (2005), however, suggest that Lake Bonneville remained at or near the Provo shoreline until 13.0 cal ka and then regressed rapidly.

Lake-level reconstructions based on sedimentological evidence indicate an abrupt ~20 m drop in the level of Bear Lake ca. 12.8 cal ka (Smoot and Rosenbaum, this volume). Over the next 1000 years, a period roughly coinciding with the Younger Dryas, the lake declined to more than 30 m below modern level, rose to near the modern level, fell again by more than 30 m, and rose once again. Other evidence suggests increasingly evaporative conditions during this period and the subsequent several hundred years. Such evidence includes a sharp increase in $\delta^{18}O$ ca. 12.0 cal ka (Dean et al., 2006) and an increase in the content of Mg in endogenic calcite from ~4 mol percent to ~8 mol percent beginning ca. 11.5 cal ka (based on X-ray diffraction data; G. Skipp, 2005, personal commun.). At 11.0 cal ka, salinity reached a threshold and aragonite began to precipitate (Fig. 6). Many studies indicate that climatic conditions in western North America were cool and moist during the Younger Dryas (Thompson et al., 1993; Phillips et al., 1994; Rhode and Madsen, 1995; Quade et al., 1998; Allen and Anderson, 2000; Reasoner and Jodry, 2000; Currey et al., 2001; Madsen et al., 2001; Polyak et al., 2004), and recent work at Great Salt Lake indicates that lake level rose to the Gilbert shoreline during this period (Oviatt et al., 2005). However, the Bear Lake results are more consistent with studies that indicate low lake levels in the Great Basin during this period (Benson et al., 1997; Licciardi, 2001).

SUMMARY

Sediments deposited in Bear Lake after ca. 26 cal ka consist of a lower siliciclastic unit, which was deposited until 15.5 cal ka, and overlying carbonate-rich sediments. For the siliciclastic material, differences in magnetic and elemental properties of fluvial sediments document changes in detrital input from three sediment source areas: the headwaters of the Bear River in the Uinta Mountains, the Bear River below the Uinta Mountains and above Bear Lake, and the local Bear Lake watershed. Under present conditions, hematite-rich material from Uinta Mountain Group rocks is a minor constituent of Bear River sediment because it is rapidly diluted below the headwaters. It is a major component, however, in the siliciclastic Bear Lake sediments, indicating not only that the Bear River was connected directly to Bear Lake but also that the river was transporting much more detritus derived from Uinta Mountain Group rocks than at present. We interpret that glaciation was the cause of enhanced transport of this material, that the Uinta Mountain Group material is largely glacial flour, and that the quantity of glacial flour is related to the extent of glaciation. The onset of extensive glaciation at 26 cal ka postdates moistening of conditions in the region indicated by the initial growth of Lake Bonneville and by changes in vegetation. The Bear Lake record indicates that maximum glaciation occurred between ca. 19 and 20 cal ka as Lake Bonneville attained its maximum depth and that rapid deglaciation began ca. 19 cal ka while Lake Bonneville remained high. The onset of deglaciation indicated in the Bear Lake record is in good agreement with cosmogenic ages from terminal moraines in the Bear River Valley (Laabs et al., 2007). The content of glacial flour in the Bear Lake sediments continued to decrease until ca. 15.5 cal ka. Shortly thereafter, the Bear River abandoned Bear Lake and endogenic carbonate minerals replaced clastic sediments. The properties used to interpret changes in provenance for sediments older than 15.5 cal ka cannot be used in the younger sediments because of the effects of the endogenic minerals and the post-depositional destruction of detrital Fe-oxide minerals.

From 15.5 to 10 cal ka, evidence of environmental change is largely based on changes in the types and compositions of endogenic carbonate minerals (Dean, this volume), and sedimentary indicators of lake-level history (Smoot and Rosenbaum, this volume). This evidence includes increasing concentration of calcite from 15.5 to 14.5 cal ka, indicating withdrawal of the Bear River from Bear Lake and increasing evaporative conditions. This interval in the Bear Lake record coincides with a period when Lake Bonneville may have been declining due to climatic conditions. Although lake levels in the Bonneville Basin apparently rose during the Younger Dryas, evidence from Bear Lake suggests generally low but fluctuating lake levels and increasingly evaporative conditions during this period.

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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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