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Mid-Wisconsin sediment record from Baldwin Lake reveals hemispheric climate dynamics (Southern CA, USA)

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Abstract

Recently acquired cores from Baldwin Lake, Southern California, document the first regional, terrestrial-based evidence for glacial period millennial-to-orbital scale climate variability. Eight AMS ¹⁴C dates on a 14-m core from the lake's present day depocenter provide initial age control over the interval from 20,000 to 48,000 years before present (BP). A linear age model extends the record to a minimum age of 65,000 years BP. A combination of lithologic description and one cm contiguous sedimentological analyses indicates significant changes in the dominant type of depositional environment over the length of the record at millennial-to-orbital time scales. As a first-order interpretation, the dominant sedimentary environments alternate between permanent and ephemeral lake systems. Orbital-scale forcing includes long-term winter-summer insolation variability and its modulation of winter storm tracks and the North American monsoon, respectively. Millennial-scale variability is attributed to extra-tropical, ocean-atmosphere dynamics akin to historical interdecadal Pacific climate variability. In addition, there is notable correspondence to the independently dated Greenland Ice Core record (GISP 2) at millennial-to-orbital time scales suggesting that Baldwin Lake contains, in addition to its local/regional record, a hemispheric record of climate change — similar to Owens, Pyramid, and Summer Lake of central and northwestern North America. An initial comparison to GISP2 $\delta^{18}\text{O}_{(\text{ice})}$ indicates that North Atlantic interstadials correlate to permanent lake environments in coastal southwestern North America. These results present a notable conflict with the proposed “super-ENSO” phenomenon in the western tropical Pacific. These results also highlight the necessity for acquiring additional high-resolution glacial period records for resolving questions of spatial-temporal phasing of late-Quaternary climates.

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1. Introduction

The last glacial period is characterized by high amplitude, high frequency climate change (Dansgaard et al., 1993). The majority of glacial-age, high-resolution data are derived from either high-latitude ice cores or deep

marine sites (e.g., Behl and Kennett, 1996; Stuiver and Grootes, 2000). Conversely, there is a disproportionate number of terrestrial, glacial-age climate records. As a result, it is not yet understood sufficiently how marine or high latitude ice core climates transfer to terrestrial climates, particularly at sub-orbital timescales. It is critical, therefore, to acquire and develop high resolution, glacial-age terrestrial records. One of the regions where there are few high-resolution, glacial-age, terrestrial climate records is coastal southwestern North America (i.e.,

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greater Southern California). This region is home to more than 10% of the United States' population. Moreover, the region is highly susceptible to hydrologic variability (e.g., droughts). As a result, it is critical to develop and evaluate the baseline of natural climate variability and its forcings for Southern California over a variety of timescales.

To evaluate this baseline of variability, a series of lake studies are underway in coastal southwestern North America (hereafter referred to as CSWNA) (Kirby et al., 2004, 2005; Bird and Kirby, 2006). For this paper our objectives are two-fold: 1) to characterize terrestrial, glacial climate in CSWNA at millennial-to-orbital timescales; and, 2) to suggest first order forcing mechanisms to explain the observed glacial-age climate variability at millennial-to-orbital scales. Here, we present the initial results from a new study site in CSWNA, Baldwin Lake, which contains a 14-m glacial-age climate record spanning 20,000 to 65,000 years before present.

What do we know about glacial-age climate in the greater region of CSWNA? Records from the Mojave Desert and Death Valley indicate that glacial-age climate was characterized by generally greater moisture availability than modern, with maximum lake high stands approximately coeval to the last glacial maximum (Spaulding and Graumlich, 1986; Li et al., 1996; Anderson and Wells, 2003; Enzel et al., 2003; Yang et al., 2005). Within the region of Southern California, specifically, Anderson et al. (2002) used pollen data to infer 4–5 °C cooler temperatures than today 41,000 years BP. From Northern Baja, a lacustrine sediment record spanning 44,000 to 13,000 years BP indicates greater total effective moisture throughout the mid-Wisconsin and late-glacial (Lozano-Garcia et al., 2003). Age control or sediment resolution limit higher frequency (sub-millennial-to-millennial) climate interpretations from these records. Together, these terrestrial records provide important first-order, glacial-age climate information for the region. However, none of these records resolve sufficiently high-frequency climate variability from the terrestrial environment. From the marine realm, pollen and $\delta^{18}\text{O}_{(\text{foram})}$ data indicate both a wetter and cooler glacial climate as well as high amplitude climate variability, often in close correspondence to the GISP2 ice core record (e.g., Heusser, 1998; Hendy and Kennett, 1999; Sirocko et al., 1999).

Conversely, to the north, there is an abundance of high-resolution, glacial-age climate records, largely due to the occurrence of more common, permanent lakes at higher latitudes (Benson et al., 1996, 1998; Negrini, 2002; Grigg and Whitlock, 2002; Zic et al., 2002; Benson et al., 2003). Taken together, these central to northwestern North American records indicate a strong

temporal relationship to the North Atlantic glacial climate (Benson et al., 2003). These records also indicate, within the limits of dating, a coherent spatial pattern of centennial-to-millennial scale glacial climate in western North America (Benson et al., 2003). These authors suggest that the position of the polar front jet stream moderated by variable sea surface temperatures is the essential link tying the spatially-diverse climate regimes of central and northwestern North American to the North Atlantic (Zic et al., 2002; Benson et al., 2003).

2. Background

2.1. Regional climatology

The climatology of CSWNA is relatively straightforward. The modern climate is Mediterranean — wet, cool winters and dry, hot summers (Sheeley and Dorman, 1979). In Southern California, precipitation amount is a function of the average position of the winter season polar front as related to changes in the position of the eastern Pacific subtropical high. Generally, dry winters in Southern California are associated with a strong high-pressure ridge off the western coast of the United States, which steers storms over the northwestern United States. Wet winters are linked to a weakening of the subtropical high, causing the storm track to shift southward (Weaver, 1962; Pyke, 1972; Cayan and Roads, 1984; Lau, 1988; Schonher and Nicholson, 1989; Enzel et al., 1989; Redmond and Koch, 1991; Enzel et al., 1992; Friedman et al., 1992; Ely, 1997). In turn, the large-scale atmospheric patterns that control the average position of the polar front are modulated by Pacific Ocean sea-surface conditions (Namias, 1951; Weaver, 1962; Pyke, 1972; Namias and Cayan, 1981; Douglas et al., 1982; Lau, 1988; Namias et al., 1988; Schonher and Nicholson, 1989; Latif and Barnett, 1994; Trenberth and Hurrell, 1994; Cayan et al., 1998; Dettinger et al., 1998; Biondi et al., 2001; D'Arrigo et al., 2001). There are also numerous studies that have linked interannual precipitation variability over Southern California with ENSO (El Niño = higher ppt. in southern CA and vice versa in northern CA) and inter-decadal precipitation variability to the PDO (+ PDO similar to El Niño effects) (Schonher and Nicholson, 1989; Redmond and Koch, 1991; Biondi et al., 2001; Mantua and Hare, 2002; MacDonald and Case, 2005).

As the position of the polar front changes, the source and trajectory of storms tracking across Southern California also changes. These changes in storm tracks produce the characteristic “seasonality” of climate variability in Southern California. Kirby et al. (2004) examined the

relationship between historic lake levels at Lake Elsinore and regional winter precipitation. The analysis indicates that there is a positive relationship ($r=0.53$; $\alpha=0.01$) in the historic record between total winter precipitation for regional precipitation and Lake Elsinore lake level. The same positive relationship is observed between total winter regional precipitation and lake level at Baldwin Lake, the focus of this study ($r=0.75$; $\alpha=0.005$) (French and Busby, 1974). We also compared the average latitude of the winter (Dec.–Feb.) polar vortex at the 500-hPa geopotential height field between 110° and 165°W longitude (Burnett, 1993a,b; Kalnay et al., 1996) to Baldwin Lake level between 1949 and 1972 AD ($r=0.45$; $\alpha=0.01$) using the same technique as (Kirby et al., 2001). Although a short data set, the analysis illustrates that years of high (low) lake levels are associated with an average polar vortex that is expanded (contracted) to more southern (northern) latitudes. This simple analysis corroborates the observation that strengthening and weakening of the eastern Pacific sub-tropical high strongly modulates atmospheric circulation, storm tracks, and moisture source and thus climate in CSWNA.

Although our lake level-vortex data represent annual-to-interannual variations, Douglas et al. (1982) argue that atmospheric processes on the annual-scale can be extrapolated confidently to longer time scales due to the

coherency of atmospheric dynamics (i.e., the quasi-stationary planetary wave forms). Together, these results suggest that Baldwin Lake serves as a valid barometer of regional precipitation variability and large-scale atmospheric conditions. As a result, we assert that the climatic information extracted from Baldwin Lake is transferable to the larger region of CSWNA, specifically, and western North America, in general.

Under present conditions, the impact of summer–fall precipitation on Southern California is minimal in any form (i.e., monsoonal rains, convective thunderstorms, or infrequent eastern Pacific hurricanes) (Adams and Comrie, 1997; Maloney and Hartmann, 2000). There is, however, paleoclimatological evidence that the present day winter-dominated distribution of precipitation has not been constant over the Holocene (Spaulding and Graumlich, 1986; Enzel et al., 1989; Ely et al., 1993; Graumlich, 1993; Bird and Kirby, 2006). In fact, there is compelling evidence that the early Holocene in Southern California was much wetter than today, characterized by a stronger monsoon and more frequent flood producing summer(?) storms (Spaulding and Graumlich, 1986; Bird and Kirby, 2006; Kirby et al., 2005). Bird and Kirby (2006) showed that the modern North American monsoon expands, occasionally, to Big Bear Lake (a reservoir) (Fig. 1). Although winter precipitation dominates the

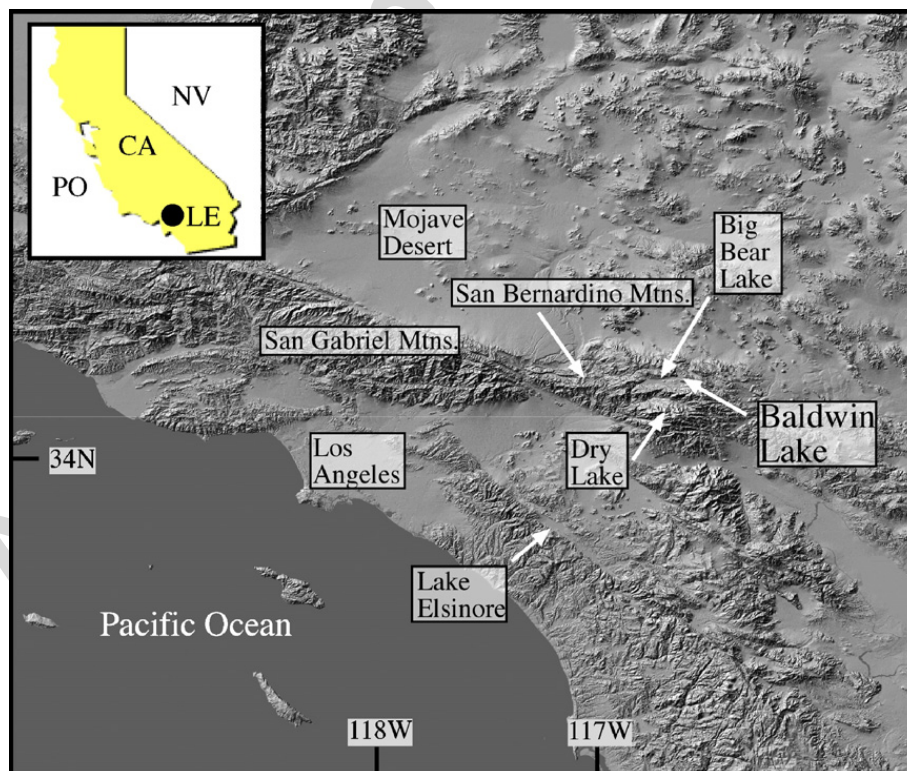


Fig. 1. Regional map showing important sites in CSWNA. Inset shows regional perspective: PO=Pacific Ocean; CA=California; NV=Nevada.

annual cycle (DJF average total=96 mm), historical data indicate a second summer precipitation peak at Big Bear Lake during August (24.9 mm). Big Bear Lake is located in the same valley as Baldwin Lake – approximately 3 km east of Big Bear Lake (Fig. 1). As a result, it is reasonable to conclude that the North American monsoon also impacts Baldwin Lake in the modern system. During the early Holocene summer insolation maximum, the spatial extent of the North American monsoon is suggested to have increased greatly producing distinct storm event sediment facies at Dry Lake. Dry Lake is located approximately 20 km due south of Baldwin Lake (Fig. 1) (Bird and Kirby, 2006). Therefore, Bird and Kirby (2006) concluded that intervals of higher than modern summer insolation favor the expansion of the North American monsoon into CSWNA. Using this same line of reasoning, we suggest that the spatial extent and magnitude of the North American monsoon waxed and waned throughout the last glacial period in response to orbital scale changes in the summer insolation. Evidence to support this assertion is presented in the Discussion section.

2.2. Study site

Baldwin Lake is an alpine ephemeral lake located at 2040 m above sea level with a small drainage basin

(78 km²) (Figs. 1 and 2) (French and Busby, 1974). Geologically recent thrust faulting is a likely origin for the east–west trending Big Bear Valley (Stout, 1976). The lake is closed with no modern outlet, and it is dry — on average — 3 to 4 out of every 10 years (French and Busby, 1974). Shoreline features indicate a maximum depth of 5.3 m from modern lake bottom (French and Busby, 1974). Leidy (2003) suggests that Baldwin Lake may have been part of a much larger Big Bear glacial lake during the late-Quaternary. Well data indicates up to 35 m of “lake” sediment underlying Baldwin Lake and another 70 m of older alluvium underlying the lake sediments; however, these wells are from the south branch of Baldwin Lake and likely underestimate the lake’s actual subsurface sediment thickness (Stout, 1976). Human activity on, and near, the lakebed is suspected to have produced a significant hiatus spanning ~20,000 cy BP through to the 20th century (Baldwin Lake Historical Society, per. com.: see Section 4.1 for details).

3. Methods

3.1. Core collection and description

Three sediment cores (BLDC03-1 [1000 cm], BLDC04-1 [1450 cm], and BLDC04-2 [1450 cm]) were extracted

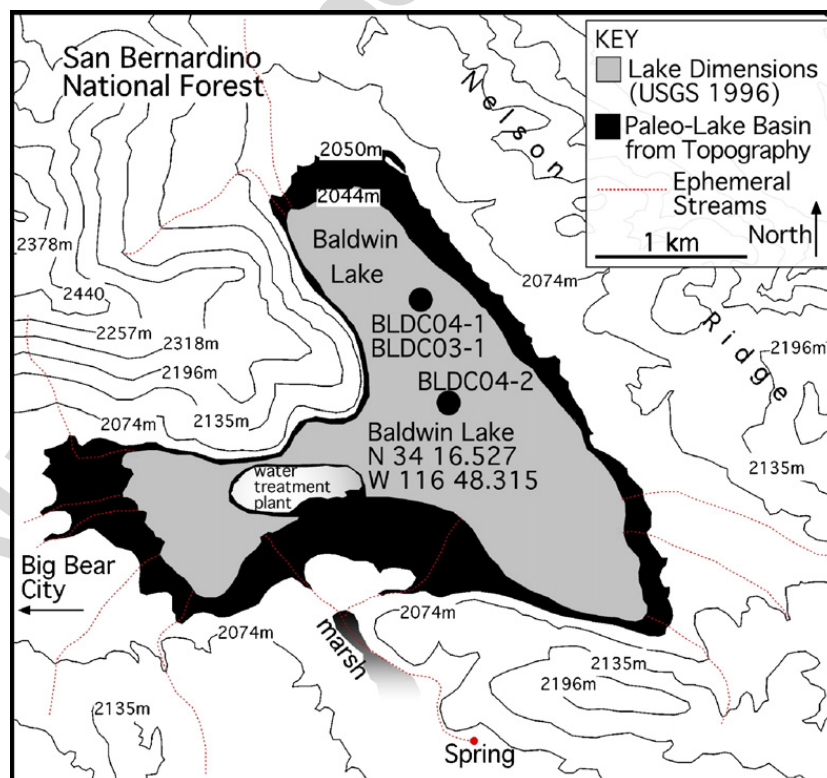


Fig. 2. Study site map with core locations.

using a hollow-stemmed auger drill core (Fig. 2). Cores BLDC03-1 and BLDC04-1 were taken from within 200 m horizontal distance from one another near the lake's present day northeast extension (Fig. 2). Core BLDC04-2 was extracted from the lake's present day depocenter (Fig. 2). Our assumption regarding sediment gaps is that all core drives using the hollow-stemmed auger drill core were to the measured depth. Any "missing" core sections were subtracted from the top of core's individual drive and assumed a product of over-auguring between drives. Similarly, any "re-worked" sediment at the core top was assumed a product of drilling and was not used for sediment analysis. Only core BLDC04-2 is presented in this study as that it contains the most continuous sediment section with the most complete suite of sedimentological analyses (approximately 12% missing sediment). Core BLDC04-2 (hereafter referred to as core BL-2) was split, described, and archived in cold storage at Cal-State Fullerton.

3.2. Age control

Eight AMS ^{14}C dates were measured on core BL-2 (Table 1) using either macro-organics (i.e., grasses, insect remains and/or mixture) or bulk organics. Materials were measured at the University of California, Irvine Keck AMS Facility. Macro-organic samples were pre-treated with an acid wash to remove carbonate; bulk organic samples were pre-treated with an acid–base–acid wash.

3.3. Magnetic susceptibility

Samples were extracted from BL-2 at 1.0 cm contiguous intervals ($n = 1306$). The samples were placed in pre-weighed 8 cm³ plastic cubes. Mass magnetic susceptibility was measured twice on each sample with the y-axis rotated 180° once per analysis. All samples were analyzed using a Bartington MS2 Magnetic Suscepti-

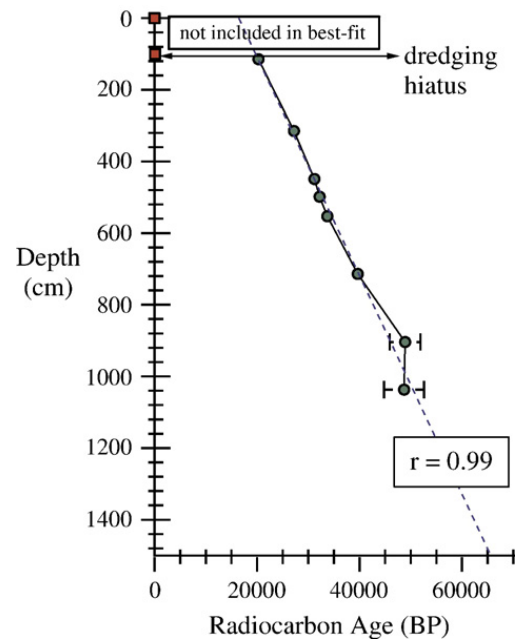


Fig. 3. Age–depth diagram. Note that the upper 80 cm of modern sediment are not included in the best fit line due to late-19th century dredging.

bility instrument at 0.465 kHz. All magnetic susceptibility measurements were determined on same day as cores were split and described to minimize possible magnetic mineral diagenesis with exposure to air. Following measurement of magnetic susceptibility, samples were weighed to obtain total sediment wet weight. The average magnetic susceptibility value for each sample was then divided by the sample weight to account for mass differences. Measurements are reported to the 0.1 decimal place as mass magnetic susceptibility ($\text{CHI} = \chi$) in SI units ($\times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$).

3.4. LOI 550 °C (percent total organic matter)

Total organic matter was determined using the loss on ignition method (Dean, 1974; Heiri et al., 2001; Shuman,

Table 1
AMS radiocarbon dates

UCIAMS #	Sample depth (cm)/material	AMS ^{14}C age (BP)	Calibrated age (BP)*	2-sigma range	$\delta^{13}\text{C}$
10317	114–117/bulk	17,020±80	20,276	19,622–20,929	–18.7
10318	315–316/grass	27,210±210	NA		–14.3
10319	449–450/grass	31,200±2000	NA		–4.9
14905	498–499/insect	32,210±210	NA		–9.5
10320	553–554/grass	33,720±610	NA		–16.0
10321	714–715/bulk	39,650±940	NA		–20.9
10322	904–905/bulk	48,900±3000	NA		–18.9
10323	1037–1038/bulk	48,700±3900	NA		–13.2

* CALIB REV4 4.2 (Stuiver et al., 1998); NA=not applicable.

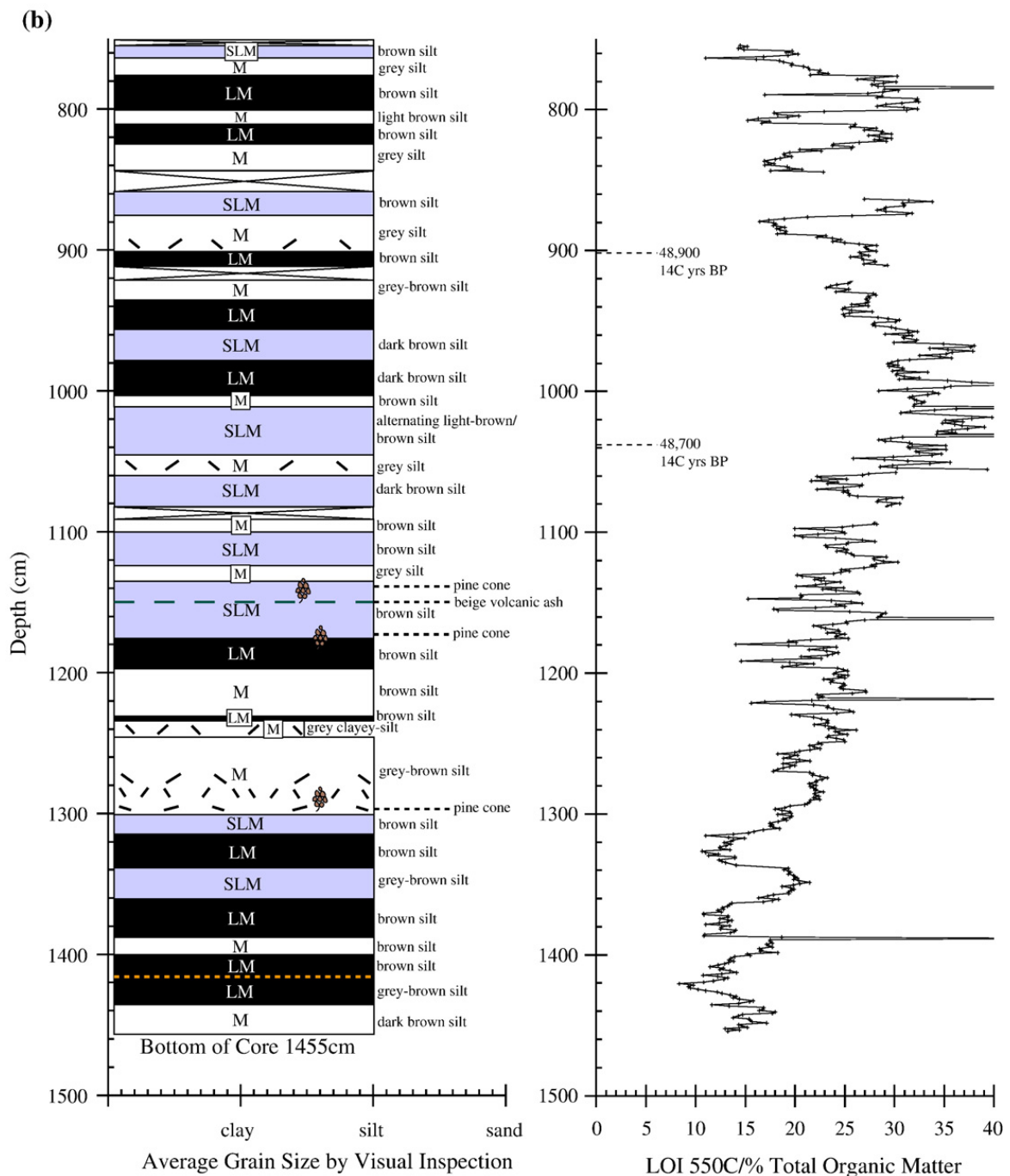


Fig. 4 (continued).

BL-2 at 1.0 cm contiguous intervals ($n=1306$). Following the 550 °C analysis and weighing, crucibles were re-heated to 950 °C for two hours in an Isotemp muffle oven. After two hours the samples were re-weighed and percentage total carbonate was calculated. As shown by Dean (1974), three to four percent total weight loss after 950 °C may be a function of clay de-watering. Consequently, we interpret values less than three to four percent as essentially zero percent total carbonate.

4. Results

4.1. Age control

Age control for core BL-2 is based on eight AMS ^{14}C dates (Table 1; Fig. 3). A best-fit line ($r=0.99$) to the age–depth data suggests that sedimentation rates are relatively uniform over the interval studied. Any significant changes in sedimentation rates or intervals of non-deposition or sediment removal will produce step-

function changes in the age–depth relationship; we do not observe any significant changes in the age–depth relationship based on our present age control (Fig. 3). The occurrence of several ephemeral lake sediment facies indicates intervals of possible slowed sedimentation or non-deposition (Fig. 4). However, only 5 intervals, summing 47 cm combined sediment, show evidence for mud cracks (i.e., sustained surface desiccation). The modern ephemeral lake system — intact since modification by humans ca. late 19th to early 20th century (see below) — is over ~110 cm sediment length. Using this for comparison, we suggest that none of the four prior desiccation episodes represent more than a century of time, including compaction. Consequently, at the time-scales of interpretation for this paper, we suggest that eight dates provide sufficient age control to infer millennial-to-orbital scale climate variability. The age data are extended to the core bottom using the linear fit line to provide an estimated minimum basal age of 65,000 years BP (Fig. 3). It is noted, however, that we do not construct an age model. As a result, we plot all data versus depth, not age.

Lastly, the apparent 20,000 year hiatus at ~114 cm depth is a probable artificial hiatus produced by human activity (Baldwin Lake Historical Society, 2003); the post-modification ages are not included in the best-fit line (Fig. 3). Regardless of the reason for this hiatus, it is our contention that Baldwin Lake's modern hydrology (see Section 2.1) and sedimentology still responds directly to climate forcing despite any anthropogenic modifications of the basin. Kirby et al. (2004) showed that the sediments from nearby Lake Elsinore, which have been impacted significantly by humans for over 150 years, still record a strong climate signal. We assume the same climate response despite human modification at Baldwin Lake. As a result, it is suggested that the modern ephemeral lake is a satisfactory analog for assessing past ephemeral lake sediment facies (see Discussion).

4.2. Core description

BL-2 is characterized by homogenous, semi-laminated, or laminated silts and clays (Fig. 4a,b). Table 2 lists the criteria for homogenous/massive, semi-laminated, and laminated sediment units. The y -axis in Fig. 4 represents the average observed grain size based on texture and visual appearance. Notable sedimentological features include: 1) the color change from the core bottom to 1260 cm; 2) the occurrence of well-preserved pine cones from 1300 to 1140 cm; 3) a beige volcanic ash layer at 1145 cm (~1 mm thick); 4) a thick sediment interval

Table 2
Sediment type descriptions

Sediment type	Structure	Laminae thickness	Color
Homogenous/massive	No structure; occasional mudcracks and/or blocky/rotational features	NA	Grey to grey-brown
Semi-laminated	Discontinuous and poorly defined laminae;	>0.5 to 2 cm	Variegated browns
Laminated	Continuous and well-defined laminae	Sub-mm to <1 cm	Variegated browns

NA=not applicable.

between 1060 and 660 cm characterized by alternating laminated and semi-laminated, organic-rich, brown silts and homogenous grey clays; 5) the occurrence of charcoal and organic-rich thin laminae between 720 and 560 cm; 6) the preponderance of grasses and fibrous organics(?) features between 560 and 300 cm in largely brown, organic-rich, laminated to semi-laminated silts; 7) the transition to grey clays and silts from 220 through to 140 cm with occasional charcoal, grasses, and CaCO₃ crystals; 8) a homogenous silty clay from 128 to 65 cm; and, 9) the occurrence of the modern ephemeral lake sediments with mud cracks from 65 cm through to the core top.

4.3. Magnetic susceptibility, LOI 550 °C, and LOI 950 °C

Mass magnetic susceptibility is characterized by high-frequency variability superimposed on a general decreasing trend from the core bottom to 930 cm (Fig. 5). High amplitude, low frequency change demarcates the interval from 900 to 740 cm. From 740 to 600 cm, the CHI values are high and relatively uniform. At 600 cm, the magnetic susceptibility abruptly decreases and then rises uniformly through to the core top. Total organic matter (LOI 550 °C) is characterized by decimeter variability superimposed on an uniform increase in values from the core bottom to 1060 cm (Fig. 5). From 1060 to 960 cm, total organic matter values are high and sustained. A decrease occurs between 960 and 930 cm. From 930 to 700 cm, large amplitude, low frequency variability characterizes the total organic matter data. An interval of low and sustained values occurs between 700 and 600 cm after which the values abruptly increase to a peak at 500 cm. From 500 cm through to the core top, the total organic matter values decrease reaching a core low-point at the modern playa surface. There is also a negative exponential relationship between CHI and total organic matter ($r=0.61$; $n=1306$). Total carbonate (LOI

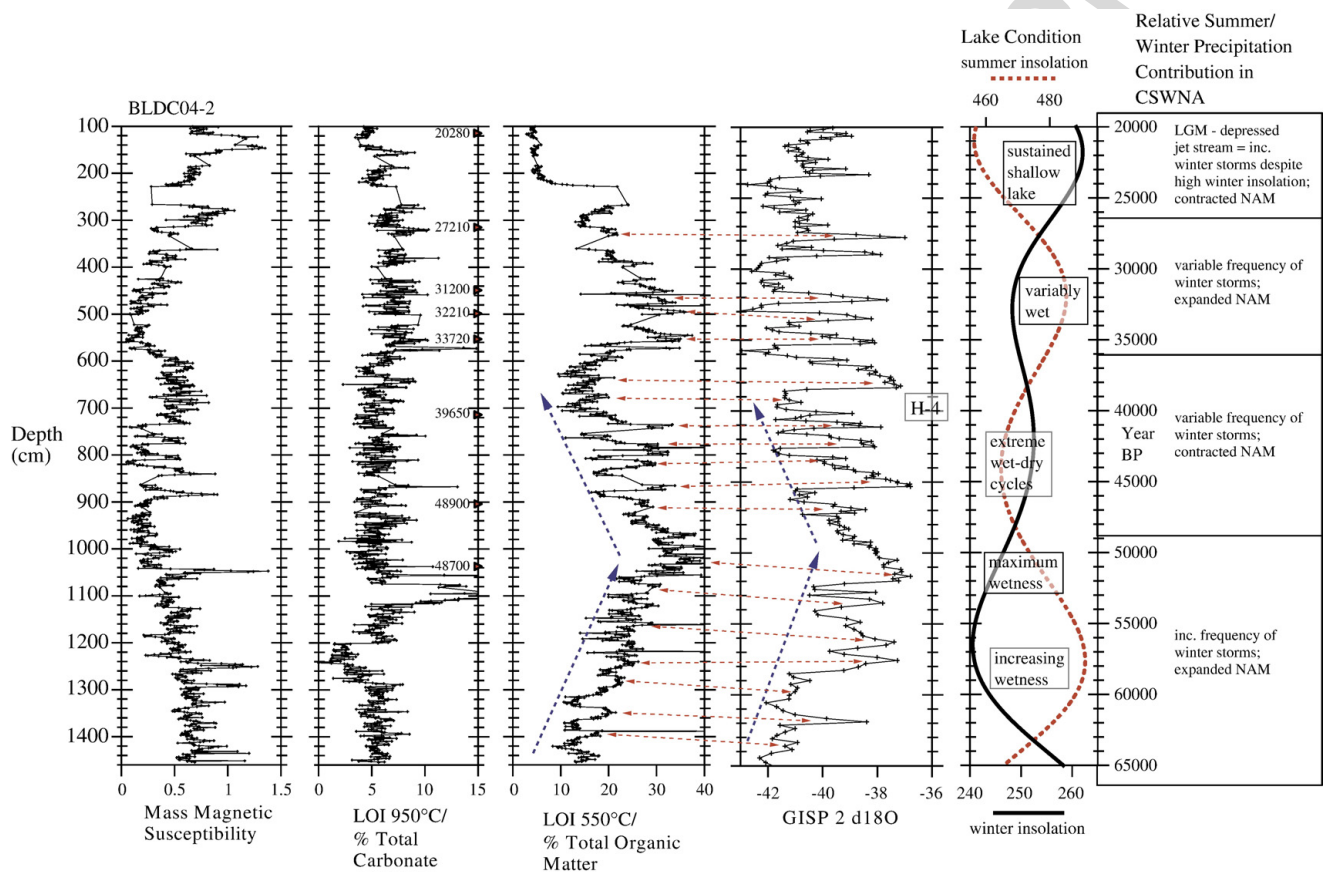


Fig. 5. BL-2 sedimentological data, GISP $\delta^{18}\text{O}_{(\text{ice})}$ data, and winter-summer insolation data (Laskar, 1990). From left to right: mass magnetic susceptibility; % Total carbonate (LOI 950 °C); % Total organic matter (LOI 550 °C); GISP2 $\delta^{18}\text{O}_{(\text{ice})}$; winter-summer insolation at 30°N latitude and general lake condition (wet vs. dry etc.). Heinrich event 4 (H-4) location is shown on GISP2 $\delta^{18}\text{O}_{(\text{ice})}$ graph. Relative summer/winter precipitation contribution to CSWNA is shown to the right of the insolation data. Dashed lines with arrows show suggested tie-points between the %TOM BL-2 data and the GISP2 $\delta^{18}\text{O}_{(\text{ice})}$ data. Note that the BL-2 data are not plotted as an age model; they are plotted versus depth. Only the ice core and insolation data are plotted versus age. LGM=last glacial maximum; NAM=North American monsoon.

950 °C) is generally uniform (~5%) with a $\pm 2\%$ range of variability from the core bottom through to the core top with the exception of two notable features: 1) an interval of low values between 1280 and 1200 cm; and, 2) an interval of high values from 1120 to 1080 cm (Fig. 5).

5. Discussion

5.1. Sedimentology

The most conspicuous sedimentological features in Baldwin Lake are the alternating units of: A) homogenous/massive grey to grey-brown, organic-poor, high CHI silts; and, B) laminated to semi-laminated variegated brown, organic-rich, low CHI silts (Figs. 4a,b and 5; Table 2). The differences in sedimentology suggest a change in the type of deposition and thus a change in the processes that drive sedimentation, such as climate. Inorganic laminae are diagnostic of specific processes such as storms, seasonality, anoxia, or non-storm related, pulsed sedimentation (e.g., rhymites) (Hardie et al., 1978; Smoot, 1991; Last and Vance, 1997; Hovorka, 1997; Anderson, 2001). It is possible that any one, or several, of the former processes are responsible for the laminae in Baldwin Lake.

In the present day Baldwin Lake system, the lake sediments are devoid of laminae (Fig. 4a). In fact, the modern lake sediments are grey, homogenous, organic-poor, high CHI, high CaCO₃ silts or clays with evidence for desiccation (e.g., mud cracks). These latter sediments are consistent with the modern ephemeral lake depositional environment. As a result, we adduce the modern ephemeral lake sediments as a template for interpreting past ephemeral lake facies in the Baldwin Lake sediment record (e.g., Hovorka, 1997; Wells et al., 2003). Assuming this modern analog technique is valid, it is apparent that ephemeral lake sedimentation occurred for brief intervals throughout the last glacial period at Baldwin Lake. In fact, five of the older homogenous, grey silt units preserve mud cracks and/or rotational features indicative of periodic desiccation (Fig. 4a,b). Using this modern analog technique, we interpret grey, homogenous silts as a first-order proxy for intervals of ephemeral lake sedimentation. To a lesser extent, magnetic susceptibility, which is often higher in the grey, homogenous silts, is also a first-order indicator of lake level, (i.e., higher magnetic susceptibility=lower lake level) (Figs. 4a,b and 5).

If the homogenous, grey silts represent ephemeral lake sedimentation (low lake levels), what do the laminated to semi-laminated, variegated brown, organic-rich, low CHI silts represent? Unlike textbook hyper-

saline playa lakes, glacial-age Baldwin Lake does not contain significant evaporites (Hardie et al., 1978; Rosen, 1994; Last and Vance, 1997; Lowenstein et al., 1999). Total carbonate values are consistently less than 7% in Baldwin Lake glacial sediments with one brief excursion at 1100 cm (Fig. 5). Therefore, we are fairly confident that the laminae do not represent evaporitic layers formed by mineral precipitation in hypersaline environments (Hardie et al., 1978; Rosen, 1994; Last and Vance, 1997; Wells et al., 2003). Smear slide analysis did not reveal any crystalline deposits in the laminated to semi-laminated facies. Instead, we interpret the laminated to semi-laminated, brown silts as a product of a deeper lake environment characterized by pulsed storm sedimentation, re-worked organics from the drainage basin and from within the lake environment, and possible seasonal sedimentation processes. Again, this interpretation is supported by research on similar ephemeral lakes, which show the formation and preservation of laminated sediments during sustained high lake stands (e.g., Hovorka, 1997; Wells et al., 2003). At 2040 m ASL, Baldwin Lake will freeze during winter months, particularly during the last glacial period when annual temperatures were lower than today (Anderson et al., 2002). As a result of this seasonal freezing, the laminae may represent varves formed during permanent lake stages. Until additional research is produced, however, the interpretation of the laminae as varves is wholly speculative. Nonetheless, it is our contention that the laminated to semi-laminated, brown, organic-rich, low CHI silts represent deeper lake environments. In addition, total organic matter, which is generally higher in the laminated to semi-laminated brown silts, is used in this research as a first-order proxy for relative lake level (i.e., higher total organic matter=high lake levels) (Figs. 4 and 5).

5.2. Orbital scale climate interpretations

Estimates of paleo-temperatures and paleo-precipitation in CSWNA during the last glacial indicate a significantly cooler (-9 °C below avg.), wetter (+700 mm above avg.) climate (Barbour, 1988; Heusser, 1998). This cooler, wetter climate is largely a function of the position of the jet stream and its associated storm tracks (Heusser, 1998; Negrini, 2002; Enzel et al., 2003). The presence of the North American ice sheet forced the jet stream south of its present average position (e.g., Bartlein et al., 1998; Negrini, 2002). A lower latitude jet stream would have increased the frequency of winter storms across the study region, thus favoring more permanent lakes in CSWNA during the cooler glacial climate (Lowenstein et al., 1999;

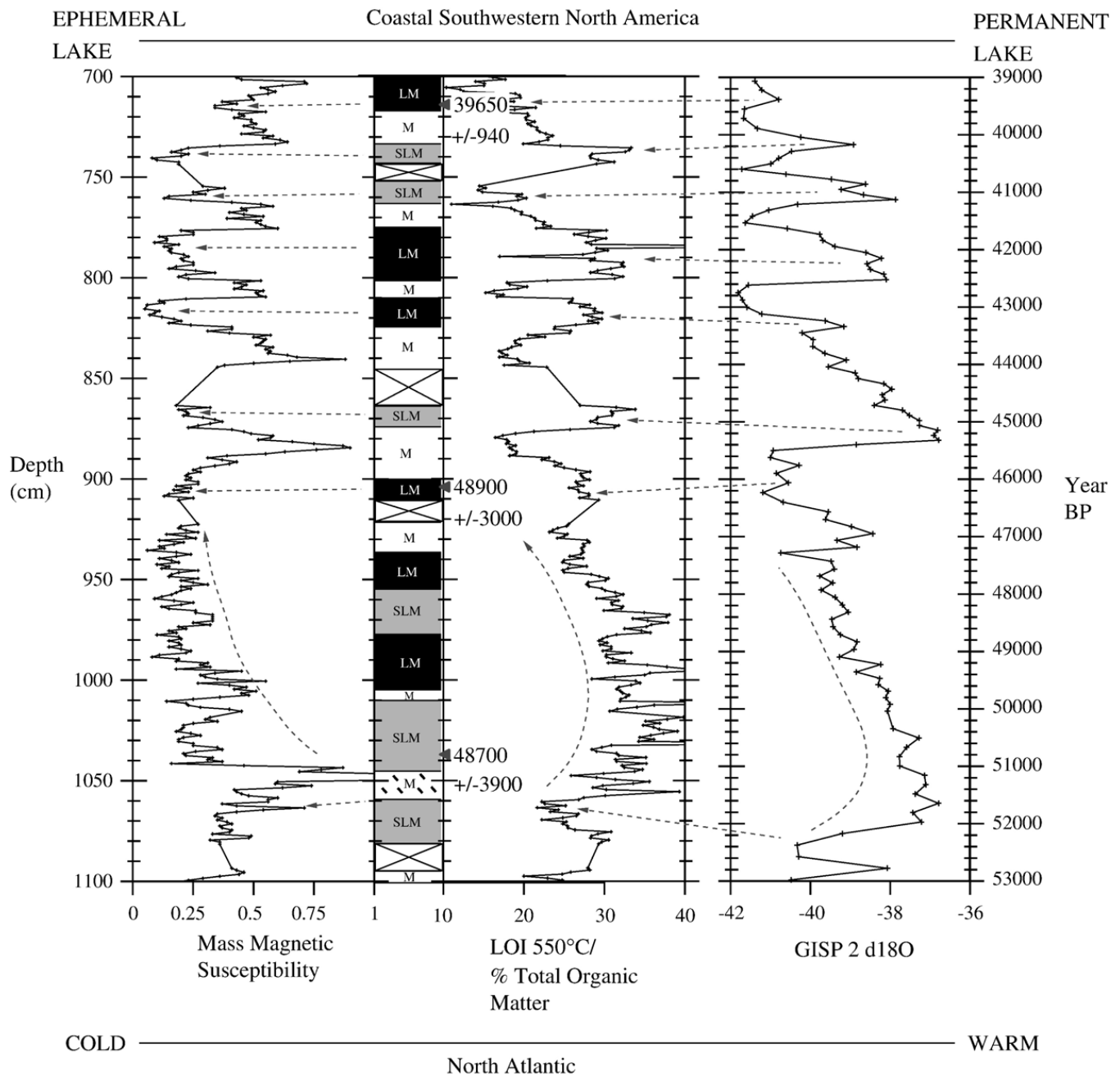


Fig. 6. Close-up view of the core section (BL-2 CHI and LOI 550 °C) and GISP2 $\delta^{18}\text{O}_{(\text{calcite})}$ data for the interval of alternating laminated to semi-laminated and homogenous sediment facies. Note that the core sediment data are not plotted as an age model. Only the GISP2 $\delta^{18}\text{O}_{(\text{calcite})}$ data are plotted versus depth. Dashed lines with arrows are suggested tie points between the two data sets. Millennial-scale similarities exist between the two independently and distal data sets.

Anderson et al., 2002; Anderson and Wells, 2003; Enzel et al., 2003; Kirby et al., 2005; Yang et al., 2005). Superimposed on the ice sheet-displaced jet stream is orbital-scale insolation forcing (Harrison, 1989). Long-term changes in winter–summer insolation should modulate winter storm tracks and the dynamics of the North America monsoon, respectively. Therefore, it is reasonable to conclude that there should be a relationship between orbital-scale, hydrologic dynamics at Baldwin

Lake and winter–summer insolation variability. To assess this relationship, we compared winter and summer insolation at 30°N latitude for the interval 20,000 to 65,000 years BP to Baldwin Lake sedimentology. Our reason for this comparison is two-fold: 1) orbital scale changes in winter insolation should produce changes in the average position of the winter jet stream and its associated storm tracks modulating the amount of winter precipitation in CSWNA; and, 2) orbital scale changes in

summer insolation should modulate the magnitude and spatial extent of the North American monsoon, which should control the amount of summer precipitation received in CSWNA.

A comparison of summer and winter insolation at 30°N latitude to Baldwin Lake sedimentology reveals an interesting first-order relationship to inferred, long-term lake dynamics (Fig. 5). Long-term variations in winter insolation show an inverse relationship — within the errors of dating — to the total organic matter curve, a proxy for relative lake level (Fig. 5). Generally, intervals of lower winter insolation correspond with periods high or rising total organic matter (higher lake levels) and vice versa. A decrease in winter insolation may have served to strengthen the polar front jet stream and favor more frequent winter storms across CSWNA. Summer insolation also varies on orbital timescales. Kirby et al. (2005) and Bird and Kirby (2006) recently suggested that the early Holocene in CSWNA, a time of maximum summer insolation, was characterized by higher regional lake levels and more frequent summer season storms than the late Holocene. These authors attribute the wetter early Holocene climate to the influence of the North American monsoon, which expanded more frequently into CSWNA. Here, it is argued similarly that during the last glacial period the North American monsoon would expand during intervals of higher summer insolation. Total organic matter — a proxy for relative wetness — from Baldwin Lake indicates that orbital-scale variations in summer insolation, or the strength of the NAM, influence long-term lake-level status. Intervals of high summer insolation are generally characterized by higher, inferred lake-levels (i.e., high or rising total organic matter); whereas, intervals of low summer insolation are generally characterized by low, inferred lake-levels (i.e., low, falling, or highly variable total organic matter) (Fig. 5). If, like the early Holocene, these intervals of an expanded North American monsoon occur simultaneously as a winter insolation minimum (i.e., more frequent winter storms), it is reasonable to conclude that the net effect on CSWNA is an increase in total annual precipitation (Fig. 5). The hydrologic response to this combined affect is to increase regional wetness and raise lake-levels. We note that in both intervals where winter minimum insolation corresponds to summer maximum insolation (~33 and ~57 ka), the % TOM is at or near its highest levels in the record (Fig. 5). This occurrence suggests that the combined affect of winter minimum and summer maximum insolation produce wetter climates capable of sustaining permanent lakes at our study site.

One interval of apparent contradiction between insolation forcing and inferred lake condition is from

220 to 140 cm (ca. 24,000 to 22,000 years BP), wherein a distinct change in sedimentology occurs (Figs. 4a and 5). The climate proxy data from BL-2 infer a low lake level — low %TOM and the occurrence of calcite crystals. However, the rapid change to clay-dominated sediment and the absence of mud cracks favors a deeper lake interpretation. Summer and winter insolation are lowest and highest, respectively, for the past 50,000 years, both of which favor a reduction in total annual precipitation. So, the question arises whether Baldwin Lake was ephemeral or permanent during the interval 24,000 to 22,000 years BP? It is worth noting that this time interval corresponds approximately to the onset of the last glacial maximum. This time interval also corresponds to the occurrence of large lakes in the Mojave Desert (Wells et al., 2003). It is hard to imagine a scenario wherein the Mojave is wet and the source region for the Mojave's water (i.e., the San Bernardino Mtns.) is dry. Therefore, we conclude that Baldwin Lake was a permanent, but shallow lake — where calcite crystals precipitated in super saturated waters and/or sediment pore water — during the interval 24,000 to 22,000 years BP. The unfavorable conditions for precipitation based on winter–summer insolation dynamics were diminished by the affect of an expanded North American ice sheet during the last glacial maximum and its influence on the jet stream's average position. As a result, CSWNA and its interior were wet during a period otherwise unfavorable to increased precipitation. This interplay between orbital forcing and ice sheet forcing likely occurred throughout the last glacial and may explain the imperfect relationship between Baldwin Lake inferred lake conditions and orbital forcing over the past 65,000 years BP.

Despite the latter interval of contradiction, we contend that the combined affect of changing summer and winter insolation and its modulation of storm tracks over the last glacial period acted to drive the orbital-scale variations in lake-level at Baldwin Lake (Fig. 5).

We also compare the Baldwin Lake record to the GISP2 ice core $\delta^{18}\text{O}$ record at orbital time scales (Fig. 5) (Stuiver and Grootes, 2000). This comparison is straightforward. We have not stretched our record to match the GISP2 ice core in any way. The lake sediment data are simply plotted against the independently dated GISP2 ice core $\delta^{18}\text{O}$ data (Fig. 5). The lake sediment record covers the interval 20,000 to 65,000 years based on 8 AMS ^{14}C dates and a linear extrapolation. As a result, the GISP2 $\delta^{18}\text{O}$ ice core record was plotted for the same time interval — 20,000 to 65,000 years BP. Unexpectedly, and without any manipulation, the Baldwin Lake sedimentological data follow closely the GISP2 $\delta^{18}\text{O}$ ice core data even at timescales as short as centuries. Taken at face value, the first-order relationship

between the two records suggests that intervals of increasing wetness in CSWNA correspond to intervals of North Atlantic warming (Fig. 5). North Atlantic warming between 65,000 and 52,000 years BP corresponds to a long-term increase in total organic matter (i.e., higher lake levels) in Baldwin Lake (Fig. 5). From 52,000 to 40,000 years BP, there is a first-order cooling in the North Atlantic and a general decrease in lake-level (Fig. 5). Between 40,000 and 35,000 years BP, the correspondence between Baldwin Lake and GISP2 is less straightforward. One possible explanation for this incongruity is attributed to Heinrich event 4. Kirby and Andrews (1999) argue that the mid-Wisconsin following Heinrich event 4 represents a major reduction in the size of the Laurentide ice sheet as well as an interval of dramatic climate change. Perhaps the discordance between the two records following Heinrich event 4 represents a distal response to a mid-Wisconsin climate restructuring? It should be noted that such discordance between 40 and 30 ka is not observed in lake records to the north (e.g., Zic et al., 2002; Benson et al., 2003). In any event, the first-order relationship between North Atlantic climate and CSWNA climate at orbital time-scales provides additional data for hemispheric climate teleconnections during the last glacial period.

5.3. Millennial-scale climate interpretations

In addition to the orbital-scale variability discussed above, the Baldwin Lake sediment record also reveals millennial-scale variability that bears intriguing similarities to the GISP2 $\delta^{18}\text{O}_{(\text{ice})}$ record (Fig. 5). To examine the BL-2/GISP $\delta^{18}\text{O}_{(\text{ice})}$ relationship more closely, we plotted the interval 700 to 1100 cm from BL-2 to the interval 39,000 to 53,000 years BP in GISP2 (Fig. 6). This sediment interval is selected for comparison because it represents an interval of distinct alternating sediment facies (i.e., wet [laminated to semi-laminated]–dry [homogenous/massive] cycles?). There are 9 apparent wet–dry cycles between 700 and 900 cm (Fig. 6). These wet–dry cycles are characterized by facies changes from grey, homogenous, high CHI, low TOM silts to variegated brown, laminated to semi-laminated, low CHI, high TOM silts (Fig. 6). Between 900 and 1040 cm, the millennial-scale cycles are less distinct; this interval is characterized by a trend from wet (1040 cm) to drier climate (910 cm) based on %TOM and CHI. Each of these sediment facies changes and inferred climate states are correlated to the GISP2 $\delta^{18}\text{O}$ ice core data. From this comparison, it is suggested that GISP2 interstadials (warm North Atlantic) correspond to wet intervals in CSWNA and vice versa (Fig. 6).

This relationship between the climate of the North Atlantic (warm/interstade) and that of CSWNA (wet/interstade) are similar to those from several lakes within the Great Basin (Zic et al., 2002; Benson et al., 2003). The new Baldwin Lake record, however, is at odds with pollen data from the Santa Barbara basin (Heusser, 1998). Heusser's (1998) 500–1000 year resolved pollen data seem to indicate that some North Atlantic interstadials are associated with an increase in Oak pollen in Southern California, a proxy for more xeric conditions. However, the broadly sampled Santa Barbara basin pollen record precludes a definitive comparison to Baldwin Lake at this time. Alternatively, high-resolution $\delta^{18}\text{O}_{(\text{foram})}$ data from Santa Barbara Basin reveal remarkable coherency between the GISP2 $\delta^{18}\text{O}_{(\text{ice})}$ record and sea surface temperature changes (Hendy and Kennett, 1999). GISP $\delta^{18}\text{O}_{(\text{ice})}$ interstadials (warm) are associated with rapid increases in sea surface temperature in Santa Barbara Basin (Hendy and Kennett, 1999). Modern studies from Santa Barbara Basin show a positive relationship between sea surface temperature and El Niño occurrence (Thunell et al., 1999). Furthermore, it is well documented that El Niño generally increases precipitation in CSWNA (Schonher and Nicholson, 1989; Redmond and Koch, 1991). Extending these relationships between North Atlantic interstadials, sea surface temperature, and El Niño activity back into the glacial record implies that interstadials should be associated with enhanced precipitation in CSWNA. This statement agrees with our findings at Baldwin Lake, which suggest increased wetness during North Atlantic interstadials. But, is El Niño (i.e., the tropical western Pacific) the source, or driving force, of precipitation in CSWNA during the last glacial?

It is clear that western North America paleoclimate sites record hemispheric climate dynamics (e.g., Benson et al., 2003). It remains unclear, however, where this hemispheric climate signal originates (see [Wu et al., 2003] for review). Is the source of this climate signal tropical or extratropical (Latif and Barnett, 1994; Knutson and Manabe, 1998; Turney et al., 2004; Vimont, 2005)? Recent records from the western tropical Pacific indicate that North Atlantic interstadials correspond to lower salinities in the western tropical Pacific (Stott et al., 2002). Historically, lower salinities/enhanced atmospheric convection in the western tropical Pacific are associated with La Niña or weakened El Niño climate states (Mo and Higgins, 1998). In CSWNA, La Niña or weakened El Niño climate states produce, on average, less precipitation (Cayan et al., 1999; Castello and Shelton, 2004). Heusser and Sirocko (1997) and Sirocko et al. (1999) use pollen data from Santa Barbara Basin to

suggest that the same relationship between El Niño and precipitation in CSWNA existed in the late glacial period. As a result, there is no reason to conclude that glacial El Niño events did not produce, like today, more precipitation in CSWNA. As already discussed, Thunell et al. (1999) demonstrate a modern relationship between Santa Barbara Basin sea surface temperatures and El Niño. Paleoclimate records from Baldwin Lake and Santa Barbara Basin, however, do not support the marine evidence from the western tropical Pacific for La Niña dominance during North Atlantic interstadials (Stott et al., 2002). Quite the opposite, the Baldwin Lake data show that North Atlantic interstadials are associated with wet conditions in CSWNA, producing organic-rich, laminated sediments. Our findings are in agreement with the relationship between the North Atlantic, Santa Barbara Basin sea surface temperatures, and its expected influence on regional precipitation (Hendy and Kennett, 1999; Thunell et al., 1999). Although this paper cannot resolve this apparent conflict between the western Pacific and CSWNA, it does suggest that the dynamics, particularly the spatial dynamics, of glacial period ENSO variability is not fully understood.

If sustained El Niño states, according to the western Pacific record, are not producing the requisite precipitation for permanent lakes in CSWNA during the last glacial period, specifically during the interstadials, then what is the precipitation source? Is ENSO's spatial expression limited to a lower tropical domain during full glacials? Furthermore, what is driving this millennial-scale hydrologic variability? Perhaps the source of enhanced precipitation in CSWNA during North Atlantic interstadials is related to large-scale, extra-tropical, Pacific-derived ocean–atmosphere processes, similar to the Pacific Decadal Oscillation (Mantua and Hare, 2002; MacDonald and Case, 2005)? Or, is the source of this glacial climate variability some combination of tropical–extratropical signals such as the ENSO-like decadal variability proposed by Zhang et al. (1997)? Zic et al. (2002) presents an intriguing argument linking ocean–atmosphere processes in the North Pacific to the North Atlantic. Using a modern calibration, they show that wetter conditions in Oregon correspond to warmer conditions in the North Atlantic. Zic et al. (2002) argues that changes in multi-decadal, ocean–atmosphere dynamics modulate the polar front jet stream and its associated storm tracks. Benson et al. (2003) then demonstrated that the Great Basin, in general, show similar wet/interstadial relationships using the same jet stream/storm track argument. Here, we present new results, which implicate an extra-tropical origin for precipitation variability in CSWNA during the last glacial period. Perhaps, in lieu of

“super-ENSOs”, “super”-PDOs (Pacific Decadal Oscillation), or preferred, Pacific-origin climate states, drive the glacial climate of CSWNA, specifically, and western North America, generally?

6. Summary

A new lake sediment record from CSWNA reveals millennial-to-orbital scale climate variability over the period 20,000 to 65,000 years BP. Using a modern sedimentological comparison, past depositional environments are inferred. These environments alternate from ephemeral lake sediment facies (drier) to permanent lake sediment facies (wetter). The sedimentology indicate that the general glacial climate was wetter than today; however, superimposed on orbital scale climate trends are packages of alternating wet–dry, millennial-scale cycles. The first-order, orbital scale climate trends are explained by long-term, winter–summer insolation forcing and their modulation of winter storm tracks and the North American monsoon, respectively. A comparison of these orbital-scale climate trends from Baldwin Lake to the GISP2 $\delta^{18}\text{O}$ ice core record shows remarkable correspondence within the limits of age control. Generally, a warmer North Atlantic is associated with a wetter CSWNA. At millennial time scales, the Baldwin Lake record appears, at times, to also correspond to the GISP2 $\delta^{18}\text{O}$ ice core record – showing a similar phase relationship as climate records from the Great Basin (warm North Atlantic interstadials = wetter western North America). There is also agreement between the Baldwin Lake paleoclimate record and Santa Barbara Basin paleo-sea surface temperatures, which imply an increase in regional precipitation during North Atlantic interstadials based on modern sea surface temperature/precipitation dynamics (Thunell et al., 1999). The Baldwin Lake record, however, is at conflict with climate data from the western tropical Pacific where interstadials are associated with La Niña climate states, which should reduce precipitation in CSWNA. As a working hypothesis, we suggest, like Zic et al. (2002) and Benson et al. (2003), that extratropical, ocean–atmosphere dynamics drive glacial climate variability in western North America. This research makes clear the need for additional, high-resolution, multi-proxy paleoclimate archives for understanding better the spatial dynamics and phasing of glacial hemispheric climate.

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