



Late Glacial and Holocene record of climatic change in the southern Rocky Mountains from sediments in San Luis Lake, Colorado, USA

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ABSTRACT

Large rapid climate changes occurred over the last glacial cycle in the southwestern United States and elsewhere in many regions of the world. Some of these changes were attributed to alternations between stadial and interstadial conditions in the North Atlantic. But intense debate exists on how climate anomalies in the North Atlantic transmit to the southwest. Here we report a sediment record from San Luis Lake in southern Colorado, through analyses of grain size, magnetic susceptibility, Mg/Ca, total inorganic carbon, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, to indicate climatic and environmental changes in the southern Rocky Mountains over the last 16.5 ka. We found that San Luis Lake remained hydrologically closed most of the time but overflowed during the second half of the Mystery Interval (the Big Wet: 15.7–14.9 ka) and the latter part of the mid-Holocene (the Neopluvial: 4–3 ka). Over the course of the last deglaciation, San Luis Lake underwent a series of large millennial-scale hydroclimatic changes such as the Big Dry (16.5–15.7 ka), the Big Wet, the Bølling–Allerød dry (14.9–12.7 ka), and the Younger Dryas wet (12.8–11.6 ka), corresponding to warm/cold phases in the high-latitude Northern Hemisphere. The North American monsoon waxed during the Pre-Boreal interval (11.6–10.5 ka) and waned through the Holocene, in phase with northward and southward displacement of the intertropical convergence zone (ITCZ). The San Luis Lake basin was relatively dry in the early Holocene (10.5–6.7 ka), wet and fluctuating in the mid-Holocene (6.7–2.6 ka), and dry and less variable in the late Holocene (2.6–0 ka). We found evidence that extreme pluvial episodes of the southern Rocky Mountains and elsewhere in the American Southwest were coeval with cold phases of the North Pacific. Our results highlight the role of the North Pacific in modulating atmospheric circulations over the region on millennial timescales.

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1. Introduction

The southern Rocky Mountains are the headwaters for several large rivers (e.g., the Colorado River and the Rio Grande) and represent a critical water resource for many fast growing communities in the arid American Southwest (Costigan et al., 2000), a region where recent warming is among the most rapid in the United States (Karl et al., 2009). The 2002–2004 drought is a reminder that the future changes in climate may exacerbate the ecological vulnerability of this already dry region (Quiring and Goodrich, 2008). Numerical climate models have already predicted that the ongoing warming will enhance the existing pattern of effective moisture ($P-E$) and cause modern subtropical drylands to become even more arid (Held and Soden, 2006). Nevertheless, constraining the climate models with geologic records is an essential step toward improving our ability to understand climate change and plan for the future.

Over the last decades, efforts to search for the past changes in climate have recovered a number of paleoclimate records across the

southwestern United States which documented periods of wet anomalies, extreme droughts, warmer and/or cooler temperatures, based on plant macrofossils and pollen in packrat middens (e.g., Van Devender, 1977; Thompson and Anderson, 2000; Betancourt et al., 2001), aquatic fossils in lakes (Shafer, 1989; Anderson, 1993; Jimenez-Moreno et al., 2008), speleothems in caves (Polyak and Asmerom, 2005; Asmerom et al., 2007; Wagner et al., 2010), and floral distributions at high plains (Fall, 1997; Vierling, 1998; Toney and Anderson, 2006). Many of these records spanning the Late Glacial and Holocene are broadly consistent in indicating an orbital-scale transition from a cooler and wetter Late Glacial to a warmer and drier Holocene. But much uncertainty regarding the timing and nature of millennial-scale climatic changes remains. There is a long-standing debate about the relative aridity of the mid-Holocene in this region (Spaulding, 1991; Barron et al., 2012). Some studies suggested that the mid-Holocene was a time of drier conditions relative to those of today (Menking and Anderson, 2003; Toney and Anderson, 2006; Shuman et al., 2009), while others indicated that wetter conditions prevailed at least parts of this time period (Kridler, 1998; Anderson et al., 2008; Briles et al., 2012).

Sediments from closed-basin lakes represent a key archive of climatic and environmental changes because they are highly sensitive to changes

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in hydroclimate and widely distributed on land (Street and Grove, 1979). Oxygen isotope record of Owens Lake documents the existence of millennial-scale hydrologic oscillations during the last glacial termination (Benson et al., 1997). Holocene records from Walker and Pyramid Lakes indicate decadal to centennial-scale hydroclimatic variability in the Sierra Nevada (Benson et al., 2002; Yuan et al., 2004). Stable isotope records from alpine lakes over the Colorado Rocky Mountains suggest that the climate shifted from a greater summer precipitation in the early Holocene to a winter-dominated precipitation regime in the mid-Holocene (Friedman et al., 1988; Anderson, 2011; Anderson, 2012). These studies provide us important isotopic data on the past changes in climate over the American Southwest. However, lake-based $\delta^{18}\text{O}$ records spanning the entire Late Glacial and Holocene transition (LGHT) are scarce in this region.

Here we describe our efforts to reconstruct climatic and environmental changes in the southern Rocky Mountains during the Late Glacial and Holocene. We chose San Luis Lake mainly because it sits at the southern edge of the annual latitudinal range of the Pacific winter storm tracks and on the northern limit of the North American monsoon (NAM) rainfall regime (Metcalfe et al., 1997; Barron et al., 2012; Ellis and Barton, 2012). Changes in either winter or summer precipitation regime may alter the lake's hydrology, isotope geochemistry and depositional environment. Past work on this basin has showed that deposits from certain locations may be appropriate for paleoclimate reconstructions (Shafer, 1989; Rogers et al., 1992; De Lanois, 1993). We collected sediment cores from San Luis Lake and carried out a series of physical and chemical analyses, including magnetic susceptibility, grain size, total inorganic carbon (TIC), Mg/Ca, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$, to indicate climatic and environmental changes over the last 16.5 ka. Results from radiometric dating analyses (C-14, Pb-210, Cs-137 and Ra-226) are obtained for age control. Our sediment record from San Luis Lake documented a detailed history of climatic and environmental changes in the southern Rocky Mountains since the last glacial maximum. We compared our record from San Luis Lake with existing paleoclimate data from Colorado and elsewhere in the American Southwest and distant regions to gain novel insights into the changes in hydroclimate over the southern Rocky Mountains during the Late Glacial and Holocene.

2. Study area

San Luis Lake (37.675°N, 105.723°W) is located in a large intermountain basin between the San Juan Mountains and the Sangre de Cristo Mountains in southern Colorado (Fig. 1). Geologically, this basin is a structural depression that formed during the Cenozoic stretching of the Rio Grande rift (Cordell, 1978; Brister and Gries, 1994), with a drainage area of about 8300 km² and an average altitude of 2350 m (Emery, 1979). The flat floor of the basin is now occupied by a complex array of eolian, fluvial, and alluvial deposits, underlain by a suite of sediment formations with ages from Eocene to Pleistocene which overlies on the Precambrian basement (Brister and Gries, 1994). The basin had remained hydrologically closed, disintegrated with ancestral Rio Grande, and sustained a large freshwater lake called Lake Alamosa (Siebenthal, 1910) for about three million years before it drained back to the Rio Grande approximately 440 ka (Rogers et al., 1992; Machette et al., 2007). San Luis Lake is a small closed-basin lake today, with a surface area of ~3.6 km², which lies in a topographically low area near the eastern margin of the basin (Fig. 1b). Saguache and San Luis creeks are two major streams in the basin but become ephemeral before reaching San Luis Lake. As many wetlands investigated previously (Wurster et al., 2003), San Luis Lake is hydrologically affected by the water table of the basin (Mayo et al., 2007).

The climate of the region is characterized as arid, with an average annual temperature of 5.5 °C (Emery, 1979). There is an inverse relationship in precipitation seasonality between the basin floor and the surrounding mountains (Doerken and McKee, 1989). The mountain precipitation (70 cm/yr) is largely from winter storms originating in the

North Pacific Ocean whereas the basin floor precipitation (18 cm/yr) is dominated by summer rainfall from the NAM (Mitchell, 1976; Doerken and McKee, 1989). As a result, a bimodal precipitation distribution is present in this basin (Shafer, 1989). Winter precipitation over the region is known to be associated with the El Niño Southern Oscillation (ENSO). The amount of winter precipitation usually increases during El Niño events and decreases during La Niña events (Redmond and Koch, 1991; Cayan, 1996). In contrast, the amount of monsoonal rainfall is affected by the ENSO in opposing circumstances to that of winter precipitation (Higgins et al., 1998; Weiss et al., 2009). El Niño favors a weaker and more southward-displaced monsoon ridge (Castro et al., 2001) and tends to reduce the number of monsoonal storms (Webb and Betancourt, 1992).

3. Methods

3.1. Core acquisition, magnetic susceptibility, and grain-size distribution

Two sediment cores were recovered in January 2010, with a land-based vibracorer and a gasoline powered generator (Thompson et al., 1991). One was taken from the southwestern side (SL-A/B) of San Luis Lake at a water depth of ~1 m and the other from a dry wetland site (BL-01) in Blanca Wetland Area (Fig. 1b, c). Core SL-A/B had a total length of 261 cm and core BL-01 was 222 cm in length. The two cores were measured on magnetic susceptibility at 1-cm intervals with a Bartington MS2C unit, then split lengthwise, described and imaged. One half of the core was slab sampled at every 1-cm interval for sedimentologic, geochemical and isotopic analyses and the other half was sampled for radiometric dating analysis. Sediment samples were wet sieved with deionized water and divided into two portions using a 230 mesh (63 μm) sieve. The coarse portion was air dried, further sieved with a set of two sieves (250 μm and 2 mm), and weighted with an Ohaus CS200 compact digital scale. The fine portion was collected, oven dried overnight at 60 °C, weighted, and then homogenized with a mortar and pestle (Yuan et al., 2006b). Sediment powder was soaked in 2.5% NaClO for 6–8 h to remove organic matter, vacuum filtered with a Whatman glass microfiber filter (1.6 μm), rinsed with deionized water at least five times, and oven dried at 60 °C with a petri dish prior to isotopic analyses (Yuan et al., 2006b).

The percentages of four different grain-size fractions ($\phi > 2$ mm, $2\text{ mm} > \phi > 250\text{ }\mu\text{m}$, $250\text{ }\mu\text{m} > \phi > 63\text{ }\mu\text{m}$, $\phi < 63\text{ }\mu\text{m}$) were estimated by weight. Grain-size distribution for each sediment sample was evaluated with the weight percentages. A 3-point log-linear interpolation was used to estimate the effective grain size (d_{10}), the mean grain size (d_{50}), and the grain size that is 60% finer by weight (d_{60}). The uniformity coefficient of a sediment sample, as an indicator of sediment sorting, was calculated by the ratio of d_{60} to d_{10} (Fetter, 2000).

3.2. Elemental and isotopic analysis

The molar ratio of Mg/Ca was determined on acid extracts of sediment samples with 10% HNO₃, using an inductively coupled plasma optical emission spectrometer and the %TIC content was determined through coulometric analysis of CO₂ produced after acidifying sediment samples with 2 N HClO₄ (Engleman et al., 1985), using a UIC CM5014 coulometer at Case Western Reserve University. Oxygen and carbon isotopic analyses were performed simultaneously on a Micromass Optima gas source mass spectrometer with a MultiPrep automated sample preparation device at University of Albany, New York. The isotopic results, calibrated against NBS-19, are reported in the delta (δ) notation as per mil (‰) relative to the Vienna Pee Dee Belemnite (PDB) standard. The overall precision for internal and external standards was $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$.

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