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

M.D. Shapley,1* E. Ito1 and J.J. Donovan2

(1Limnological Research Center, Department of Geology and Geophysics, University of Minnesota, 310 Pillsbury Drive SE, Minneapolis MN 55455, USA; 2Department of Geology and Geography, West Virginia University, 330 Brooks Hall, Morgantown WV 26506, 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 throughput, 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 δ18O 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 δ18O 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 (Harshbarger 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; Reaasoner and Jodry, 2000; Yang and Wright, 2001; Kovanen and Easterbroook, 2002), and late-Holocene modal changes in hydrologic balance (Stone and Fritz, 2006; Hofmann et al., 2006; Stevens et al., 2006).
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 δ¹⁸O and δ¹³C 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
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™ 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™ diffractometer using Cu Kα radiation over 5° to 70° 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:

\[
\% \text{ mineral}_{\text{norm}} = \frac{\% \text{ mineral}_{\text{XRD}}}{\sum \% \text{ carbonate minerals}_{\text{XRD}}} \times \text{TIC} 
\]

(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:

\[
\% \text{ silicate}_{\text{norm}} = \frac{\% \text{ calcite}_{\text{norm}}}{\% \text{ calcite}_{\text{XRD}}} \times \% \text{ silicate}_{\text{XRD}} 
\]

(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 cobbles interiors was removed by chiseling and ground. Analyses of δ13C and δ18O 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 δ13C and δ18O 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 14C 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 14C 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 (Foët al., 1993; Osborn and Gerloff, 1997), so the significance of this departure is uncertain. An alternative age model incorporating linear interpolation between our lowermost 14C 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

Table 1 Radiocarbon sample results and age model departures

| AZ lab ID | Corrected sample depth (cm) | Reported age  
\(^{14}\text{C} \) yr BP | \(^{14}\text{C} \) age error (σ) | Calibrated age (median) | Model age prediction | Model age minus calibrated age |
<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>AA41910</td>
<td>137.9</td>
<td>1618</td>
<td>35</td>
<td>1502</td>
<td>1510</td>
<td>8</td>
</tr>
<tr>
<td>AA39436</td>
<td>198.4</td>
<td>2451</td>
<td>83</td>
<td>2535</td>
<td>2450</td>
<td>−85</td>
</tr>
<tr>
<td>AA39437</td>
<td>338.3</td>
<td>4090</td>
<td>65</td>
<td>4608</td>
<td>4624</td>
<td>16</td>
</tr>
<tr>
<td>AA41911</td>
<td>409.1</td>
<td>4865</td>
<td>44</td>
<td>5608</td>
<td>5724</td>
<td>116</td>
</tr>
<tr>
<td>AA39439</td>
<td>605.2</td>
<td>7940</td>
<td>110</td>
<td>8797</td>
<td>8772</td>
<td>−25</td>
</tr>
<tr>
<td>AA39440</td>
<td>729.5</td>
<td>9465</td>
<td>73</td>
<td>10735</td>
<td>10705</td>
<td>−30</td>
</tr>
</tbody>
</table>

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

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

Thicknesses incorporate depth corrections applied to the age model (Figure 2). Age boundaries interpolated from median-age calibrations of AMS ¹⁴C results in Table 2 and correlation of ²¹⁰Pb 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.
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 ≥ 20% of sediment mineral fraction to near 0% over a sediment interval representing ≤ 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 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

**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 abundance 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.
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 CaCO$_3$ in lakes is considered to be controlled by Mg:Ca in precipitating waters; elevated 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 $P_{CO_2}$, 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, SiO$_2$, MgO), elements of primarily detrital origin (Al$_2$O$_3$, TiO$_2$, Na$_2$O, K$_2$O) and elements with strong redox sensitivity in lake systems (S, Fe, Mn) (Figure 5a–c).

Relative concentrations of CaO and SiO$_2$ converge in sediments deposited from 12 700 and 10 000 cal. yr BP, mostly through increasing CaO and secondarily through declining SiO$_2$. After 10 000 cal. yr BP, CaO and 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 SiO$_2$.

Concentrations of Al$_2$O$_3$, TiO$_2$, Na$_2$O, and K$_2$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.

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 SO$_2$ maxima.

CaO and 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 (12 250–65 cal. yr BP). Detrital mixing in Units IX, VIII, and I causes breakdown of the CaO/SiO$_2$ covariance and development of a negative CaO/Al$_2$O$_3$ correlation at high Si concentrations, where silicate minerals become important (Figure 6b).
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 δ13C 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 ± 0.2‰ aragonite:calcite fractionation using a different experimental method. We used aragonite:calcite fractionations of +0.6‰ δ18O and +1.6‰ δ13C to normalize mixed-mineral results.

To estimate the effects of the binary aragonite–calcite mixture on the δ18O and δ13C 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 Analysersies 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

\[
\delta^{18}O_{\text{aragonite}} = \delta^{18}O_{\text{bulk}} + [(1-\text{fraction aragonite}) \times 0.6\%] \quad (3)
\]

and

\[
\delta^{18}O_{\text{calcite}} = \delta^{18}O_{\text{bulk}} - [(1-\text{fraction calcite}) \times 0.6\%] \quad (4)
\]

with analogous conversions for the δ13C series.

Values of δ18O 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 δ18O values occurs, coincident with excursions in mineralogy and inorganic carbon concentration. δ18O values begin an abrupt 2‰ recovery at 10 700 cal. yr BP (transition to Unit IV). Values of δ18O continue a general increase to about 9500 cal. yr BP. After 9500 cal. yr BP, most variability in δ18O values occurs at century to decadals 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 centuryscale 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 δ18O is maximized. From 3000 to 1000 cal. yr BP, century-scale δ18O 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 δ13C covary strongly with δ18O at multicentury and shorter periods. Long-term Holocene trends differ between δ13C and δ18O, however. Average values of δ13C continue upward through the mid-Holocene, increasing by about 2‰ between 10 000 and 6000 cal. yr BP, while δ18O declines slightly following a plateau from 10 000 to 8000 cal. yr BP. After about 2000 cal. yr BP, δ13C experiences an extended 4‰ downward trend, culminating in the abrupt decrease of the historic era. Prior to the historic era, this trend in δ13C is accompanied by a nearly flat average value of δ18O. Multidecadal covariance between the two isotopes continues during this time, however.

As a pooled data set, δ13C and δ18O covary in a manner common in lakes with extended residence time (Talbot, 1990) and variously attributed to parallel effects of evaporation on δ18O and water temperature, solute balance effects (Li and Ku, 1997), or parallel seasonal timing of winter DIC accumulation and low – δ18O lake inflow (Drummond et al., 1995). Explanations invoke coinciding but functionally separate mechanisms, since δ13C and δ18O respond to different environmental processes. Units IX and VIII (pre-12 500 cal. yr BP) have widely scattered low-δ 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 δ13C and δ18O, before

Figure 6  Sediment elemental associations: (a) CaO and SiO2 correlate inversely where carbonate minerals and diatoms dominate sedi ment mix. (b) Al2O3 is independent of CaO except at elevated Al2O3, where detrital mixing becomes important.
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 (10,700–8,875 cal. yr BP) first shows movement toward the extreme for the core in δ¹⁸O, while δ¹³C remains at intermediate values. In Unit III (8,875–1150 cal. yr BP), all the highest values of δ¹³C are attained, while the mean δ¹⁸O declines from Unit IV. In Unit II (1150–65 cal. yr BP), the mean δ¹³C decreases, but δ¹⁸O 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 δ¹⁸O 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 δ¹⁸O 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 δ¹⁴C of carbonate minerals. This apparent decoupling between endogenic mineralogy and fluid balance (δ¹⁴C) 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
decadal- and century-scale mineral $\delta^{13}$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 $\delta^{18}$O) precipitation to groundwater in the later Holocene may also contribute to the subdued millennial trend, offsetting the $\delta^{18}$O effects of shorter lake residence time.

From 12 000 to 10 000 cal. yr BP, generally rising aragonite concentrations coincide with $\delta^{18}$O values lower than in the late Holocene. This implies a differing relationship between lake Mg:Ca and $\delta^{18}$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 $\delta^{18}$O values of groundwater inflow under a relatively evaporative early-Holocene climate.

Values of $\delta^{18}$O and $\delta^{13}$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 $\delta^{18}$O; 6000 to 4000 cal. yr BP in $\delta^{13}$C) and the systematic $\delta^{13}$C decline after 4000 cal. yr BP has no correspondence in the $\delta^{18}$O curve. Coupling at short timescales combined with divergence over millennial scales implies that $\delta^{13}$C is responding indirectly to changes in fluid balance that drive $\delta^{18}$O excursions, but also to long-term transitions in the lake ecosystem and watershed carbon cycle. The general coincidence between decreasing $\delta^{13}$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 $\delta^{13}$C-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 $\delta^{18}$O and $\delta^{13}$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 Al$_2$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‰ $\delta^{18}$O$_{max}$ decline can plausibly be due to dilution by detrital sediments (Table 3), with the remainder explained by lake water compositional change resulting in lowered $\delta^{18}$O of endogenic calcite. Isotopic sensitivity modeling suggests that sustained lake-water
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 mineralogic and isotopic trends. Records of NE Pacific alkene-inferred coastal sea surface temperature and Pacific coastal speleothem $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 (Mikolajewisz 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-$\delta^{18}O$ composition of groundwater recharge, and reduced evaporative evaporation 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 $^{14}$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 $\delta^{18}O$ sensitivity to detrital carbonate minerals

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

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 $\delta^{18}O$ 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 14C control. However, incorporation of the Glacier Peak tephra into a non-linear Jones Lake 14C 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 2σ 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 flow 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 (Reasner 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 δ18O and δ13C 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 δ18O anomaly involve (1) reduced evaporation: precipitation and/or (2) enhanced contribution of low δ18O winter precipitation to aquifer recharge. Either mechanism is consistent with the lake highstand inferred from diatom records in the immediate aftermath of Mazama fallout at Foy Lake (Stone and Fritz, 2006), another small groundwater-influenced lake 160 km NW of Jones Lake. Based mainly on seismostratigraphic 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.

**Paleoaridity 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-δ18O 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 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 δ18O 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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