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Using paleolimnology to track Holocene climate fluctuations and aquatic ontogeny in poorly buffered High Arctic lakes

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ABSTRACT

Fossil diatom assemblages, and spectrally-inferred dissolved organic carbon (DOC) and sedimentary chlorophyll-*a* (SedChl*a*) were analysed on lake sediment cores from two poorly buffered lakes on Pim Island (High Arctic Canada) to assess their responses to Holocene climate changes and to document lake ontogeny. Following deglaciation, diatom assemblages were dominated by small benthic *Fragilaria sensu lato* taxa. During the mid-Holocene, there was an abrupt shift to more circumneutral and slightly acidophilous taxa dominated by *Achnanthes* and *Navicula* taxa. In the most recent sediments, we recorded an increase in the planktonic taxon *Cyclotella radiosa*. This shift of the last century is the most ecologically unique in the Holocene record and is indicative of longer ice-free summers consistent with modern climate warming. Inferred DOC and SedChl*a* track some of the main Holocene climatic trends documented in the region, including the Holocene Thermal Maximum and Neoglacial period; however, changes in lakewater DOC did not likely drive any of the recorded shifts in diatom assemblages. Compared to nearby well-buffered sites, our poorly buffered lakes recorded a more dynamic diatom response to Holocene environmental change. The decreasing trend in diatom-inferred pH is likely due to changes in the acid neutralizing capacity (ANC) driven by the release of alkalinizing base cations from the easily weathered glacial deposits in the early Holocene and later by climate-driven pH dynamics and within-lake dissolved inorganic carbon (DIC) dynamics. The diatom community composition in our study lakes is different and undergoes greater changes than in nearby well-buffered lakes suggesting that softwater lakes in the high Arctic may respond most sensitively to climate and other environmental stressors.

1. Introduction

Paleolimnological studies have demonstrated that recent temperature increases over the past ~150 years have given rise to unprecedented changes in the structure and functioning of aquatic biological communities in Arctic landscapes (Smol et al., 2005; Rühland et al., 2008). Although the limnological responses to climate changes of the last few centuries are well-documented (Smol and Douglas, 2007a), Holocene-scale studies in the Mid and High Canadian Arctic are few. Some well-documented fluctuations in climate over this period are known to have existed and include the Holocene thermal maximum (HTM) around 9500–4500 cal yr BP, interrupted by cold reversals at e.g. 8200 cal yr BP, the Neoglacial cooling after c. 4500 cal yr BP and the recent anthropogenic warming (beginning ~150 years ago) (Kaufman et al., 2004; Smol et al., 2005; Wanner et al., 2008; Axford et al., 2009).

Regional variations in Holocene diatom (and other proxy) records from northeast Greenland have demonstrated the importance of catchment processes on the structure and functioning of lakes (Cremer et al., 2001; Wanner et al., 2008). Marked changes in aquatic biota recorded in response to recent warming also raise questions on the mechanisms driving these shifts (ACIA, 2005; Schindler and Smol, 2006; Smol and Douglas, 2007a,b). Factors influencing diatom assemblages in Arctic freshwaters include lakewater pH, conductivity, nutrients, dissolved organic carbon (DOC), water temperature and habitat availability, all of which can be linked to climate (Saulnier-Talbot et al., 2003; Smol et al., 2005; Rühland et al., 2008). In poorly buffered Arctic and alpine lakes, lakewater pH is commonly identified as a main driver of diatom assemblages, and appears to show a direct link to climate-driven ice-cover dynamics (Koinig et al., 1998; Wolfe, 2002; Michelutti et al., 2007). In brief, warm intervals result in higher than usual pH values due to enhanced loss of CO_2 to the atmosphere and greater utilization of limnetic CO_2 by algal photosynthesis, compared to cooler periods.

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In lakes with calcareous bedrock, leaching of carbonates would normally buffer the lake to such changes in dissolved inorganic carbon (DIC) speciation dynamics.

The nature and magnitude of diatom changes occurring in well--buffered lakes and ponds, such as those at Cape Herschel, east-central Ellesmere Island (Douglas et al., 1994, 2000), are generally well-understood (Douglas and Smol, 1994, 2010; Smol and Douglas, 2007a). However, less is known about the ecological responses of lakes with low alkalinity. Previous paleolimnological studies indicate a more diverse diatom flora with a greater number of assemblage shifts compared to well-buffered systems. The implication is that low alkalinity lakes may be especially sensitive to climate fluctuations and, therefore, ideal study sites for paleolimnological climate reconstructions (Michelutti et al., 2006; Devlin and Finkelstein, 2011).

Here, we present fossil diatom stratigraphies of Holocene age in two poorly buffered lakes from Pim Island, eastern-central Ellesmere Island (Fig. 1). We used newly developed techniques in spectral reflectance to infer sedimentary chlorophyll-*a* (SedChl*a*) and lakewater DOC concentrations to adopt a multi-proxy approach in assessing long-term change (Michelutti et al., 2010; Rouillard et al., 2011). Since the sediment cores date back to the lakes' inceptions, we have the opportunity to investigate the diatom responses to climate fluctuations first, during the initial well-buffered stage when fresh glacial tills dominated the catchment and second, the later poorly buffered stage after the alkalinizing base cations in the catchment were depleted due to weathering processes. The ultimate aim of our study is to assess the influence of climate on algal diatom assemblages, and primary production-related variables such as chlorophyll-*a* and lakewater DOC over Holocene timescales. These data and trends in lake ontogeny will be compared with sediment core data from nearby well-buffered high Arctic lakes.

2. Sites description

The two study lakes, unofficially named "West Lake" (78°44.283′N; 74°37.983′W) and "260 m Lake" (78°42.483′N; 74°30.783′W), are located within 4 km of one another on Pim Island, a small island (~86 km^2) with a maximum elevation of 550 m asl, located near the east-central coast of Ellesmere Island, Nunavut (Fig. 1). Field observations from the catchment basins of West Lake and 260 m Lake document less than 5% vegetation cover, consisting mainly of cushion forbs. Shallower ponds from this region typically have an ice-free season of ~ two months (Douglas and Smol, 1994), however observations from previous field seasons show that larger lakes can maintain persistent ice cover through the summer months.

Pim Island bedrock geology is composed of Precambrian granites, migmatites, and associated rocks of the Canadian Shield. Calcareous till, derived from Paleozoic bedrock to the northwest, north and northeast, was however very reduced in the drainage areas of the two topographically closed basins, resulting in limited buffering capacity to local lakes (Blake, 1992). This is in marked contrast to nearby Cape Herschel, whose surface waters are predominantly influenced by calcareous tills and therefore, are extremely well-buffered (Douglas and Smol, 1994). Paleolimnological records on Pim Island are constrained by the Wisconsinian glacial history ending with the retreat of the Innuitian Ice Sheet 10400 ± 1500 years ago (Blake, 1992; Zreda et al., 1999). A small carapace ice cap still remains near the centre of the Island (Fig. 1).

Cape Herschel and Pim Island are influenced by the same sub-regional climatic system (Fig. 1), although the higher elevation of Pim Island makes its local climate colder (Maxwell, 1981). Pim Island is in the transition zone between the Eastern (Northern Baffin Bay - Lancaster Sound sub-region) and the Northern (Nares Strait sub-region) climatic regions of the Canadian Arctic Islands (Fig. 1) (Maxwell, 1981). Largely influenced by sea ice extent in Smith Sound and remaining cyclonic activities coming from Davis Strait in the south (originating from the warm West Greenland Current), this coastal area is characterized by a mean annual precipitation of around 200 mm and a mean July temperature of ~3 °C (Maxwell, 1981). Pim Island is in an area where polar desert dominates the landscape, characterized by the quasi-absence of soil horizon development, absence of organic matter, with minimal but persistent vascular plant cover (<5%) and low standing crop (mostly herbaceous and non-vascular) (Bridgland and Gillett, 1983; Lévesque, 1997).

Several shallow, yet relatively large, lakes and ponds are situated on Pim Island at different elevations. Both study lakes are located in sheltered depressions, although West Lake is somewhat more exposed to strong winds due to its higher location on the large western plateau of the island (Fig. 1). Black water marks on boulders and cliffs

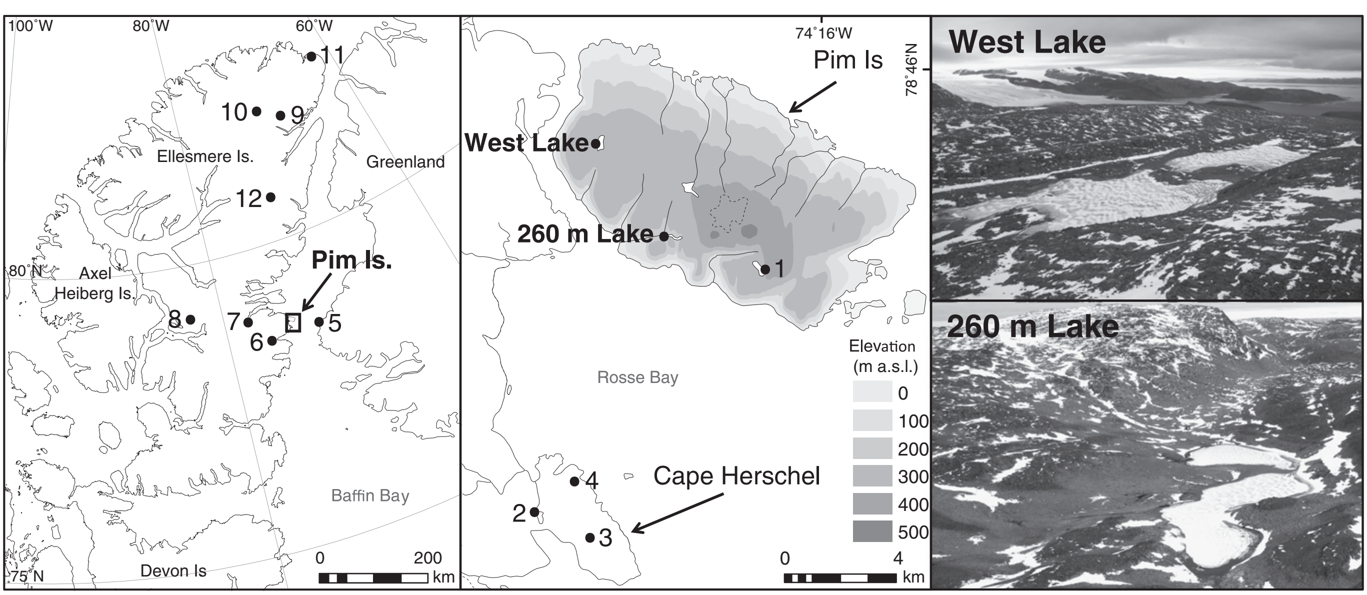

Fig. 1. Map of Pim Island and the study sites West Lake and 260 m Lake (black dots) with elevation and areas with permanent snow and ice-cover (dashed line), located on the east-central coast of Ellesmere Island (Nunavut, Canada). Other numbered sites referred in the text are: (1) Proteus Lake (Howard, 1989); (2) Elison Lake, (3) Col Pond, (4) Camp Pond (Douglas et al., 1994); (5) Kap Inglefield Sø (Blake et al., 1992); (6) Rock Basin Lake (Michelutti et al., 2006); (7) Stygge Nunatak Pond (Paul et al., 2010a); (8) Sawtook Lake (Perren et al., 2003) and Solstice Lake (Wolfe, 2000) on Fosheim Peninsula; (9) Skeleton Lake, ponds EP2 and EP3 at Lake Hazen (Keatley et al., 2008); (10) Appleby and Brainard lakes on Hazen Plateau (Smith, 2002); (11) Self Pond, Alert (Antoniades et al., 2005); (12) Agassiz Ice Cap (Kaufman et al., 2004). Original geographic data scale 1: 50 000 (source: National Topographic Data Base). Generated with Arc-GIS Desktop ver. 9.3. West Lake and 260 m Lake photographs were taken in July 2009 by A. Rouillard.