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Patterns of hydroclimatic change in the Rocky Mountains and surrounding regions since the last glacial maximum

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A B S T R A C T

The paleohydrologic record of western North America since the last glacial maximum reveals a wide range of hydroclimatic variability in time and space. To improve the understanding of abrupt hydroclimatic shifts and millennial-scale hydrologic changes in the central Rocky Mountains, we reconstruct the lake-level histories of two small lakes in the Beartooth and Bighorn Mountains in northern Wyoming over the past 17 ka. To do so, we use ground-penetrating radar (GPR) and sediment cores to track the elevations of shoreline sediments within the lakes through time. We compare the stratigraphies with those from four other lakes in Wyoming and Colorado, and find widespread evidence for a Terminal Pleistocene Drought from 15 to 11 ka, an early Holocene humid period from 11 to 8 ka, and mid-Holocene aridity from 8 to 5.5 ka. The northern Wyoming lakes also provide evidence of high levels in the Pleistocene, possibly before ca. 15 ka, and rapid hydroclimatic changes that may have correlated with Heinrich Event 1 (ca. 16.8 ka). We place the changes in a broad context by summarizing and mapping water-level changes from 107 additional, previously studied lakes. Important patterns include 1) extensive drying across the western U.S. after 15 ka; 2) sub-regional differences during the Pleistocene-Holocene transition; 3) a north-south contrast from 9 to 6 ka consistent with a northward shift in storm tracks as the influence of the Laurentide Ice Sheet diminished; and 4) rapid increases in effective moisture across much of western North America from 6 to 4 ka.

1. Introduction

Many small lakes and ponds throughout the Rocky Mountains, and western North America broadly, contain stratigraphic evidence of water level changes since the Last Glacial Maximum. The evidence includes sand layers and unconformities that interrupt sequences of lake muds near the shorelines of the lakes (Weng and Jackson, 1999; Abbott et al., 2000; Anderson et al., 2005; Shuman et al., 2009a; Bird et al., 2010; Shinker et al., 2010; Shuman et al., 2015). As water levels fluctuated, shorelines and the zone where mud accumulated in deep water expanded and contracted producing alternating sequences of sand and muds near shore in each lake. By using geophysical surveys and sediment cores to study the stratigraphic sequences, the hydrologic changes can be reconstructed (Pribyl and Shuman, 2014; Shuman et al., 2015).

Here, we synthesize both new and previously published evidence of late-Pleistocene and Holocene lake-level changes from Wyoming and Colorado, and place the changes in the context of lake-level records spanning from Alaska to New Mexico. The goal is a synthesis of the direct sedimentary and geomorphic evidence of lake shoreline changes in the region. This goal differs modestly from a synthesis of all evidence for wet or dry conditions in the past because lake levels respond to different aspects of the hydroclimate than vegetation (pollen, packrat middens), stable isotopes (speleothems, lake carbonates), lake salinities (diatoms, ostracodes), and other records. Previous work has summarized patterns within these other types of records individually (Bartlein et al., 1998; Fritz et al., 2001; Anderson et al., 2016), and insightful syntheses of many data types exist for western North America (Ritchie and Harrison, 1993; Thompson et al., 1993; Harrison et al., 2003; Metcalfe et al., 2015). This paper adds new detail, and focuses specifically on updating previous lake-level syntheses (e.g., Schweger and Hickman, 1989) with new data from the central and southern Rocky Mountains.

The results show both long-term hydrologic changes throughout the Rocky Mountains and evidence of short-lived and abrupt hydrologic fluctuations. Regional influences included the

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effects of long-term orbital change, changes in the extent of the North American ice sheets, and fluctuations in ocean temperatures and attendant atmospheric circulation patterns (Bartlein et al., 1998; Harrison et al., 2003; Diffenbaugh et al., 2006; Diffenbaugh and Sloan, 2004; Barron and Anderson, 2009; Lyle et al., 2012; Oster et al., 2015). The records show evidence of millennial-scale events detected elsewhere in western and central North America during both the late Pleistocene (Broecker et al., 2009; Broecker and Putnam, 2012; Munroe and Laabs, 2013a, 2013b) and the Holocene (Williams et al., 2010; Grimm et al., 2011; Shuman et al., 2015; Steponaitis et al., 2015; MacDonald et al., 2016).

We first summarize new geophysical survey and sediment core data from two lakes in the Bighorn and Beartooth Mountains of northern Wyoming (Fig. 1A and B), and compare these results with existing data from other similar lakes from northwest Wyoming to central Colorado (Fig. 1C–F) (Shuman et al., 2010, 2014, 2015; Pribyl and Shuman, 2014). Common features of the lake stratigraphies indicate that some hydrologic changes were regional in extent, and we further evaluate the patterns by quantitatively reconstructing the water-level history of each lake (Pribyl and Shuman, 2014). We place the water-level changes in the context of changes across western North America using a synthesis of evidence from 113 total lakes. Maps show the major patterns of regional change over the past 20,000 years and expand the regional analyses beyond the southwest U.S., which has received the greatest attention to date (Street and Grove, 1979; Thompson et al., 1993; Broecker et al., 2009; Lyle et al., 2012; Munroe and Laabs, 2013b; Reheis et al., 2014).

2. Study sites

Two new studies of late-Quaternary lake-level change were conducted at Duncan and Rainbow lakes, Wyoming (Fig. 1A and B). Both lakes occupy high-elevation depressions at the head of their watersheds and have only limited, seasonal stream connections. No streams flow into the lakes, which fluctuate seasonally on the order of 25–50 cm. Instead, snowmelt and summer precipitation flow into the lakes directly over the surface and through the subsurface. Throughout the summer and fall, the lakes then drain through evaporative losses, small seasonal outlet streams, and leakage to the sub-surface, but the small watersheds have limited potential for groundwater storage (e.g., only thin till coverage). Based on their high topographic locations, regional groundwater inputs are also absent. Indeed, mean annual precipitation, groundwater, and lake waters have similar hydrogen and oxygen isotopic values consistent with the rapid flow of precipitation through the watersheds, subsurface, and lakes (Schlaepfer et al., 2014). The lakes appear, therefore, to be highly sensitive to changes in precipitation and evapotranspiration across their watersheds.

Duncan Lake (44.65°N, 107.45°W, 2845 m elevation, 4 ha area) has a maximum depth today of 5 m. Situated 15 km south of Burgess Junction, Wyoming, at the crest of the Bighorn Mountains, the lake lies on middle Archean plutonic bedrock. It formed outside Pinedale-age (LGM) moraines that descend down the drainage of the East Fork of the South Tongue River (Love and Christiansen, 1985), but is dammed by till. A small, seasonal outlet stream (dry in July 2011 when the lake was surveyed and cored) drains steeply eastward to the river. The small shallow watershed comprises only the densely forested hills immediately around the lake and the catchment-to-lake area ratio is less than 3:1. The hydrogen and oxygen isotopic composition of the lake water in July 2011 (δD: −122‰ VSMOW; $\delta^{18}O$: −14.5‰ VSMOW) shows modest evaporative enrichment compared to water sampled from the South Tongue River and two near-by USFS wells (δD: −145 to −148‰ VSMOW; $\delta^{18}O$: −19.1 to −19.5‰ VSMOW) (Schlaepfer et al., 2014).

Rainbow Lake is located on the high plateau of the Beartooth Mountains, northeast of Yellowstone National Park in northwestern Wyoming (44.94°N, 109.50°W, 2963 m elevation, 6.5 ha area, 4.2 m maximum water depth). Located near the Beartooth National Scenic Byway, approximately 35 km southwest of Red Lodge, Montana,

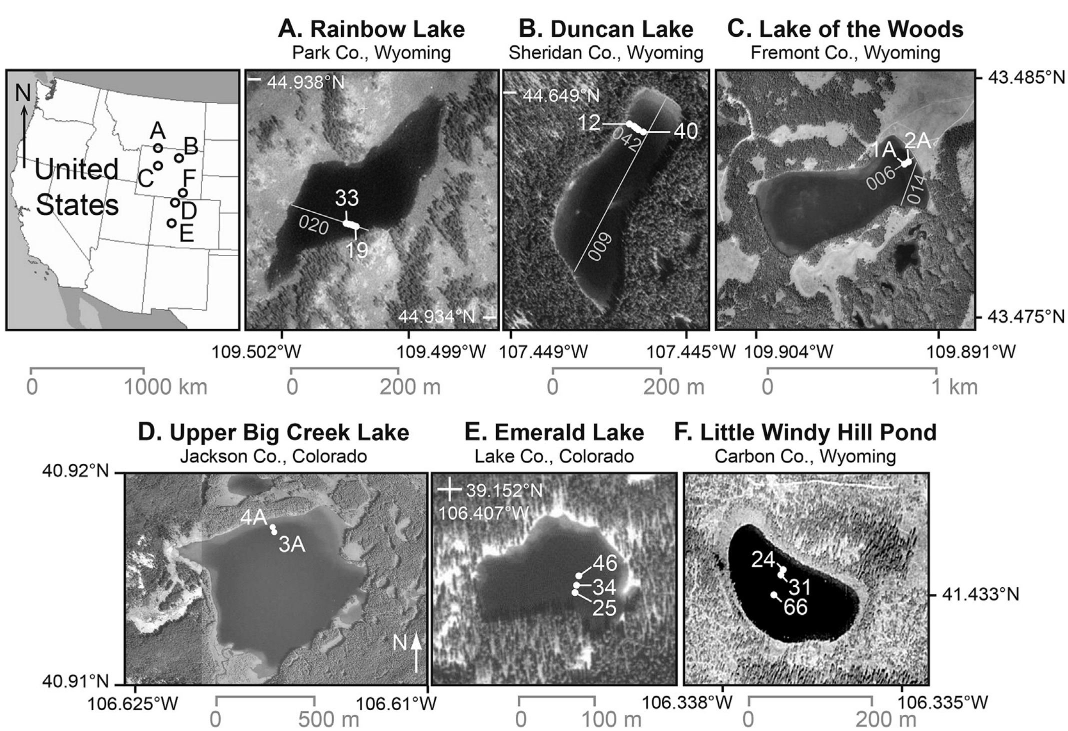

Fig. 1. Locations and aerial photos of the primary study sites (A, B) and four comparator sites (C–F). Labeled circles show the locations of sediment cores discussed, and gray lines indicate the locations of ground-penetrating radar (GPR) profiles in Fig. 2.