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A multi-proxy paleolimnological reconstruction of Holocene climate conditions in the Great Basin, United States

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ABSTRACT

A sediment core spanning ~7000 cal yr BP recovered from Stella Lake, a small sub-alpine lake located in Great Basin National Park, Nevada, was analyzed for subfossil chironomids (non-biting midges), diatoms, and organic content (estimated by loss-on-ignition (LOI)). Subfossil chironomid analysis indicates that Stella Lake was characterized by a warm, middle Holocene, followed by a cool "Neoglacial" period, with the last two millennia characterized by a return to warmer conditions. Throughout the majority of the core the Stella Lake diatom-community composition is dominated by small, periphytic taxa which are suggestive of shallow, cool, alkaline, oligotrophic waters with extensive seasonal ice cover. A reconstruction of mean July air temperature (MJAT) was developed by applying a midge-based inference model for MJAT (two-component WA-PLS) consisting of 79 lakes and 54 midge taxa ($r^2_{\mathrm{jack}} = 0.55$, RMSEP = 0.9°C). Comparison of the chironomid-inferred temperature record to existing regional paleoclimate reconstructions suggests that the midge-inferred temperatures correspond well to regional patterns. This multi-proxy record provides valuable insight into regional Holocene climate and environmental conditions by providing a quantitative reconstruction of peak Holocene warmth and aquatic ecosystem response to these changes in the Great Basin, a region projected to experience increased aridity and higher temperatures.

Introduction

The Earth's globally averaged surface temperature increased ~0.17°C per decade between 1979 and 2005 (Cole et al., 2002; Smith and Reynolds, 2005). This increase in near-surface temperature is spatially heterogeneous with high-latitude and high-elevation regions experiencing greater rates of warming (Diaz and Bradley, 1997; Pepin and Lundquist, 2008). For example, the Intermontane region of the United States has warmed at the rate of 0.40°C per decade between 1979–2005 (Smith and Reynolds, 2005). Projected changes in regional hydroclimatology in the western United States are expected to lead to decreased stream-flow, increased forest fires, and pathogen outbreaks (Cayan et al., 2001; Westerling et al., 2003; Knowles et al., 2006; Tomback and Resler, 2007). The Intergovernmental Panel on Climate Change (IPCC) (2007) strongly advocates focusing climate change research at regional and local scales to improve our understanding of local and regional climate dynamics, which would provide valuable insight to the possible nature of future conditions and the potential feedbacks that may be important in future warm climate scenarios. The Great Basin of the United States, characterized by a highly variable climate and sensitive to changes in regional hydroclimatology, is such a region (Brown and Comrie, 2004; Diffenbaugh et al., 2008).

Alterations to the hydroclimatological regime of the Great Basin will be significant given how important and potentially limiting water resources are in this region (Deacon et al., 2007; MacDonald, 2007; Seager et al., 2007). The Great Basin states are experiencing rapid population growth with the population of the three fastest growing states, Nevada, Arizona, and Utah, increasing by 28.4%, 23.5%, and 18.5%, respectively, between 2000 and 2007 (U.S. Census Bureau, 2007). The principal concern is whether sufficient freshwater will be available in the future (MacDonald, 2007; Seager et al., 2007; Barnett and Pierce, 2008; Barnett et al., 2008) to meet the needs of the rapidly growing urban centers in these states. The central Great Basin and particularly Great Basin National Park (GBNP) are located in a transitional zone between the Pacific Northwest and a winter-dominated precipitation regime and the desert southwest and a summer-dominated precipitation regime (Redmond and Koch, 1991; Dettinger et al., 1998; Brown and Comrie, 2004; Wise, 2009). Modifications to the timing of the seasonal precipitation maximum resulting from shifts in the location of this transitional zone would alter synoptic hydrology and likely have an impact on aquatic and terrestrial ecosystems in this region.

During the late Quaternary the Great Basin experienced large fluctuations in its thermal and precipitation regimes. Extensive research conducted on lake (Benson et al., 2002; Mensing et al., 2004; Potito et al., 2006) and meadow sediments (Thompson and Anderson, 2000), cave deposits (Grayson, 2000; Madsen et al., 2001;

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Smith and Betancourt, 2006), and tree rings (Lamarche, 1974; Feng and Epstein, 1994) has revealed that the middle Holocene in the western United States was warmer and drier than at present (Thompson et al., 1993; Bartlein et al., 1998; Mock and Brunelle-Daines, 1999; Grayson, 2000). This warmer and drier climate could possibly serve as an analogue for the effects of current and future climate change (Mock and Brunelle-Daines, 1999). However, as Diffenbaugh and Sloan (2004) demonstrated, more work is needed to characterize the complex regional climate signals that proxy records reveal prior to utilizing the middle Holocene as an analogue for future conditions.

In this paper we develop chironomid and diatom stratigraphies, for a small, sub-alpine lake located in GBNP, spanning the last ~7000 cal yr BP and we apply a previously developed chironomid-based inference model for mean July air temperature (MJAT) to develop a quantitative reconstruction of Holocene thermal conditions for the region. We also make use of loss-on-ignition (LOI) and diatom data to make qualitative inferences of lake productivity and the duration of ice cover. The Stella Lake record is related to existing paleoclimate records available from the region with an emphasis placed on the middle Holocene, which we identify as the interval between ~7000 and 4000 cal yr BP.

Study area

The study area, situated in GBNP, is located in the Snake Range, Nevada, which is located in the central Great Basin (Fig. 1). This region is characterized by horst and graben topography with north–south trending mountains and valleys (Eaton, 1982). The relief of the Snake Range influences local climate; steep temperature and precipitation gradients are associated with elevation. The valley floors experience average summer (JJA) temperatures of ~22.0°C and average winter (DJF) temperatures of −1.0°C, while high elevations are characterized by summer temperatures of ~13.5°C and winter temperatures of −7.0°C (WRCC, 2008). Annual precipitation is dominated by snowfall in winter and early spring, with lesser amounts during the summer resulting from convectional thunderstorms (WRCC, 2008). The climatology of the southwest United States is influenced by conditions in the tropical Pacific (Shin et al., 2006). Through its influence on general circulation patterns and the synoptic climatology of the region, El Niño Southern Oscillation (ENSO) is the most significant driver of inter-annual climate variability in the Great Basin (Redmond and Koch, 1991). In the modern context, episodes of prolonged aridity in the Great Basin are associated with a strengthened subtropical ridge (Mock and Brunelle-Daines, 1999). The North American Monsoon also plays a role in the moisture regime by enhancing summer precipitation, but its effect is typically limited to the southern portion of the Great Basin (Harrison et al., 2003; Adams and Comrie, 1997).

The study site, Stella Lake (39°00.324′N, 114°19.140′W) (Fig. 1), is a small (3 ha), sub-alpine lake, located within the GBNP on the east side of the Snake Range at 3170 m a.s.l. The lake is situated near the head of a drainage basin with no clear inflowing stream and currently no active outflow; however, during periods of high lake level, Stella Lake may have overtopped morainal deposits located at the north end of the lake and drained into Lehman Creek. Stella Lake is underlain by quartzite of Precambrian and Cambrian age, with late Quaternary glacial till present at the surface (Whitebread, 1969). The vegetation surrounding Stella Lake consists of ~80% *Picea engelmannii* (Engelmann Spruce), ~10% *Pinus flexilis* (Limber Pine), and ~10% *Populus tremuloides* (Quaking Aspen), with additional herbaceous cover present (Baker, G., personal communication, 2007).

Methods

Field

Sediment cores were recovered in the deepest portion (~1.5 m) of Stella Lake in August 2007 (Fig. 1) using a modified Livingstone piston corer, deployed from a platform. Two replicate cores, both 328 cm in

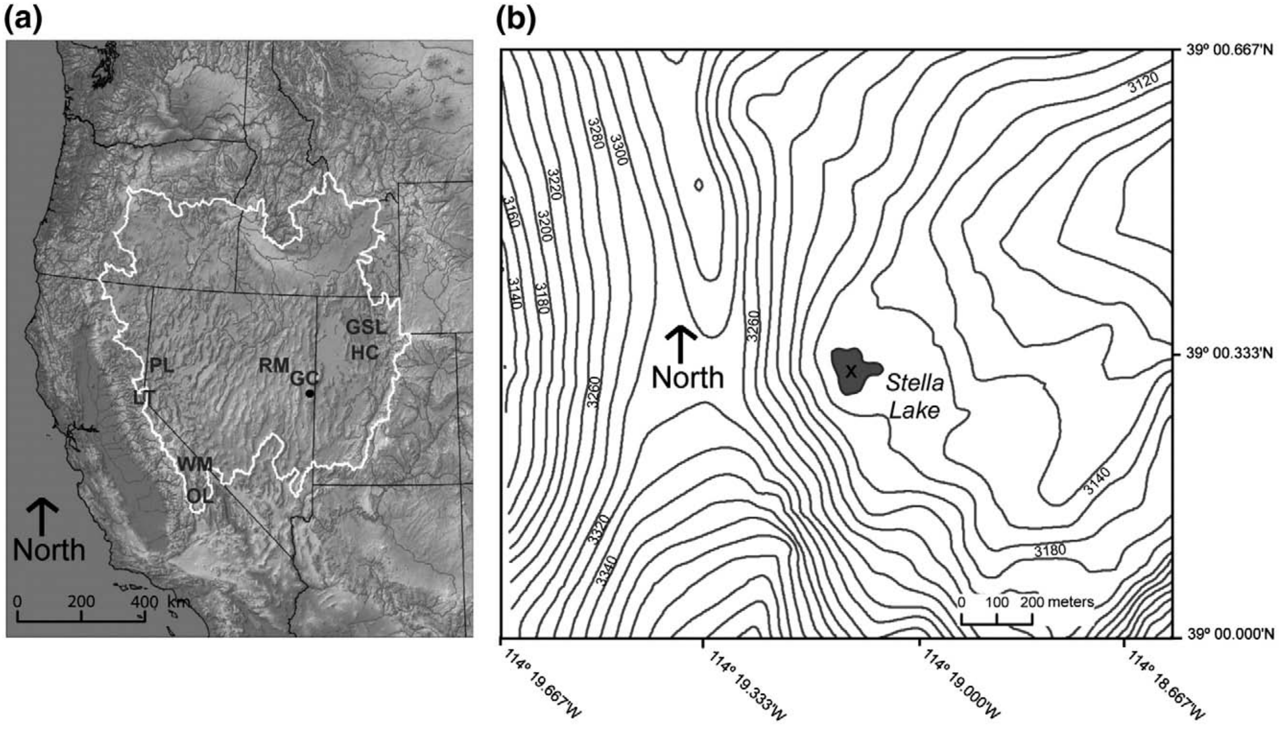

Figure 1. Map of study area along with location of other regional records. (a) Overview map of western United States depicting the Great Basin outlined in white, along with the study site, Stella Lake, Great Basin National Park = ●. Sites discussed in text: WM = White Mountains, California; OL = Owens Lake, California; PL = Pyramid Lake, Nevada; LT = Lake Tahoe, Nevada; RM = Ruby Lake Marshes, Nevada; GC = Goshute Cave, Nevada; HC = Homestead Cave, Utah; GSL = Great Salt Lake, Utah. (b) Stella Lake study site located within GBNP (x = coring location).

Table 1
Selected limnological and environmental measurements for Stella Lake.

Variables	Stella Lake
Elevation (m a.s.l.)	3170
Depth (m)	2.50
Surface area (ha)	3.0
Secchi depth (m)	Unlimited
pH	7.23
Measured SWT (°C)	13.80
Average summer SWT (JJA) (°C)	15.89
Average Summer AT (JJA) (°C)	13.50

Averages were taken from data collected from 2005 to 2007. SWT = surface water temperature; AT = air temperature; JJA = June, July and August.

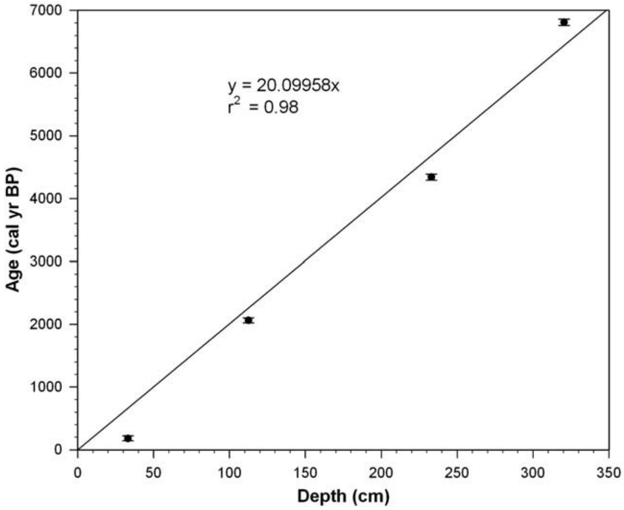

Figure 2. Age–depth model for Stella Lake. The model is based on a linear regression through all four dates. Error bars represent 2σ cal yr BP age range.

length, were recovered to provide enough sediment for subsequent analysis; however, analyses were limited to one of the cores. Sediment cores were extruded in the field, wrapped in plastic and aluminum foil and transported to The Ohio State University. The upper 60 cm of sediment was recovered using a plastic tube, preserving the flocculent surface sediment. The surface core was sectioned in the field at 0.25 cm intervals. After being placed into Whirl-paks© the samples were kept cool and dark. During sediment collection, measurement of limnological variables such as water temperature, dissolved oxygen, salinity, pH, conductivity, and specific conductivity were obtained with a YSI 556 multi-parameter meter (Table 1).

Laboratory

The sediment core was split, and stratigraphy, texture, and color were described. Following visual inspection the core was sectioned at 0.25 cm intervals. Chronological control for the core was provided by AMS ^{14}C dates on samples consisting of either small wood fragments or conifer needles (Table 2). The radiocarbon dates were provided by The National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) (Woods Hole, Massachusetts). CALIB version 5.0.2 was used to convert radiocarbon dates (^{14}C yr BP) to their calibrated ages (cal yr BP) (Reimer et al., 2004). The midpoint of the 2σ cal yr age range with the highest probability of occurrence was utilized to develop the age–depth model (Telford et al., 2004). The age–depth model is based on a simple linear regression (Fig. 2). LOI analysis at 550°C was conducted at 0.5 cm resolution following the approach outlined in Heiri et al. (2001). The sediment cores recovered with the plastic tube and the Livingstone barrel were matched using stratigraphy and LOI to form a single composite core.

Chironomid analysis followed standard procedures (Walker, 2001). A minimum of 0.5 mL of sediment per sample was deflocculated in a 10% KOH solution, heated at 30°C for approximately 30 min, washed with distilled water, passed through a sieve with a 95 μm mesh and backwashed into a beaker. The samples were examined in a Bogorov plankton counting tray using a Zeiss Stemi 2000-C Stereo microscope. The chironomid head capsules were hand picked using a pair of fine tweezers, placed in a drop of distilled water on a cover slip and upon drying permanently mounted using Entellan®. Identification of the subfossil remains was conducted at 400× and was based on Wiederholm (1983), Brooks et al. (2007), and an extensive reference collection of subfossil midge remains housed at The Ohio State University. A minimum of 45 head capsules per sample were used in all statistical analyses (Quinlan and Smol, 2001; Heiri and Lotter, 2001), with the amount of sediment required to obtain this amount varying from 0.5–2.0 mL. The sample resolution was ~100 yr per sample for the middle to late Holocene (0–4800 cal yr BP) and ~40 yr per sample between 4800 cal yr BP and 7000 cal yr BP.

Diatoms were analyzed from 46 samples at approximately 10-cm intervals throughout the core. This resulted in ~200-year sample resolution per diatom sample, with the exception of 309.75–320.75 cm which was analyzed at 1-cm intervals (~20 yr per sample). Following procedures discussed in Battarbee et al. (2001) approximately 0.5 g of sediment for each sample was treated with nitric and sulfuric acids (50:50 M) and heated to fully digest the organic matter. The samples were then successively rinsed with deionized water until neutral. The resulting diatom slurries were mounted onto glass microscope slides using Naphrax® (refractive index = 1.74). A minimum of six hundred diatom valves (average = 683) were identified and enumerated per sample along horizontal transects on each microscope slide using a Leica DM2500 microscope with differential interference contrast (DIC) optics at 1000× magnification. Primary identification references included Krammer and Lange-Bertalot (1986–1991) and Cumming et al. (1995). Raw diatom counts were converted to relative abundance data for each sample. The Simpson Index of Diversity was also calculated for each sample to quantify the biodiversity (Bloom, 2006).

Chironomid inference model and ordination

A chironomid-based mean July air temperature (MJAT) inference model designed specifically for use in the intermountain west was developed using a weighted-averaging partial least squares (WA-PLS) approach. The training set used in the calibration of the inference model is based on a suite of 90 lakes from the Sierra Nevada, California, and Uinta Mountains, Utah. The MJAT inference model consists of 79 lakes and 54 midge taxa and is based on a two-component WA-PLS inference model ($r^2_{\text{jack}} = 0.55$, RMSEP = 0.9°C, maximum bias = 1.66°C) (Porinchu et al., accepted with moderate

Table 2
AMS ^{14}C dates for the Stella Lake core.

Lab code	Depth in core (cm)	Material	^{14}C yr BP $\pm 1\sigma$	2σ Age range (cal yr BP)	Relative area under distribution	Calibrated age (cal yr BP)
OS-64661	33	Conifer needle	185 ± 30	137–224	0.556	180
OS-64648	112.5	Plant/wood	2080 ± 35	1985–2145	0.955	2065
OS-64661	233	Plant/wood	3920 ± 35	4242–4438	0.990	4340
OS-64649	320.5	Plant/wood	5970 ± 40	6713–6902	0.962	6810

Lab code refers to The National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) identification number.

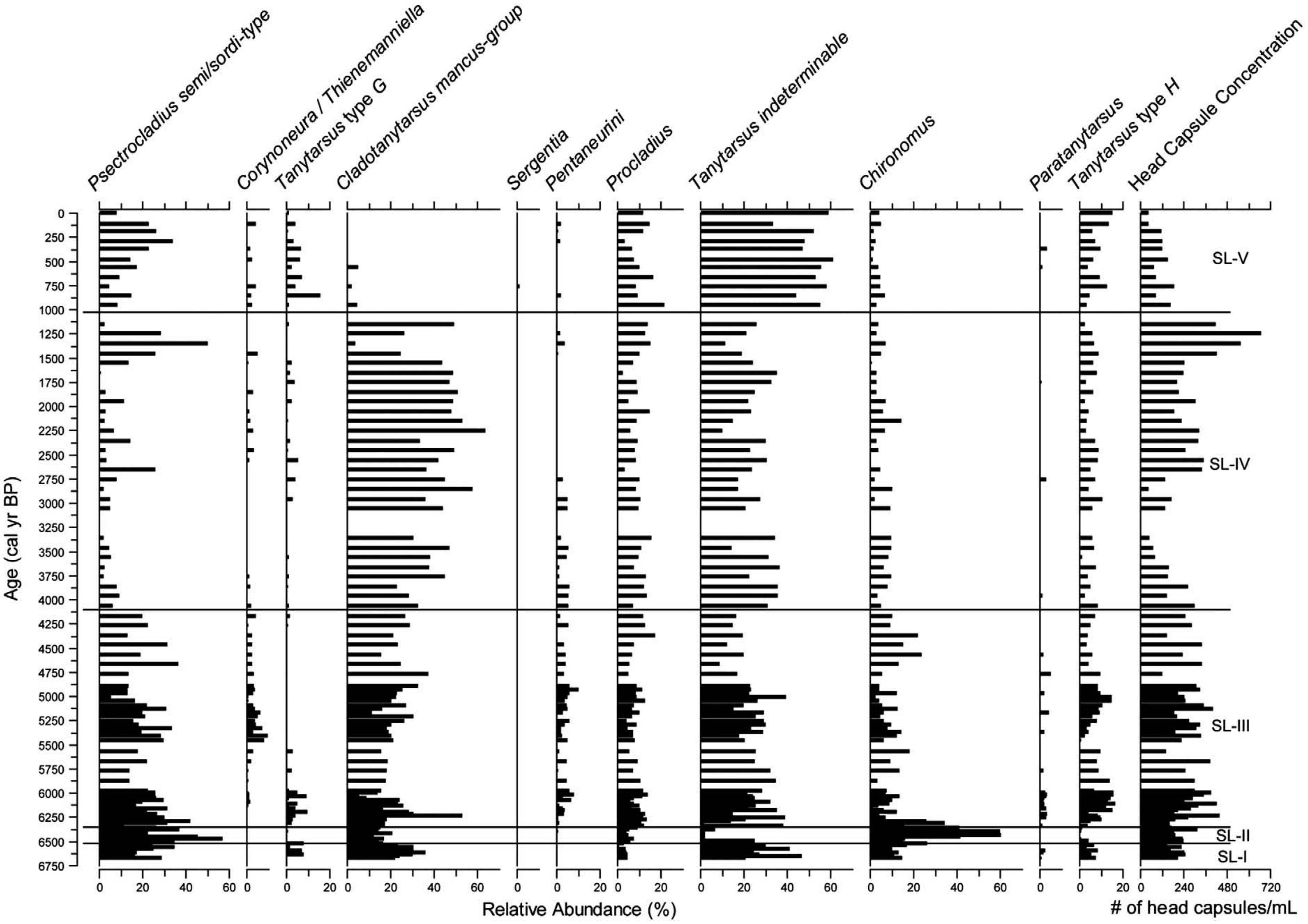

Figure 3. Chironomid relative abundance diagram for Stella Lake. *Psectrocladius semi*/*sordid*-type = *Psectrocladius semicirculatus*/*sordidellus*.

revisions). Further details describing the training set lakes are available in Porinchu et al. (2007). Paleoenvironmental reconstructions based upon subfossil assemblages that have >95% of the subfossil taxa present in the calibration set are very reliable; reconstructions with >90% of the subfossil taxa present in the calibration set are considered reliable (Birks, 1998). The proportion of rare taxa present in downcore samples can also be used to evaluate the reliability of inference model estimates. A taxon is classified as rare if it has an effective number of occurrences or Hill's N2 ≤ 5 (Hill, 1973). Taxa with Hill's N2 values ≥ 5 in a training set can be considered well-represented and will likely provide reliable estimates of temperature optima (Brooks and Birks, 2001). Detrended correspondence analysis (DCA) was implemented using CANOCO version 4.5 (ter Braak and Šimilauer 2002) and based upon relative abundance data, which was square-root transformed to maximize the 'signal to noise' ratio (Prentice, 1980).

Results

Chronology and loss-on-ignition

The AMS radiocarbon dates indicate that the basal sediment in the core was deposited approximately 7000 cal yr BP (Table 2). The age–depth model suggests that the sedimentation rate remained constant through the entire length of the core (Fig. 2). The core consists primarily of organic rich gyttja, with dark organic bands, interspersed throughout the core (see Fig. 6 for further stratigraphic detail).

An increase in organic content, as estimated by LOI (Fig. 5), from ~10% to ~30%, characterizes the interval between 6900 and 6500 cal yr BP. The LOI values abruptly decrease at ~6500 cal yr BP, reaching ~10% for a short interval (~100 yr), increase to ~30% at ~6400 cal yr BP, and fluctuate around this value between 6400 and 1200 cal yr BP, varying between 25% and 35%. An abrupt shift to extremely low LOI (~8%) occurs between 1200 and 1000 cal yr BP. Organic content steadily increases in the post-1000 cal yr BP interval reaching a present day value of ~54%.

Chironomid percentage diagram

A total of eleven midge taxa were identified in the Stella Lake core (Fig. 3). Taxonomic richness varies throughout the core, with samples consisting of between eight and ten extant taxa. Head capsule concentrations vary between 45 and 670 head capsules per mL. Zonation of the chironomid stratigraphy, which was done visually and based on rates of compositional turnover as indicated by chironomid DCA axis-1, resulted in five zones (SL-I–SL-V). The midge community present in Zone SL-I (6700–6500 cal yr BP) is dominated by *Cladotanytarsus mancus* group (~20%) and *Tanytarsus* (~25%). An abrupt shift in community composition occurs in Zone SL-II (6500–6350 cal yr BP) with the contribution of *C. mancus* group and *Tanytarsus* decreasing and a large increase in *Chironomus* (~55%) and *Psectrocladius semicirculatus/sordidellus* (~40%) occurring. It is notable that the abundance of *Chironomus* in Zone SL-II is three times greater than its relative abundance in the remainder of the core. The midge community present in Zone SL-III (6350 to 4100 cal yr BP) is characterized by high relative abundances of *Chironomus*, *P. semicirculatus/sordidellus*, *C. mancus* group, and *Tanytarsus*. This zone is also characterized by the appearance of *Corynoneura/Thienemanniella*, which reaches a core maximum of ~10% at 5400 cal yr BP and a slight increase in *Procladius*. Zone SL-IV (4100–1000 cal yr BP) is characterized by a decrease in the relative abundance of *Chironomus* and *P. semicirculatus/sordidellus* to between 5% and 10%. This zone is also characterized by the presence of abundant subfossil remains belonging to *C. mancus* group (30–40%). Towards the top of Zone SL-IV, *Pentaneurini* is extirpated from the core between ~2600 and 1500 cal yr BP. A large increase in *Tanytarsus* and the disappearance of *C. mancus* group occur in Zone SL-V (1000 cal yr BP–present). *Sergentia* appears only once in the sediment record at ~800 cal yr BP. The interval between 100 cal yr BP and the present is characterized by an increase in *Tanytarsus* type H and a decrease in *P. semicirculatus/sordidellus*.

Diatom percentage diagram

Thirty diatom taxa from 14 genera were identified and enumerated from the 46 Stella Lake sediment samples analyzed for diatoms (Fig. 4). Planktonic diatom taxa were absent from the record. Diatoms are interpreted following the same zones identified in the chironomid data. Zone SL-I only included one diatom sample. This sample is heavily dominated by *Fragilaria construens* var. *venter* (~85%), which results in low diatom diversity (~1.4). Zone SL-II is dominated by small, periphytic, alkaliphilous *Fragilaria* (*F. brevistriata*, *F. construens* var. *venter*, *F. pseudoconstruens*, and *F. pinnata*) with combined abundance values for these *Fragilaria* ranging from ~77–84% for this zone, which is less than Zone SL-I (~95%). *F. construens* var. *venter* decreases from the previous zone, while *F. brevistriata* increases and peaks (~34%). Also notable in this zone, and throughout the core, is that in samples for which *F. construens* var. *venter* values are higher, *F. pinnata* values are lower, and vice versa. Although still low (<5%), abundances of non-*Fragilaria* genera (e.g., *Achananthes*, *Cymbella*, *Gomphonema*, *Navicula*, *Nitzschia*, *Pinnularia*, and *Stauroneis*) increase and, in some cases, reach their maximum in Zone SL-II. As a result, diatom diversity reaches its highest level (~4.6). Small *Fragilaria* continue to dominate in Zone SL-III, with increases in both *F. construens* var. *venter* and *F. pinnata*. In addition, the non-*Fragilaria* taxa evident in Zone SL-II decline or disappear, resulting in a dramatic loss of diversity (minimum = ~1.3). In Zone SL-IV, small *Fragilaria* remain high, with *F. construens* var. *venter* dominating and reaching its maximum (~94%). *F. brevistriata* increases at certain times during this zone, while *F. pinnata* decreases overall. Of particular interest in Zone SL-IV is the presence and peak of *Achnanthes minutissima* (~28%), *Achnanthes pusilla* (~6%), and *Gomphonema parvulum* (~7%) and corresponding crash of small *Fragilaria* (e.g., *F. construens* var. *venter* decreases by slightly more than half) in the sample representing ~1400 cal yr BP Coincident with this, diatom diversity rises substantially, reaching its second highest value of the core (~3.8), the highest value since Zone SL-II. Additional samples will need to be analyzed to explore this anomaly further. In Zone SL-V small *Fragilaria* continue to dominate. Even though low (<5%), it is still notable that with the onset of this top zone *Navicula* cf. *minima* increases to values comparable with Zone SL-II.

Chironomid-based MJAT reconstruction

The taxa present in Stella Lake are well-represented in the intermountain west calibration set (Porinchu et al., accepted with moderate revisions). All eleven chironomid taxa comprising the Stella Lake chironomid stratigraphy are present in the intermountain west training set; therefore, the MJAT reconstructions are considered very reliable (Birks, 1998). The values for Hill's N2 diversity index range between 19 and 74, providing further support that the quantitative midge-based MJAT reconstructions can be considered robust (Brooks and Birks, 2001). The chironomid-inferred MJAT reconstruction for Stella Lake is presented in Figure 5. The sample-specific error estimates of the MJAT inferences varied between 1.0°C and 1.6°C. The MJAT reconstruction for the past ~7000 yr illustrates a trend of increasing MJAT during the early and middle Holocene, with a peak value of ~11.0°C occurring at ~5400 cal yr BP. Peak warmth was followed by steadily decreasing MJAT between 5400 and 1800 cal yr BP, with a minima in midge-inferred MJAT, ~9.4°C, occurring at ~1800 cal yr BP. The post-1800 cal yr BP interval is characterized by a steady rise in MJAT, with 20th century MJAT approaching middle

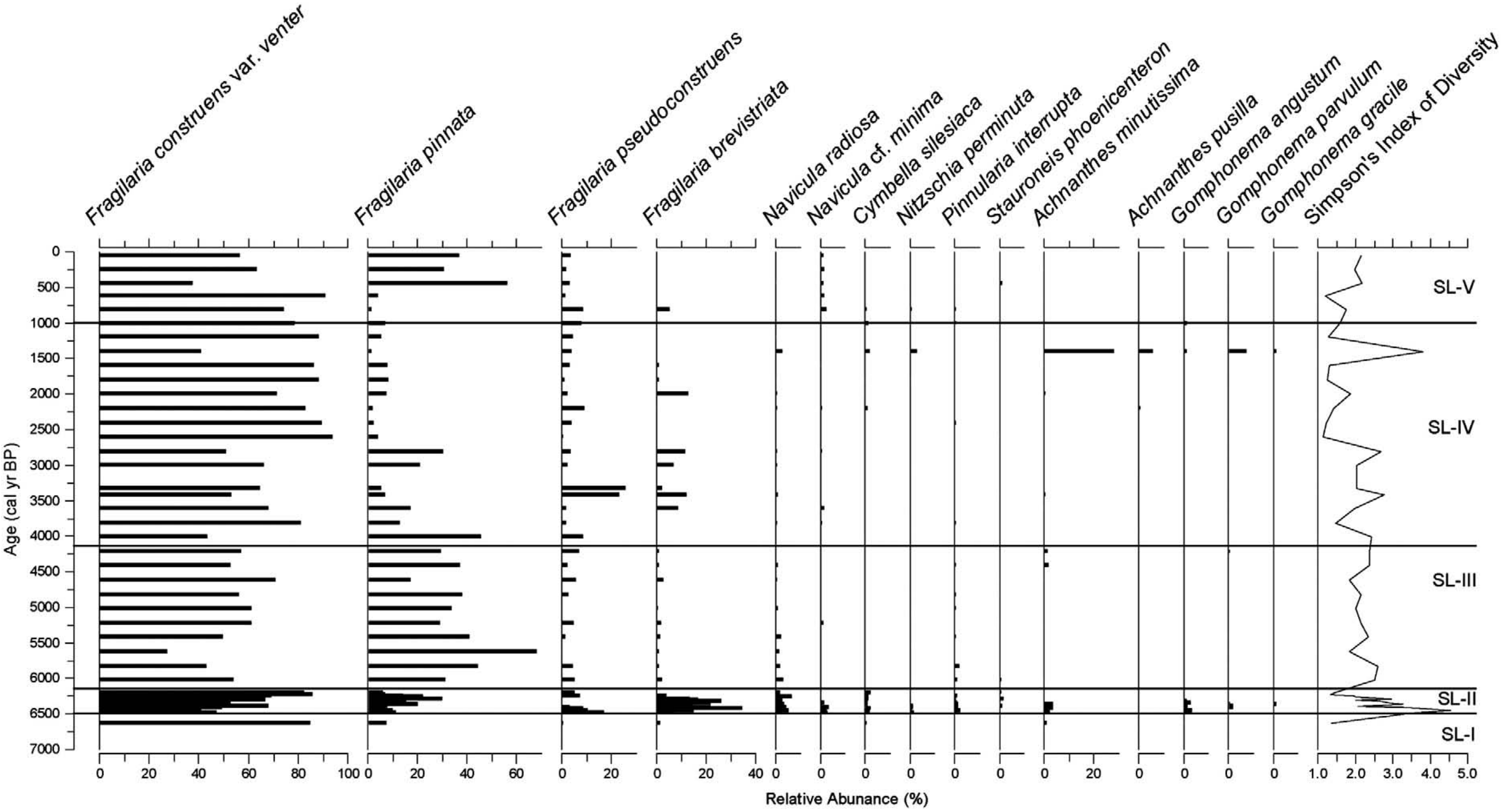

Figure 4. Diatom relative abundance diagram and Simpson's Index of Diversity for the diatoms from Stella Lake.

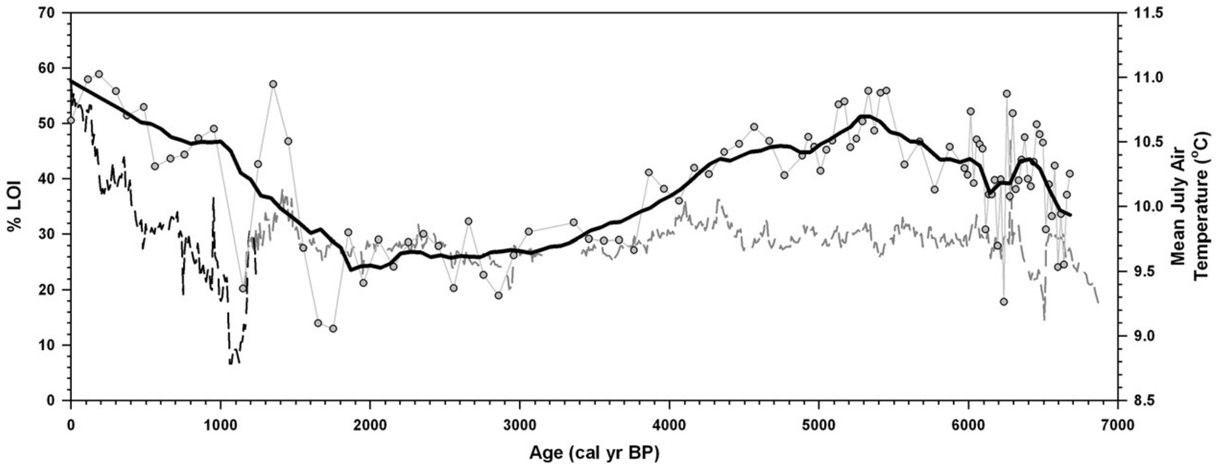

Figure 5. Loss-on-ignition (LOI, black dashed line [plastic tube] and grey dashed line [Livingstone core]), chironomid-inferred MJAT (grey line with circles), LOWESS smooth (span = 0.10) of chironomid-inferred MJAT (thick black line).

Holocene values. The warm conditions in the Great Basin that existed between ~5400 and 5000 cal yr BP are notable. The MJAT reconstruction indicates that this was the warmest interval in the previous 7000 yr. During this interval the midge-inferred MJAT remained consistently high, fluctuating around 10.9°C, with peak warmth (11.0°C) occurring at ~5400 cal yr BP.

Discussion

Biological and geochemical proxies such as pollen, packrat middens, chironomids, diatoms, and stable isotopes extracted from sediment archives and cave deposits in the Great Basin have been used to reconstruct, with varying spatial and temporal resolutions, late Quaternary environmental and climate changes for this region (e.g., Lamarche, 1973, 1974; Grayson, 2000; Thompson and Anderson, 2000; Madsen et al., 2001; Benson et al., 2002; Mensing et al., 2004; Bloom, 2006; Potito et al., 2006; Smith and Betancourt, 2006). These records are valuable as they can be used to identify the timing, magnitude, and variability of regional climate change during the Holocene. Relating the quantitative midge-based inferences of MJAT and the diatom-based qualitative inferences of hydrologic conditions from Stella Lake to these existing records (Fig. 6) will help identify whether the alterations in the thermal and/or hydrologic regimes at Stella Lake are due to site-specific conditions or rather are indicative of a re-organization of regional climate patterns during the Holocene.

The overall diatom-community composition at Stella Lake is suggestive of shallow, cool, slightly alkaline, oligotrophic waters with increased ice cover (i.e., longer ice-covered period) which is supported by measurements of lake level (2.05 m) and pH (7.45) during July 2007. Depending on the year, a semi-permanent ice field reaches Stella Lake. The lake is fairly well-sheltered and during high snow years, ice persists on the lake into early summer, which decreases the length of time the lake is partially or completely ice-free. The diatom assemblage is dominated by taxa abundant in Arctic lakes and ponds (reviewed in Douglas and Smol, 1999). Although the midge-inferred temperature changes seen in the Stella Lake chironomid record are not directly evident in the diatom record, temperature is indirectly affecting the diatoms primarily through the amount and duration of ice and snow cover. This affects lake productivity and habitat availability for the diatoms (Smol, 1988). Small, periphytic, alkaliphilous *F. construens* var. *venter* dominates Zones SL-I and SL-II with lesser amounts of *F. brevistriata*, *F. pinnata*, *F. construens* var. *venter*, and *F. pseudoconstruens*. Based on research in northeastern Alberta, Prather and Hickman (2000) conclude that the dominance of *F. construens* var. *venter* and co-dominance by *F. pinnata*, *F. brevistriata*, and *F. construens* indicate lower water levels, transparent water, and/or decreased nutrients in the water column and resulted in the lack of planktonic taxa. It has been shown that high abundances of small *Fragilaria* and low planktonic diatoms indicate prolonged ice cover (e.g., Smol, 1988; Douglas and Smol, 1999; Lotter and Bigler, 2000). Therefore, the lack of planktonic diatom taxa at Stella Lake is not surprising and is most likely related to lake level and ice cover. Stella Lake is shallow (average depth ~1.50 m, based on repeat measurements from 2005–08) and likely freezes to the bottom seasonally, especially when depths are less than 1 m. Planktonic diatoms are typically found in lakes with higher water levels, not shallow “ponds” (<1 m) which freeze to the bottom each winter (Douglas and Smol, 1994). The chironomid community within Zones SL-I and SL-II experience rapid compositional turnover. High faunal turnover coupled with highly variable, yet low LOI values, is also indicative of fluctuating lake levels. For the diatoms, habitat availability is lower during colder periods (e.g., rocks and sediment); however, with warming, additional habitats become available (e.g., macrophytes) due to the lengthened growing season, and with increased algal growth more diverse diatom communities can develop (reviewed in Douglas and Smol, 1999). Therefore, the presence of *Achananthes*, *Cymbella*, *Gomphonema*, *Navicula*, *Pinnularia*, and *Stauroneis* during SL-II in the diatom community suggests decreased ice/snow cover and increased habitat availability, resulting in higher diatom diversity. These taxa also suggest acidophilic conditions with increased nutrient availability. Specifically, epiphytic *Gomphonema angustum* and *Gomphonema gracile* have both been shown to occur in macrophyte-rich lakes of higher productivity (Hay et al., 2000). The chironomid data support this inference with SL-II characterized by large increases in *Chironomus* and *P. semicirculatus/sordidellus*, taxa which are typically associated with eutrophic lakes (Brooks et al., 2007; Porinchu et al., 2007).

The Stella Lake record indicates that the central Great Basin was characterized by higher midge-inferred temperatures during the middle Holocene, which is in agreement with existing paleoclimate records from the region. Thompson et al. (1993) identified an interval spanning the middle Holocene of higher summer temperatures and periods of prolonged aridity. The existence of an interval of prolonged aridity and/or decreased effective moisture during the middle Holocene in Great Basin is indicated from desiccation polygons in Great Salt Lake (Currey, 1980; Madsen et al., 2001) and $\delta^{18}O$ records from Owens Lake, California and Pyramid Lake, Nevada (Benson et al., 2002). Smith and Betancourt (2006) identified an inverse relationship between packrat body size and ambient air temperature and made use of this relationship to infer that warmer conditions existed through the middle Holocene. An investigation of packrat middens at Homestead Cave (Grayson, 2000) revealed that species richness and

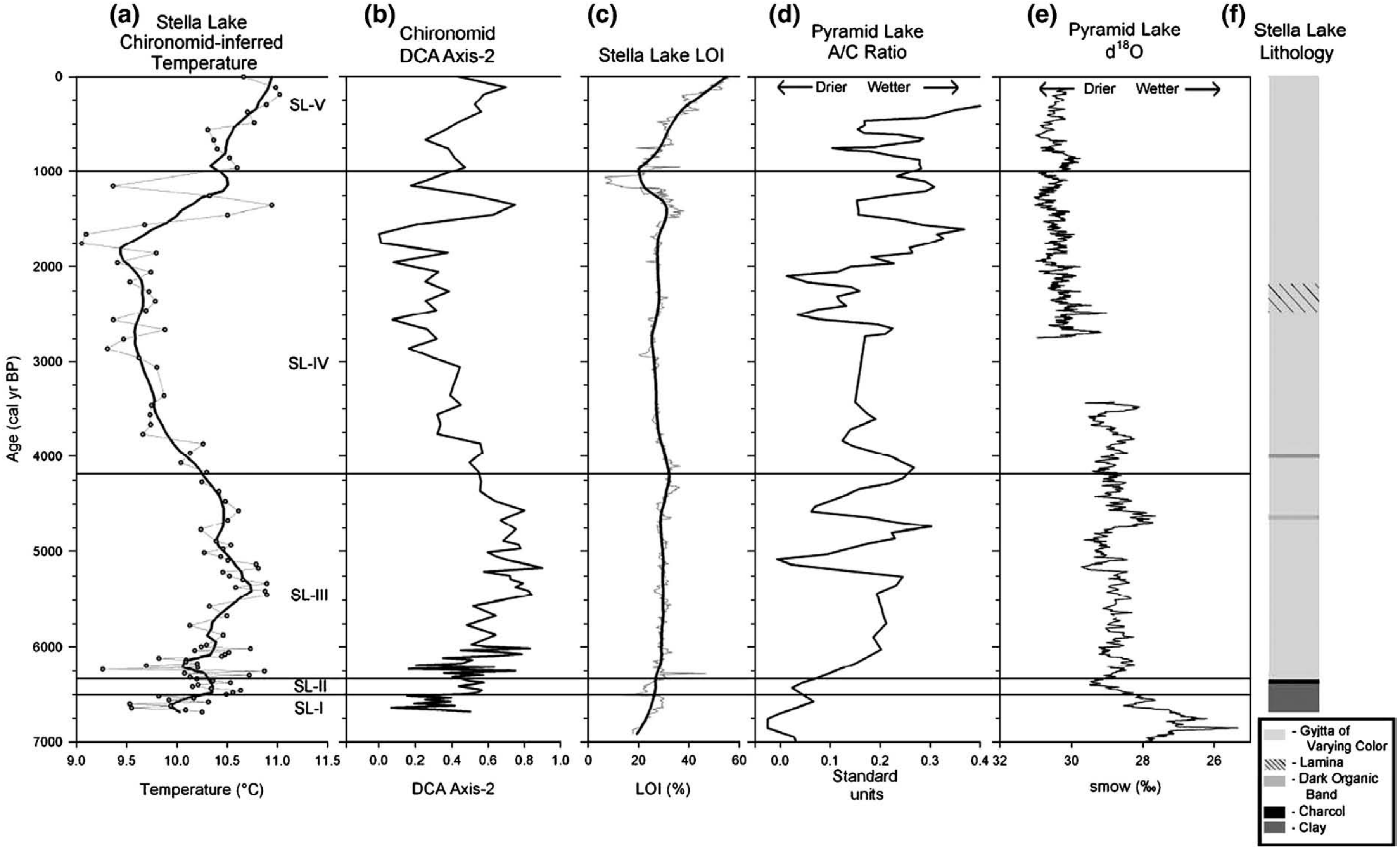

Figure 6. Summary diagram of existing select published Great Basin paleoclimate records and data from Stella Lake. (a) Stella Lake chironomid-inferred MJAT, (b) Stella Lake Chironomid DCA Axis-2 (c) Stella Lake LOI, (d) pollen A/C ratio from Pyramid Lake (Mensing et al., 2004), (e) $\delta^{18}O$ data from Pyramid Lake (Benson et al., 2002), and (f) composition of sediment from Stella Lake.

evenness of small mammals decreased at ~8300 cal yr BP. In addition, this interval was also characterized by decreases in the relative abundance of small mammals associated with cool, moist environments of the Great Basin and a marked increase in species adapted to warm and arid conditions. Warm, arid conditions are also indicated by the $\delta^{18}O$ records developed from stalagmites in Goshute Cave in central Nevada, which are ~1.5‰ heavier than full glacial times (Denniston et al., 2007).

Radiative forcing and conditions in the tropical Pacific affected the climate of the Great Basin during the middle Holocene by altering large-scale circulation patterns primarily resulting in a strengthened subtropical ridge over the western United States (Shin et al., 2006). Regional climate models reveal that at 6000 cal yr BP the Great Basin experienced temperature anomalies of approximately 1 to 2.5°C relative to present (Diffenbaugh and Sloan, 2004). Features associated with atmosphere–ocean feedbacks during the middle Holocene, such as ENSO, were comparable to modern day conditions (Moy et al., 2002; Shin et al., 2006). For example, relative to modern conditions, ENSO events were similar in frequency and amplitude during the middle Holocene (Moy et al., 2002).The high degree of correspondence between the climate forcings that existed during the middle Holocene and the contemporaneous environment facilitate comparisons between paleoclimate reconstructions and model simulations of past climates (Mock and Brunelle-Daines, 1999; Shin et al., 2006; Edwards et al., 2007). Improving our understanding of the conditions that existed during the middle Holocene will help to constrain model simulations of past, present, and future climates. The Stella Lake record provides insight to the temperature conditions that characterized the central Great Basin, by providing a quantitative reconstruction of MJAT during the Holocene and also during peak Holocene warmth at ~5400 cal yr BP in the Great Basin.

Midge-inferred peak Holocene warmth, which occurred at ~5400 cal yr BP, was ~11.0°C. Increases in *P. semicirculatus*/*sordidellus* and *Corynoneura*/*Thienemanniella*, thermophilous taxa with MJAT optima of 11.7 and 12.0°C, respectively, are responsible for the high midge-inferred temperatures that characterize Zone SL-III. In the Great Basin, *P. semicirculatus*/*sordidellus* has been identified as a common constituent of warm low and mid-elevation lakes present in the training set (Porinchu et al., 2002; Porinchu et al., 2007). *Chironomus* has also been used as an indicator of warm, productive lakes (Brooks et al., 2007). Interestingly, the diatom community does not show a distinct change at the time of the midge-inferred temperature increase at ~5400 cal yr BP. This is not completely surprising because of the low diatom diversity in Stella Lake, as well as, the absence of planktonic taxa. Also, in the nearby Sierra Nevada, California, diatoms were shown to be more closely affected by hydrological conditions such as lake level, salinity, and nutrients (Bloom et al., 2003; Bloom, 2006). However, a regional signal of peak warmth occurs at ~5400 cal yr BP and is evident at multiple sites in the Great Basin (Lamarche, 1973; Lindström, 1990; Thompson, 1992; Mensing et al., 2004). Based on a decrease in the *Artemisia*:Chenopodiaceae ratio (A/C ratio) and evaporative enrichment of $\delta^{18}O$ in Pyramid Lake sediment, Mensing et al. (2004) inferred the occurrence of a severe, prolonged drought between 5200 and 5000 cal yr BP (Fig. 6). The presence of submerged, rooted tree stumps in Lake Tahoe, which dates between 6300 and 4800 cal yr BP, suggests that the eastern Great Basin during this interval experienced a prolonged period of decreased effective moisture (Lindström, 1990). Tree-ring records from bristlecone pine in the White Mountains in eastern California indicate that treeline was displaced ~100 m above modern between approximately 5400 to 5000 cal yr BP, likely as a result of increased summer temperatures (Lamarche, 1973). Pollen analysis of sediment cores recovered from the Ruby Lake Marshes, reveals that water levels in the Marshes dropped to below modern conditions between 7000 cal yr BP and ~5000 cal yr BP (Thompson, 1992). The warm and dry conditions that existed between 5400 and 5000 cal yr BP in the Great Basin extended south to central Mexico (Metcalfe et al., 2000). The northern Great Plains were also characterized by an intense, episodic drought between 5400 to 5200 cal yr BP (Valero-Garces et al., 1997). However, it is worth noting that some studies suggest that peak middle Holocene warmth occurred earlier than ~5400 cal yr BP in the Great Basin. Variations in stable isotopes extracted from Bristlecone pines in the White Mountains of California suggest that peak Holocene warmth occurred at ~6800 cal yr BP (Feng and Epstein, 1994). Lake Tahoe was almost 4 m below its natural sill level between 7500 and 6300 cal yr BP (Lindström, 1990; Tausch et al., 2004). The Pyramid Lake record infers peak and aridity and warmth occurring at ~6500 cal yr BP from the A/C ratio and $\delta^{18}O$ values (Benson et al., 2002; Mensing et al., 2004). It is relevant to notice that these sites all occur in the western Great Basin.

The midge-inferred depression in MJAT that occurs in Zone SL-IV is due to a decrease in *P. semicirculatus*/*sordidellus* and an increase in *Tanytarsus* type G (*TAG*), which has the lowest MJAT optima (10.4°C) of the taxa present in the Stella Lake midge stratigraphy. *C. mancus* group, which also increases in abundance in Zone SL-IV, is typically an indicator of cool conditions in the intermountain west (Porinchu et al., 2007). The late Holocene was characterized by the re-advance of glaciers throughout the North American Cordillera, likely in response to lower temperatures (Porter and Denton, 1967; Armour et al., 2002; Viau et al., 2002; Menounos et al., 2008). This interval, which has been labeled the "Neoglacial" (Porter and Denton, 1967) is evident at Stella Lake with midge-inferred MJAT decreasing ~1.5°C from peak Holocene warmth to ~9.5°C (Fig. 5). Decreasing shadscale abundance after ~4300 cal yr BP in the Ruby Lake Marshes of central Nevada (Thompson, 1992) provides support for cooler and moister conditions during the late Holocene. A positive excursion in the Pyramid Lake $\delta^{18}O$ record at ~3100 cal yr BP is identified as a transition to colder and wetter climate (Benson et al., 2002).

From approximately 2000 cal yr BP to the present (Zone SL-IV and Zone SL-V), the interval which includes the Medieval Climatic Anomaly (MCA) and the Little Ice Age (LIA), the record is characterized by increasing MJAT inferences and sediment organic content. The rise in midge-inferred temperatures during this interval is associated with an increase in the relative abundance of *P. semicirculatus*/*sordidellus*, and a reduction in *Tanytarsus* type G and the extirpation of *C. mancus* group. The diatom community does not vary much between Zones SL-IV and SL-V, with the exception of a pronounced change at ~1400 cal yr BP which warrants further investigation to assess if it is indeed an anomaly. The dramatic, short-lived decline in the small *Fragilaria* and coincident rise in *A. minutissima*, *A. pusilla*, and *G. parvulum*, which result in a diversity level near that of SL-II, is indicative of less ice cover. Increased temperatures are noted in the midge-inferred temperature record at this time, with reconstructed values also nearing that of SL-II. During the MCA (~AD 800–1300) (Crowley, 2000; Bradley et al., 2003) the Great Basin experienced multi-decadal droughts, which were greater in intensity and magnitude than droughts that have occurred in the last 140 yr (Stine, 1994). Mensing et al. (2008) provide evidence from multiple sites in the Great Basin for centennial droughts during the last 2000 yr, with one event ending at ~1200 cal yr BP. As well, multicentennial drought events were observed at Kirman Lake, in the eastern Sierra Nevada, during the late Holocene based on diatom-community composition and the application of a diatom–inference model for lake level from the Sierra Nevada (Bloom, 2006). Interestingly, a dramatic decline in the level of Kirman Lake occurred at ~1400 cal yr BP (Bloom, 2006). Due to the uncertainty in the ^{14}C-derived chronology, the relatively coarse temporal resolution (~100 yr per sample) and the potential for smoothing of the sediment-based climatic signal, it is difficult to identify with any certainty whether evidence for either the MCA or LIA exists in Stella Lake.

Subfossil chironomid analysis has been successfully used to reconstruct large-magnitude late Quaternary climate change in the western United States (Porinchu et al., 2003; Potito et al., 2006; MacDonald et al., 2008). In addition, recent studies have also demonstrated that chironomids are able to reliably reconstruct temperature changes of smaller magnitude, for example, 0.5–2.0°C (Larocque and Hall, 2003; Larocque et al., 2009; Millet et al. 2009). Yet, although the results from DCA reveal that compositional turnover along DCA axis-2 closely matches the midge-based temperature reconstruction (Fig. 6), a large amount of variance remains unexplained (DCA axis-1). This unexplained variance likely reflects the influence of additional abiotic and biotic factors on midge community composition (Velle et al., 2005). Changes in lake level, the length of ice-free season, and the position of local timberline all likely played a role in influencing the composition of the Stella Lake midge community. For example, fluctuations in lake level at Stella Lake, a relatively shallow lake with an extensive near-surface bench located in the eastern quadrant, would greatly alter the proportion of littoral and benthic habitats. This bench would have been exposed during intervals of low lake level, decreased available littoral habitat and reduced the ratio of littoral to benthic taxa, which in turn may impact the midge-inferred temperature reconstruction.

The influence of changing lake levels on the midge community in Stella Lake may account for some of the potential inconsistencies that exist between the midge-inferred temperature reconstruction and other existing regional paleoenvironmental records during the middle Holocene (e.g., ~6800–6000 cal yr BP) and late Holocene (e.g., ~2500–2000 cal yr BP). For example, during the late Holocene the Stella Lake midge-based temperature inferences reach a near minimum value of ~9.5°C (Fig. 5); whereas, at Pyramid Lake A/C ratios are indicative of drier conditions between ~2500 and 2000 cal yr BP (Fig. 6) and are akin to those seen in the middle Holocene (Mensing et al., 2004). Pollen records from throughout the Great Basin also suggest a time of recurring droughts through this interval (Tausch et al., 2004; Mensing et al., 2008). In addition, the O^{18} record and the A/C data from Pyramid Lake indicate that the driest and presumably warmest interval during the Holocene occurs at ~6800 cal yr BP (Benson et al., 2002) compared to Stella Lake, with midge-inferred peak warmth occurring at ~5400 cal yr BP. This emphasizes the need to incorporate additional proxies and approaches, e.g. compound-specific isotope ratios and lake basin coring transects, to provide independent estimates of past environmental and climate conditions to improve our understanding of regional climate dynamics at Stella Lake.

Conclusion

This study provides further support that the Great Basin was characterized by a warm and arid middle Holocene, a cool and moist “Neoglacial” and a return to warmer conditions during the late Holocene. This is evidenced by a relative increase in thermophilous chironomid taxa such as *Chironomus* and *P. semicirculatus*/*sordidellus*, during the middle Holocene and cool indicator taxa, *C. mancus* group, during the late Holocene. The overall dominance of small, benthic *Fragilaria* throughout the Stella Lake core suggests the existence of extensive ice and snow cover; however, there are periods during the record, specifically SL-II and within SL-IV at ~1400 cal yr BP, when non-*Fragilaria* taxa increase due to less extensive ice cover indicating increased habitat availability and decreased lake water alkalinity. Application of the midge-based MJAT inference model provides a quantitative estimate of peak Holocene warmth (~11.0°C), which occurred at ~5400 cal yr BP. Development of additional multi-proxy, high-resolution paleoclimate records within the Great Basin is required to better characterize the spatial imprint of this phenomenon. The Stella Lake record broadens our knowledge of the thermal conditions that existed during the Holocene in the Great Basin by providing an independent quantitative reconstruction of MJAT, which in turn may be useful in constraining model simulations of past climates and improving future climate projections.

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