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Reconstruction of late Quaternary paleohydrologic conditions in southeastern British Columbia using visible derivative spectroscopy of Cleland Lake sediment

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ABSTRACT

Visible derivative spectroscopy (VDS) analysis of sediment from Cleland Lake, Southeastern British Columbia provides a reconstruction of paleolimnological productivity and hydrologic change during the past 14,000 calibrated ^{14}C years before present (cal yr BP). The first five principal components (PC) of the VDS data explain 97% of the variance in the VDS data set. Four PCs correlate with standard reflectance derivative spectra for diatom, dinoflagellate algae, and cyanophyte pigments that record ecological change, while two PCs are paleohydrologic indicators. Dinoflagellate algae are predominant from 11,600 to 8600 cal yr BP then decrease to low levels after ~8500 cal yr BP. PCs 3–5 represent variations in cyanophyte abundance and exhibit peaks from 14,000 to 11,600, 14,000 to 9500, and 6100 to 5400 cal yr BP, respectively. Conditions shifted toward favoring diatoms around 9400 and lasted until 170 cal yr BP. Higher dinoflagellate-related pigment concentrations suggest a lower lake level from 11,600 to 8600 cal yr BP, followed by higher water levels and wetter conditions after 8500 cal yr BP. We propose that drier conditions transitioning from the late glacial into the Holocene were caused by summer insolation-driven, non-linear feedbacks between the northern hemisphere subtropical high-pressure systems, vegetation, and soil moisture.

Introduction

Holocene climate was once thought to have been relatively stable in comparison to the dramatic changes that occurred during the late glacial period (Mayewski et al., 2004; Overpeck and Cole, 2006). However, it is now generally accepted that substantial climate variability occurred during the Holocene over years to decades, time scales important to humans (e.g. Alley et al., 2003). Such abrupt events cannot be resolved using the relatively short instrumental climate records. Therefore it is imperative to study longer, highly resolved climate proxies such as those attainable from lake sediment.

In western North America large droughts similar to those of the 2002–2004 were a common occurrence during the 20th century (Cook et al., 2004). Studies of paleoclimate proxy data have revealed that more intense droughts of longer duration occurred in the desert Southwest during the Medieval Warm Period (~900 to 1300 AD) (Cook et al., 2004, 2010). Multi-decadal drought variability in western North America is largely attributable to Pacific ocean–atmosphere dynamics involving the El Niño southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Mann et al., 2005; McCabe et al., 2004; Nelson et al., 2011; Steinman et al., 2012), as well as the teleconnected influence of the Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO) (Cook et al., 2004; McCabe et al., 2004). Although drought variability during recent centuries is relatively well understood (Cook et al., 2004; McCabe et al., 2004; Steinman et al., 2014), the frequency, duration, and forcing mechanisms of hydroclimate variations on centennial to millennial time scales are poorly defined, particularly during the Pleistocene–Holocene transition (Galloway et al., 2011).

In semi-arid regions, small, closed-basin lakes are sensitive to changes in regional precipitation/evaporation (P/E) balance resulting from climate change. In these lakes, variability in P/E balance produces hydrologic instability, inducing changes in water level that can be recorded in the physical, biological, and chemical composition of sediment accumulating in the basin (Talbot, 1990; Battarbee, 2000; Leng and Marshall, 2004; Steinman et al., 2010a,b; Pompeani et al., 2012). Large-magnitude water-level variations resulting from non-linear responses to climate system feedbacks can give rise to changes in sediment characteristics (Fritz, 2008). Previous work has demonstrated that spectral reflectance, particularly visible derivative spectroscopy (VDS), is an efficient and non-destructive method of quantitatively analyzing

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organic matter content (including plant pigments), clays, carbonates, and iron oxides in sediment to reconstruct paleoclimate (Ortiz et al., 1999, 2009, 2012).

Fossil pigments are an important constituent of the organic matter preserved in lake sediment and can be used as a proxy for primary productivity and changes in phytoplankton community structure within lakes (Bouchard et al., 2013; Das et al., 2005; Peteet et al., 2003; Wolfe et al., 2006). Concentrations of sedimentary photosynthetic pigments have long been used as a direct and accurate method for reconstructing the response of lake phytoplankton to environmental changes (Nara et al., 2005; Sanger, 1988; Sanger and Crowl, 1979; Sanger and Gorham, 1972). Ecological succession, which occurs on a variety of time scales, is a well known principle by which community structure changes in an essentially orderly fashion in response to stochastic factors and external or internal stimuli (Connell and Slatyer, 1977; Peet and Christensen, 1980; Pickett et al., 1987). In addition to the earliest definition of succession, as the sequential changes in species, latter studies have described succession in terms of changes in characteristics such as biomass, productivity, diversity, and niche breadth (Connell and Slatyer, 1977; Wilson, 1994; Müller-Navarra et al., 1997). Phytoplankton composition in temperate lakes tends to follow a succession pattern similar to that of plants on the landscape and is strongly influenced by water chemistry and lake level (Müller-Navarra et al., 1997). Biological communities in drought-sensitive lakes are therefore a reflection of water-balance changes, such that algal pigment analysis of sediment from these lakes can be used to investigate past hydroclimate variability and community succession. To this end we present the progression of phytoplankton communities at Cleland Lake, an alkaline, surficial, closed-basin lake in southeastern British Columbia, using VDS analysis of lake sediment cores. A major objective of this paper is to validate the use of VDS methods in paleolimnological and paleoclimatic reconstructions. A secondary objective is to understand the timing and magnitude of regional environmental change, particularly during the late Pleistocene and early Holocene by reconstructing paleo-lake productivity and hydrologic balance variations.

Study area

Cleland Lake (50.82° N, 116.38° W, 1158 m) is located in the north–south trending Columbia Valley just west of the continental divide in the Rocky Mountains of southeastern British Columbia (Fig. 1). The lake has a surface area of 23.5 ha (0.235 km^2), a maximum depth of 31.7 m and is typically covered with ice from November to May. The surface inflow is limited to the relatively small, immediate catchment, while water losses are restricted to evaporation and (presumably) some groundwater seepage.

Present climate of Southeastern British Columbia

The climate of British Columbia is strongly influenced by sea surface temperature (SST) and atmospheric circulation over the Pacific Ocean (Moore et al., 2010). The north–south trending mountain ranges in the region restrict the east–west flow of the seasonably variable winds (Moore et al., 2010). The dominant modes of inter-annual to inter-decadal atmosphere–ocean variability affecting British Columbia include: ENSO, PDO, the Pacific North American Pattern (PNA), and Arctic Oscillation (AO) (Moore et al., 2010). El-Niño winters in British Columbia are warmer and drier than normal, while La-Niña winters are cooler and wetter (Moore et al., 2010). The positive phase of the PNA is characterized by a strong Aleutian Low and a high pressure ridge over the Rocky Mountains, resulting in warm, dry winters in British Columbia and vice versa (Moore et al., 2010).

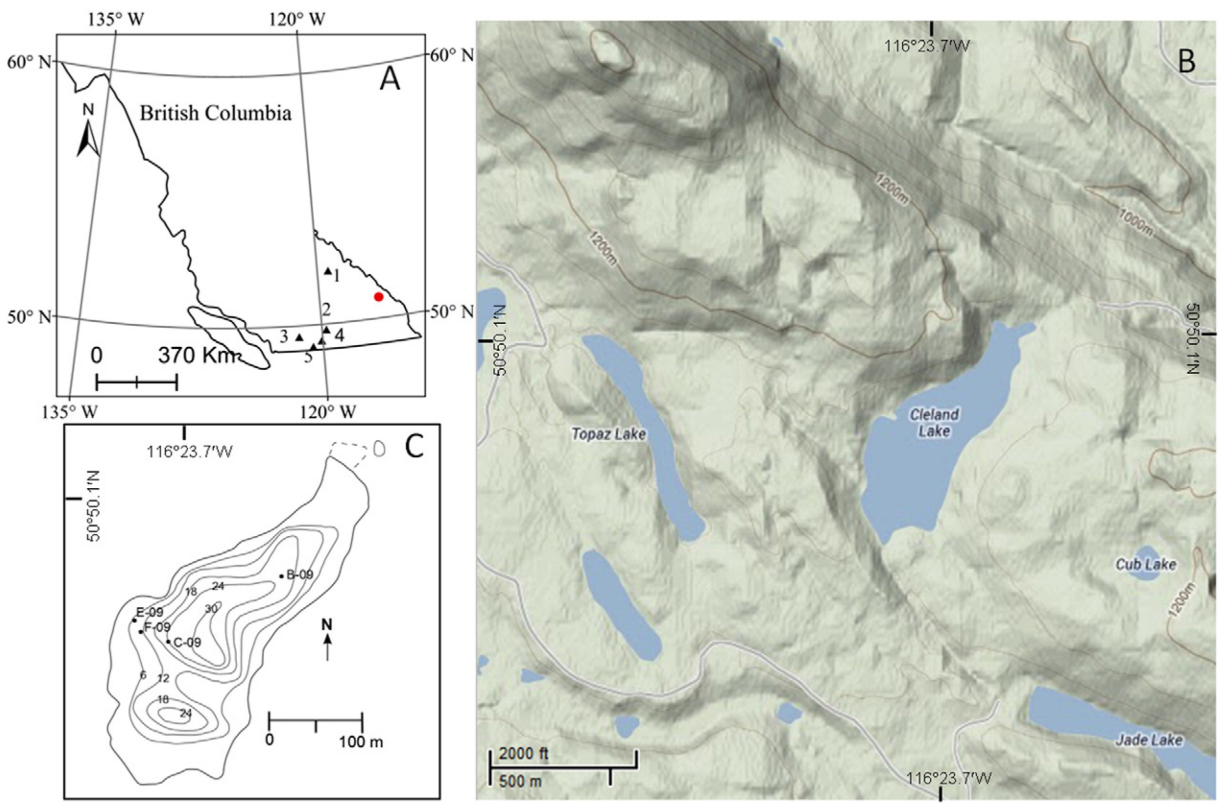

Figure 1. Cleland lake location map. A. Map of British Columbia showing the location of Cleland Lake (red dot) and selected sites referenced in the text (black triangles), 1: Eleanor Lake, 2: Windy Lake, 3: Frozen Lake, 4: North Crater Lake, 5: Lake of the Woods. B. Topographical map of watersheds in the Cleland Lake locale. C. Bathymetry map of Cleland Lake, showing the locations of core sites.