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A computational approach to Quaternary lake-level reconstruction applied in the central Rocky Mountains, Wyoming, USA

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ABSTRACT

Sediment-based reconstructions of late-Quaternary lake levels provide direct evidence of hydrologic responses to climate change, but many studies only provide approximate lake-elevation curves. Here, we demonstrate a new method for producing quantitative time series of lake elevation based on the facies and elevations of multiple cores collected from a lake's margin. The approach determines the facies represented in each core using diagnostic data, such as sand content, and then compares the results across cores to determine the elevation of the littoral zone over time. By applying the approach computationally, decisions are made systematically and iteratively using different facies classification schemes to evaluate the associated uncertainty. After evaluating our assumptions using ground-penetrating radar (GPR), we quantify past lake-elevation changes, precipitation minus evapotranspiration (Δ_{P-ET}), and uncertainty in both at Lake of the Woods and Little Windy Hill Pond, Wyoming. The well-correlated ($r = 0.802 \pm 0.002$) reconstructions indicate that water levels at both lakes fell at >11,300, 8000–5500, and 4700–1600 cal yr BP when Δ_{P-ET} decreased to −50 to −250 mm/yr. Differences between the reconstructions are typically small (10 ± 24 mm/yr since 7000 cal yr BP), and the similarity indicates that our reconstruction method can produce statistically comparable paleohydrologic datasets across networks of sites.

Introduction

Lake-status reconstructions obtained from geomorphic and sedimentary evidence provide important benchmarks for evaluating Quaternary hydrologic history (e.g., Street-Perrott and Harrison, 1985; COHMAP members, 1988; Thompson et al., 1993; Kohfeld and Harrison, 2000; Harrison et al., 2003; Shin et al., 2006). However, the reconstructions from small lakes are often presented as simple or discontinuous approximate curves rather than as quantified data series with uncertainty estimates. Detailed time series are needed to determine the timing, rates, and magnitudes of Quaternary hydrologic variability, and to enable statistical comparisons with other datasets and model output. Such time series have been produced using biotic (e.g., Bloom, 2006; Schmieder et al., 2011) and geochemical indicators (e.g., Benson et al., 2002; Nelson et al., 2011), but these approaches face some limitations (e.g., Telford and Birks, 2005; Steinman et al., 2010). As a complement, we present an approach for quantifying the water-level histories of small lakes based on direct, physical evidence of past shoreline positions.

The sediment stratigraphies of small lakes contain the details needed to produce quantitative time series of hydrologic changes (Harrison and Digerfeldt, 1993). Stratigraphic data from single sediment cores have often been used to represent relative changes in lake level, but they do not completely or linearly capture the full history of a lake's water-level changes (Shuman, 2003). Instead, combinations of cores can be used together to constrain past lake transgressions and regressions (Digerfeldt, 1986), and rigorous approaches to systematically interpreting data from multiple cores (e.g., Smoot and Rosenbaum, 2009) could produce comparable reconstructions across sites and investigators. Such reconstructions would also enable transient water budget calculations to expand upon the calculations routinely applied to individual time slices (e.g., Winkler et al., 1986; Vassiljev et al., 1998; Aebly and Fritz, 2009; Shuman et al., 2010).

Our approach iteratively applies a decision tree to the interpretation of multiple cores or sediment profiles. The decision tree uses sediment characteristics, such as sand content, to systematically categorize the sedimentary facies in each core or profile. The method then uses the facies information in combination with the elevation of the samples to reconstruct past changes in lake-shoreline elevation. The method relies on well-established sedimentological concepts (e.g., Walther's Law) to minimize the number of assumptions required, and incorporates sample elevations to account for factors such as the changing elevation of core sites caused by sediment accumulation (e.g., the location of a 3-m core in 1 m of water today may have been in 4 m of water initially). The iterative application of the decision tree accounts for uncertainties in the facies classifications by producing multiple plausible reconstructions.

The mean and uncertainty of the resulting ensemble of lake-level reconstructions can be used with water-budget models, such as the

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simple one applied here (Shuman et al., 2010), to calculate watershed moisture balance, which equals the deviation in the balance of precipitation minus evapotranspiration from today (Δ_{P-ET} in mm/yr) and is directly comparable across sites and with climate model output (e.g., Harrison et al., 2003). We apply the method to new and published data from Lake of the Woods in central Wyoming (Shuman et al., 2010), and demonstrate that the results are comparable across sites by also applying the method to published data from Little Windy Hill Pond in southern Wyoming (Minckley et al., 2012). The two records provide >11,000-year contexts for current water and snowpack trends in the Rocky Mountains (Mote et al., 2005; Barnett et al., 2008), but the full sequences of Δ_{P-ET} have not been quantified.

Before applying the approach, we discuss site-selection criteria and demonstrate the use of ground-penetrating radar (GPR) to test key assumptions about the interpretation of the data from a given site. We also provide example code (Appendix I) for implementing the method in R (R Core Development Team, 2009).

Background: study sites and selection criteria

We focus on Lake of the Woods, Wyoming (43.48°N, 109.89°W, 2816 m elevation, 42 ha area), which is a dilute, oligotrophic lake (conductivity of ~10 μS) located at Union Pass at the northern end of the Wind River Range (WRR) in northwest Wyoming (Fig. 1A). The closed-basin lake has a maximum water depth of 11 m and formed in Quaternary glacial till overlying claystone and siltstone of the Eocene Wind River Formation (Love and Christiansen, 1985). Shuman et al. (2010) drew an approximate lake-level curve based on sediment bulk-density and sediment accumulation rate data, but such an approach is subject to investigator biases and does not ensure consistently systematic interpretations. Here, we complement the bulk-density data plotted in Shuman et al. (2010) with new sediment loss-on-ignition (LOI) and sand content data for all cores. We use the sand content data to quantify the past lake-level changes.

The results form the basis for comparison with Little Windy Hill Pond (41.43°N, 106.33°W, 2980 m elevation, 2.2 ha area), a small oligotrophic kettle pond in the Medicine Bow Mountains (MBM), Carbon Co., Wyoming. Little Windy Hill Pond, like Lake of the Woods, formed after local Pinedale glaciations reached their maximum extent at ~23,700–19,000 cal yr BP (Gosse et al., 1995; Chadwick et al., 1997; Phillips et al., 1997; Dahms, 2002; Marcott, 2011), but before periods of cirque glaciation, including re-advances in the MBM at ca. 14,100, 11,400, and 10,600 cal yr BP and in the WRR at ca. 12,600 and 9600 cal yr BP (Fall et al., 1995; Gosse et al., 1995; Marcott, 2011). The LOI data from Little Windy Hill Pond used for our reconstruction were presented in Minckley et al. (2012). The lake and its watershed (10.7 ha) are an order of magnitude smaller than Lake of the Woods, and water depths only reach 1.3 m.

The differences between the two lakes demonstrate the applicability of our method to a diversity of sites. Despite their size differences, however, both lakes meet the criteria for optimal sites for stratigraphically-grounded lake-level studies (Digerfeldt, 1986; Dearing, 1997): a lake size of <100 ha, a well-defined drainage basin with a small catchment: lake ratio (<5:1), no major surface inflow or outflow, and a bathymetry with low slopes (<5%). For example, the sites have catchment:lake ratios of 4.3:1 (Lake of the Woods) and 4.9:1 (Little Windy Hill Pond). The catchments rise <20 m above the current lake surfaces with particularly low hill slopes (<2%) near our core locations. Sliding and slumping of sediment within a lake require bathymetric slopes greater than 4–14% (Hakanson, 1982), and the littoral slopes at the core locations are below this range (0.6–2.6%).

Beyond these published criteria (Digerfeldt, 1986; Dearing, 1997), our method and choice of sites build on two additional considerations. First, sites should have simple, well-defined littoral (inorganic, sandy) and profundal (organic-rich, silty) depositional environments or facies (see zonation evident in the aerial photo in Fig. 1B). Lakes with complex carbonate environments or with fringe wetlands may not be good candidates for this approach if the littoral facies cannot be easily distinguished by a simple metric, such as sand content, or if the types of littoral environments changed over time. Sandy shorelines at the two lakes discussed here were produced by erosion and winnowing of the surrounding tills. No external sources of sand, such as stream inputs or adjacent dunes, complicate the stratigraphic interpretations. Today, subalpine parkland surrounds Lake of the Woods (Fig. 1B), and closed subalpine forest surrounds Little Windy Hill Pond (Fig. 1C).

Second, climatic sensitivity and, therefore, Δ_{P-ET} reconstructions are optimized at headwater lakes with little hydrologic filtering of the annual precipitation inputs by streams, chains of lakes, or groundwater

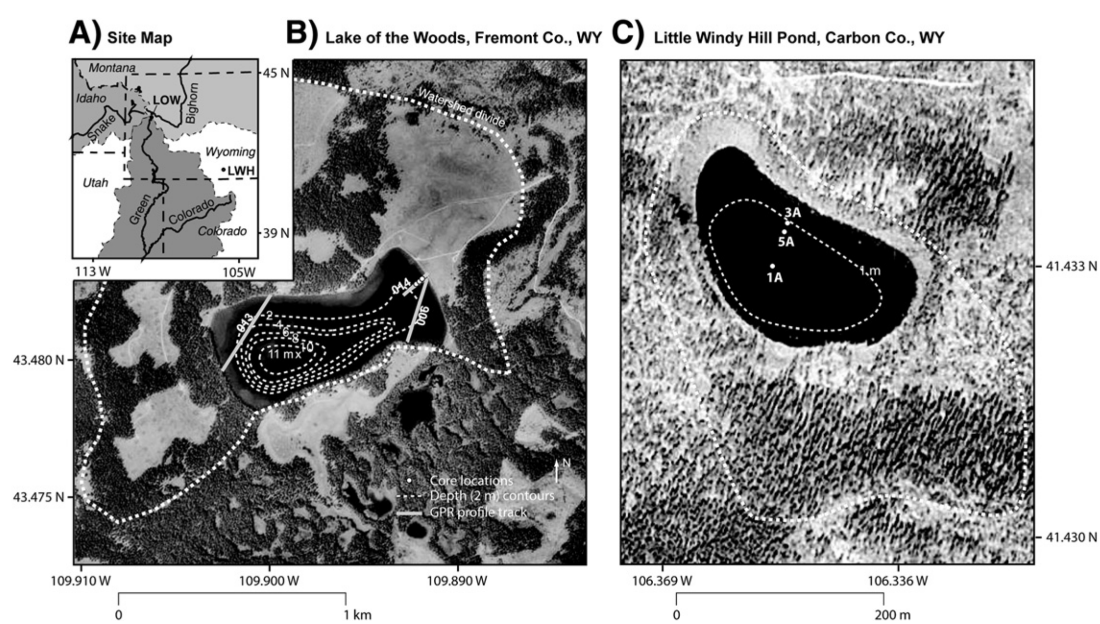

Figure 1. A) Map of the central Rocky Mountain region, USA, showing the locations of Lake of the Woods, Fremont Co., Wyoming (LOW) and Little Windy Hill Pond, Carbon Co., Wyoming (LWH) relative to the watersheds of the Colorado (darkest gray), Snake (dark gray), and Missouri rivers (light gray). Aerial photos of LOW (B) and LWH (C) show the extent of the watersheds (thick dashed line), the bathymetry (thin dashed lines), the locations of ground-penetrating radar surveys (gray numbered lines correspond with data in Figs. 3–5), and core locations (circles). "X" denotes the deepest portion of LOW.