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The evolution of a thermokarst-lake landscape: Late Quaternary permafrost degradation and stabilization in interior Alaska

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ABSTRACT

Thermokarst processes characterize a variety of ice-rich permafrost terrains and often lead to lake formation. The long-term evolution of thermokarst landscapes and the stability and longevity of lakes depend upon climate, vegetation and ground conditions, including the volume of excess ground ice and its distribution. The current lake status of thermokarst-lake landscapes and their future trajectories under climate warming are better understood in the light of their long-term development. We studied the lake-rich southern marginal upland of the Yukon Flats (northern interior Alaska) using dated lake-sediment cores, observations of river-cut exposures, and remotely-sensed data. The region features thick (up to 40 m) Quaternary deposits (mainly loess) that contain massive ground ice. Two of three studied lakes formed ~11,000–12,000 cal yr BP through inferred thermokarst processes, and fire may have played a role in initiating thermokarst development. From ~9000 cal yr BP, all lakes exhibited steady sedimentation, and pollen stratigraphies are consistent with regional patterns. The current lake expansion rates are low (0 to <7 cm yr^{-1} shoreline retreat) compared with other regions (~30 cm yr^{-1} or more). This thermokarst lake-rich region does not show evidence of extensive landscape lowering by lake drainage, nor of multiple lake generations within a basin. However, LiDAR images reveal linear "corrugations" (>5 m amplitude), deep thermo-erosional gullies, and features resembling lake drainage channels, suggesting that highly dynamic surface processes have previously shaped the landscape. Evidently, widespread early Holocene permafrost degradation and thermokarst lake initiation were followed by lake longevity and landscape stabilization, the latter possibly related to establishment of dense forest cover. Partial or complete drainage of three lakes in 2013 reveals that there is some contemporary landscape dynamism. Holocene landscape evolution in the study area differs from that described from other thermokarst-affected regions; regional responses to future environmental change may be equally individualistic.

1. Introduction

Thermokarst, the thaw of excess ice in permafrost-affected sediments that leads to ground collapse (French, 2007), is widespread in arctic and sub-arctic landscapes. Thermokarst (thaw) lakes form when water fills a basin caused by ground collapse. Thus, where unconsolidated surface material is underlain by permafrost and lakes are present, it is likely that thermokarst processes have played a role in lake formation and expansion. Recent field observations and detailed remotely sensed image time-series record current dynamism in many thermokarst lake regions (e.g., Smith et al., 2005; Jones et al., 2011; Lantz and Turner, 2015). Changes in the rate of current processes and/or the developmental direction of thermokarst lake landscapes (e.g., towards more or fewer lakes), should be expected as key drivers change. For example, climate warming is anticipated to enhance thermokarst activity in areas underlain by ice-rich permafrost. On the other hand, given permafrost degradation and/or precipitation-driven lake-level rise, lakes may drain via groundwater or surface overflow (Mackay, 1988; Yoshikawa and Hinzman, 2003; Marsh et al., 2009; Grosse et al., 2013; Jones and Arp, 2015).

Key biogeochemical processes are associated with thermokarst lakes, such as release of CO_2 and/or CH_4 from microbial processing of organic materials within lakes and underlying sediments (Bastviken, 2004; Walter et al., 2006; Zulueta et al., 2011) or sequestration of carbon as peat in drained basins (Hinkel et al., 2003; Bockheim et al., 2004; Jones et al., 2012; Walter Anthony et al., 2014). Thermokarst lakes are possibly a substantial atmospheric methane source (Walter et al.,

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2006, 2007a, 2007b). Consequently, they are a focus of interest in the Earth system science community. To understand past or future long-term contributions of thermokarst lakes to the northern carbon budget, we need to know how changes in key drivers might modify thermokarst processes. Local topography and hydrology interact to generate both increases and decreases in lake number and extent (Smith et al., 2005; Morgenstern et al., 2011; van Huissteden et al., 2011). Afforestation, peat development and vegetation mats encroaching on lakes reduce the tendency for thermokarst by increasing ground insulation (Jorgenson et al., 2010; Roach et al., 2011). Through modeling, Kessler et al. (2012) show that topography, lake developmental history and climate all play a role in determining the long-term evolution of lakes and thermokarst landscapes. Thus, any assumption of a steady state of lake formation and drainage, or of uniformity in thermokarst processes among regions, is unlikely to be realistic.

Furthermore, it may be that observed contemporary regimes of climate, permafrost, and vegetation are insufficient analogs for future responses to climate warming. A long-term perspective, however, can make use of past "natural experiments" to examine the impact of major past environmental change on thermokarst lake-rich landscapes. In this study we use field observations of Quaternary deposits, dated lake-sediment stratigraphies, and high-resolution remote sensing images and digital elevation data to investigate changes in late Quaternary thermokarst and landscape dynamics of a lake-rich upland bordering the Yukon Flats of interior Alaska (Fig. 1).

2. Thermokarst (thaw) lakes

Most northern lakes, including thermokarst lakes, are small, being <10 km in diameter (Arp and Jones, 2008; Paltan et al., 2015). Classic thermokarst lake forms include shallow (~2 m deep), often oriented lakes on the Arctic Coastal Plain of northern Alaska (Sellmann et al., 1975; Jorgenson and Shur, 2007; Arp et al., 2011). The spatial extent and drainage patterns of these lakes have been described by Hinkel et al. (2003, 2005, 2007). Deeper (~5–>20 m) so-called *yedoma* thermokarst lakes are described by Zimov et al. (1997); West and Plug (2008); Walter et al. (2006); Morgenstern et al. (2011); Hinkel et al. (2012), and Fedorov et al. (2014). These occur in deep (usually >10 m thick) Pleistocene deposits of ice-rich silt (*yedoma*; Schirrmeister et al., 2013), and are found, for example, in northeast Siberia and the northern Seward Peninsula of Alaska. Burn and Smith (1990); Burn (2002) and Lauriol et al. (2009) describe thermokarst lakes in northwest Canada. In many regions, numerous drained lake basins, often with several generations superimposed, indicate episodic or continual lake formation and drainage over centuries to millennia (Hinkel et al., 2003; Jones et al., 2012; Jones and Arp, 2015).

Stratigraphic studies that observe lake development over long time periods provide a valuable perspective on thermokarst processes. For example, on a regional scale, observations of numerous lake profiles in natural exposures in Siberia and northwest North America indicate that thermokarst activity and lake initiation were focused on the early

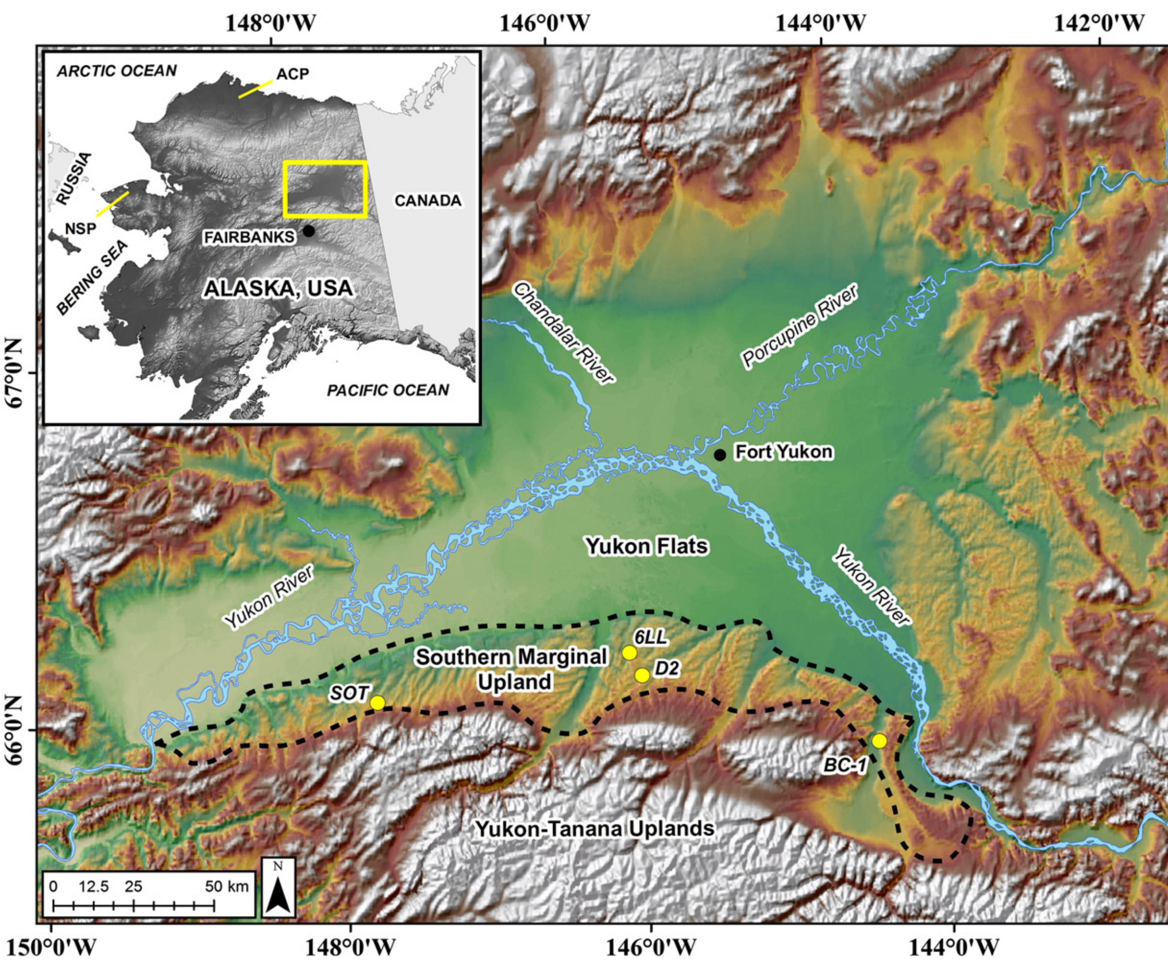

Fig. 1. Map of the study area. The southern marginal upland is enclosed by the dashed black line. SOT: Sands of Time Lake; 6LL: Six-Loon Lake; D2: Dune Two Lake; BC-1: Birch Creek section (McDowell and Edwards, 2001). Major rivers originating in the Yukon–Tanana uplands, which expose the sediments of the marginal upland in river-cut bluffs, can be seen as low-elevation corridors cutting through the marginal upland. Beaver Creek (see Fig. 4) lies just west of 6LL. On location map of Alaska, NSP indicates the northern Seward Peninsula and ACP the Arctic coastal plain.