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Spatiotemporal patterns of northern lake formation since the Last Glacial Maximum

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A B S T R A C T

The northern mid- to high-latitudes have the highest total number and area of lakes on Earth. Lake origins in these regions are diverse, but to a large extent coupled to glacial, permafrost, and peatland histories. The synthesis of 1207 northern lake initiation records presented here provides an analog for rapid landscape-level change in response to climate warming, and its subsequent attenuation by physical and biological feedback mechanisms. Our compilation reveals two peaks in northern lake formation, 13,200 and 10,400 years ago, both following rapid increases in North Atlantic air temperature. Placing our findings within the context of existing paleoenvironmental records, we suggest that solar insolation-driven changes in climate (temperature and water balance) that led to deglaciation and permafrost thaw likely contributed to high rates of northern lake formation during the last Deglacial period. However, further landscape development and stabilization dramatically reduced rates of lake formation beginning ~10,000 years ago. This suggests that temperature alone may not control future lake development; rather, multiple factors must align to enable a landscape to respond with an increase in lake area. We propose that land surfaces strongly geared toward increased lake formation were highly conditioned by glaciation. Thus, it is unlikely that warming this century will cause lake formation as rapid or as widespread as that during the last Deglacial period.

Author contributions

Laura Brosius: Writing – original draft, Conceptualization, Formal analysis, Investigation, Data curation, Visualization; Katey Walter Anthony: Conceptualization, Investigation, Supervision, Resources, Writing – review & editing, Funding acquisition; Claire Treat: Investigation, Data curation, Project administration, Writing – review & editing; Josefine Lenz: Investigation, Data curation, Writing – review & editing; Miriam Jones: Investigation, Data curation, Writing – review & editing; Marion Syndonia Bret-Harte: Writing – review & editing; Guido Grosse: Formal analysis, Resources, Funding acquisition, Supervision, Writing – review & editing

1. Introduction

Models assume projected temperature increases will lead to an increase in lake area in the 21st century (e.g., van Huissteden et al., 2011; Schneider von Deimling et al., 2015; Tan and Zhuang 2015); however, these models have rarely drawn upon paleoclimate and paleoenvironmental records to frame future projections. Here we analyze 1207 lake basal age records to explore whether warming has always led to increases in lake abundance, or whether other paleoenvironmental factors could have steered lake distribution in a different direction. A better understanding of when, where, and how northern lakes formed since the Last Glacial Maximum (LGM),

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could help predict trajectories of lake formation or disappearance with climate change. Future changes in northern lake areas have the potential to strongly impact global carbon dynamics (Cole et al., 2007; Tranvik et al., 2009; Bastviken et al., 2011), regional energy balances (Woolway et al., 2018), biogeochemical cycling (Downing and McCauley 1992), and the role of lakes as subsistence, recreational and industrial water resources (Arp et al., 2019).

The majority of Earth's lakes are concentrated at northern high latitudes (45–75°N; Verpoorter et al., 2014), where several different mechanisms of lake formation have been identified (Pienitz et al., 2008). The advance and subsequent retreat of ice sheets and glaciers over vast areas of land during the last glacial/interglacial period set the stage for widespread lake formation by reducing relief, destroying organized drainage networks, eroding bedrock depressions, and creating residual landscapes with low hydrological gradients that were conducive to lake formation (Fig. 1a; Pienitz et al., 2008). Deglacial processes emplaced moraines that dammed valleys, drainage pathways and depressions, and deposited low-permeability clays and silts that led to surface inundation (Fig. 1b). Glacial till and overburden buried residual ice blocks, which upon melt, led to the formation of kettle lakes (Fig. 1b and c; Astakhov and Isayeya 1988); and in some instances, large proglacial lakes formed and expanded in front of glaciers as extensive valleys and lowlands filled with melt water (Fig. 1b; Teller 2003). After deglaciation, isostatic rebound of the Earth's crust caused uplift that resulted in the isolation of both glacially scoured and pre-existing basins, especially near coastal margins (Fig. 1c; Lamoureux 1999; Pienitz et al., 2008). Transport and accumulation of sediments also dammed marine embayments akin to today's fjords as they emerged from beneath the ocean surface, resulting in the formation of freshwater or meromictic lakes (Pienitz et al., 2008). Here, we use an umbrella term, "postglacial," to refer to lakes formed by these mechanisms.

Lakes also occur in high concentrations on permafrost landscapes (Smith et al., 2007), where perennially frozen ground beneath the active layer impedes drainage (Fig. 1e). In these areas, thermokarst lakes and ponds form when ice-rich permafrost thaws, causing ground subsidence and creation of a water-impounding depression (Fig. 1e and f). Heat transferred through the water column can subsequently accelerate thaw of permafrost beneath and surrounding the lakes, leading to thaw bulb deepening, lateral expansion through shoreline erosion, coalescence with other lakes, and sometimes drainage (Fig. 1g) (Jorgenson and Shur 2007; Plug and West 2009; Grosse et al., 2013). Formation of large thermokarst lakes is topographically limited to relatively flat, contiguous land surfaces that preclude drainage and downslope run-off, and occurs most commonly in Pleistocene-aged, ice-rich permafrost where massive-ice displacement leads to substantial ground surface subsidence (Morgenstern et al., 2011; Kanevskiy et al., 2014). Smaller thermokarst lakes can persist in ice-rich regions with hilly topography (Edwards et al., 2016), and formation of collapse-scar ponds can result from thaw of ice-cored palsas (Vitt et al., 1994). Though buried glacial ice, responsible for the formation of kettle lakes upon melt, is defined as a part of permafrost and thus these lakes are also technically thermokarst lakes, we here classify them as postglacial lakes due to their direct association with retreating ice masses.

Other processes of northern lake formation associated with fluvial dynamics include migration of drainage pathways that create oxbow and floodplain lakes. Rarer lake types include maar

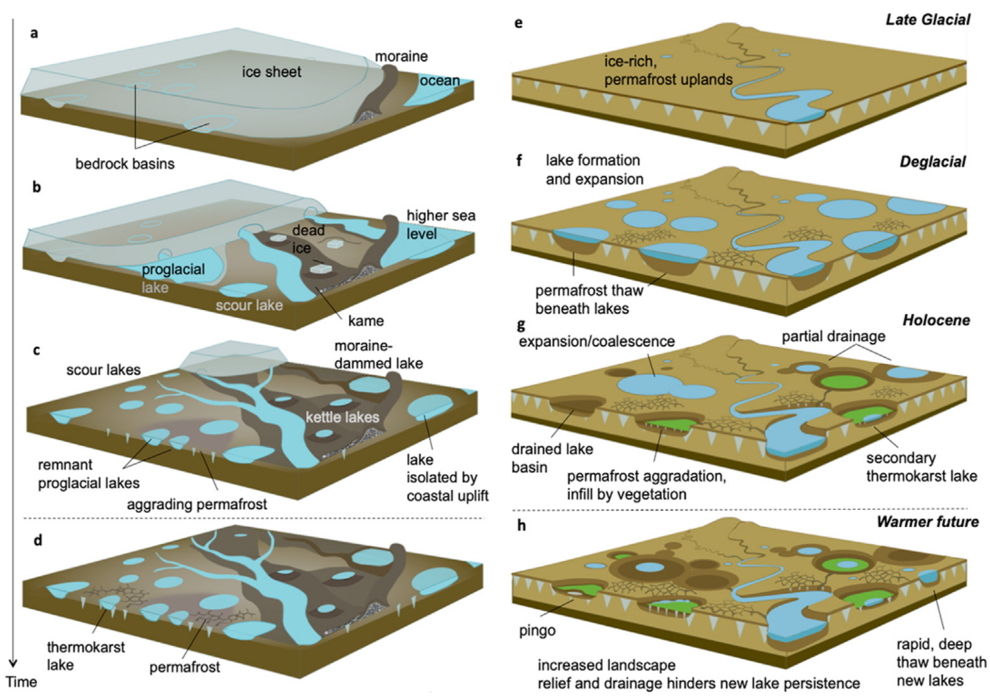

Fig. 1. Conceptual diagram of glacial landscape evolution with postglacial lake formation (a–d), and ice-rich permafrost landscape evolution with thermokarst lake formation (e–h); a) ice sheets scour the landscape carving bedrock basins and emplacing low-permeability tills; b) ice sheet retreat exposes new land surfaces and sets in motion postglacial lake-forming processes; c) ice sheet retreat slows but some lakes continue to form, landscape stabilizes and permafrost begins to aggrade where conditions are favorable; d) with future warming, possible melt of the remaining ice caps leads to new lake formation, and thaw of aggraded permafrost results in limited thermokarst lake formation; e) ice-rich, Pleistocene-aged permafrost uplands remain mostly intact; f) warming and thaw leads to rapid thermokarst lake formation and expansion, and an initial increase in landscape drainage; g) continuing thermokarst lake development, change and drainage leads to increased landscape relief, dissection and drainage; vegetation re-establishes in drained lake basins and permafrost begins to re-aggrade, secondary thermokarst lakes sometimes reform; h) future warming and wetting leads to new lake formation on both original land surfaces and within basins where permafrost has reformed, lake persistence and size are limited by existing and developing landscape relief and drainage.

lakes such as the Espenberg Maars in NW Alaska (Begét et al., 1996), impact crater lakes such as El'gygytgyn Lake in Siberia (Melles et al., 2012), and tectonically formed lakes such as those on the Tibetan Plateau (Dietze et al., 2010). Volcanic eruptions and carbonate weathering also create lakes in some northern environments (Pienitz et al., 2008).

Though common mechanisms of lake formation are known, the drivers of and controls over these lake-forming processes have never been comprehensively examined within a spatially and temporally explicit paleoclimatological context on the pan-Arctic scale. Geospatial patterns of present-day northern lakes were explored by Smith et al. (2007), who showed that lake distributions are spatially linked to landscape histories of glaciation, and to the presence of permafrost and wetlands. However, mechanisms of lake formation tied to paleoenvironmental lake sediment records have never been explicitly linked to their spatial distributions, nor has the question of when lakes formed been systematically addressed. While postglacial lakes logically formed after deglaciation, the timing of their formation in relation to ice retreat has not been synthesized. Furthermore, it is unknown which, and to what extent, past disturbances such as warming, shifts in precipitation and evaporation, and changes in fire frequency or severity have led to permafrost thaw and thermokarst lake development since the last deglaciation.

Information on the rates and timing of past lake establishment may provide critical insight to the mechanisms, drivers, and controls over lake formation potentially relevant to future climate change scenarios. Here we examine lake formation dynamics across the pan-Arctic using a new compilation of 1207 unique lake basal ages. From these data and other paleoenvironmental records, we identify the main drivers of lake formation, and examine feedbacks that may have exacerbated or mitigated lake-forming processes from the LGM to present.

2. Methods

2.1. Study domain

We compiled an extensive dataset of 1207 unique lake basal and minimum ages from both past and extant lakes within the domain of glaciation and permafrost extent during the Last Glacial Maximum (LGM) and Last Permafrost Maximum (LPM) (Lindgren et al., 2015, Fig. 2). We defined the study domain as the northern region including all areas that either (1) are affected by permafrost today (Brown et al., 1998), (2) were affected by permafrost during the LPM (Lindgren et al., 2015), or (3) were covered by ice sheets during the LGM (Ehlers and Gibbard 2003).

2.2. Extraction of lake records

We collected lake records from primary literature sources and datasets published until January 2017, relying upon author knowledge of specific studies, and Web of Science and Google Scholar searches using query terms such as "lake," "pollen," "paleo-," "sediment," "basal" and "reconstruction." We gathered lithological and morphological information from detailed literature descriptions of lake cores, peat cores and exposures and distinguished eight distinct classes of lake origin: postglacial, thermokarst, volcanic, karst, impact crater, coastal uplift, tectonic, and other (Pienitz et al., 2008). Where not indicated directly in the literature, we sought to determine lake origin from lithology, geological history and site descriptions within the text. We classified these lake origins into four main categories: postglacial, thermokarst, coastal uplift, and other/unknown. Through the majority of cores and exposures were radiocarbon-dated, we accepted robust dates obtained through a variety of methods including varve counting, optically stimulated luminescence, Pb/Cs, Th/U, wiggle matching and tephrochronology. We reported oldest sample ages in all cases, electing not to utilize basal ages derived from age-depth models extrapolated beyond dated levels due to both their high level of uncertainty and differences between methodologies used to construct each model (Blaauw, 2010). We excluded shallow lake cores that clearly did not reach basal lake sediments, or that were collected for the sole purpose of methods development or studies of recent human impacts. Records that did not include dates from lower-most cored sediments, that suffered from uncorrected reservoir effects (as noted by the authors) or that contained copious (>3) age reversals were also excluded. Some records provided distinct stratigraphic evidence of lake formation that allowed for exact determination of lake basal age, while other lithologies were more ambiguous. To address this uncertainty, we categorized each lake age as "minimum" or "basal" based on interpretation of contextual, geographical and lithological information. We excluded extremely large ice-dammed, proglacial lakes (e.g., Agassiz, Ojibway, Hitchcock, McConnell, and the proto Great Lakes) from our database due to their high spatiotemporal complexity.

We extracted dataset attributes for the full suite of 1207 basal ages, which ranged from 40 to 51,640 years old. However, we selected only basal ages less than 20,000 years old to assess the rate and timing of northern lake formation since the LGM, which resulted in the final inclusion of 1113 basal ages. Analyses of lake spatial distributions and origins utilized the entire dataset.

2.3. Analytical methods and error handling

To handle dating error, we assumed a normal distribution of error around each basal age, and a consistent standard deviation equal to the mean standard deviation ($\sigma = 200$ years) of all radiocarbon dates included in the dataset. We chose this approach to avoid artificially weighting older radiocarbon dates with larger associated error more heavily than younger dates with smaller analytical error. All ^{14}C dates were recalibrated for this study using Calib 7.0 (Stuiver and Reimer 1993).

Several sources of non-normally distributed error could have affected the accuracy of lake basal age distributions. Sampling bias toward suspected older lakes for use in paleoenvironmental analyses, carbon reservoir effects on bulk sediment samples, and possible reworking of older organic material in thermokarst lakes may all have imparted a bias toward older basal age distributions. Conversely, difficulty reaching basal sediments using common coring devices hindered determination of true formation ages according to many authors. In these scenarios, we included oldest reported ages in our dataset as "minimum" ages. Misclassification of ages where lithological ambiguities caused minimum ages to be categorized as basal ages by either the original author or by our research group may also have imparted a bias toward younger basal age distributions. For example, dates from inorganic-organic sediment transitions were commonly reported by authors as basal ages for lakes of postglacial origin despite the fact that these lakes may have formed earlier and accumulated only inorganic sediment generated by glacio-lacustrine processes initially. Additionally, most basal ages likely dated the time at which the cored site became part of the lake, not the actual moment of lake initiation. These sources of error may have imparted bias toward younger basal date distributions and may have affected our minimum/basal age distribution comparison. However, the combined magnitude and direction of error imparted by these potential sources is unknown. We therefore assume that the relatively large standard deviation of 200 years assigned to each basal age captures both the

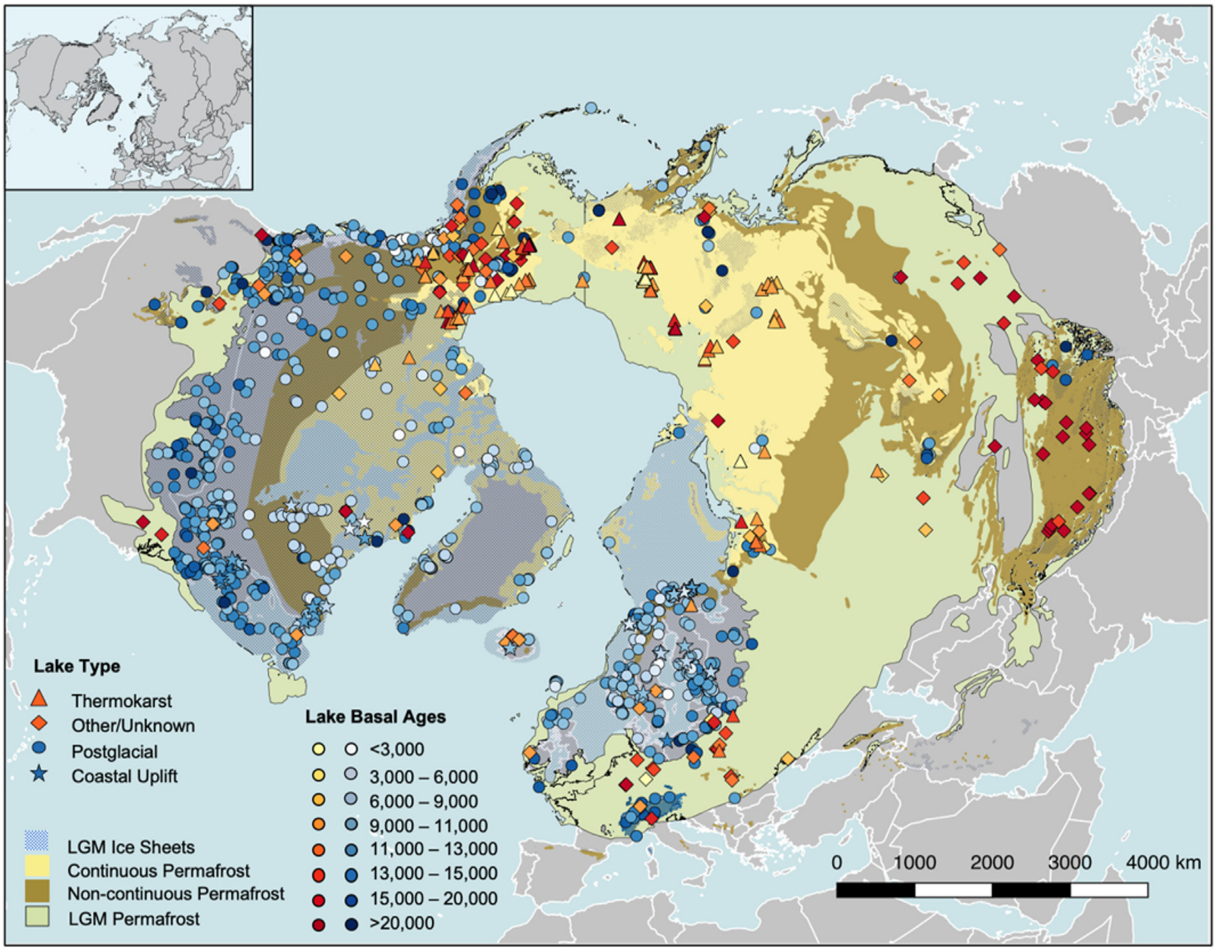

Fig. 2. Locations, origins and ages of lake records included in the lake basal age dataset. Our study domain is defined by the maximum extent of glaciation (Ehlers and Gibbard, 2003) and permafrost (Lindgren et al., 2015) at the last permafrost maximum.

analytical error associated with radiocarbon dating as well as potential error associated with sampling and stratigraphic interpretation.

To assess potential error associated with carbon reservoir effects, we compared the distribution of radiocarbon ages obtained from bulk sediment samples ($n = 410$) to that of ages obtained from a combination of macrofossils, pollen, extracted acids or other materials ($n = 745$) (Fig. 3a) using the Kolmogorov-Smirnov test. Similarly, we compared the distributions of dates categorized as "minimum" ($n = 509$) or "basal" ($n = 604$) (Fig. 3b) using the same method. Results of these tests indicate that, in each case, the two histograms were derived from the same parent distribution at the 95% confidence interval ($D < D_{crit} = 0.096$). In short, there were no significant differences between the distributions of dates obtained from different materials, or dates categorized as either basal or minimum. As a check, we also used two-tailed t-tests to examine differences over peak periods of lake formation (13.5–12.5 ka BP and 11.5–9.5 ka BP). We assumed a normal distribution of the data over these short timeframes (Fig. 3). In all cases, $p \gg 0.05$, again suggesting no difference.

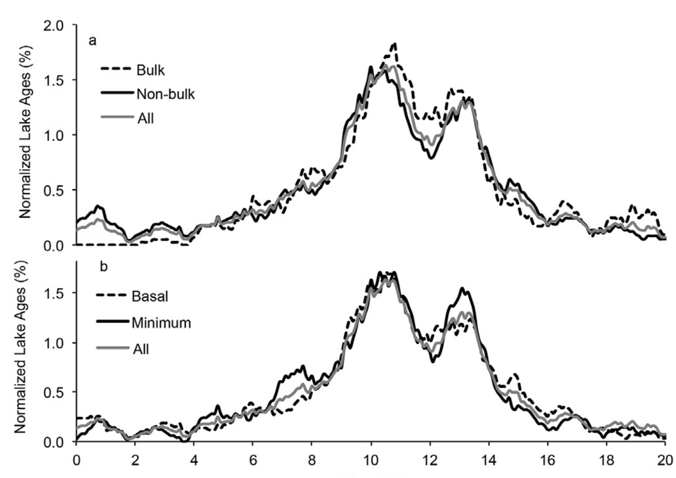

Fig. 3. Lake age distributions a) determined from radiocarbon dating of bulk inorganic sediment samples, all non-bulk materials, and all materials combined, b) categorized as "basal" or "minimum" during data compilation. "Normalized lake age" refers to the number of lakes per bin divided by the sample size, n.

2.4. Geospatial methods

We used ArcGIS to extract landscape characteristics of lake record locations using existing geospatial data layers. We first determined the distribution of lake records within our dataset by ecoregion as defined by Olson et al. (2001). We extracted additional parameters including modern permafrost regime (Brown et al., 1998), permafrost ground ice content (% by volume:

low = 0–10%, medium = >10–20%, high = >20%) (Brown et al., 2002), and glacial history (Ehlers and Gibbard 2003), in order to examine potential controls over lake-forming processes.

We used deglacial isochrones with century-to millennial-scale resolution (Dyke 2004; Stroeven et al., 2016) to infer the timing of local deglaciation for lake records within the maximum extent of North American and Fennoscandian glaciation at the LGM. Comparison of basal ages to this data revealed how quickly lakes formed following ice retreat. To determine the rates at which different lake-forming processes proceeded, we examined lag times between local deglaciation and lake formation separately for four different lake types occurring in once-glaciated regions – postglacial (not including coastal uplift), thermokarst, coastal uplift and other lakes. Though the majority of basal ages for these lakes were younger than their corresponding deglacial isochrones, 13% of basal ages appeared up to 2000 years older than their isochrone ages, and 4% appeared >2000 years older. Since glaciers typically exhibit fluctuations in ice mass in response to seasonal shifts and inter-annual climate variability, older basal ages may technically be plausible. Similarly, organic materials that originated during previous glacial retreat phases may later have been reworked and redeposited. It is also possible that discrepancies in timing were caused by reservoir effects associated with the sampling and dating of bulk inorganic sediments, which may have yielded artificially older basal ages. Lake initiation records appearing older than their corresponding isochrones were excluded from the analysis of lake formation following deglaciation. Finally, we acknowledge that basal ages obtained from inorganic-organic sediment transitions in postglacial lakes may have introduced some uncertainty to our lag-time estimates, since these lakes may have formed earlier and accumulated only inorganic sediment generated by glacio-lacustrine processes initially.

3. Results

3.1. Spatial distribution of lake records

The landscape history, permafrost regime and modern ecosystem characteristics of lake record locations are summarized in Tables 1 and 2. The majority (75%) of all lake records were recovered from areas formerly overlain by ice sheets or glaciers during the LGM (Table 2), which is in agreement with the present-day distribution of all northern lakes (Smith et al., 2007). Regardless of glacial history, 44% of the lakes in our dataset are situated on continuous (23%) or non-continuous (discontinuous, sporadic and isolated regimes combined, 21%) modern permafrost deposits with high, medium or low ice-contents (Table 2). The distribution of lake records in our dataset between continuous and non-continuous permafrost zones reflects closely that reported for all northern lakes situated on permafrost (Smith et al., 2007), suggesting that we have a representative sampling of lakes between these two environments. Within unglaciated portions of our study domain, more lake records were recovered from medium to high ice-content permafrost environments (61%) than from low ice-content permafrost environments (39%). Records from existing lakes comprise 87% of the dataset, while 161 paleolake basal ages determined from peat cores or sediment exposures comprise the remaining 13%.

Table 1
Distribution of lake records in dataset by ecoregion. Ecoregion extents are after Olson et al. (2001).

Ecoregion	n	%
Tundra	355	30
Boreal Forests/Taiga	360	30
Temperate Conifer Forests	135	11
Temperate Broadleaf and Mixed Forests	261	22
Temperate Grasslands, Savannas and Shrublands	30	2
Other	48	4

Table 2
Landscape characteristics of lake sediment record locations (this study) and all mapped circumarctic lake locations (Smith et al., (2007). Low, medium and high ice content (IC) permafrost deposits contain 0–10%, <10–20%, and >20% ice by volume, respectively (Brown et al., 1998).

	This study	Percent	Smith et al. (2007)	Percent
	n		n	
All	1207	100%	202,756[a]	100%
Unglaciated	318	26%	49,136	24%
Glaciated	889	74%	153,620	76%
All	1,207[c]	100%	202,756[a]	100%
No modern permafrost	665	55%	54,453	27%
Permafrost	542	45%	148,303	73%
All permafrost	542	100%	140,500[b]	100%
Non-continuous	249	46%	66,100	44%
Continuous	276	54%	78,900	56%
All permafrost	542	100%		
Low IC	128	24%	–	–
Medium IC	340	63%	–	–
High IC	68	13%	–	–

[a] Lakes north of 45.5°N latitude.
[b] Lakes north of 45.5°N latitude within glaciated and/or lowland terrain only.
[c] Lakes within our study domain defined by the maximum extent of glaciers and permafrost at the LGM. This domain extends south of 45.5°N in some locations and captures considerably more modern permafrost-free land area than does Smith et al., (2007).

3.2. Lake origins

Lakes within our dataset formed through a variety of different mechanisms. Postglacial processes, including scour of bedrock basins, water impoundment by transported materials, and deposition and burial of glacial ice remnants, formed 72% of lakes in our database (Fig. 4a). Thermokarst processes formed 14% of lakes, while coastal uplift accounted for 4% (Fig. 4a). Volcanic or tectonic activity, meteor impacts, carbonate weathering or other processes formed the remaining lakes in our dataset. Four percent of the lakes in our dataset are of unknown origin.

We suggest, based on lake origin data, that certain landscape characteristics are indicative of the dominant processes by which lakes were created (Fig. 4). Postglacial lake-forming processes were responsible for 89% of all lake formation on formerly glaciated landscapes (Fig. 4c). Isostatic rebound of the Earth's crust following deglaciation isolated pre-existing basins in coastal regions of Canada, Fennoscandia and northern Europe, and accounted for 5% of lake formation in formerly ice-covered regions. Thermokarst processes provided an auxiliary mechanism of lake formation in once-glaciated regions where permafrost later aggraded (3%), but

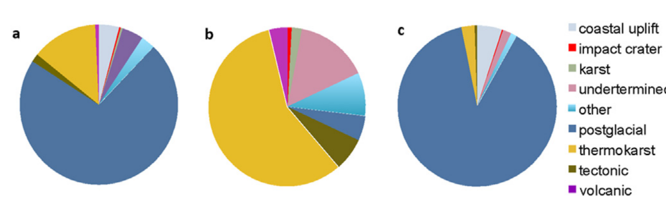

Fig. 4. Breakdown of lake origins within the entire study domain (a), and within the previously unglaciated (b) and glaciated (c) portions of our study domain. Lake formation by postglacial processes in areas that were unglaciated during the LGM resulted from prior glacial advances during previous stadial periods.

dominated (58%) in permafrost regions of Alaska, Siberia and northwestern Canada (together, Beringia) that were unglaciated during the last Ice Age (Fig. 4b). Likely, local geology, topography and tectonic activity dictated the incidence of several other lake formation mechanisms that were unrelated to either glacial history or the presence of permafrost. Tectonic and volcanic processes appear to have formed crater, maar and graben lakes in tectonically active areas of Alaska, the Tibetan Plateau and the Kamchatka Peninsula of Russia, while carbonate weathering created lakes in Poland and Belarus where local geology was conducive to karst formation. Low topographic relief and hydrological gradients likely contributed to floodplain and oxbow lake formation, and finally, meteor impacts resulted in spatially randomized lake formation.

3.3. Rates and timing of lake formation from the LGM to present

Basal ages of lakes within our dataset suggest low rates of northern lake formation during the Late Glacial period (20–15 ka BP, Fig. 5). Later increases in lake establishment followed abrupt increases in North Atlantic air temperature occurring 14.7 ka BP and 11.6 ka BP. Dual peaks in lake formation (13.2 ka BP and 10.4 ka BP) following these increases were separated by a brief decline coincident with cooling in the northern hemisphere during the Younger Dryas (YD, 12.9–11.6 ka BP, Fig. 5a and b). After reaching an absolute peak at 10.4 ka BP, rates of total northern lake formation decreased by 65% over the next two millennia (Fig. 5a and b). Rates of lake establishment decreased steadily 8–4 ka BP, and were much lower from 4 ka to present (Fig. 5b).

We observed similar temporal patterns of lake formation in both glaciated and unglaciated regions of our study domain (Fig. 5c). However, changes in rates of lake formation in unglaciated regions were typically more dynamic than those in glaciated regions (Fig. 5c). Maximum rates of lake establishment following initial Bølling-Allerød (BA) warming at 14.7 ka BP in unglaciated regions of our study domain (0.9% century^{-1}) were 36% lower than in glaciated regions (1.4% century^{-1}, *t*-test: $p < 0.001$ over the period 14–12 ka BP), but exhibited a proportionally larger decrease (53% vs. 34%) during YD cooling (Fig. 5c). After the YD, lake establishment in unglaciated regions accelerated more quickly and peaked higher (2.3% century^{-1}, Fig. 5c) than did lake formation on glaciated terrain (1.7% century^{-1}, *t*-test: $p = 0.022$ over the period 11.5–9.0 ka BP, Fig. 5c) in response to higher-magnitude and more sustained Preboreal (PB) warming at 11.6 ka BP. In contrast, normalized lake formation in glaciated areas accelerated slightly faster in response to initial BA warming than to PB warming (Fig. 5c). Though rates of lake formation in both regions began to increase at the onset of each warming event, peak rates of lake formation lagged abrupt BA and PB temperature increases by approximately 1500 years and 1000 years, respectively (Fig. 5a and b).

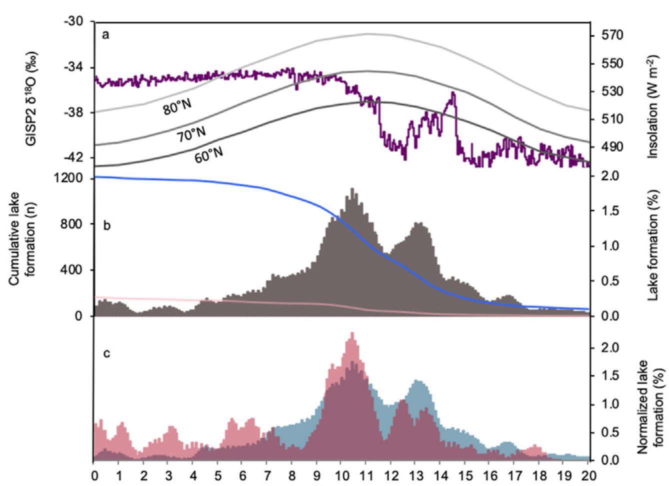

Fig. 5. Temporal distribution of northern lake formation according to our lake basal age dataset; a) northern hemisphere insolation (gray; Berger and Loutre 1991), and Greenland ice core $\delta^{18}O$ indicative of North Atlantic air temperature (purple; NGRIP members, 2004); b) histogram of total lake formation within our study domain (gray bars), cumulative lake formation in once-glaciated regions of our study domain (blue line) and unglaciated regions of our study domain (pink line); c) normalized rates of lake formation in glaciated regions (blue bars), and in unglaciated regions (pink bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

After reaching an absolute peak at 10.4 ka BP, lake establishment on unglaciated landscapes decreased by 85% between 10 ka BP and 8 ka BP, while lake establishment on once-glaciated landscapes decreased by only 57% over the same time period. After 8 ka BP, lake formation in unglaciated regions varied throughout the Holocene, exhibiting several small peaks and declines that were not observed in records of lake formation on formerly glaciated landscapes (Fig. 5c). Between 8 ka BP and 4 ka BP, normalized rates of lake formation in glaciated regions decreased steadily from 0.52% century^{-1} to 0.09% century^{-1}, and were on average 0.06% century^{-1} from 4 ka BP to present. A minimum rate of total northern lake formation (0.05% century^{-1}) occurred 1.8 ka BP (Fig. 5b and c).

3.4. Timing of lake formation with respect to local deglaciation

Comparison of lake basal age spatial distributions to millennial- and sub-millennial-scale deglacial isochrones (Dyke 2004; Stroeven et al., 2016, Fig. 6c) reveals that 75% of postglacial lakes formed more than 1000 years after local deglaciation (median lag = 2280 years). Fig. 6a depicts the distribution of lag times between local deglaciation and lake formation, which also varied with lake origin. We found significant differences in lag times between lake formation by coastal uplift and other postglacial methods (*t*-test: $p = 0.005$) and between thermokarst and postglacial methods (*t*-test: $p < 0.0001$) (Fig. 6b).

3.5. Timing of lake formation with respect to permafrost ice-contents

An analysis of permafrost characteristics for each lake record location within the unglaciated portion of our study domain suggests that only permafrost with medium (10–20%) to high (>20%) modern ground ice-content by volume (Brown et al., 1998) was vulnerable to thaw under cold, dry conditions (Fig. 8c), and that thaw of these deposits accounted for some of the first lake formation by thermokarst processes between 20 ka BP and 15 ka BP (Fig. 8e). Continued lake formation in permafrost with medium to high ice-contents, and initial thaw of ice-poor deposits, which appear to have been stable under prior, cooler, climate conditions, followed rapid warming that occurred 14.7 ka BP (Fig. 8c). Lake formation in unglaciated regions that were perennially frozen during the LGM, but which are permafrost-free today (e.g. parts of the midwestern and western United States, much of western and central Europe, and western Russia; Fig. 2) also accelerated quickly following abrupt warming 14.7 ka BP (Fig. 8c).

4. Discussion

4.1. Drivers of widespread lake formation during the deglacial period

Changes in orbital precession and solar insolation leading to climate warming, changes in precipitation/evaporation, and

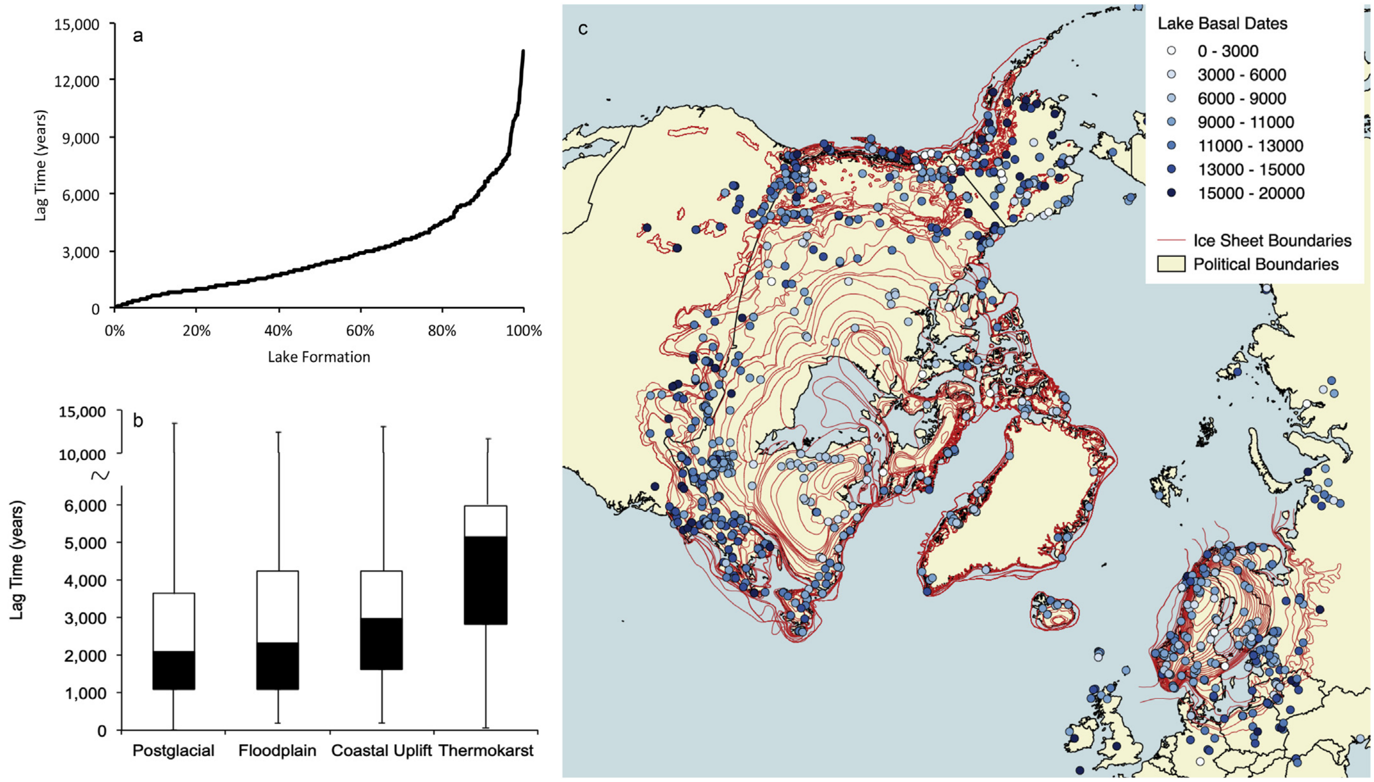

Fig. 6. Comparison of lake basal age distributions with reconstructed ice sheet extents; a) distribution of lag times between local deglaciation and subsequent lake formation in North America and Fennoscandia; b) distribution of lag times by lake origin (black and white boxes show inner quartiles, whiskers show min/max values); c) map showing calibrated lake basal ages and reconstructed glacial extents (isochrones) (Dyke 2004; Stroeven et al., 2016) used in this analysis.

deglaciation, broadly drove increases in northern lake establishment during the Deglacial period (15–9 ka BP, Fig. 5). On glaciated terrain, lake formation was coincident with deglacial warming events and meltwater pulses (Fairbanks 1989; Peltier 2005) that correspond with sea-level rise indicative of rapid glacial melt (Fig. 7b,d). We suggest that rapid ice melt increased the fraction of the land surface undergoing rapid geomorphic change during the initial, high-energy phase of postglacial landscape evolution. Once exposed, it appears that new lakes began to form upon land surfaces immediately, and that lake formation continued, albeit more slowly, for several millennia after local ice retreat (Fig. 6).

In unglaciated regions of our study domain, rapid Deglacial warming drove two major increases in thermokarst lake development beginning 14.3 ka BP and 11.6 ka BP (Fig. 8). Spatiotemporal patterns of thermokarst lake formation were additionally determined by permafrost ground ice-contents, and likely influenced by changes in precipitation and wildfire frequency. Thermokarst lakes formed earliest and most often in permafrost environments with medium to high ice-contents (Fig. 8c, Table 2) where water impoundment associated with ground surface subsidence provided a strong positive feedback to permafrost thaw by modifying surface energy balances (Jorgenson et al., 2010; Nauta et al., 2015), and where thaw of ice-rich deposits led more often to lake (vs. peatland) formation as a result of greater ice displacement and ground subsidence (Kanevskiy et al., 2014). Though initial deglacial warming beginning 14.7 ka BP caused thaw of vulnerable permafrost deposits, peak thermokarst lake formation occurred in response to more sustained, higher magnitude warming beginning at 11.6 ka BP that has persisted into modern times (Fig. 8). Prolonged climate warming was likely required to initiate widespread degradation and thaw of colder or more resilient permafrost deposits. In regions with low ground ice content, where paludification and peatland formation may have dominated initially, continued thaw of ice-poor deposits to greater depths over longer timescales may also have been necessary to achieve adequate ice displacement and ground subsidence for lake formation.

Along with increases in temperature, changes in precipitation also likely influenced rates of thermokarst lake formation since soil moisture strongly influences soil energy balances (Langer et al., 2011), and surface water ponding provides a strong positive feedback to permafrost thaw even under stable, cold conditions (Jorgensen et al., 2010; Nauta et al., 2015). Increases in precipitation peaking ~11 ka BP in Alaska and northwest Canada (Viau et al., 2008; Viau and Gajewski 2009) (Fig. 8b), and wetter-than-modern conditions in Siberia during the early Holocene (11.6–8 ka BP) (Andreev et al., 2003), correlate with high rates of thermokarst lake establishment during this time (Fig. 8d). In central Europe and Fennoscandia, increases in winter precipitation beginning ~11 ka BP (Mauri et al., 2015) may also have contributed to permafrost warming and thaw that led to lake formation, since thicker snow cover can insulate permafrost, preventing cooling and stabilization during the winter months.

Evidence for increasing wildfire frequency during the Deglacial period suggests that fire may have exacerbated rates of permafrost thaw and thermokarst lake formation. Wildfires contribute to permafrost degradation in modern boreal and tundra ecosystems by removing insulating organic matter from the soil surface, causing an increase in ground temperature and depth of the seasonally thawed active layer (Yoshikawa et al., 2003; Liljedahl et al., 2007). Thaw subsidence resulting from this process, which could potentially lead to water ponding and lake formation, was observed in 34% of a recently burned tundra site, compared to only

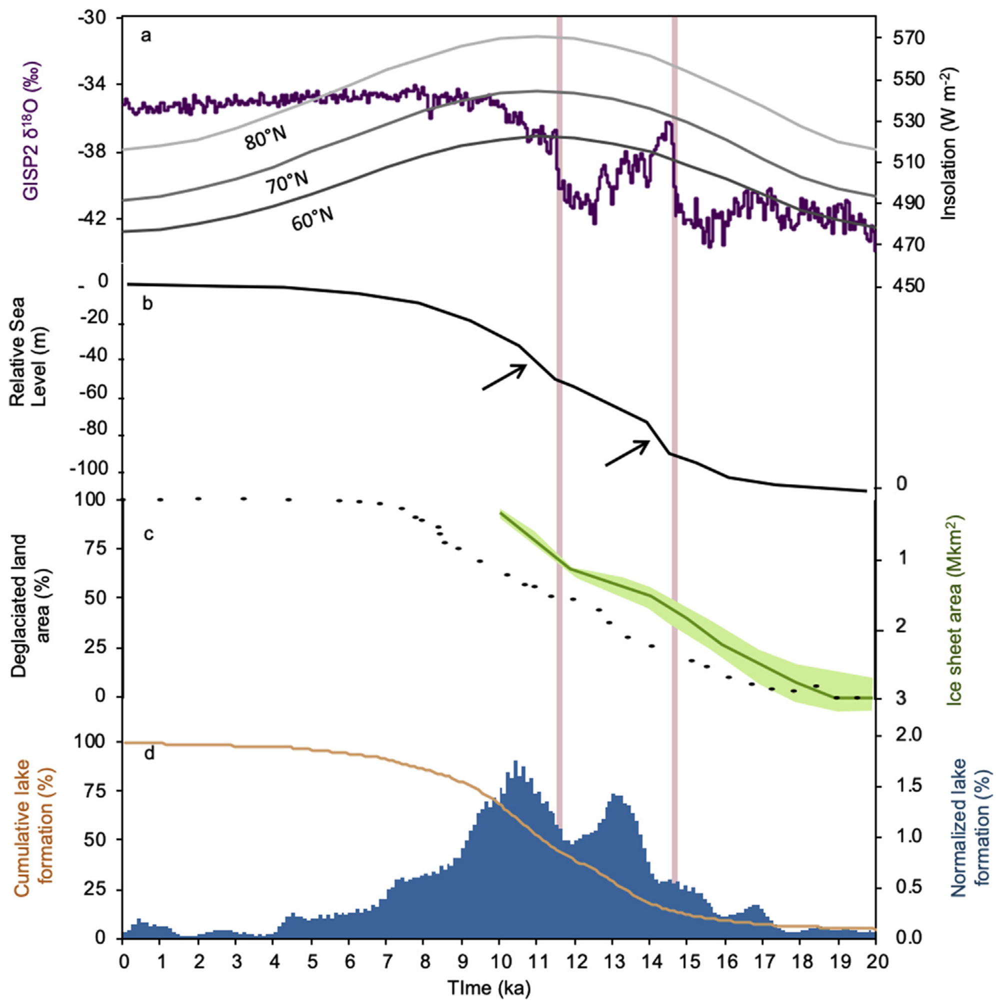

Fig. 7. Rates of lake formation in once-glaciated regions of our study domain compared with records of insolation, temperature, sea level rise, ice melt and glacial retreat; a) northern hemisphere insolation (gray; Berger and Loutre 1991), and Greenland ice core $\delta^{18}O$ indicative of North Atlantic air temperature (purple; NGRIP members, 2004); b) relative sea level rise showing meltwater pulses (arrows, Peltier et al., 2015); c) deglaciated land area in North America as percent of modern deglaciated land area (black dots, Dyke 2004), Scandinavian Ice Sheet area (green, Hughes et al., 2016); d) normalized frequency of lake formation (blue bars), and cumulative establishment of lakes (orange line) in once-glaciated regions of our study domain. Red shaded bars show abrupt warming events 14.7 ka BP and 11.6 ka BP. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

1% in undisturbed areas (Jones et al., 2015). In tundra ecosystems, a well-documented shift from herb to shrub tundra that is thought to have increased terrestrial biomass, and thus fuel availability, is associated with a marked increase in fire frequency beginning 14 ka BP (Higuera et al., 2008). An initial increase in thermokarst lake formation beginning 14.3 ka BP correlates well with this occurrence, and with increasing fire frequency in both North America and western Europe (Marlon et al., 2009; Doyon et al., 2015) (Fig. 8d and e), while a second increase beginning 11.6 ka BP appears coincident with high fire activity in eastern Siberia during the early Holocene (Katamura et al., 2009). Though fire may have exacerbated permafrost thaw during the deglacial period, further study of the interactions that lead specifically to lake development, as well as more and longer-term paleo-fire records from high northern latitudes are needed to elucidate this relationship.

4.2. Decreasing lake formation with landscape change

Though peak rates of northern lake formation followed abrupt increases in temperature 14.7 ka and 11.6 ka BP, lake establishment slowed dramatically between 10 ka and 8 ka BP despite sustained early Holocene warmth. A combination of abiotic and biotic landscape changes, in addition to stabilizing temperatures, likely reduced rates of lake formation during this period. Shrinking ice-marginal environments and glacial landscape stabilization through energy loss (Carrivick and Heckmann 2017) (Fig. 1 a-c), permafrost formation (Kokelj et al., 2017) and new vegetation establishment (Haugland 2006; Klaar et al., 2015) that occurred as ice sheets approached their minimum extents (Fig. 7; Dyke 2004; Hughes et al., 2016) likely explain the 67% decrease in postglacial lake formation 10–8 ka BP (Fig. 7d). Formation and expansion of peatlands (e.g. Hudson Bay Lowlands; Smith et al., 2004; MacDonald et al., 2006; Loisel et al., 2014) may have further stabilized these landscapes, and could have reduced lake formation and persistence in lowland areas by infilling glacially-formed depressions, changing surface hydrology, and protecting both permafrost that had aggraded since deglaciation, and buried relict glacial ice responsible for kettle lake formation, from thaw (Mann et al., 2010).

Similarly, cumulative fragmentation of original, ice-rich permafrost uplands by thermokarst lake formation, modification and drainage, as well as thermo-erosional processes (Fig. 1e and f),

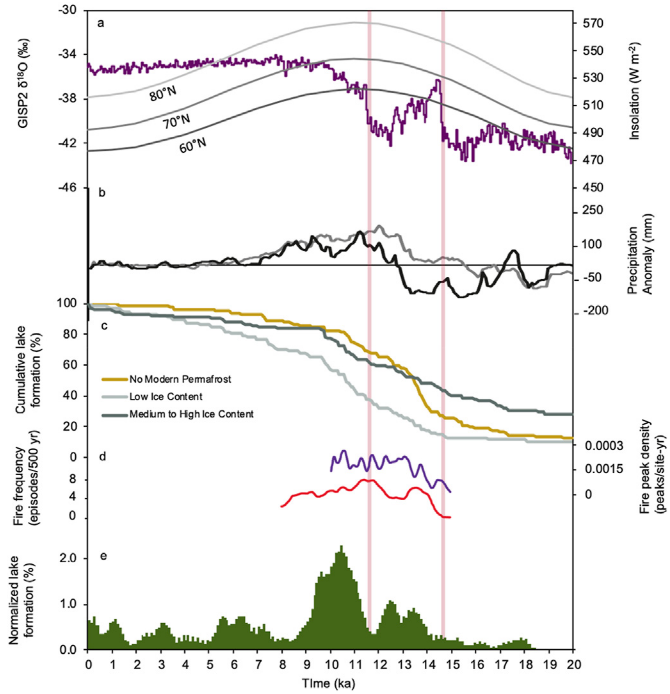

Fig. 8. Rates of lake formation in unglaciated regions of our study domain compared with records of insolation, temperature, precipitation and fire frequency; a) northern hemisphere insolation (gray, Berger and Loutre 1991), and Greenland ice core $\delta^{18}O$ indicative of North Atlantic air temperature (purple, NGRIP members, 2004); b) total annual precipitation for Eastern Beringia relative to modern day, derived using the modern analog technique applied to the best single analog (black), and the top five analogs (gray, Viau et al., 2008); c) cumulative lake formation on unglaciated permafrost landscapes characterized by low, and medium to high ice-contents, and in regions that hosted permafrost during the LGM, but which are permafrost-free today; d) inferred fire frequencies for western Europe (red, Doyen et al., 2015) and North America (purple, Marlon et al., 2009); e) normalized frequency of lake formation in unglaciated regions of our study domain (green bars). Pink shaded bars show abrupt warming events 14.7 ka BP and 11.6 ka BP. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

may have strongly controlled new lake persistence and size in unglaciated regions during the early Holocene (Fig. 1g), since forming or expanding lakes would have been more likely to drain via pre-existing slopes or channels (van Huissteden et al., 2011; Kessler et al., 2012). High rates of peat initiation and accumulation in a range of unglaciated boreal locations (Smith et al., 2004; Jones and Yu 2010; Peteet et al., 2016; Loisel et al., 2014) also suggest an accumulation of insulating peat and organic matter able to stabilize and protect permafrost from thaw (Shur and Jorgenson 2007; Mann et al., 2010; Gaglioti et al., 2014). Climate-driven shifts from shrub-to tree-dominated vegetation communities during the Deglacial and early Holocene (Bigelow et al., 2003; Brubaker et al., 2005; Edwards et al., 2005; Anderson and Lozhkin 2015; Kaufman et al., 2016) furthermore provided shade, reduced sub-canopy snow accumulation, encouraged soil moisture retention and growth of insulating understory mosses (Shur and Jorgenson 2007). The development of these ecosystem protections likely buffered permafrost from prolonged climate forcing during the early Holocene, strongly reducing the frequency of thermokarst lake development by 8 ka BP (Fig. 8e).

4.3. Variable lake formation during the mid-to late-Holocene

Sources of variation in rates of lake formation after 8 ka BP are harder to discern, but were likely associated with regional changes in temperature and/or precipitation, and more recently, potentially fire (Burn and Smith 1990). A small peak in thermokarst lake formation ~6 ka BP (Fig. 8d) appears to have been broadly coincident with Holocene global thermal maximum conditions (Kaufman et al., 2020) specifically observed in northwest Canada, Alaska (Kaufman et al. 2004, 2016), northern and eastern Siberia (Andreev et al., 2003; Nazarova et al., 2013), and Fennoscandia (Mauri et al., 2015). Lake level reconstructions and moisture-sensitive proxies highlight the variability of changes in water balance and precipitation over regional scales during the mid-Holocene (8–4 ka BP) (Kaufman et al., 2016), but these too likely played an important part in controlling rates of lake formation. Regionally coherent patterns of permafrost aggradation in peatlands since 3 ka BP (Treat and Jones 2018) could also have created conditions conducive to small peaks in thermokarst lake formation observed 3 ka BP and from 1 ka BP to present, despite Arctic cooling in progress from 2 ka BP until the industrial era (Kaufman et al., 2009).

Lake establishment in glaciated terrain decreased steadily from 8–4 ka BP. Continuing lake formation during this period likely resulted from delayed postglacial processes (Fig. 6) such as isostatic adjustment, and thaw of buried glacial ice. Formation of thermokarst lakes on glaciated landscapes also occurred on average > 5000 years after local deglaciation (Fig. 6b), once permafrost had aggraded. The re-advance of alpine glaciers at 2.8 ka BP in the North American cordillera (Denton and Karlén 1973) may have set the stage for a small increase in postglacial lake formation beginning 1.5 ka BP (Fig. 7d). Retreat of glaciers following their re-advance during the Little Ice Age has similarly resulted in more recent lake formation in some locations (Engstom et al., 2000).

4.4. Implications for future lake formation

Our results suggest that preconditioning of northern environments by the extreme climate of the last glacial period was essential to widespread lake formation during deglaciation. The highest concentrations of lakes in the northern hemisphere are coincidentally found in glacier- and permafrost-affected regions (Smith et al., 2007). On glaciated terrain, proglacial processes directly associated with deglaciation created most lakes. In unglaciated terrain, the formation of ice-rich permafrost deposits under persistent cold, dry, glacial conditions was an essential precursor to widespread thermokarst lake initiation. In the millennia since deglaciation, however, both biotic and abiotic processes have heavily modified northern landscapes, changing the initial boundary conditions for predicting the effect of warming on lake area change moving forward.

As we are currently in an interglacial phase, it is unlikely that projected warming will cause extensive postglacial lake formation on the order of that observed during the Deglacial and early Holocene; although, melt of the remaining Greenland and Antarctic ice caps could lead to lake formation in these areas over multi-millennial timescales (Pattyn et al., 2018). With warming in the near future, recession of smaller ice caps and glaciers currently in progress will likely accelerate, hastening observed formation and expansion of moraine-dammed lakes in mountainous regions (Sakai 2012; Thompson et al., 2012). The frequency of outburst floods resulting from breach of these moraine dams is also expected to increase with future warming, posing a significant human threat (Harrison et al., 2018). Thaw of permafrost-preserved glacial landscapes recently observed in NW Canada (Kokelj et al., 2017) will also likely continue, and may contribute to future lake formation on once-glaciated terrain. Finally, thaw of permafrost that has aggraded since deglaciation could drive future lake formation on formerly glaciated landscapes, but may be limited by the potentially lower ice-contents of these younger deposits, which can favor changes in vegetation and/or peatland formation over lake establishment (Payette et al., 2004; Bouchard et al., 2014), and by ecosystem protections to permafrost that have developed over the Holocene and which remain in place today (Fig. 1d).

Whether anticipated warming and thaw of permafrost soils will lead predominately to new lake formation and expansion, or to further landscape erosion and drying will depend on local hydrology and topography, as well as the texture, thickness and excess ice-contents of permafrost soils throughout the Arctic (Fig. 1h). Thaw of remaining thick, ice-rich, late-Pleistocene-aged permafrost deposits covering >1 million km^2 (Schirrmeister et al., 2013; Strauss et al., 2017) represents the largest possibility for extensive thermokarst lake formation with future warming and wetting. Though these land surfaces supported very high rates of lake formation during deglaciation, they have since been heavily modified by thermokarst and thermo-erosional processes. Highly incised landscapes with well-developed drainage networks may be less likely to support water ponding (Fig. 1h), which initiates and accelerates new lake formation through changes in surface energy balances, despite predicted increases in precipitation relative to evapotranspiration in the Arctic (Lique et al., 2016). Thus, future potentials for forming new large lakes in such matured landscapes may be very small (Morgenstern et al., 2011), and possibilities for further lake expansion may be limited due to the likelihood that laterally expanding lakes will intersect existing drainage gradients (van Huissteden et al., 2011). Contemporary thaw of excess ground ice in modern continuous permafrost environments resulting in landscape erosion and drying (Liljedahl et al., 2016) also suggests that permafrost thaw does not always lead lake formation, especially if surface water can drain. In areas with thin permafrost and hydraulically conductive soils, subsurface drainage has also curtailed lake development and persistence during past periods of permafrost degradation (Bateman and van Huissteden 1999; Kolstrup 2007; Kasse et al., 2007). Continued formation of new lakes on relatively in-tact, ice-rich permafrost uplands remains likely, however.

At the landscape scale, warming over recent decades has resulted in net lake area increases in some northern regions, and net lake area decreases in others (Nitze et al., 2018; Walter Anthony et al., 2018 and references therein), suggesting that landscape level responses to future warming may vary. Better predictions of thermokarst lake area change will therefore rely upon enhanced earth-atmosphere models that utilize improved digital elevation models, maps of permafrost ice-contents, soil properties and vegetation cover, and account for anticipated feedbacks to climate warming such as northward shrub expansion and increased fire frequency.

5. Conclusion

We found that climate-driven deglaciation and permafrost thaw contributed to high rates of northern lake formation during the last Deglacial period. However, landscape stabilization by both physical processes and ecological feedbacks to warming attenuated rates of lake formation beginning 10 ka BP. This suggests that temperature alone may not control lake development; rather multiple factors must align to poise the landscape toward a response of lake area increase. We propose that land surfaces strongly geared toward increased lake formation were highly conditioned by glaciation. Thus, it is unlikely that warming this century will cause new lake formation as rapid or as widespread as that during the last Deglacial period.

Data availability

The compilation of 1207 lake basal ages is freely available as a dataset in the open access PANGAEA archive: https://doi.pangaea.de/10.1594/PANGAEA.894737.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2020.106773.

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