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Lake Bonneville fluctuations and global climate change

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ABSTRACT

Lake Bonneville, the largest late Pleistocene closed-basin lake in the North American Great Basin, fluctuated widely in response to changes in climate. The geochemistry and mineralogy of endogenic calcium carbonate deposited in deep water, and stratigraphic studies of shore-zone deposits, provide evidence of millennial-scale lake-level fluctuations that had amplitudes of about 50 m between 30 and 10 ka. Falling-lake events occurred at 21, 18.5–19, 17.5, 16–15.5, 14–13, and 10 ka (radiocarbon years) synchronously with the terminations of Heinrich events H1 and H2 and other smaller scale iceberg-rafting events (a, b, c, and Younger Dryas) in the North Atlantic Ocean. The Lake Bonneville results thus support other climate records that suggest that late Pleistocene millennial-scale climate change was global in extent. The size and shape of the Northern Hemisphere ice sheets, which determined the mean positions of storm tracks, may have been the primary control on late Pleistocene water budgets of Great Basin lakes.

INTRODUCTION

Increasing evidence from a variety of sources and localities around the world shows that changes in global climate were synchronous with Heinrich events, which were episodes of increased iceberg discharge with periods of 5–10 k.y. during which large volumes of rock debris were deposited in North Atlantic sediments (Heinrich, 1988; Bond et al., 1992, 1993; Grimm et al., 1993; Phillips et al., 1994; Clark and Bartlein, 1995; Clark et al., 1995; Lowell et al., 1995; Porter and Zhisheng, 1995). Smaller-scale iceberg-rafting events, which occurred on millenial time scales, have also been documented in the North Atlantic (Bond and Lotti, 1995). Here I present evidence that Lake Bonneville regressions, referred to as falling-lake events, were coincident with the terminations of Heinrich events H1 and H2, and with the terminations of smaller-scale events referred to by Bond and Lotti (1995) as a, b, c, and Younger Dryas.

Lake Bonneville was the largest of the late Pleistocene pluvial lakes in the North American Great Basin (Fig. 1; Gilbert, 1890; Benson et al., 1990; Currey, 1990) and fluctuated as a climatically sensitive, closed-basin lake between 30 and 10 ka (Fig. 2; Thompson et al., 1990; Oviatt et al., 1992). The lake rose beginning at ca. 28 ka, reached its highest level (the Bonneville shoreline) at ca. 15 ka, then at 14.5 ka dropped 100 m due to catastrophic downcutting at the outlet (Fig. 2). Following a period of stabilization and the formation of the Provo shoreline, the lake regressed rapidly between 14 and 12 ka to very low levels. A moderate rise to the Gilbert shoreline ended about 10 ka.

METHODS

The stratigraphy and chronology of shoreline deposits give direct clues to lake-level changes (see descriptions below). In addition, two cores containing deep-water endogenic carbonate sediments in Lake Bonneville were obtained from isolated outcrops on the basin floor (Figs. 1 and 2). Five accelerator mass spectrometry (AMS) radiocarbon ages determined on ostracodes, two basaltic volcanic ashes of known age, and a distinctive stratigraphic marker bed (BF) produced during the catastrophic drop in lake level at 14.5 ka provide age control for these cores (Table 1). Lake level can be estimated for each dated horizon in the cores (Fig. 3) by comparison with the independently dated radiocarbon chronology of Lake Bonneville (Fig. 2). The two cores were analyzed for percent $CaCO_3$ by Chittick analysis (Machette, 1986), aragonite/calcite ratio by X-ray diffraction, and $\delta^{18}O$ and $\delta^{13}C$ in fine-grained (<44 µm) endogenic carbonate by mass spectrometry (precision on replicate samples ± 0.1‰).

RESULTS

Chemical and mineralogical variations within the cores reflect changing conditions in the lake.

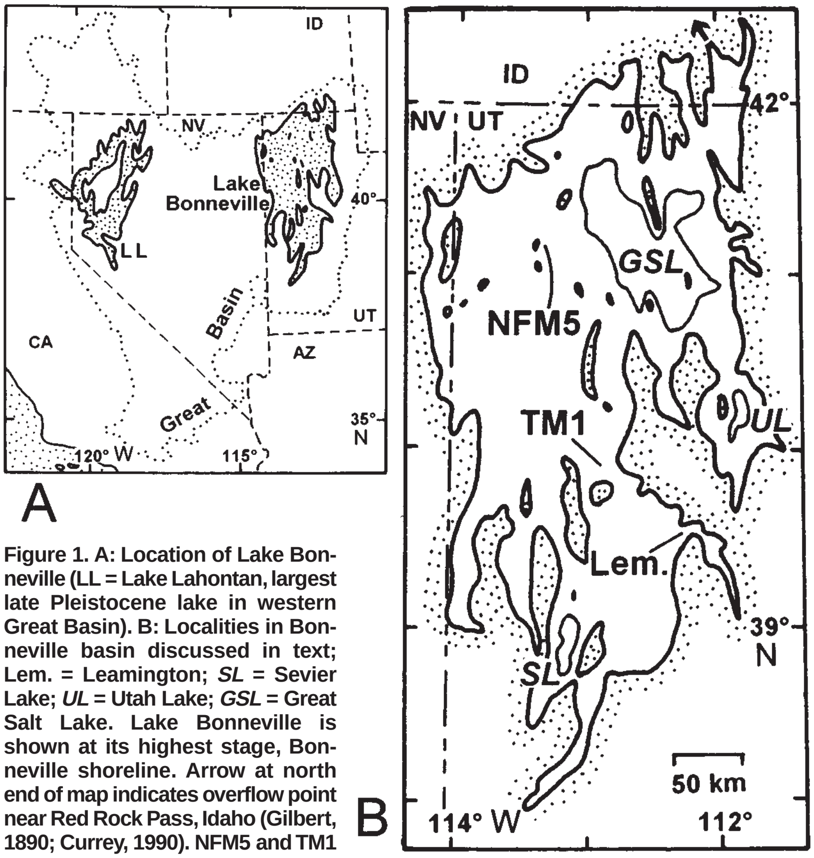

Figure 1. A: Location of Lake Bonneville (LL = Lake Lahontan, largest late Pleistocene lake in western Great Basin). B: Localities in Bonneville basin discussed in text; Lem. = Leamington; *SL* = Sevier Lake; *UL* = Utah Lake; *GSL* = Great Salt Lake. Lake Bonneville is shown at its highest stage, Bonneville shoreline. Arrow at north end of map indicates overflow point near Red Rock Pass, Idaho (Gilbert, 1890; Currey, 1990). NFM5 and TM1 are cores discussed in text.

The percentage of endogenic calcium carbonate is a function of the lake's total dissolved solids (TDS) (McKenzie, 1985), which, given an initial condition, varies with the ratio of evaporation to inflow. Aragonite precipitation is dependent on both TDS (which is an inverse function of lake volume) and the Mg/Ca ratio of the water (which is related to lake volume and inflow water chemistry) (Spencer et al., 1984). The $\delta^{18}O$ of the carbonates is a function of the ratio of evaporation to inflow, changes in basin hydrography, or changes in precipitation source (Talbot, 1990). The $\delta^{13}C$ of the carbonate minerals varies as a function of changing nutrient levels and photosynthetic consumption of ^{12}C (McKenzie, 1985), changing $\delta^{13}C$ of inflowing waters, or changing rates of exchange of CO_2 between the lake and atmosphere (determined by such factors as water pH, salinity, composition, and dissolved CO_2; Talbot, 1990; Kelts and Talbot, 1990). Percent calcium carbonate, the aragonite/calcite ratio, and the stable isotopes are highly correlated (e.g., in TM1 $\delta^{18}O$ vs. $\delta^{13}C$, $r^2 = 0.96$, and %$CaCO_3$ vs. arag/cal, $r^2 = 0.84$; in NFM5 the respective r^2 values are 0.97 and 0.47).

Although the exact causes of variation in the core data have not been identified, in both cores percent calcium carbonate, the aragonite/calcite ratio, and the stable isotopes are inversely correlated with lake level during the transgressive phase of the lake and therefore are interpreted as empirical proxies of lake-level change. From the core data, significant falling-lake events during the transgressive phase of Lake Bonneville can be inferred at about 18.5–19, 17, and 15–15.5 ka (U1, U2, and U3, respectively, in Table 2; Figs. 2 and 3).

Outcrops of shore-zone deposits provide independent stratigraphic evidence of transgressive-phase lake-level fluctuations, including clues to the upper and lower elevational limits of those fluctuations. During the Stansbury oscillation (ca. 22–20 ka; Fig. 2), tufa-cemented gravel and barrier beaches of sand and gravel were deposited near an elevation of 1350 m during one or more fluctuations that had a maximum amplitude of about 45 m (Oviatt et al., 1990). The lake reached the lowest point of the Stansbury oscillation at about 21 ka. At elevations between 1400 and 1420 m, wave-zone gravel wedges between fine-grained deep-water units indicate lake transgression, regression, and transgression ca. 19 ka (Fig. 2).

Two younger gravel wedges are exposed in an outcrop near the town of Leamington, Utah (Gilbert, 1890; McCoy, 1987; Varnes and Van Horn, 1991; Oviatt et al., 1994b). Lacustrine snail shells in the lower gravel wedge date at 17.5 ka (L-711C), and snails and Pahvant Butte basaltic ash (directly above the upper wedge) are dated as 15.4 ka (L-774N) (Broecker and Kaufman, 1965; Oviatt et al., 1994b). Disconformities associated with the wedges have been mapped downslope to elevations 40 to 50 m below the gravel (Varnes and Van Horn, 1991) and indicate that the lake-level fluctuations had an amplitude similar to the Stansbury oscillation. Gravel wedges at similar elevations have been found at other locations in the basin.

In summary, four fine-coarse-fine sequences in shore-zone deposits of the transgressive phase of Lake Bonneville indicate falling-lake events ca. 21, 19, 17.5, and 16 to 15.5 ka (Table 2). All of these events are also expressed in the cores of deep-water carbonates (SO, U1, U2, U3, respectively). In addition, major regressions of Lake Bonneville occurred at 14 to 13 ka and immediately after 10 ka (Fig. 2).

Although the precise amplitude of the transgressive-phase lake-level fluctuations listed in Table 2 is not known, stratigraphic and geomorphic evidence suggests that each spanned 30–50 m. Lake-level fluctuations of this magnitude translate to water-volume fluxes of 500–1500 km^3 and surface-area changes of 4000–7000 km^2 (changes of 20%–50% and 15%–20%, respectively), depending on the amplitude of the fluctuation and its elevation range in the basin (Fig. 2). The post-Provo and post-Gilbert regressions constituted >90% reductions in volume and surface area. All these falling-lake events represent major shifts in the water budget of Lake Bonneville caused by climate change in the lake basin.

DISCUSSION

Table 2 compares the approximate ages of the known falling-lake events in the Bonneville basin with those of abrupt reductions in iceberg-rafted debris in North Atlantic sediments (Bond and Lotti, 1995). Falling-lake events U1, U2, and U3 were synchronous with the terminations of iceberg-rafting events c, b, and a, respectively; the Stansbury oscillation, the post-Provo regression, and the post-Gilbert regression were synchronous with the terminations of Heinrich events H2, H1, and the Younger Dryas, respectively. Climate in the North Atlantic region warmed abruptly immediately after each of these events (Bond et al., 1993; Bond and Lotti, 1995). The coincidence be-

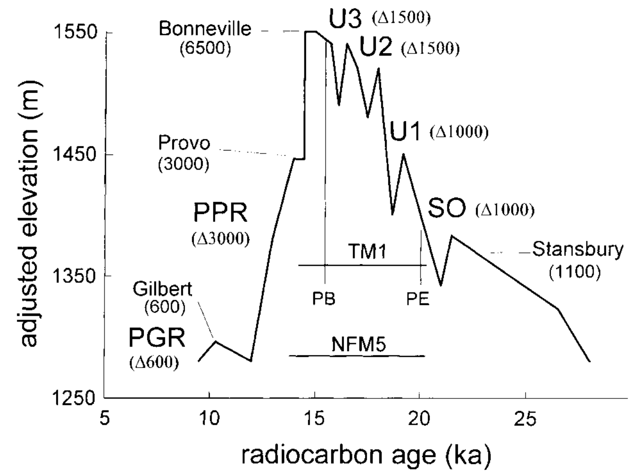

Figure 2. Chronology of Lake Bonneville, modified from Oviatt et al. (1992). Age in radiocarbon yr B.P.; elevations are adjusted for effects of differential isostatic rebound in basin (Oviatt et al., 1992). PB = Pahvant Butte basaltic ash; PE = Pony Express basaltic ash; horizontal lines labeled TM1 and NFM5 show elevations and time ranges of two cores discussed in text. Bonneville Flood caused 100 m catastrophic drop in lake level from Bonneville shoreline to Provo shoreline and created distinctive lithologic marker bed in deep-water sediments (BF in Table 1). Elevational limits of lake-level fluctuations U1, U2, and U3 (see Table 2) are approximate and are shown here schematically. PGR = post-Gilbert regression, PPR = post-Provo regression, and SO = Stansbury oscillation. Numbers in parentheses represent water-volume totals at major shorelines or water-volume fluxes at lake-level fluctuations or regressions (in cubic kilometres).

TABLE 1. CHRONOLOGIC CONTROL FOR LAKE BONNEVILLE MARL CORES

Core	Depth (cm)	Age (^{14}C yr B.P.)	Basis* for age	Lab number	Reference
NFM5	13.8	14500	BF	----	Oviatt et al. (1994a)
	51-55	15840 ± 60	AMS	Beta-85908	this paper
	100.5-102.5	17100 ± 60	AMS	Beta-85983	this paper
	133.5-135.5	19200 ± 70	AMS	Beta-85909	this paper
TM1	~11	14500†	BF	----	Oviatt et al. (1994a)
	~13	15500†	PB	----	Oviatt and Nash (1989)
	20-26.5	14920 ± 70†	AMS	Beta-85912	this paper
	73.5-75.5	19650 ± 60	AMS	Beta-85982	this paper
	80	20000	PE	----	Oviatt et al. (1994a)

*BF = Bonneville Flood lithologic marker bed; AMS = accelerator mass spectrometry age of ostracode valves; PB = Pahvant Butte basaltic ash; PE = Pony Express basaltic ash.

†In core TM1 the interval from 0-16 cm was disturbed, so the depths for BF and PB had to be approximated. In addition, for unknown reasons AMS sample Beta-85912 appears to be slightly too young. A conservative interpretation is that the core interval from ~11-26.5 cm ranges in age from 15.5-14.5 ka.

TABLE 2. BONNEVILLE FALLING-LAKE EVENTS AND POSSIBLE EQUIVALENT NORTH ATLANTIC ICEBERG-RAFTING EVENTS

Bonneville event*	Age† (~ka)	Name of event	Possible marine equivalent	Age§ (~ka)
PGR	9.5-10	post-Gilbert regression	Younger Dryas	9.5-10
PPR	13-14	post-Provo regression	H1	13.5
U3	15.5-16	unnamed**	a	15.5
U2	17-17.5	unnamed	b	17.5
U1	18.5-19	unnamed	c	18.5
SO	21	Stansbury oscillation	H2	20.5

*Compare with Figure 2.

†Ages in radiocarbon years B.P.

§Radiocarbon ages of abrupt terminations of ice-rafting events in North Atlantic core VM23-081; see Figures 2 and 3 in Bond and Lotti (1995).

**Keg Mountain oscillation (?); see Oviatt et al. (1992).

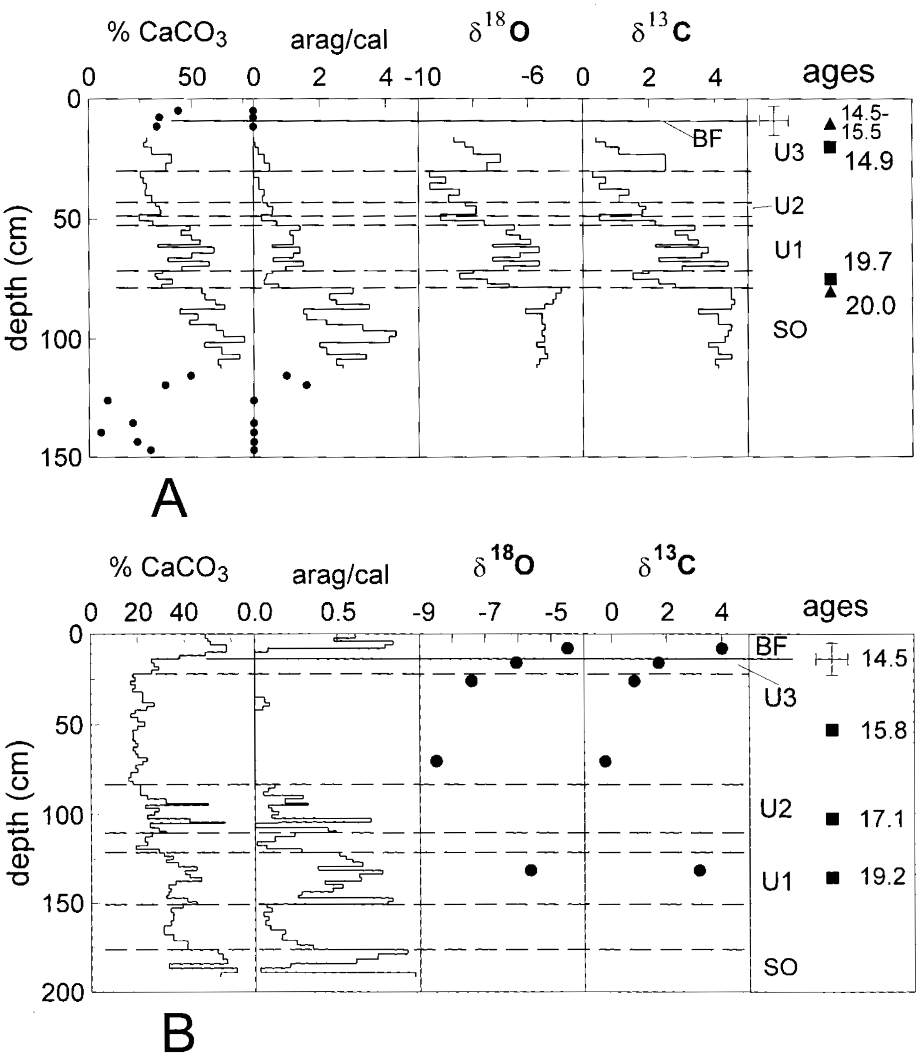

Figure 3. Geochemical data for cores TM1 (A), collected near Table Mountain, Utah (Oviatt et al., 1994a), and NFM5 (B), collected near New Foundland Mountains, Utah. Square-curve lines are for contiguous samples averaging 2 cm in thickness; dots represent isolated samples. Ages (Table 1) based on accelerator mass spectrometry radiocarbon age of ostracodes (solid squares), dated basaltic volcanic ashes (solid triangles), and the Bonneville Flood lithologic marker bed (cross).

tween Lake Bonneville and the North Atlantic events supports the hypotheses that Heinrich events are correlated with climate changes in western North America (Clark and Bartlein, 1995), and that higher-frequency climatic events with periods of 2–3 k.y. affected both the Laurentide ice sheet and western North America (Allen and Anderson, 1993; Phillips et al., 1994).

One hypothesis to explain the Bonneville falling-lake events is that changes in the size and shape of the Northern Hemisphere ice sheets associated with massive discharges of ice into the North Atlantic caused shifts in the Northern Hemisphere atmospheric circulation that affected regions far beyond the North Atlantic region. Antevs (1948) proposed that the Cordilleran ice sheet deflected storm tracks into the Great Basin, thus increasing precipitation to create the large pluvial lakes. Geologic and modeling studies support a refined and expanded version of Antevs's hypothesis, which involves the larger Laurentide ice sheet (Benson and Thompson, 1987; COHMAP Members, 1988; Allen and Anderson, 1993). Although temperature changes were certainly involved in water-budget shifts, at least in the northern Great Basin (see Mears, 1981), major pluvial-lake cycles in western North America were broadly correlative with even-numbered oxygen-isotope stages (Scott et al., 1983). On a millennial time scale, a moderate to large shift in the mean position of westerly storm tracks would have had a profound effect on water balances in the Great Basin, especially in the Bonneville basin, where precipitation in the high mountains to the east of the lake was enhanced by the lake itself (Hostetler et al., 1994).

CONCLUSIONS

If changes in the size and shape of the Northern Hemisphere ice sheets caused shifts in the mean trajectories of storm tracks in western North America, the details of lake-level records from different basins across latitudinal or even longitudinal transects should not be expected to be perfectly correlated. Further work, including chronological refinements, will eventually permit compilations of high-resolution and well-dated lake-level records from numerous lake basins that are likely to reveal an intricate pattern of shifting storm tracks linked to late Pleistocene global climate change.

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