Quaternary Science Reviews 40 (2012) 89–106

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

An organic geochemical record of Sierra Nevada climate since the LGM from Swamp Lake, Yosemite

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ARTICLE INFO

Article history:
Received 23 April 2011
Received in revised form
27 January 2012
Accepted 28 February 2012
Available online 31 March 2012

Keywords:
Sierra Nevada, California
Paleoclimate
Paleolimnology
Sedimentary organic matter
Stable isotopes

ABSTRACT

Sediment records from Swamp Lake (SL) in the central Sierra Nevada, California, provide evidence of climatic change on millennial and centennial timescales over the last ~20,000 years. Total organic carbon (TOC) abundance varied in concert with elemental and isotopic tracers of organic matter (C/N, $\delta^{13}C_{org}$, $\delta^{15}N$), biogenic silica content, total magnetic susceptibility, and sediment lithology. We interpret the down-core proxy records as representing the response of the lake environment, in terms of temperature, seasonal ice cover, mixing regimes, runoff and *in situ* OM and nutrient cycling, to shifting climate states. These environmental factors in turn drove changes in algal productivity, OM sources, microbial OM regeneration and secondary production, and detrital input. The late Pleistocene (~19.7–10.8 cal. kyr BP) was dominated by fluctuations between relatively warm/dry intervals with high TOC (17.4–16.5, 15.8–15.0, 13.9–13.2, 11.4–11.0 cal. kyr BP) and cold/wet intervals (16.5–15.8, 14.8–13.9, 13.1–11.6, 11.0–10.7 cal. kyr BP) characterized by low TOC and high detrital input. The Holocene (~10.7 cal. kyr BP – present) was characterized by three abrupt increases in TOC (after ~10.8, 8.0, and 3.0 cal. kyr BP) and numerous century-scale fluctuations. TOC increases reflected enhanced lake productivity and OM recycling, and reduced detrital input, in response to changing winter temperature and hydrologic regimes. Inferred environmental changes at SL correlate with other Sierra Nevada paleorecords, and with reconstructed sea surface temperatures along the California margin. Parallel changes in the SL and SST records over the past ~20,000 years provide new evidence that continental climate in the Sierra Nevada and the California Current system have responded, on multiple timescales, to common drivers in North Pacific ocean-atmospheric circulation.

1. Introduction

The pacing of natural climatic variability is of particular importance in California, where a limited water supply is dependent on snowmelt runoff from the Sierra Nevada, and is thus sensitive to changes in mean values and seasonal patterns of precipitation and temperature (Wilkinson et al., 2002; Miller et al., 2003). In light of the short instrumental record, only paleoclimatic records can reveal patterns of variability operating on timescales longer than a few decades. These patterns may influence regional water supplies and the occurrence of extreme events such as floods and droughts, and obscure or intensify the effects of human interference with global climate.

Climate variability in California and western North America is affected by Pacific Ocean surface conditions that influence basin-wide atmospheric circulation patterns (Seager and Vecchi, 2010). For example, interannual cycles in tropical Pacific sea surface temperature (SST) (El Niño-Southern Oscillation, ENSO) are associated with anomalous temperature and precipitation throughout western North America and warm SST off California (e.g., Redmond and Koch, 1991; McGowan et al., 1998; Dettinger et al., 2001; Diaz et al., 2001; Higgins et al., 2002; Castello and Shelton, 2004). Likewise, decadal shifts in North Pacific SST and atmospheric circulation are linked to changes in regional temperature, precipitation, snow accumulation, streamflow and runoff timing, and related ecological processes (Dettinger and Cayan, 1995; Mantua et al., 1997; McCabe and Dettinger, 2002; Millar et al., 2004; Tootle et al., 2005; Hunter et al., 2006). The regional influences of

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doi:10.1016/j.quascirev.2012.02.017

ENSO and the Pacific Decadal Oscillation (PDO) have been detected in paleorecords spanning the last millennium (e.g., Biondi et al., 2001; Benson et al., 2003; Cook et al., 2004; MacDonald and Case, 2005; Graham et al., 2007; Herweijer et al., 2007; Conroy et al., 2009), but our understanding of the relationship between ocean conditions and climate in western North America over longer timescales, and during climate regimes of the more distant past, remains fragmentary (Barron and Anderson, 2011). This is particularly true of the large Sacramento-San Joaquin River watershed draining the Sierra Nevada.

To date, only a handful of published paleoclimatic records from sites in the Sierra Nevada region combine high temporal resolution (centennial-scale and finer) and length (full Holocene or longer) (e.g., Hughes and Graumlich, 1996; Benson et al., 2002; Mensing et al., 2004). Previous research has linked millennial-scale climatic and environmental change to insolation, continental ice sheet dynamics and local glacial advances/retreats, and various ocean processes (e.g., Davis et al., 1985; Davis and Moratto, 1988; Anderson, 1990; Smith and Anderson, 1992; Anderson and Smith, 1994; Koehler and Anderson, 1994, 1995; Benson et al., 1996, 1997, 1998; Davis, 1999a, b; Mensing, 2001; Brunelle and Anderson, 2003; Porinchu et al., 2003; Mensing et al., 2004; Bacon et al., 2006; Negrini et al., 2006; Oster et al., 2009). However, these studies have only occasionally addressed variability on sub-millennial timescales during climate regimes prior to the late Holocene.

In the present study we use organic geochemical analyses of bulk sediments from Swamp Lake (SL), a mid-elevation lake in Yosemite National Park (Fig. 1), to reconstruct paleoenvironmental variability in the Sierra Nevada at ~100-year resolution over the past ~20,000 years. Lake sedimentary organic matter (OM) derives from both autochthonous production (algae, bacteria and aquatic plants) and the input of terrestrial plant material from the surrounding watershed, and is thus an important archive of paleoenvironmental change in the lake basin. Carbon and nitrogen elemental abundances (TOC, TN, C/N) and isotopic compositions ($\delta^{13}C_{org}$, $\delta^{15}N$) in sedimentary OM respond to changes in the balance of OM sources, vegetation distribution, primary production and lake trophic status, nutrient inputs and sources, and carbon utilization and cycling (e.g., Meyers and Takemura, 1997; Hodell and Schelske, 1998; Brenner et al., 1999; Meyers, 2003). These proxies may therefore provide sensitive indicators of climate-driven environmental change (Meyers and Takemura, 1997; Meyers and Lallier-Verges, 1999; Talbot and Laerdal, 2000). At SL, we apply OM proxies to gather new insight into the Late Pleistocene–Holocene climate history of the Sierra Nevada. In particular, we attempt to better define the major climatic regimes of the last 20 kyr, patterns of century-scale variability within these regimes, and their relationship to existing reconstructions of SST in the eastern North Pacific (e.g., Seki et al., 2002; Barron et al., 2003). The SL record provides a western Sierra point of comparison with records from eastern Sierra drainages (Benson et al., 1996, 1997, 1998, 2002, 2010; Davis, 1999a; Mensing et al., 2004; Briggs et al., 2005; Bacon et al., 2006), and contributes to the synthesis of a more complete picture of regional paleoclimate in western North America since the last glacial maximum (LGM).

2. Materials and methods

2.1. Study area

Swamp Lake is a mid-elevation tarn lake located in Yosemite NP in the central Sierra Nevada (1554 m elevation, 37°57′N, 119°49′W) (Fig. 1). Thanks to its location less than 2 km east of the maximum westward (and downslope) edge of Tioga stage glaciation (Smith and Anderson, 1992), SL was ice-free earlier than high-elevation sites, and the sediments accumulating here provide the longest continuous paleoenvironmental record yet recovered from the western Sierra. The granitic SL basin covers ~1.3 km^2, while the lake itself has a surface area of 0.08 km^2 and reaches a maximum depth of 20 m. Inlet and outlet streams to the lake are ephemeral, operating only from the winter-wet season to early summer, though perennial subsurface inflow and outflow may occur. At present, SL does not freeze during the winter, with water temperatures reaching a minimum of ~5 °C (Fig. 2a). Continuous air temperature readings taken in Dec–Feb of 2006–2007 fluctuated between −7 and 5 °C (Roach, 2010), with no below-zero excursion

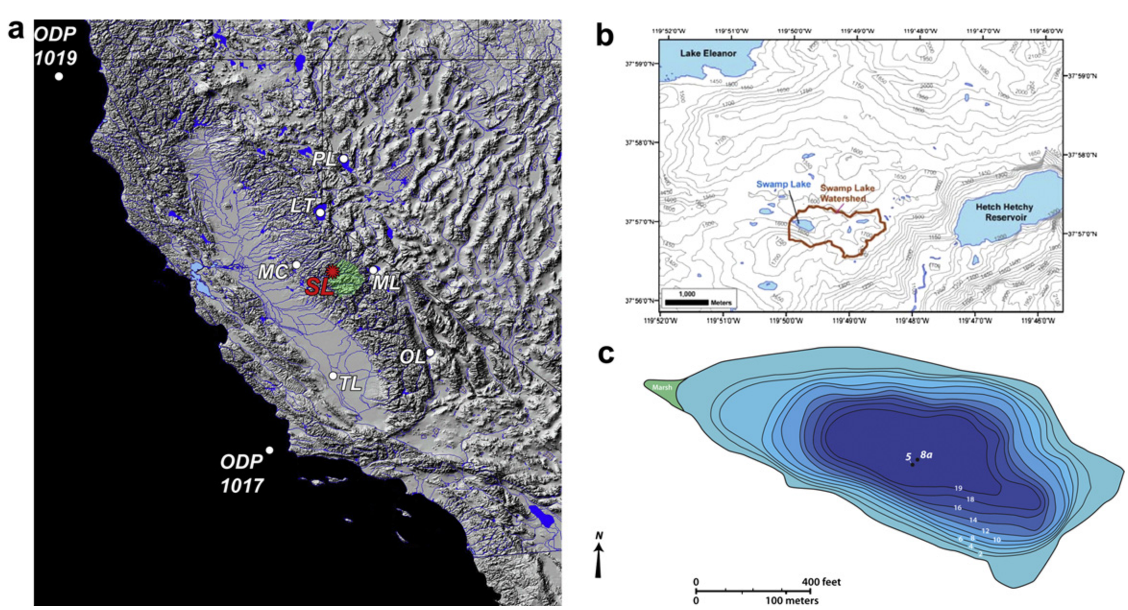

Fig. 1. (a) Map of California, with locations of Swamp Lake (SL, star), Yosemite (green shading) and the sites of other paleorecords in the region: LT, Lake Tahoe; MC, Moaning Cavern; ML, Mono Lake; OL, Owens Lake; PL, Pyramid Lake; TL, Tulare Lake. (b) Topographic map of the Swamp Lake drainage basin in northwestern Yosemite NP. Adapted from Roach (2010). (c) Bathymetric map of Swamp Lake and coring locations. Contours in meters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)