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Facies analysis of yedoma thermokarst lakes on the northern Seward Peninsula, Alaska

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ABSTRACT

Thermokarst lakes develop as a result of the thaw and collapse of ice-rich, permanently frozen ground (permafrost). Of particular sedimentological importance are thermokarst lakes forming in late Pleistocene icy silt (yedoma), which dramatically alter the land surface by lowering surface elevation and redistributing upland sediment into lower basins. Our study provides the first description of yedoma thermokarst lake sedimentology based on the cross-basin sampling of an existing lake. We present lake sediment facies descriptions based on data from sediment cores from two thermokarst lakes of medium depth, Claudi and Jaeger (informal names), which formed in previously non thermokarst-affected upland yedoma on the northern Seward Peninsula, Alaska. We identify four prominent facies using sedimentological, biogeochemical, and macrofossil indicators: a massive silt lacking aquatic macrofossils and other aquatic indicators situated below a sub-lacustrine unconformity (Facies 1); two basal deposits: interbedded organic silt and chaotic silt (Facies 2–3); and a silt-rich mud (Facies 4). Facies 1 is interpreted as yedoma that has thawed during lake formation. Facies 3 formed adjacent to the margin due to thaw and collapse events from the lake shore. Material from Facies 3 was reworked by wave action to form Facies 2 in a medium energy margin environment. Facies 4 formed in a lower energy environment toward the lake basin center. This facies classification and description should enhance our ability (i) to interpret the spatial and temporal development of lakes and (ii) to reconstruct long-term patterns of landscape change.

1. Introduction

Thermokarst landforms are prevalent across Arctic and sub-Arctic lowlands (Jorgenson et al., 2008a, 2008b) and include features such as thermokarst lakes and drained lake basins (Grosse et al., 2013, and references therein), thermo-erosion gullies (Godin and Fortier, 2012), retrogressive thaw slumps (Burn and Lewkowicz, 1990), and thermokarst pits (Osterkamp et al., 2000; Jorgenson et al., 2006). Thermokarst lakes and drained lake basins are the most ubiquitous of these landforms (Côté and Burn, 2002; Hinkel et al., 2005; Jones et al., 2011; Morgenstern et al., 2011), contributing to landscape evolution by redistributing large volumes of sediment (Murton, 1996) and initiating changes in surface elevation, topography, vegetation composition (Katamura et al., 2006), wildlife habitat (Jorgenson and Osterkamp, 2005), and hydrology (Yoshikawa, 2003). In areas of yedoma (silty, organic rich, perennially frozen sediment containing massive syngenetic Pleistocene ice wedges; Schirrmeister et al., 2013), thermokarst lakes and drained lake basins are abundant, affecting up to 73% of the land surface (Jones et al., 2011; Grosse et al., 2013) (Fig. 1). Herein we refer to yedoma soils as "organic rich" in the context of mineral soils (as opposed to peat).

Thermokarst lakes forming in yedoma uniquely develop from the gradual thaw of large syngenetic Pleistocene ice-wedge networks. Thermokarst lakes usually initiate due to a disturbance to the ground thermal regime (e.g., wildfire or climate warming; Burn and Smith, 1990; Murton, 2009), which results in the thaw of excess ground ice, collapse of the ground surface, and subsequent collection of water in a closed depression (Van Everdingen, 1988; French, 1996). Thermokarst lakes go through distinct stages of development that likely cause shifts in sediment composition as well as both vertical and lateral sediment distribution (Czudek and Demek, 1970; Murton, 1996; West and Plug, 2008). After initial ponding, water body diameter and depth continue to increase via lateral thermo-erosion and vertical thaw settlement, respectively, forming a lake (Burn, 1992). In our study area on the northern Seward Peninsula, Alaska, the upland margins that characterize first-generation lakes (those forming in upland yedoma as opposed to drained lake basin lowlands) today expand at mean rates of 0.18 m/yr, while regional rates including all margin types are 0.39 m/yr (Jones et al., 2011). Settlement depths (the height difference between

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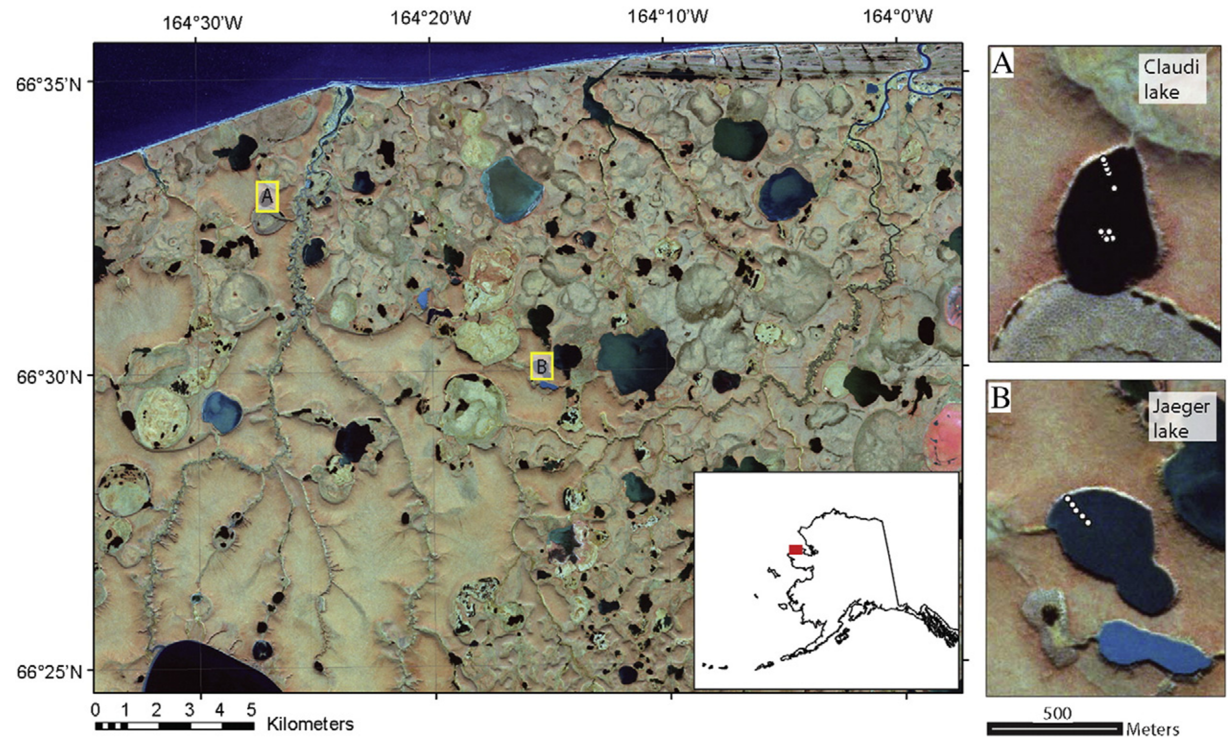

Fig. 1. Study area on the northern Seward Peninsula, Alaska. Claudi and Jaeger lakes are labeled A and B, respectively. White dots on lakes Claudi and Jaeger indicate sediment coring locations. Image: © SPOT 2008-09-29.

surrounding bluff tops and the bottom of the lake water column) of up to 40 m have been reported for yedoma deposits in central Yakutia (Czudek and Demek, 1970). Remnant mounds of sediment, termed baydjerakhs, remain once massive syngenetic ice wedges have thawed (Kanevskiy et al., 2011). These mounds are an important characteristic of yedoma thermokarst lake bathymetry, especially along lake margins. As lake development continues and the water depth becomes greater than maximum winter lake ice thickness, ice-rich yedoma deposits beneath the lake thaw year round (Ling et al., 2012). This area of continuously thawed sediment beneath a water body is termed a "thaw bulb" or "talik" (West and Plug, 2008), and the sediments within it are termed "taberal" (Hubberten and Romanovskii, 2003). Taberal sediments are therefore originally deposited subaerially but thawed and modified in situ underneath the lake.

Numerous papers have investigated morphological aspects of thermokarst lake behavior, such as lake orientation (Livingstone, 1954; Côté and Burn, 2002), lake cycling (Billings and Peterson, 1980; Jorgenson and Shur, 2007), lake drainage (Mackay, 1988; Hinkel et al., 2003; Marsh et al., 2009), lake influence on Arctic landscape evolution (Czudek and Demek, 1970; Soloviev, 1973), and development of thermokarst sedimentology and morphology (Burn and Smith, 1990; Murton, 1996; Morgenstern et al., 2013). Yet currently there is a knowledge gap regarding the sedimentology and geomorphological development of modern day yedoma thermokarst lakes.

Our goal was to better understand yedoma thermokarst lake development by studying sediment cores from two first-generation lakes that formed in upland yedoma on the northern Seward Peninsula, Alaska. Specific objectives were to establish (1) the key facies present, (2) the depositional environment represented by each facies, and (3) the stages of lake development based on vertical and horizontal facies distribution. Sediment composition, the range of depositional facies present, and facies distribution are used to infer relative stages of lake development. We chose to study first-generation thermokarst lakes as they would have been most prevalent across yedoma lowlands during the early Holocene, a time during which such lakes likely contributed significantly to high-latitude atmospheric methane flux (Walter et al., 2007a; Brosius et al., 2012; Walter Anthony et al., 2014). Results from this study should improve our ability to date thermokarst lake development more accurately and aid the reconstruction of landscape evolution during the late Pleistocene and Holocene. Furthermore, they may allow for a better understanding of their past and present role in carbon cycling in the Arctic and aid modeling of thermokarst landscape evolution.

2. Study area

We studied the composition and distribution of sediment in Claudi Lake in detail and supplemented this data set with additional cores from Jaeger Lake (Figs. 1, 2, Table 1). Claudi Lake is a first-generation lake that formed in upland yedoma. Claudi Lake is oval in shape and has a lake surface area of 16.27 ha and a maximum depth of 9.2 m. A paleo-drainage channel has eroded the North Bank of the lake and appears close to reactivation. The southern margin of Claudi Lake is eroding into a first-generation drained lake basin, that of former Pear Lake (Plug and West, 2009).

Jaeger Lake is a first-generation lake that also formed in yedoma upland. An active outlet is located on the western margin. Jaeger Lake is hourglass in shape and has a lake surface area of 24.06 ha and a maximum depth of 12.73 m. The bathymetry of lakes Claudi and Jaeger is characterized by the presence of baydjerakhs. The variable microtopography they create affects local sediment distribution in the lake bed (Hopkins and Kidd, 1988). The macrophyte zones of both Claudi and Jaeger are sparsely vegetated by *Hippuris* spp., *Carex aquatillis*, and *Calamagrostis canadensis*.

The study area is located in the coastal lowlands of the northern Seward Peninsula, Alaska, on the eastern side of the Bering Strait (Fig. 1). This region has abundant thermokarst lakes and several large maar lakes (Arp and Jones, 2009). Surficial geology is dominated by late Pleistocene ice-rich syngenetic yedoma deposits and Holocene lacustrine and bog deposits (Hopkins and Kidd, 1988; Charron, 1995; Jones et al., 2012; Wetterich et al., 2012). Widespread thermokarst development in the Arctic is thought to have last occurred during the Holocene thermal maximum (Walter et al., 2007a; Mann et al., 2010), suggesting that this was the time period when many lakes in our