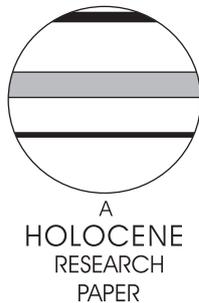


# Lateglacial and Holocene hydroclimate inferred from a groundwater flow-through lake, Northern Rocky Mountains, USA

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**Abstract:** Climate-driven variations in lake–groundwater exchange are recorded by sediments in groundwater-dominated lakes. A groundwater flow-through lake in west-central Montana (USA) registers latest Pleistocene and Holocene hydroclimatic variation in fluid and solute balance, as controlled by rates and timing of groundwater recharge. Early Holocene warming occurred under conditions of relative aridity and low groundwater throughflow, punctuated by a *c.* 450-yr episode of lake dilution centered on 11 000 cal. yr BP. Maximum evaporative concentration of lake waters, registered in both  $\delta^{18}\text{O}$  values and mineralogy of endogenic carbonates, coincided with the early-Holocene peak in insolation seasonality at about 9750 cal. yr BP. Subsequently, progressively decreasing lake residence time drove a sustained long-term decline in salinity while having a very subdued effect on mean  $\delta^{18}\text{O}$  values. We explain this decoupling by (1) limits placed on oxygen isotope sensitivity by groundwater throughflow, and (2) a shift toward greater summer rain contribution to lake inflow after mid-Holocene time. Superimposed multidecadal- and century-scale variation in lake–groundwater exchange generated high-frequency but low-amplitude isotopic oscillations throughout the record. High rates of groundwater throughflow maintaining low lake salinity similar to that observed today were established around 1400 cal. yr BP. We infer reduced regional stream baseflow, decrease in permanent wetlands (relative increase in ephemeral wetlands) and enhanced lake and wetland salinity prior to this time, relative to the late Holocene.

**Key words:** Endogenic carbonate mineralogy, aragonite, oxygen isotopes, lakes and groundwater, western North American paleoclimate.

## Introduction

Hydroclimatic variation affects groundwater flow by altering recharge and discharge rates. Changing groundwater fluxes are of specific interest in considering the effects of climate variability on wetland function and stream baseflows, important management issues linked to the status of groundwater (Rosenberry and Winter, 1997; Smith *et al.*, 1997; Winter, 1999). Sedimentology of groundwater-controlled lakes provides an avenue for inferring changes in groundwater balance resulting from climate variability over time (Almendinger, 1993; Fritz *et al.*, 2000; Smith *et al.*,

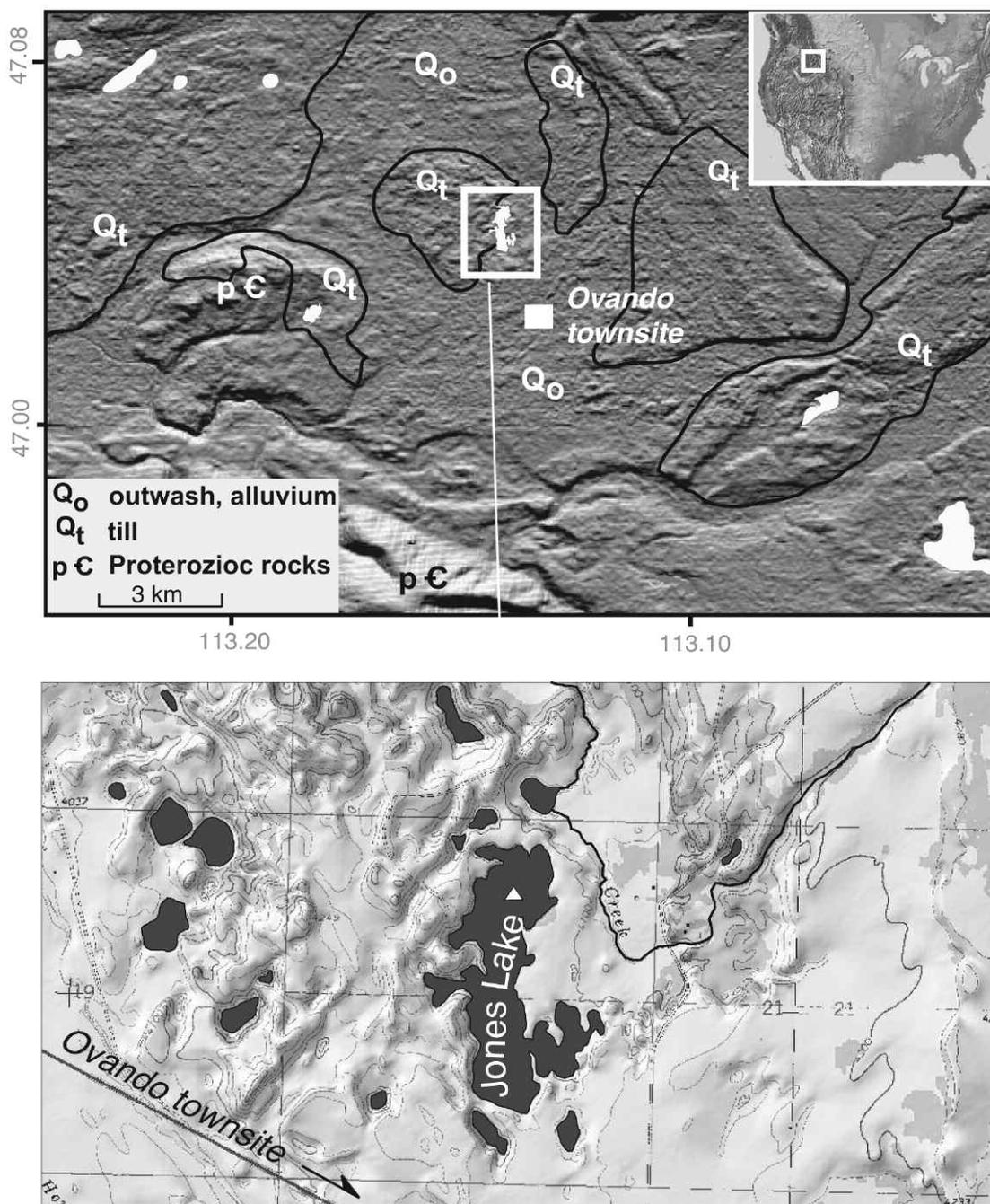
2002; Shapley *et al.*, 2005). In particular, mineralogy and isotopic composition of endogenically precipitated carbonate minerals reflect lake residence time; in groundwater-dominated lakes residence time is a function of rates of lake–groundwater exchange.

Modern hydroclimatic variability in the Pacific Northwest and Northern Rockies reflects multidecadal Pacific Ocean circulation and sea-surface temperature variations (Harshburger *et al.*, 2002; Graumlich *et al.*, 2003; McCabe *et al.*, 2004). On longer timescales, paleoclimate evidence across the region is interpreted to record Holocene orbital variation (Whitlock and Bartlein, 1993; Thompson *et al.*, 1993), Lateglacial–early Holocene periods of transience (Mikolajewicz *et al.*, 1997; Reasoner and Jodry, 2000; Yu and Wright, 2001; Kovanen and Easterbrook, 2002), and late-Holocene modal changes in hydrologic balance (Stone and Fritz, 2006; Hofmann *et al.*, 2006; Stevens *et al.*, 2006).

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Here we evaluate the response of shallow groundwater to these modes of variation through the carbonate sedimentology of Jones Lake, a low-elevation (1200 m a.s.l.), 32 ha kettle lake formed in late-Pleistocene till and ice-contact sediments of the Ovando Valley, Montana, USA (Figure 1; Dea, 1981). Previous work shows that modern geochemistry and sedimentation in Jones Lake depend strongly on groundwater fluxes through surficial aquifers and on lake/groundwater boundary states (Shapley *et al.*, 2005, 2008). Jones Lake hydrology is controlled by groundwater inflow–outflow dynamics and atmospheric exchanges. Groundwater recharge is focused on numerous closed depressions distributed across the landscape. Locally steep terrain produced by stream incision induces high rates of groundwater outflow and short (1.5–2 years) lake hydraulic residence time. Groundwater outflow discharges to a tributary of the Blackfoot River.

Ionic concentrations, aqueous stable isotopes and lake thermochemical profiles were used to model patterns of lake evolution and sedimentation in this semi-arid region, where evaporation exceeds precipitation by ~2:1 (Shapley *et al.*, 2005, 2008; Myrbo and Shapley, 2006). The lake system is strongly influenced by its flow-through groundwater regime, particularly by the ratio of net lake evaporation to groundwater outflow. Jones Lake thus provides an advantageous setting for observing the influence of Holocene climatic variability on water balance of a shallow groundwater system, as registered by compositional change in carbonate sediments. This analysis is focused primarily on temporal changes in the ratio of calcite to aragonite (sensitive to Ca:Mg in precipitating waters) and on  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  of endogenic carbonate minerals (sensitive to lake fluid balance and carbon cycling). Mechanisms of groundwater influence over lake composition, examined in previous work, help



**Figure 1** Regional setting and generalized geology of the Ovando Valley and the Jones Lake coring location (triangle). The Ovando Valley is one of numerous fault-controlled structural basins occurring in the Northern Rocky Mountains of Montana

**Table 1** Radiocarbon sample results and age model departures

AZ lab ID	Corrected sample depth (cm)	Reported age <sup>14</sup> C yr BP	<sup>14</sup> C age error (2σ)	Calibrated yr BP (median)	Model age prediction	Model age minus calibrated age
AA41910	137.9	1618	35	1502	1510	8
AA39436	198.4	2451	83	2535	2450	-85
AA39437	338.3	4090	65	4608	4624	16
AA41911	409.1	4865	44	5608	5724	116
AA39439	605.2	7940	110	8797	8772	-25
AA39440	729.5	9465	73	10 735	10 705	-30

Corrected sample depths include minor adjustments for core deformation and apparent dip; tephra are assigned thicknesses of zero. Calibrations are median ages (Calib 4.3; Stuiver *et al.*, 2002).

explain complexities of solute and isotope response to hydroclimatic forcing occurring over different Holocene timescales.

## Methods

Jones Lake was cored in June of 1997 using square-rod piston coring tools (Wright, 1967). Two cores encompassing Holocene and latest Pleistocene sediments were collected in 1 m sections from near the deepest point in the modern lake (13 m), cased in PVC and transported to the Limnological Research Center (LRC) Core Lab at the University of Minnesota. Field-extruded surface cores were used to characterize latest Holocene sediment.

Cores were split and imaged with a line scanner prior to initial core description. Description entailed correlation of sedimentary structures in the two overlapping cores, visual description of sediment composition and structure, and petrographic examination of a library of smear slides. Half of one core was continuously sampled on 2 cm centers for analyses of bulk density, carbon content, mineralogy and elemental composition. Remaining sediment was sectioned on 1 cm centers for stable isotope analysis of carbonate minerals.

All 2 cm samples were analyzed for total carbon (TC) and total inorganic carbon (TIC) content with a UIC<sup>TM</sup> coulometric carbon analyser. Replicate analyses were performed on 15% of field samples; replication is generally within ±2% of measured concentration.

Alternate 2 cm samples were analyzed for mineralogy by x-ray diffraction (XRD) and for elemental composition by x-ray fluorescence (XRF). XRD analyses were performed on a Phillips Model 1200<sup>TM</sup> diffractometer using Cu Kα radiation over 5° to 75° in 2θ. Mineral identification used automated peak-search, and peak areas were quantified against standards for quartz, calcite, aragonite, dolomite and chlorite. Raw XRD mineral percentages have precision of ±5% at best. XRD data were normalized to coulometric TIC to improve precision of carbonate mineral percentages. Normalization of carbonate minerals was by:

$$\% \text{ mineral}_{(\text{norm})} = \frac{[\% \text{ mineral}_{(\text{XRD})}]}{(\Sigma \% \text{ carbonate minerals}_{(\text{XRD})} - \text{siderite})} * (\text{TIC}) \quad (1)$$

with siderite (a minor phase in Jones Lake sediments) excluded from the normalization because of known poor reactivity in the TIC coulometer. Major silicate mineral phases were then normalized to TIC-normalized calcite percentages by:

$$\% \text{ silicate mineral}_{(\text{norm})} = \frac{[\% \text{ calcite}_{(\text{norm})}]}{[\% \text{ calcite}_{(\text{XRD})}] * (\% \text{ silicate mineral}_{(\text{XRD})})} \quad (2)$$

XRF analyses of elemental composition were performed on a Phillips PW1480 spectrometer. Data are reported as oxides normalized to 100% of sample mass.

Homogenized 1 cm subsamples were pretreated for isotope analysis by 24 h digestion in ~45 ml of 2.5% sodium hypochlorite, then sieved (125 μm) to remove ostracode shells and other coarse materials. Cobbles of Proterozoic-aged Belt Supergroup metasediments were analyzed to evaluate the influence of detrital contaminants on isotopic composition of lake sediments; unweathered material from cobble interiors was removed by chiseling and ground. Analyses of δ<sup>13</sup>C and δ<sup>18</sup>O of carbonate minerals were conducted on a Finnigan-MAT 252 isotope ratio mass spectrometer with a Kiel II automated carbonate preparation device; analytical precision is 0.1‰. Results for δ<sup>13</sup>C and δ<sup>18</sup>O are given with respect to the VPDB standard. Five samples of fine charcoal and one seed were assembled from 1–2 cm sections for AMS <sup>14</sup>C dating. Charcoal fragments were picked manually from 250 μm and 125 μm sieve residues. Dried samples were pretreated and analyzed by the University of Arizona AMS lab on a 2.5 MV General Ionex accelerator mass spectrometer.

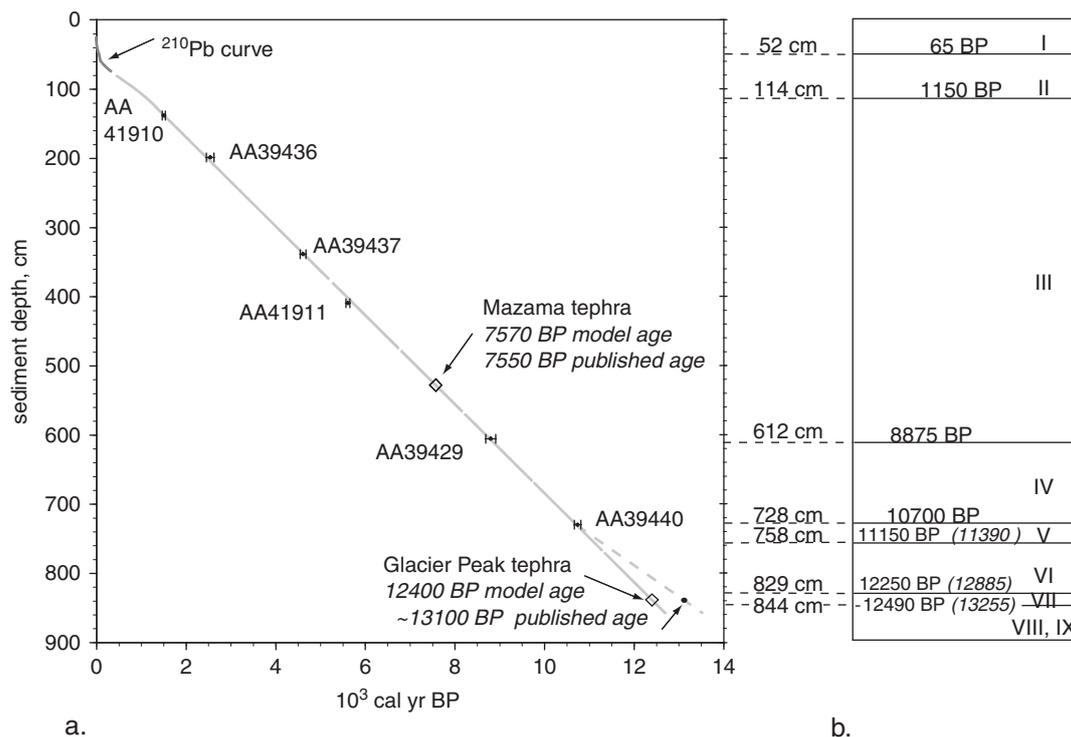
## Results

### Chronology

Results of <sup>14</sup>C analyses and calibrations (Calib 4.3; Stuiver *et al.*, 2002) are summarized in Table 1; Data File 1 (available online) shows sampling locations relative to core imagery. The resulting age–depth relationship is highly collinear; the linear best-fit model falls within 2σ errors for four of six radiocarbon dates and marginally outside 2σ for another (Figure 2a). The model produces an inferred age of 7570 cal. yr BP for the Mazama tephra, in excellent agreement with recent dating of the Mazama airfall (Hallett *et al.*, 1997; Zdanowicz *et al.*, 1999) applied to other western North American chronostratigraphies (eg, Colman *et al.*, 2004). Model-inferred age of the presumptive Glacier Peak (GP) ‘G’ tephra (12 400 cal. yr BP), which lies below the dated horizons in the Jones Lake core, is several hundred years younger than published central estimates for the GP tephra in the Northern Rockies. The stratigraphy and age of distal GP tephras remains unsettled, however (Foit *et al.*, 1993; Osborn and Gerloff, 1997), so the significance of this departure is uncertain. An alternative age model incorporating linear interpolation between our lowermost <sup>14</sup>C data and the GP horizon is shown in Figure 2, and its significance evaluated in the Discussion section.

### Lithologic description and classification

Based on sediment structure, composition and petrographic character, nine lithostratigraphic units are recognized in Jones Lake sediments (Figure 2b and Table 2; Data File 1). Sediment classification follows the usage of Schnurrenberger *et al.* (2003). Banded and laminated carbonate mud dominates the sediment sequence, with intervals of diatom ooze. Basal sediments consist of poorly



**Figure 2** (a) Age–depth model for the Jones Lake core. Depths are corrected for core section breaks; Mazama and Glacier Peak tephras are assigned thicknesses of zero. Upper 20 cm of Unit I sampled by surface core. Ages are calibrated <sup>14</sup>C yr BP as shown in Table 1 and <sup>210</sup>Pb years from Shapley *et al.* (2005). Steepened depth/age slope in uppermost sediment reflects high water content and enhanced sediment production in modern era. (b) Depths and model ages of lithostratigraphic units in the Jones Lake core. Italicized ages reflect an alternate basal age model segment incorporating an age of 13.1 cal. ky BP for the GP tephra. See Table 2 and Electronic Data File 1 for lithologic descriptions

sorted sand, gravel and silt interpreted as till and early lake-basin inwash from the recently deglaciated landscape.

**Bulk density and carbon stratigraphy**

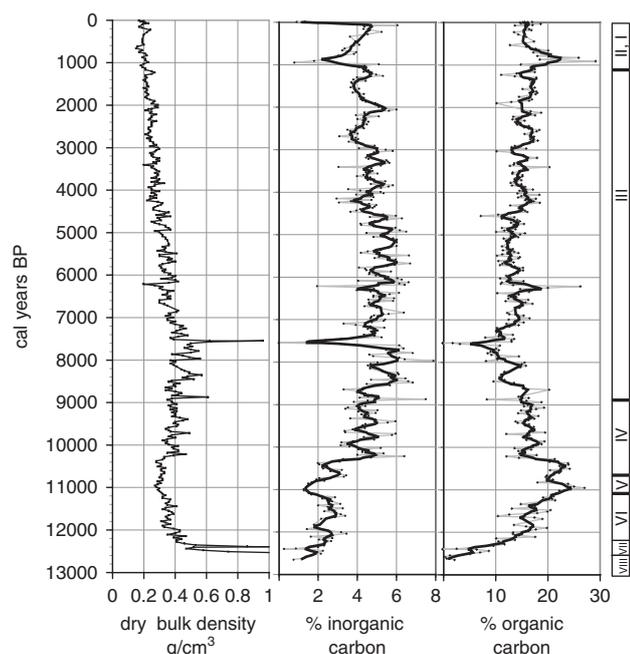
Bulk density declines up-core prior to 11 000 cal. yr BP, then generally increases between 11 000 and 7500 cal. yr BP. This trend is coincident with increasing carbonate mineral concentration; both decline after 7500 cal. yr BP (Figure 3). TIC concentrations are high

throughout most of the Holocene; TIC averaging ~5% between 10 500 and 1000 cal. yr BP translates to carbonate mineral concentrations near 40 wt.%. A prominent interval of reduced TIC centered on 11 000 cal. yr BP corresponds to lithostratigraphic Unit V. Between ~10 500 and 3000 cal. yr BP, TIC oscillates with crude century- to multicentury-scale periodicity. Between ~3000 cal. yr BP and the beginning of the historic era, TIC shows three prominent millennial-scale oscillations with superimposed century-scale variations.

**Table 2** Summary lithology and age boundaries of lithostratigraphic units in the Jones Lake core

Unit	Age (cal. yr BP)	Dominant lithologies	Corrected thickness and structure
I	65 – present	Dark greenish-brown diatom ooze	52 cm; banded
II	1150–65	Greenish brown to grey-brown diatom ooze and carbonate mud (calcite)	62 cm; banded, rarely laminated
III	8875–1150	Olive to dark brown carbonate mud (aragonite)	498 cm; laminated and banded; bundling
IV	10 700–8875	Olive to dark brown carbonate mud (aragonite) with occasional thin pyrite lamellae	116 cm; laminated and banded
V	11 150–10 700	Very dark brown diatom ooze	27 cm; laminated
VI	12 250–11 150	Olive to dark brown carbonate (aragonite) mud and carbonate-rich diatom ooze	71 cm; laminated and banded; bundling
VII	12 490–12 250	Brown calcareous silt and white carbonate mud (aragonite) lamellae	15 cm; very finely laminated
VIII	–	Greenish-grey sandy silt or silty clay with abundant pyrite	4 cm; massive
IX	–	Grey, poorly sorted sand and angular gravel	≥ 5 cm; massive

Thicknesses incorporate depth corrections applied to the age model (Figure 2). Age boundaries interpolated from median-age calibrations of AMS <sup>14</sup>C results in Table 2 and correlation of <sup>210</sup>Pb results from a nearby surface core (Shapley *et al.*, 2005). Tabulated lithologies and structures represent dominant core characteristics; see Data File 1 (available online) for detailed descriptions.



**Figure 3** Bulk density and carbon chemistry, shown with lithostratigraphic units on right. Heavy TIC and TOC curves are smoothed by a five-point running mean. Prominent bulk density maxima near 12 400 and 7500 cal. yr BP reflect the presence of Glacier Peak and Mt Mazama tephras. Analytical error is near the scale of data points

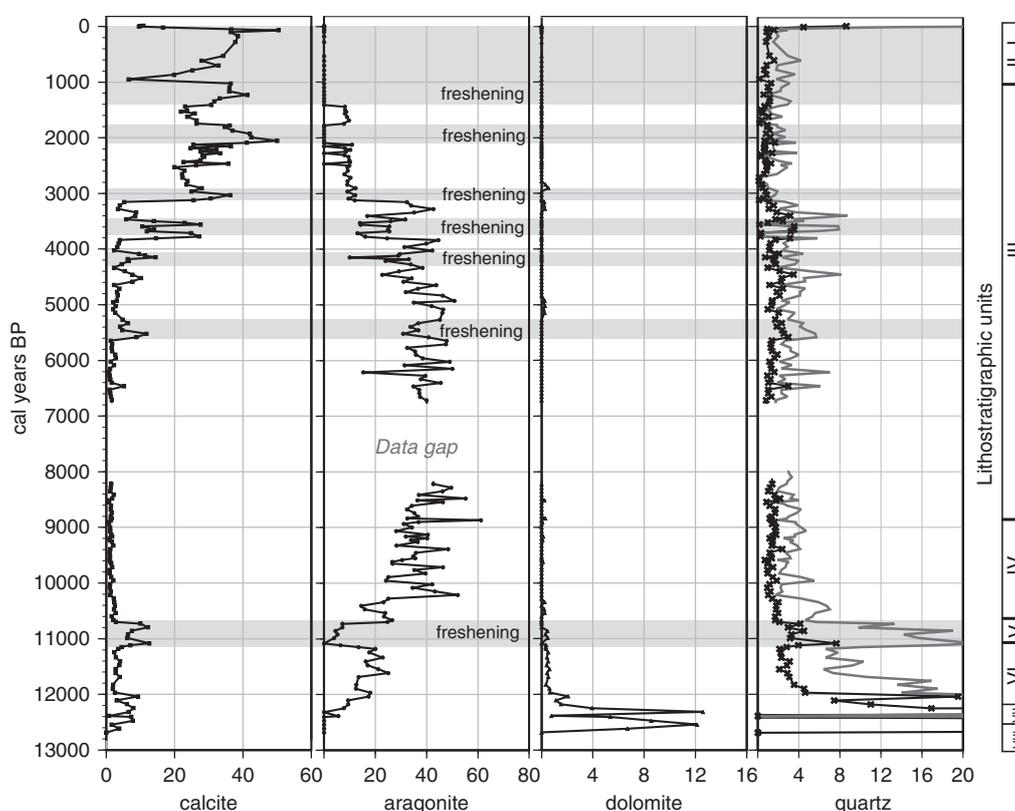
Organic matter and carbonate minerals are the main components of most sediment intervals, resulting in a dilution-controlled inverse correlation between TOC and TIC (Figure 3). Correlation

breaks down where tephras and diatom frustules dilute both carbonate minerals and organic matter, and where detrital mineral concentrations are significant (prior to 12 000 cal. yr BP).

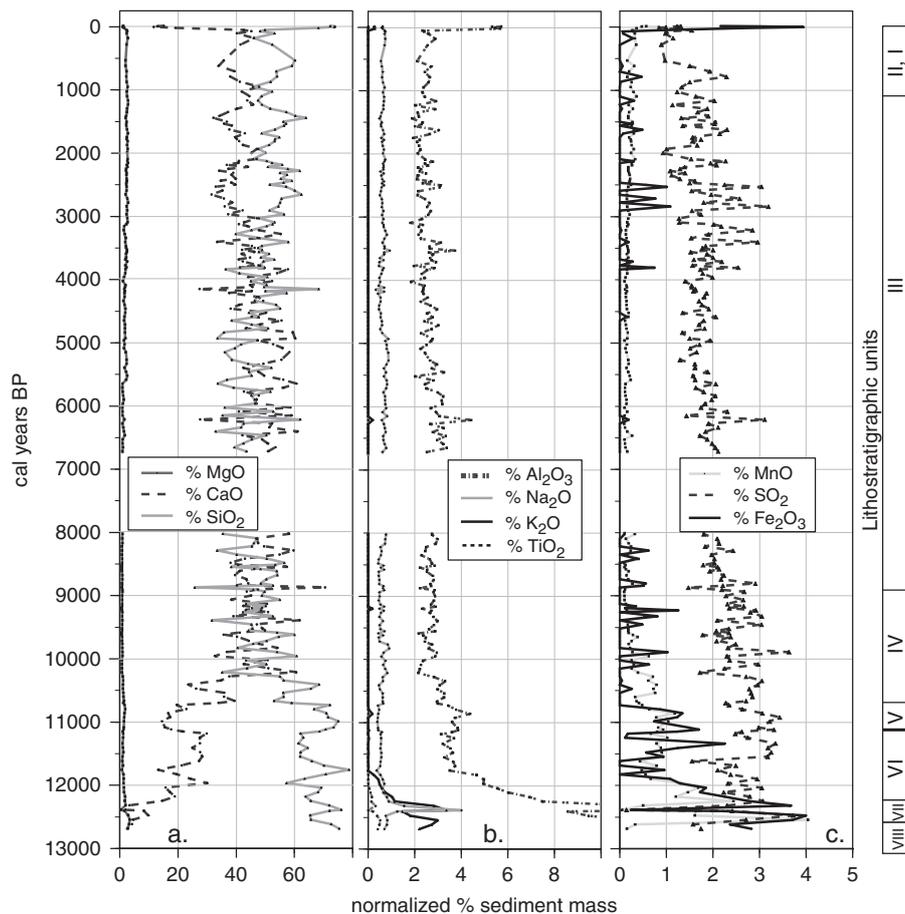
### Sediment mineralogy

Major carbonate mineral phases present are aragonite, calcite and, rarely, dolomite (a detrital mineral in this setting). Carbonate mineralogy between 12 700 and 12 400 cal. yr BP is calcitic and dolomitic with no detectable aragonite (Figure 4). By ~12 500 cal. yr BP, dolomite concentrations were declining rapidly and aragonite was being deposited. From ~12 500 to ~11 200 cal. yr BP, aragonite became the most abundant carbonate mineral. At ~11 150 cal. yr BP deposition of lithostratigraphic Unit V began. During this excursion, aragonite declined rapidly from  $\geq 20\%$  of sediment mineral fraction to near 0% over a sediment interval representing  $\leq 100$  years. Aragonite remained subordinate to calcite until ~10 700 cal. yr BP, when concentrations comparable to those prior to 11 150 cal. yr BP were abruptly regained. Subsequently, aragonite concentrations rose to reach 30–50% of sediment mineral fraction by 10 200 cal. yr BP; similar concentrations were maintained until ~5000 cal. yr BP. From 5000 to 1400 cal. yr BP, aragonite remained an important but declining component of sediment endogenesis, while calcite concentrations increased. Generally declining aragonite concentrations were punctuated by several episodic reversals in trend. Aragonite is not detected in sediments younger than 1400 cal. yr BP.

With the exception of rare mollusk shells, aragonite is necessarily a product of lake endogenesis, as no nearby detrital source exists. Calcite occurs in Proterozoic rocks regionally (Roberts, 1986) and may be present as a minor detrital component over restricted intervals. However, petrographic observations of abundant euhedral forms and very sparse ostracode valves indicate that calcite, too, is mainly endogenic in origin. Dolomite, also present



**Figure 4** Normalized mineral abundances (as percent of whole sediment) and time windows of inferred lake freshening. Calcite and aragonite are of dominantly endogenic origin, while dolomite and quartz are indicators of detrital influence. Mineral abundances are normalized using coulometric measurements of total inorganic carbon (TIC). Raw quartz abundances are shown in gray. The data gap from 8200 to 6800 cal. yr BP is due to unexpected decommissioning of an XRD instrument and resulting unavailability of fully comparable data over this time window



**Figure 5** XRF elemental stratigraphy of the Jones Lake core, normalized to the sum of analyzed elements (a). Constituents of major endogenic and biogenic sediment components (b). Constituents of primarily detrital sediment components (c). Redox-sensitive sediment constituents

in regional Proterozoic rocks, occurs primarily early in lake history and in association with detrital silicate minerals. Preferential formation of the aragonite or calcite polymorphs of  $\text{CaCO}_3$  in lakes is considered to be controlled by Mg:Ca in precipitating waters; elevated  $\text{Mg}^{2+}$  inhibits calcite formation, favoring aragonite (Bischoff and Fyfe, 1968; Müller *et al.*, 1972). Empirical thresholds of Mg:Ca for lacustrine aragonite formation have been suggested (Müller *et al.*, 1972; Eugster and Kelts, 1983). However, observations vary (eg, Frisia *et al.*, 2002), indicating that the Mg:Ca association with aragonite formation is complex and may be influenced by  $P_{\text{CO}_2}$ , degree of mineral supersaturation and ion complexation. In the Ovando Valley, lake Mg:Ca correlates positively with salinity (Shapley *et al.*, 2005) as ionic composition evolves through carbonate mineral formation (Eugster and Jones, 1979). Today, Jones Lake has Mg:Ca near 1 and forms calcite only; nearby Evans Lake, with Mg:Ca > 100, forms aragonite as a primary precipitate. Present-day Jones Lake groundwater inflow has Mg:Ca near 0.6 prior to mineral precipitation.

Deposition of detrital minerals declined rapidly between 12 600 and 12 000 cal. yr BP. After 12 000 cal. yr BP, normalized quartz concentrations remain low except in Unit V (11 150–10 700 cal. yr BP), where total carbonate mineral concentrations are diminished, and in the historic era (Unit I), when early agricultural land use led to enhanced erosion in the watershed. Feldspars (not shown) occur only at very low concentrations except in early lake-basin detrital assemblages and in tephras.

### Sediment elemental composition

Elemental XRF data reflect the system (Na + Mg + Al + Si + P + S + K + Ca + Ti + Mn + Fe) normalized as oxides to 100% of

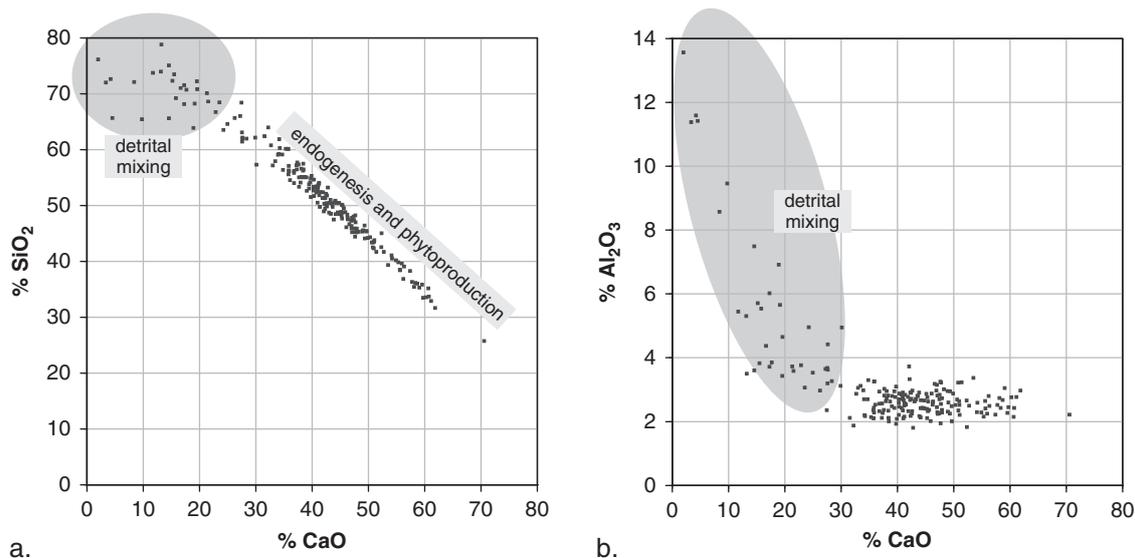
whole sediment. Concentrations of elements of atomic weight < 23 (Na) were not determined. Time series of oxide concentrations are shown grouped by major elements of endogenic and biogenic lake production (CaO,  $\text{SiO}_2$ , MgO), elements of primarily detrital origin ( $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ ) and elements with strong redox sensitivity in lake systems (S, Fe, Mn) (Figure 5a–c).

Relative concentrations of CaO and  $\text{SiO}_2$  converge in sediments deposited from 12 700 and 10 000 cal. yr BP, mostly through increasing CaO and secondarily through declining  $\text{SiO}_2$ . After 10 000 cal. yr BP, CaO and  $\text{SiO}_2$  reflect variable mixing in a system with two dominant components. Multicentury variations are apparent, but long-term mean concentrations show little trend in either element. Historic-era (Unit I) data show a prominent downward excursion in CaO and a compensating increase in  $\text{SiO}_2$ .

Concentrations of  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$  declined rapidly before 12 000 cal. yr BP, increased slightly in Unit V (11 150–10 700 cal. yr BP), and thereafter remained low until historic times.

$\text{SO}_2$  shows an apparent long-term decline over the course of the Holocene, as well as an apparent increase in the amplitude of variability after about 4000 cal. yr BP. Iron is an abundant sediment component early in the record but after about 10 000 cal. yr BP is detected mainly as episodic peaks, often associated with  $\text{SO}_2$  maxima.

CaO and  $\text{SiO}_2$  concentrations show a clear linear relationship over most sediment intervals (Figure 6a), reflecting the dominance of biogenic silica and endogenic carbonate minerals in lithostratigraphic Units VII through II (12250–65 cal. yr BP). Detrital mixing in Units IX, VIII, and I causes breakdown of the CaO/ $\text{SiO}_2$  covariance and development of a negative CaO/ $\text{Al}_2\text{O}_3$  correlation at high Si concentrations, where silicate minerals become important (Figure 6b).



**Figure 6** Sediment elemental associations: (a) CaO and SiO<sub>2</sub> correlate inversely where carbonate minerals and diatoms dominate sediment mix. (b) Al<sub>2</sub>O<sub>3</sub> is independent of CaO except at elevated Al<sub>2</sub>O<sub>3</sub>, where detrital mixing becomes important

### Stable isotopes of carbonate minerals

Isotopic results reflect varying proportions of endogenic calcite and aragonite; interpretation requires evaluating the influence of changing mineral percentages on the isotopic signal. Oxygen isotope fractionation between aragonite and calcite has been the subject of continuing debate (Tarutani *et al.*, 1969; Grossman and Ku, 1986; Kim and O'Neil, 1997; Zheng, 1999). Comparatively small positive (+0.6‰) aragonite–calcite fractionations determined from experimental results (Tarutani *et al.*, 1969) and field observations (Grossman and Ku, 1986) remain consistent with most relevant observations (Kim and O'Neil, 1997). Romanek *et al.* (1992) found  $\delta^{13}\text{C}$  of inorganically precipitated aragonite to be 1.6‰ higher relative to calcite, with no temperature dependence in fractionation between the two polymorphs. This result is in good agreement with Rubinson and Clayton (1969), who found a  $+1.8 \pm 0.2\text{‰}$  aragonite:calcite fractionation using a different experimental method. We used aragonite:calcite fractionations of +0.6‰  $\delta^{18}\text{O}$  and +1.6‰  $\delta^{13}\text{C}$  to normalize mixed-mineral results.

To estimate the effects of the binary aragonite–calcite mixture on the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  series, the fractions of calcite and aragonite were calculated from XRD results, then re-sampled to a constant time step (15 years) comparable with the sampling frequency of the isotopic data set (~17 years) using a linear integration function in Analyseries 1.2 (Paillard *et al.*, 1996); the raw isotopic data were also re-sampled to a 15-yr time step. Ratios of resampled aragonite:calcite were then used to convert isotopic series by

$$\delta^{18}\text{O}_{(\text{aragonite})} = \delta^{18}\text{O}_{(\text{bulk})} + [(1 - \text{fraction aragonite}) \times 0.6\text{‰}] \quad (3)$$

and

$$\delta^{18}\text{O}_{(\text{calcite})} = \delta^{18}\text{O}_{(\text{bulk})} - [(1 - \text{fraction calcite}) \times 0.6\text{‰}] \quad (4)$$

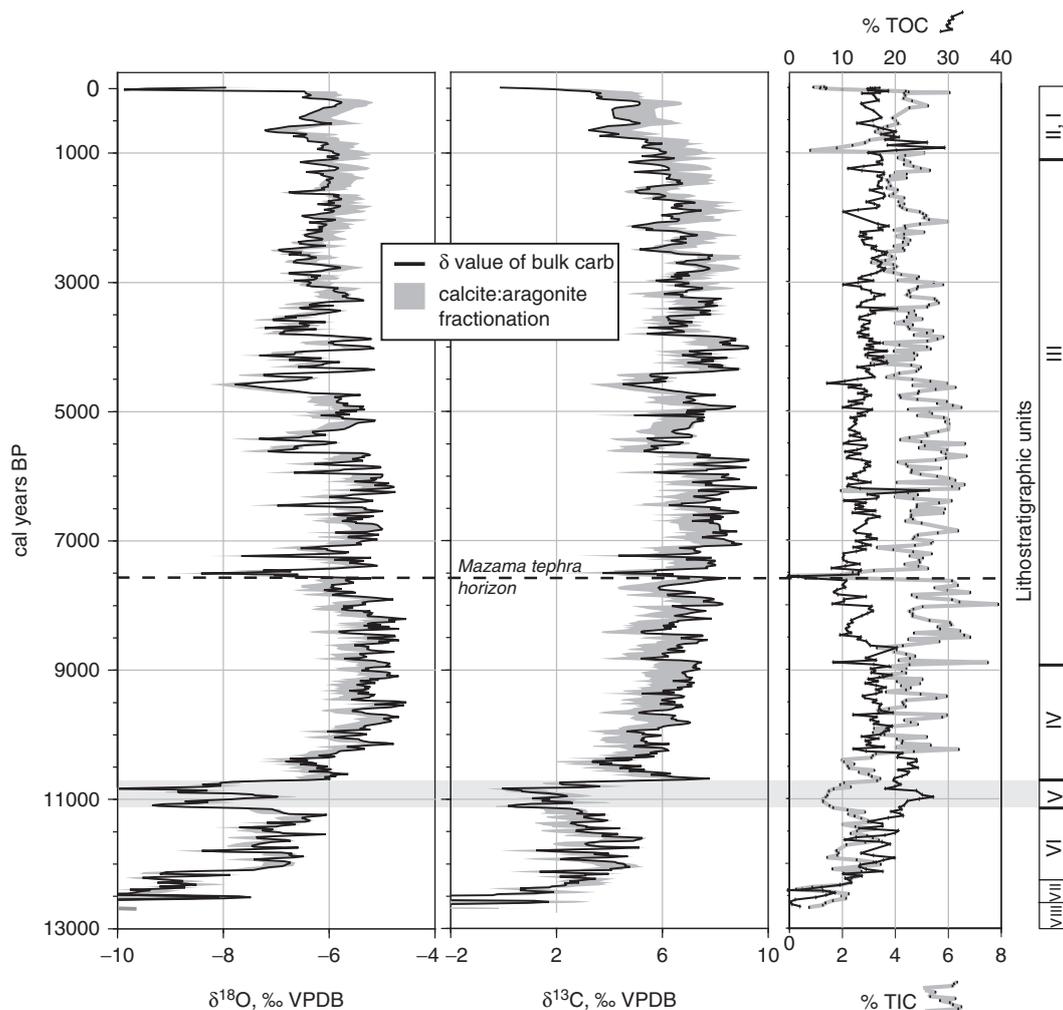
with analogous conversions for the  $\delta^{13}\text{C}$  series.

Values of  $\delta^{18}\text{O}$  generally increase prior to 11 150 cal. yr BP (Units IX–VI) (Figure 7). From 11 150 to 10 700 cal. yr BP (Unit V), a 2‰ decline in  $\delta^{18}\text{O}$  values occurs, coincident with excursions in mineralogy and inorganic carbon concentration.  $\delta^{18}\text{O}$  values begin an abrupt 2‰ recovery at 10 700 cal. yr BP (transition to Unit IV). Values of  $\delta^{18}\text{O}$  continue a general increase to about 9500 cal. yr BP. After 9500 cal. yr BP, most variability in

$\delta^{18}\text{O}$  values occurs at century to decadal scales, superimposed on a long-term decrease of around 0.5‰ from mid-Holocene (Unit III) to late-Holocene (Unit II) values. In addition to the excursion from 11 150 to 10 700 cal. yr BP, prominent century-scale negative excursions of 1–2‰ occur near 7500 cal. yr BP (immediately following the deposition of the Mazama tephra), near 7250 cal. yr BP, 5600 cal. yr BP, 4700 cal. yr BP, 3800 cal. yr BP and in the historic era. Oscillations at the 0.7‰ to 1‰ level occur throughout the record and are especially prominent between 9000 and 6000 cal. yr BP, when mean  $\delta^{18}\text{O}$  is maximized. From 3000 to 1000 cal. yr BP, century-scale  $\delta^{18}\text{O}$  variability is relatively muted. Between 4000 and 2000 cal. yr BP, aragonite:calcite is near 1 during the intermittent transition from aragonite to calcite dominance. Over this interval, the corrected isotopic signal is potentially sensitive to undetected changes in mineral composition; otherwise the sensitivity to errors in mineral percentage is low, owing to the preponderance of one carbonate or the other.

Values of  $\delta^{13}\text{C}$  covary strongly with  $\delta^{18}\text{O}$  at multicentury and shorter periods. Long-term Holocene trends differ between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ , however. Average values of  $\delta^{13}\text{C}$  continue upward through the mid-Holocene, increasing by about 2‰ between 10 000 and 6000 cal. yr BP, while  $\delta^{18}\text{O}$  declines slightly following a plateau from 10 000 to 8000 cal. yr BP. After about 2000 cal. yr BP,  $\delta^{13}\text{C}$  experiences an extended 4‰ downward trend, culminating in the abrupt decrease of the historic era. Prior to the historic era, this trend in  $\delta^{13}\text{C}$  is accompanied by a nearly flat average value of  $\delta^{18}\text{O}$ . Multidecadal covariance between the two isotopes continues during this time, however.

As a pooled data set,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  covary in a manner common in lakes with extended residence time (Talbot, 1990) and variously attributed to parallel effects of evaporation on  $\delta^{18}\text{O}$  and water temperature, solute balance effects (Li and Ku, 1997), or parallel seasonal timing of winter DIC accumulation and low  $\delta^{18}\text{O}$  lake inflow (Drummond *et al.*, 1995). Explanations invoke coinciding but functionally separate mechanisms, since  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  respond to different environmental processes. Units IX and VIII (pre-12 500 cal. yr BP) have widely scattered low- $\delta$  values in both isotopes, largely overlapping with compositions of Proterozoic carbonate cobbles (Figure 8). Units VII and VI (12 500–11 150 cal. yr BP) show up-section increases in  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ , before



**Figure 7** Time series of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ . Data are presented as bulk (mixed component) results. Shaded band shows calculated difference between  $\delta$  values in calcite (lower) and aragonite (higher), weighted by XRD results. Since calcite:aragonite is usually far from 1, the bulk curve is usually closely equivalent to one of the single-mineral compositions. Significant mineral-ratio effects on bulk  $\delta$  values are likely only from 4 ka to 2 ka, where the bulk curve reflects significant contribution from both minerals. In the XRD data gap (Figure 5), high aragonite:calcite based on mean values from adjacent depth intervals is assumed

returning to lower values in Unit V (11 150–10 700 cal. yr BP). The up-section progression through Units IV, III and II highlights decoupling between long-term trends in the two isotope systems. Unit IV (10 700–8875 cal. yr BP) first shows movement toward the extreme for the core in  $\delta^{18}\text{O}$ , while  $\delta^{13}\text{C}$  remains at intermediate values. In Unit III (8875–1150 cal. yr BP), all the highest values of  $\delta^{13}\text{C}$  are attained, while the mean  $\delta^{18}\text{O}$  declines from Unit IV. In Unit II (1150–65 cal. yr BP), the mean  $\delta^{13}\text{C}$  decreases, but  $\delta^{18}\text{O}$  values show little change from Unit III. In Unit I (historic era), compositions return to values similar to Unit V.

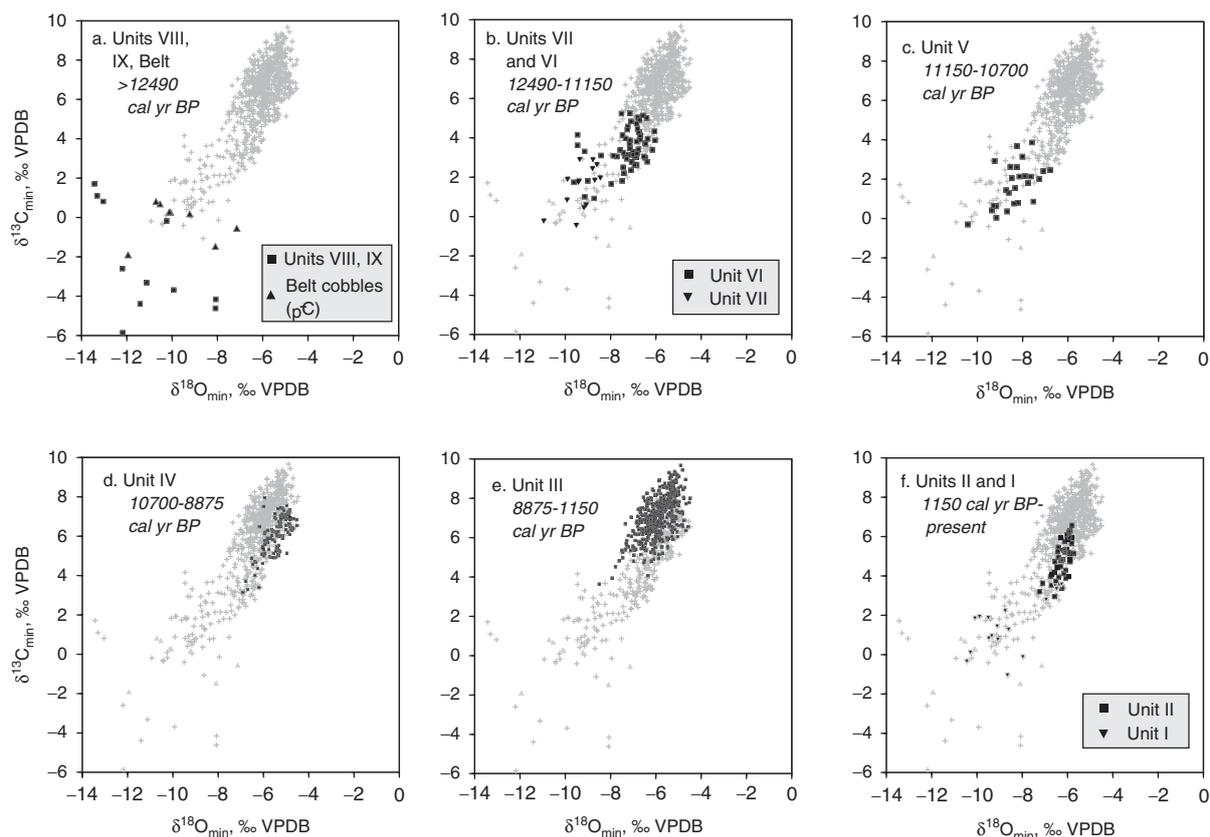
## Discussion

### Geochemical relationships

Aquifer-controlled water and solute balance in the Ovando region affects both spatial distribution of chemistry among lakes, and sensitivity of particular lakes to different tempos of climatic forcing (Shapley *et al.*, 2005, 2008). The persistent dominance of endogenic carbonate minerals requires a dynamic balance between groundwater inflow, evaporative concentration and groundwater outflow, as detailed in other lake systems (Sanford and Wood, 1991; Donovan, 1992). In groundwater-dominated lakes,

sediment geochemistry becomes closely linked to changes in lake–groundwater exchange and groundwater recharge at all timescales. Detrital mineralogy and elemental composition indicate that physical stabilization of the postglacial land surface surrounding Jones Lake was mostly complete by ~12 000 cal. yr BP. Sedimentation from 12 000 cal. yr BP until the historic era therefore reflects mainly lake endogenic and biogenic processes acting under the influence of varying groundwater exchange.

Maximum Holocene  $\delta^{18}\text{O}$  values were reached between 10 000 and 8000 cal. yr BP. A subtle decline of around 1‰ ends by about 5000 cal. yr BP, after which little long-term change in mean  $\delta^{18}\text{O}$  is evident. The 6000–1500 cal. yr BP transition from aragonite dominance as an endogenic mineral (inferred high Mg:Ca ratio) to absence of aragonite is accompanied by little sustained change in  $\delta^{18}\text{O}$  of carbonate minerals. This apparent decoupling between endogenic mineralogy and fluid balance ( $\delta^{18}\text{O}$ ) is explained by low steady-state isotopic sensitivity of a system with the hydrologic boundary configuration of Jones Lake. Modeling of Jones Lake shows that steady-state lake isotopic composition can be quite unresponsive to changes in rate of groundwater inflow, because of a topographically controlled high-rate groundwater outflow boundary. The modeled transient isotopic response during lake volume adjustment to changing inflow, seen here in the



**Figure 8** Covariance of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  by age window and lithostratigraphic unit. Data points plotted are bulk values, uncorrected for aragonite-calcite fractionation. Specified time windows shown in black; shaded points show the complete data set. Highest  $\delta^{18}\text{O}$  values and strongest isotopic covariance occur in Unit IV (10 700–8875 cal. yr BP); highest  $\delta^{13}\text{C}$  and widest range in  $\delta^{18}\text{O}$  occur in Unit III (8875–1150 cal. yr BP). Variation in  $\delta^{18}\text{O}$  relative to  $\delta^{13}\text{C}$  declines (slope steepens) in Unit II between 1150 and 65 cal. yr BP, and the apparent range in  $\delta^{18}\text{O}$  is at its lowest since the earliest Holocene. Unit I (historic era)  $\delta$  values are low, reflecting manipulated water balance and detrital sediment influx

decadal- and century-scale mineral  $\delta^{18}\text{O}$  spectrum, is much more pronounced (Shapley *et al.*, 2008). Similar buffering of lake isotopic composition explains complexities in isotopic records from other lakes with volumetrically important groundwater interactions (Smith *et al.*, 1997; Dean *et al.*, 2002; Donovan *et al.*, 2002). In the case of Jones Lake, progressively greater contribution of warm-season (higher  $\delta^{18}\text{O}$ ) precipitation to groundwater in the later Holocene may also contribute to the subdued millennial trend, offsetting the  $\delta^{18}\text{O}$  effects of shorter lake residence time.

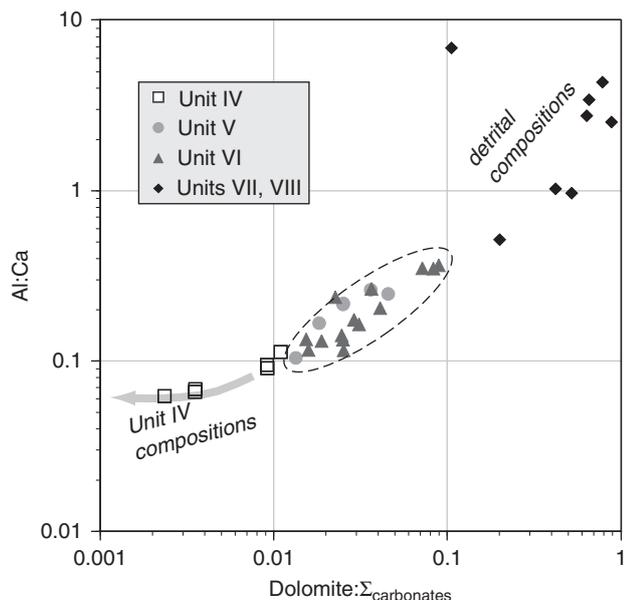
From 12 000 to 10 000 cal. yr BP, generally rising aragonite concentrations coincide with  $\delta^{18}\text{O}$  values lower than in the late Holocene. This implies a differing relationship between lake Mg:Ca and  $\delta^{18}\text{O}$  values before and after 10 000 cal. yr BP. Lower condensation air temperatures in latest glacial and earliest Holocene time, and/or more winter-dominated precipitation and groundwater recharge may account for this transition, through maintaining low  $\delta^{18}\text{O}$  values of groundwater inflow under a relatively evaporative early-Holocene climate.

Values of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  covary more strongly at high frequencies than at low frequencies. Most multidecadal excursions are shared by the two isotope records. Millennial trends in the early Holocene also mirror each other closely, but Holocene maxima are reached at different times (10 000 to 8000 cal. yr BP in  $\delta^{18}\text{O}$ ; 6000 to 4000 cal. yr BP in  $\delta^{13}\text{C}$ ) and the systematic  $\delta^{13}\text{C}$  decline after 4000 cal. yr BP has no correspondence in the  $\delta^{18}\text{O}$  curve. Coupling at short timescales combined with divergence over millennial scales implies that  $\delta^{13}\text{C}$  is responding indirectly to changes in fluid balance that drive  $\delta^{18}\text{O}$  excursions, but also to long-term

transitions in the lake ecosystem and watershed carbon cycle. The general coincidence between decreasing  $\delta^{13}\text{C}$  and increasing TOC/TIC indicates long-term reallocation of carbon between inorganic and organic carbon pools, involving changes in lake productivity and/or rates of organic and inorganic sedimentation. Generally moister conditions after 1500 cal. yr BP (inferred from the termination of aragonite deposition) may also have shifted terrestrial carbon inputs toward lower (more C3-rich) compositions.

### The Unit V (11 150–10 700 cal. yr BP) anomaly

The most prominent non-volcanic geochemical excursion in Jones Lake is recorded from 11 150 to 10 700 cal. yr BP as lithostratigraphic Unit V. Over this interval TOC reached a maximum, TIC dropped to concentrations not reached again until the historic era, and the increase in aragonite concentration beginning shortly after lake formation was abruptly reversed (Figure 3). Mineral-corrected values of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  declined sharply, reaching compositions similar to Belt cobbles (Figures 7, 8). Unit V shares a common compositional signature with Unit VI (12 250 to 11 150 cal. BP; Figure 9), and two-component mixing of quartz and  $\text{Al}_2\text{O}_3$  concentrations suggests that the composition of Unit V reflects at most 10–30% mixing of detrital material similar to Lateglacial sediment. This implies that no more than ~0.8‰ of the ~2–3‰  $\delta^{18}\text{O}_{\text{min}}$  decline can plausibly be due to dilution by detrital sediments (Table 3), with the remainder explained by lake water compositional change resulting in lowered  $\delta^{18}\text{O}$  of endogenic calcite. Isotopic sensitivity modeling suggests that sustained lake-water



**Figure 9** Elemental and mineral trends in the Unit V geochemical anomaly, with other late-Pleistocene and early-Holocene lithologic units for comparison. Unit V shows near-complete overlap with aragonitic Unit VI, and no apparent displacement in the direction of detrital compositions, indicating that Unit V isotopic excursions cannot be attributed to detrital mineral influx

$\delta^{18}\text{O}$  change of this magnitude probably required a large decrease in hydraulic residence time, a decline in the  $\delta^{18}\text{O}$  of inflow, or both (Shapley *et al.*, 2008). The abrupt, contemporaneous decline in aragonite concentration lends strong support to an interpretation of sustained lake freshening. Preservation of organic matter was enhanced, suggesting that well-stratified lake conditions encouraged partial hypolimnetic dissolution of carbonate minerals, similar to the modern response to management-driven increases in groundwater inflow (Myrbo and Shapley, 2006). Foy Lake (160 km to the NW) experienced abrupt diatom community changes interpreted as lake highstand at closely correlative time (Stone and Fritz, 2006), indicating regional scope to the 11 150 cal. yr BP episode.

The amplitude and duration of the Unit V anomaly are unmatched in subsequent sediments, suggesting that the excursion represents a widespread abrupt climate reversal associated with the Pleistocene/Holocene transition. Alternative (non-climatic) explanations would require abrupt but temporary reorganization of groundwater flow paths and/or surface drainage patterns. We see no geomorphic or sedimentological evidence for such events during the postglacial history of Jones Lake.

Evidence of transitional Holocene oscillations defined from circum-Atlantic records is recognized in various paleoclimate records from western North America (Reasoner and Jodry, 2000;

Yu and Wright, 2001). The Jones Lake Unit V highstand began near 11 150 cal. yr BP by our linear age model; a non-linear model using an age of 13.1 cal. yr BP for the GP tephra places the initiation of Unit V at ~11 400 cal. yr BP. Termination at 10 700 cal. yr BP is marked by abrupt reversal of Unit V mineralogical and isotopic trends. Records of NE Pacific alkenone-inferred coastal sea surface temperature and Pacific coastal speleothem  $\delta^{18}\text{O}$  show abrupt transience at correlative time. Barron *et al.* (2003) found an abrupt reversal of early-Holocene sea surface warming at ODP Site 1019 shortly after 11 200 cal. yr BP, and suggest an episode of strengthening of the California Current. Vacco *et al.* (2005) interpret a prominent speleothem  $\delta^{18}\text{O}$  anomaly centered on 11 000 cal. yr BP as evidence of increased air temperature. The Unit V excursion also began within dating error of the initiation of the Preboreal Oscillation (PBO) recognized in European records (Björck *et al.*, 1996) and is nested within the longer 11 600 to 10 300 cal. yr BP 'Post-Younger Dryas Interval' of Kirby *et al.* (2002), defined by anomalously elevated sediment  $\delta^{18}\text{O}$  of Fayetteville Green Lake (New York State).

PBO cooling has been linked to North Atlantic circulation anomalies caused by freshwater pulses from the Baltic Ice Lake (Björck *et al.*, 1996; Hald and Hagen, 1998) or glacial Lake Agassiz (Fisher *et al.*, 2002; Teller *et al.*, 2002). Modeling experiments suggest propagation of a North Atlantic thermal anomaly to the North Pacific region occurs primarily via atmospheric teleconnection, with pressure patterns implying an intensification of cyclonic activity in the eastern North Pacific (Mikolajewicz *et al.*, 1997). Resulting increases in Pacific moisture delivery to the Northern Rockies might then explain the dilute lake highstand recorded from Unit V, through enhanced groundwater recharge and/or reduced lake evaporation. Kirby *et al.* (2002), by contrast, interpret their Post Younger Dryas Interval as a period of locally expanded circumpolar vortex extent and enhanced meridional moisture advection in the NE USA, linked to rejuvenated post-Younger Dryas thermohaline circulation in the North Atlantic.

In the Unit V anomaly, we find indirect support for Barron *et al.*'s (2003) implied strengthening of the California Current near 11 200 cal. yr BP. Negative values of the Pacific Decadal Oscillation Index or PDO (vigorous California Current) correlate with high winter precipitation and spring streamflow in northern Idaho (Mantua *et al.*, 1997; Harshburger *et al.*, 2002), conditions likely to promote both a low- $\delta^{18}\text{O}$  composition of groundwater recharge, and reduced evaporative evolution of lake water in adjacent northwestern Montana. By contrast, high lake fluid balance between 11 150 and 10 700 cal. yr BP is less easily reconciled with Vacco *et al.*'s (2005) interpretation of warming of the California coast at that time, which seemingly implies a PDO+ condition correlated in the instrumental era with winter drought in the Rocky Mountains north of 45° latitude.

Correlation of Unit V timing with these post-Younger Dryas (YD) early-Holocene climatic episodes follows from AMS  $^{14}\text{C}$  sample AA39440 (Table 1), taken from the upper lithological contact of Unit V and dated to 10 735 cal. yr BP. Published ages

**Table 3** Compositions and mixing estimates for Unit V with inferred  $\delta^{18}\text{O}$  sensitivity to detrital carbonate minerals

Constituent	%, Detrital composition	%, Unit VI composition	%, Unit V composition	Unit VI/detrital ratio	Implied $\delta^{18}\text{O}$ sensitivity
Quartz	60	8	20	77/23	~0.8‰
$\text{Al}_2\text{O}_3$	11.4	3.5	3.8	92/8	~0.3‰

End-member compositions are drawn from XRD and XRF analyses of the underlying Unit VI, and of the dominantly detrital units VII and VIII. Independent calculations based on mineral and elemental composition indicate the contribution of detrital material is probably of less than 25% of whole sediment, with an inferred  $\delta^{18}\text{O}$  sensitivity of at most -0.8‰.

near 13 100 cal. yr BP for the Glacier Peak tephra suggest that sedimentation rates decline below AA39440, our oldest  $^{14}\text{C}$  control. However, incorporation of the Glacier Peak tephra into a non-linear Jones Lake  $^{14}\text{C}$  age model does not result in alignment of Unit V with the YD. An alternative chronology equating Unit V with the YD (Alley, 2000) would require both a calendar age well outside the  $2\sigma$  error on AA39440, and explanation for the apparently brief duration of the Unit V anomaly relative to the YD.

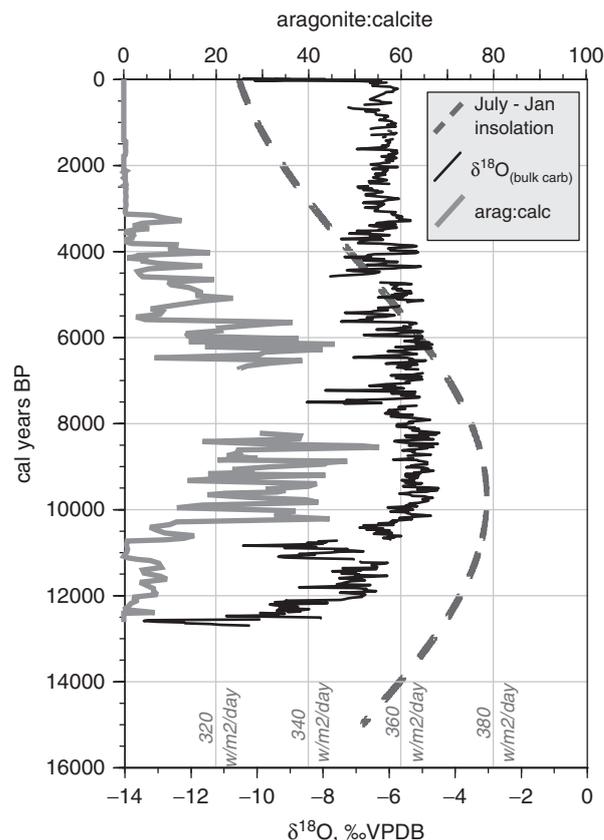
Unit V registers a multicentury positive change in fluid balance in Jones Lake, postdating the YD chronozone. The absence of a distinct YD geochemical signal in Jones Lake, in apparent contrast with some Rocky Mountain records (Reasoner and Jodry, 2000; Yu and Wright, 2001) seems to reflect a dry YD climate in the region, in keeping with the interpretation of precipitation-sensitive Pacific Northwest records (eg. Heine, 1998). Persistent Unit VI aragonite production in Jones Lake supports relatively evaporative conditions during the YD time window. Widespread climate oscillations of the Lateglacial/Holocene transition thus seem to have registered contrasting (YD/cool but dry; post-YD/cool and wet) signals on regional hydrology.

### Post-Mazama isotope anomaly

Prominent negative excursions in  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values, beginning ~7550 cal. yr BP and persisting for several decades, immediately overlie the Mazama tephra. Their stratigraphic position implies these anomalies may be related to tephra deposition and/or to post-eruptive climatic effects. Estimates of the hemispheric effects of Mt Mazama aerosols suggest that atmospheric impacts were significant but persisted for less than a decade (Zdanowicz *et al.*, 1999). Coupled ocean-atmosphere modeling indicates that volcanically induced cooling has multidecadal memory in the form of anomalously cool subducted water masses (Gleckler *et al.*, 2006), providing a possible mechanism for extended hydroclimatic excursions. Alternatively, ash deposition may have had persistent proximal effects on both lake carbon cycling and watershed hydrology, perhaps by altering soil properties and vegetation communities and thereby changing distribution of precipitation between runoff and groundwater recharge. In this case, the most probable explanations for a negative post-Mazama  $\delta^{18}\text{O}$  anomaly involve (1) reduced evaporation:precipitation and/or (2) enhanced contribution of low  $\delta^{18}\text{O}$  winter precipitation to aquifer recharge. Either mechanism is consistent with the lake highstand inferred from diatom records in the immediate aftermath of Mazama fall-out at Foy Lake (Stone and Fritz, 2006), another small groundwater-influenced lake 160 km NW of Jones Lake. Based mainly on seismostatigraphic relations, Hofmann *et al.* (2006) inferred a lowstand following Mazama tephra deposition at Flathead Lake (a large runoff-dominated lake 120 km to the NW), with subsequent rising lake stage. Reconciling a post-Mazama Flathead Lake lowstand with contemporaneous high fluid balance in Jones and Foy lakes is not straightforward, and may require a more detailed chronological framework for the Flathead Lake lowstand.

### Paleoridity and hydrologic inferences

Broad trends in the Jones Lake sedimentary record suggest that the local climate of the latest Pleistocene and earliest Holocene (12 500 to 10 000 cal. yr BP) was more arid than regional syntheses suggest (Thompson *et al.*, 1993), with relatively low rates of low- $\delta^{18}\text{O}$  groundwater recharge and extended lake residence time. Following the Unit V (11 150–10 700 cal. yr BP) freshwater excursion, Jones Lake sediments record a broad peak in evaporative evolution centered ~9000 cal. yr BP (Figure 10), in general agreement with interpretations of maximum Holocene aridity from regional syntheses (Schweger and Hickman, 1989; Ritchie and Harrison, 1993; Thompson *et al.*, 1993) and in phase with the



**Figure 10** Carbonate mineral  $\delta^{18}\text{O}$  (black) and aragonite:calcite (gray) compared with insolation seasonality (July-January) for the latitude of the Ovando Valley (dashed gray). Both sediment parameters reach peaks near the early Holocene seasonality maximum; mineralogy also correlates with the later Holocene downward limb in seasonality, while isotopic composition is insensitive to low-frequency forcing after the mid-Holocene. Insolation data from Laskar (1990).

summer insolation and insolation seasonality maxima for this latitude (Laskar, 1990; Paillard *et al.*, 1996). Evidence for increasing effective moisture begins to appear in the isotopic record after 8000 cal. yr BP and becomes prominent in the mineralogical record after 6000 cal. yr BP. Calcite:aragonite ratios indicate that several reversals interrupted this lake freshening trend. Fully 'modern' freshwater conditions were not established until after 1400 cal. yr BP, consistent with the timing of late-Holocene highstand conditions in Flathead Lake (Hofmann *et al.*, 2006) and of abrupt increase in diatom-inferred lake level in Foy Lake (Stone and Fritz, 2006). Shallow groundwater conditions and lake salinity distributions similar to the present probably became established at this time in the Blackfoot River basin. This transition was likely accompanied by an increase in summer precipitation contribution to lakes and groundwater, partially offsetting decreased lake isotopic evolution through a higher amount-weighted  $\delta^{18}\text{O}$  value of lake inflow.

An inferred Foy Lake highstand is generally coincident with the 11 150–10 700 cal. yr BP freshening episode in Jones Lake. Similarly, enhanced Foy Lake alkalinity centered on 9000 cal. yr BP is coincident with peak Jones Lake aragonite formation. These results suggest synchrony in shallow aquifer water budgets across intermontane basins of northwestern Montana. With the exception of the 11 150–10 700 cal. yr BP period, we infer that average regional stream baseflow was reduced, wetland extent restricted, and lake and wetland chemistry salinized relative to conditions since ~1400 cal. yr BP.

## Summary and conclusions

Sediments from Jones Lake reveal a pervasive dominance of calcium carbonate endogenesis from early-Holocene time until the historic era. Beginning shortly after deglaciation, mineralogy indicates that lake Mg:Ca and probably salinity were elevated relative to modern conditions. Oxygen isotopes point toward maximum evaporative forcing early in the Holocene, by or before 9000 cal. yr BP. Mineralogical indicators of lake salinity decline gradually after 6000 cal. yr BP but freshening was episodically reversed and modern lake geochemistry was achieved late in the Holocene, after 1400 cal. yr BP. The Lateglacial–Holocene transition is marked by an abrupt and sustained geochemical anomaly reflecting reduced evaporative forcing and lake freshening. The timing of this unique episode postdates the Younger Dryas Event and correlates with early-Holocene oscillations in both the North Atlantic and Northeast Pacific regions.

Pervasive decadal- and century-scale variations in sediment geochemistry relate to groundwater-driven fluid-balance variations occurring on multiple timescales. Oxygen isotopes record a rich spectrum of high-frequency variation interpreted as dominantly transient response to fluid balance change, but are relatively insensitive to low-frequency changes better reflected in sediment mineralogy. Oxygen and carbon isotopes covary closely at high frequencies but are decoupled at low frequencies by long-term lake basin changes in carbon cycling. Lower groundwater fluxes relative to the present, implied by sediment geochemistry, suggest that the groundwater inflow central to modern river management and conservation under low-flow conditions has typically been smaller during the Holocene than shown in the instrumental record.

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