

# The imprint of catchment processes on Greenlandic ice cap proglacial lake records: analytical approaches and palaeoenvironmental significance

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**ABSTRACT:** Lakes fed by Greenlandic mountain glaciers and ice caps (GICs) contain important archives of Arctic palaeoenvironmental change. GIC proglacial lake records have been increasingly used to reconstruct Holocene glacier behaviour, largely focusing on macrostratigraphy. However, despite the wide range of topographic settings and catchment characteristics, there has been little systematic analysis of the ways that catchment conditions are registered in the clastic sediments of GIC lakes. Such signals provide valuable insights into landscape processes and palaeoenvironmental conditions that are not routinely captured in other Quaternary glacial morphosedimentary archives. This review synthesises sedimentological and geochemical evidence from existing Holocene GIC proglacial lake records to establish: how catchment-wide conditions have been recorded in the lacustrine sequences; and our ability to isolate these signals to enhance palaeoenvironmental reconstruction. Our review shows that with careful sedimentological and targeted (bio)geochemical analyses coupled with a clear process-based understanding, catchment and in-lake signals can be effectively identified in the microstratigraphic and mineral grain record. Such signals include wind patterns, mass wasting, precipitation events and seasonal lake ice cover, that can complement broader palaeoclimatic proxy evidence. The approaches collated here, if more widely applied, could considerably enhance environmental reconstructions not only in Greenland, but in glaciated catchments elsewhere.

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**KEYWORDS:** catchment processes; glaciers; Greenland; Holocene; ice caps; lake sediments

## Introduction

Throughout the Holocene, the Greenland Ice Sheet (GrIS), its peripheral glaciers and ice caps (GICs), and their catchments, have undergone profound changes in response to regional climate forcing (e.g. Briner *et al.*, 2016; Long *et al.*, 2011; Vinther *et al.*, 2009). Present-day deglaciating forelands demonstrate that these systems can undergo rapid shifts in sediment flux, drainage organisation, slope stability and biological processes in response to higher temperatures and rainfall events (Hasholt *et al.*, 2000; Rasch *et al.*, 2000; Stevenson *et al.*, 2021). Such transformations are likely to be exacerbated under future Arctic climate projections, which point to ongoing air temperature rise, glacial melt and precipitation increases of up to 60% (McCrystall *et al.*, 2021). Reconstructions of warm wet Arctic climates earlier in the Holocene (e.g. Thomas *et al.*, 2018; Axford *et al.*, 2021), would also have been accompanied by increased runoff and sediment transfer in newly exposed, labile forelands. Understanding these catchment processes during the Holocene will therefore provide important context for future change.

Proglacial lakes contain detailed sedimentary archives of palaeoenvironmental conditions, and there is now a long history of glaciolacustrine analysis in Greenland (e.g. Iversen, 1952; Bennike 2000; Cremer *et al.*, 2008), with a recent focus on reconstructing post-Last Glacial Maximum

GrIS behaviour (e.g. Bennike *et al.*, 2010; Weidick *et al.*, 2012; Larsen *et al.*, 2015; Bjørk *et al.*, 2018; Lesnek *et al.*, 2020; Mallalieu *et al.*, 2021). In comparison, although there are over 20 000 GICs (Rastner *et al.*, 2012), until recently, much less was known about their Holocene history, and even less about their catchment dynamics. These GICs and their catchments are important because their small size and environmental sensitivity compared with much larger GrIS basins, coupled with their confined topographic settings, means that GIC proglacial lakes can capture a wealth of catchment-derived palaeoenvironmental indicators.

An increasing number of studies have examined Holocene GIC proglacial lake sequences with specific emphasis on the timing of glacier fluctuations. Many of these studies are based on macrostratigraphy of clastic and organic units, with less attention paid to the microstratigraphy of the mineral record, including characteristics of individual mineral grains. Such grains, though volumetrically small, offer valuable insights into past environmental conditions including wind patterns, catchment runoff and lake ice cover. Recent work in GIC catchments has begun to address this by applying a range of analytical techniques to examine microstratigraphic changes in glacially and non-glacially derived clastic lake sediments (e.g. van der Bilt *et al.*, 2018; Adamson *et al.*, 2019). Such approaches can enhance our understanding of land-surface processes not only in Greenlandic catchments, but in glacial environments elsewhere.

This study provides the first systematic review of sedimentological data from existing Holocene GIC proglacial lake

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records, including (1) studies that focus explicitly on detailed catchment-derived mineral grain analysis, and (2) revisiting sedimentological data from studies where mineral analysis was outside the original scope, to examine:

1. The imprint of catchment and in-lake processes on GIC glaciolacustrine records, and what this can tell us about landscape processes and palaeoenvironmental conditions.
2. The sedimentological and geochemical approaches used to isolate climate, glacial and catchment signals and enhance palaeoenvironmental insights.

## Methods

Thirty-four lake sequences have been included in this review (Table 1; Fig. 1) and are, to our knowledge, all existing published lake records that examine Holocene GIC and catchment change to date. The sites span a range of topographic settings, including ice-dammed, ice-distal and low-elevation coastal basins. To facilitate regional syntheses, sites are categorised into four zones: North, East, West and South Greenland (Table 1; Fig. 1), broadly following the GIC latitudinal zonations of Rastner *et al.* (2012). With a specific focus on catchment-wide and in-lake signals, physical sedimentary and biogeochemical evidence from the target sequences has been collated, including:

1. core sequences, based on the original sedimentological and stratigraphic descriptions, to produce idealised core logs for all sites;
2. sediment properties including loss on ignition (LOI %), dry bulk density (DBD), magnetic susceptibility (MS), X-radiographs, computerised tomography (CT) scans and grain size;
3. geochemical parameters including X-ray fluorescence (XRF) and X-ray diffraction (XRD);
4. biological proxies such as pollen, biomarkers, microbial profiling, biogenic silica, total organic and inorganic carbon (TOC and TIC).

Geochronological frameworks discussed in the text follow the original publications, and thus include a combination of calibrated radiocarbon-based chronologies,  $^{210}\text{Pb}$ , optically stimulated luminescence, and cosmogenic nuclide-based age models. Where calibrated radiocarbon age ranges were not reported, ages have been recalibrated separately, for consistency, using OxCal (IntCal20). We acknowledge that many studies included in this synthesis incorporate evidence from beyond the lake basin, most notably geomorphological mapping, cosmogenic dating, moss kill dates, equilibrium line altitude (ELA) and climate modelling. These elements are not within the scope of this review, but are discussed where relevant to the findings. We also acknowledge the large number of GIC studies that have not used glaciolacustrine records. These have been reviewed elsewhere and are referred to here only where relevant to the discussion (e.g. Kelly and Lowell, 2009).

Average accumulation rates were calculated from the onset of lacustrine sedimentation (total sequence depth/reported basal age) (Table 1). Notwithstanding considerable variation in accumulation rate in each basin over time, this crude indicator provides a basis for discussion, especially where age–depth models are unavailable.

Holocene Arctic climate patterns and GIC activity are briefly summarised for context (*Holocene Arctic climate change and GIC behaviour*), before GIC lake sedimentary records and geochemistry are synthesised in detail (*GIC proglacial lake*

*sedimentology and stratigraphy* and *GIC proglacial lake geochemical analysis of catchment processes*). These findings are discussed in the *Discussion*, which examines the use of GIC proglacial lakes as archives of a range of catchment palaeoenvironmental conditions.

## Holocene Arctic climate change and GIC behaviour

Holocene Arctic air temperatures were closely tied to Northern Hemisphere summer insolation, and expressed locally by variations in GrIS mass balance, sea ice and ocean circulation (Briner *et al.*, 2016, 2018; Fig. 2). The resulting regional climate patterns and GIC behaviour have been reviewed in detail by others, spanning a range of proxies (e.g. Briner *et al.*, 2016; McKay *et al.*, 2018; Larsen *et al.*, 2019; Larocca and Axford, 2021; Osman *et al.*, 2021) and are outlined only briefly here.

### Holocene climate patterns

Prior to current anthropogenic forcing, Holocene Arctic climate can be broadly divided into two phases (Fig. 2):

- (1) *Early Holocene warming, with many sites reaching peak temperatures in the mid-Holocene – the Holocene Thermal Maximum (HTM) or Hypsithermal.* In South and West Greenland, evidence from lake sediments places the onset of peak temperatures at 9.8–8.5 ka (Briner *et al.*, 2016), with some locations recording maximum summer temperatures by 6–4 ka (Briner *et al.*, 2016; McKay *et al.*, 2018). In North and East Greenland, lake records indicate a thermal maximum in the early to middle Holocene, in some catchments at ~8 ka (Wagner and Bennike, 2015; Schmidt *et al.*, 2011; McKay *et al.*, 2018) and 8–4 ka (Briner *et al.*, 2016). Evidence suggests early Holocene temperatures up to 5°C higher than the present day in northwest and central Greenland, and up to 2°C warmer in the south (McFarlin *et al.*, 2018; Axford *et al.*, 2019, 2021) with major changes in precipitation patterns and ocean currents in central West Greenland (Thomas *et al.*, 2016, 2018).
- (2) *Colder temperatures from the mid- to late Holocene, culminating in the Neoglacial and Little Ice Age (LIA).* The Neoglacial has been identified in many Arctic records and is considered a regional, but locally moderated, phenomenon, tentatively linked to Atlantic meridional overturning circulation (McKay *et al.* 2018). McKay *et al.* (2018) identified two phases marking the onset or acceleration of cooling: the first at 7 ka with subsequent glacier advance by 4.5–2.0 ka, and the second from 2.0 ka to the LIA. Against the backdrop of Neoglacial cooling, the last millennium saw distinct centennial- to decadal-scale climate excursions (Fig. 1), notably the Medieval Climate Anomaly (MCA, ~900–1250CE, Solomina *et al.*, 2016), and the LIA (~1450–1850CE, Ahmed *et al.*, 2013). The onset, length, and intensity of these phases varied across Greenland, and in some palaeoclimate records are absent altogether (e.g. D'Andrea *et al.*, 2011). Ice core evidence from West Greenland shows regional variations in snow accumulation of up to 40% over the last two millennia, highlighting the importance of hydroclimate for GIC behaviour and catchment conditions (Osman *et al.*, 2021).

Recent warming is driving major changes across the Arctic system including precipitation patterns, sea ice extent, and permafrost thaw (Box *et al.*, 2019; McCrystall *et al.*, 2021). Almost all Arctic GICs are retreating (Leclercq *et al.*, 2012;

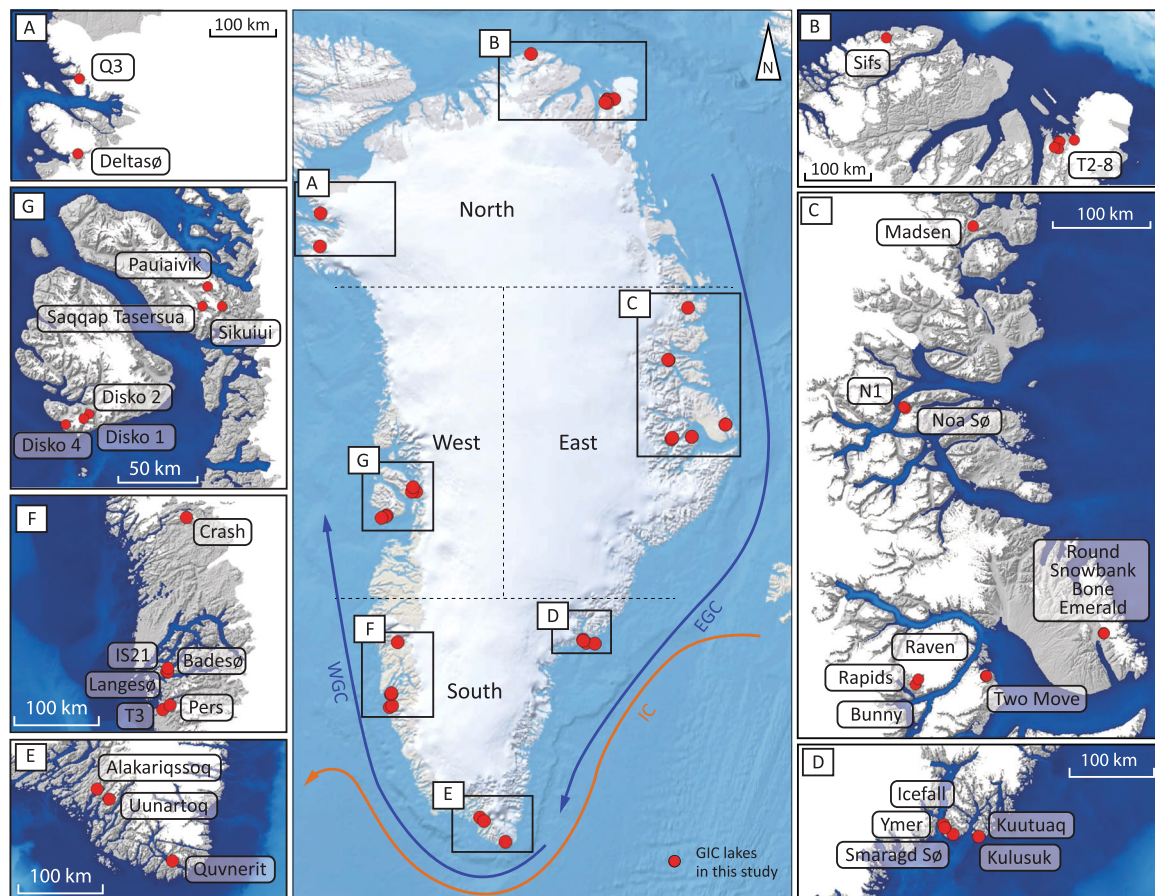
**Table 1.** Summary of key information for the GIC lakes discussed in the text

Reference	Lake name	Lake location	Lake altitude (m asl)	Lake area (km <sup>2</sup> )	Lake core depth (cm)	Max. core age (ka)	Mean accumulation rate (mm a <sup>-1</sup> )	Glacier/ice cap name
Axford <i>et al.</i> (2019)	Deltasø	76.759528°, - 67.610056°	385	North Greenland 0.30	166.0	10 800	0.15	North Ice Cap
Larsen <i>et al.</i> (2019)	T2	81.406844°, - 18.931924°	42	1.42	162.0	9100	0.18	Ice Cap 2
	T3	81.323769°, - 17.590466°	40	0.03	153.0	8900	0.17	Flade Isblink
	T4	81.356611°, - 19.499270°	2	0.81	127.5	5900	0.22	Ice Cap 1
	T6	81.393658°, - 18.822451°	61	1.40	140.0	9500	0.15	Ice Cap 2
Søndergaard <i>et al.</i> (2019)	T8	81.314012°, - 19.218370°	81	1.13	104.0	10 900	0.10	Flade Isblink
	Q3	83.528531°, - 32.261114°	15	6.50	59.0	7200	0.08	Qaanaaq Ice Cap
Möller <i>et al.</i> (2010)**	Sifs	77.697583°, - 69.356361°	20–40	-	-	-	-	Sifs Glacier
Adamson <i>et al.</i> (2019)	Madsen Lake	74.580917°, - 21.069361°	504	East Greenland 0.04	80.0	1740	0.46	Slettebreen
Wagner and Melles (2002)	Noa Sø	73.325445°, - 25.183332°	32	5.90	201.0	6600	0.30	Ice cap, unnamed
	Lake N1	73.344014°, - 25.220629°	120	0.19	704.0	7700	0.91	Ice cap, unnamed
Lusas <i>et al.</i> (2017)	Snowbank	70.886084°, - 22.278667°	448	0.0025	228.0	10 500	0.22	Istorvet Ice Cap-control lake
	Bone	70.888139°, - 22.266028°	422	0.01	174.0	10 500	0.17	Istorvet Ice Cap
	Emerald	70.883723°, - 22.275887°	419	0.004	92.0	10 500	0.09	Istorvet Ice Cap
	Round	70.883250°, - 22.266477°	420	0.03	82.0	10 500	0.08	Istorvet Ice Cap
Levy <i>et al.</i> (2014)	Two Move Lake	70.906270°, - 25.588154°	702	0.15	60.0	10 000	0.06	Bregne Ice Cap
Medford <i>et al.</i> (2021)	Bunny Lake	71.031183°, - 27.426750°	819	0.60	160.0	9500	0.17	Renland Ice Cap
	Rapids Lake	71.032483°, - 27.415350°	824	0.80	107.0	8120	0.13	Renland Ice Cap
	Raven Lake	71.066011°, - 27.311061°	1054	0.30	220.0	12 670	0.17	Renland Ice Cap – control lake
Schweinsberg <i>et al.</i> (2017)	Sikuui Lake	70.212306°, - 51.122361°	604	West Greenland 0.40	99.5	9400	0.11	Qangattaq Ice Cap
Schweinsberg <i>et al.</i> (2019)	Saqqap Tasersua	70.198487°, -	274	72.00	249.5	10 800	0.23	Qangattaq Ice Cap (Continued)

Table 1. (Continued)

Reference	Lake name	Lake location	Lake altitude (m asl)	Lake area (km <sup>2</sup> )	Lake core depth (cm)	Max. core age (ka)	Mean accumulation rate (mm a <sup>-1</sup> )	Glacier/ice cap name
Stevenson <i>et al.</i> (2021)*	Pauiavik	51.506392° 70.333333°, - 51.450000°	880	0.75	56.5	10 500	0.05	Sermikassak Ice Cap
	Disko 2	69.389033°, - 53.401417°	575	0.10	-	-	-	Unnamed
	Disko 1	69.353400°, - 53.490350°	299	0.23	-	-	-	Lyngmarksbraen
	Disko 4	69.297350°, - 53.809133°	214	0.15	-	-	-	Lyngmarksbraen
				South Greenland				
Schweinsberg <i>et al.</i> (2018)	Crash Lake	65.682097°, - 51.294594°	587	0.48	88.5	9300	0.10	Sukkertoppen Iskappe and Qaarajutoq
Larsen <i>et al.</i> (2017)	Badesø	64.130000°, - 51.359999°	674	0.67	147.0	8500	0.17	Qasiqiannguit Ice Cap
	Langesø	64.130000°, - 51.330000°	38	0.28	134.0	8700	0.15	RGI40-05.07208 and RGI40- 05.07196
Larocca <i>et al.</i> (2020a)	IS21	64.166158°, - 51.339858°	34	0.35	55.0	9000	0.06	Qasiqiannguit Ice Cap
	Quvnerit	59.970383°, - 43.813717°	125	0.05	437.0	9500	0.46	Two glaciers, unnamed
	Alakariqssoq	60.681783°, - 45.295083°	230	0.10	135.0	10 750	0.13	Four glaciers, unnamed
	Unartoq	60.582117°, - 45.050700°	480	0.02	50.0	5200	0.10	Several glaciers, unnamed
Larocca <i>et al.</i> (2020b)	Pers Lake	63.803200°, - 51.198689°	20	0.20	180.0	8600	0.21	Ice cap, unnamed
	T3	63.750000°, - 51.350000°	7	2.00	100.0	7500	0.13	Numerous ice caps, unnamed
Balascio <i>et al.</i> (2015)	Kulusuk Lake	65.560000°, - 37.110000°	202	0.80	350.0	9500	0.37	Two glaciers, Kulusuk glaciers
Larsen <i>et al.</i> (2021)	Smaragd Sø	65.692600°, - 37.905800°	95	0.02	240.0	7900	0.30	Mittivakkat
Van der Bilt <i>et al.</i> (2018)	Ymer Lake	65.616667°, - 37.716667°	150	0.29	228.0	10 000	0.23	Ymer glacier (cirque)
Hasholt <i>et al.</i> (2000)*	Icefall Lake	65.691556°, - 37.889694°	147	0.30	-	-	-	Mittivakkat
	Lake Kuutuaq	65.723806°, - 37.918083°	87	1.00	-	-	-	Mittivakkat

Information is based on the original publications. Where lake altitude and area were not stated, they have been measured using Google Earth Pro. Maximum core age is based on the stated age-depth models or basal ages. Average accumulation rate has been calculated using maximum age at the base divided by core depth, from the onset of glaciolacustrine sedimentation (i.e. not including basal glaciomarine facies). \*Sites discussed in the text, as present day examples, but sediment logs are not available. \*\*Site sediments are exposed in section as part of a larger sequence, and a sediment log is not presented here.



**Figure 1.** Location of proglacial lakes discussed in this review. The main Greenlandic ocean currents are shown: East Greenland Current (EGC), Irminger Current (IC) and West Greenland Current (WGC). Produced using the QGreenland package (Moon *et al.*, 2021). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

Larocca and Axford, 2021), and are expected to lose up to ~35% of their volume by the end of the century (Overland *et al.*, 2019). This continued retreat will be accompanied by ongoing catchment change and is therefore pertinent to the following review.

### Proglacial lake records of Holocene GIC activity

Figure 2 summarises Holocene GIC behaviour gleaned from proglacial lake records. Following previous syntheses (e.g. Briner *et al.*, 2016; Larsen *et al.*, 2019; Larocca *et al.*, 2020a), GIC activity is defined relative to modern day glacier size. Where documented in the original study, glacier advance and retreat phases are also indicated. Broadly, regional patterns of GIC activity derived from lake sediments can be summarised as follows.

In South and West Greenland, many of the analysed glaciers were considerably smaller or had possibly melted entirely, during the HTM (Fig. 2). Neoglacial regrowth/readvance was underway in some basins from ~5–4 ka, though the onset of glacier regrowth varies, even over relatively small distances. This has been linked, in several studies, to geographical location (e.g. altitude, latitude, local climate) and glacier characteristics (e.g. size, hypsometry) (e.g. Larocca *et al.*, 2020a). In East and North Greenland, many of the analysed glaciers persisted through the HTM, though were often smaller than at present, and some may have been non-existent for extended periods. Several basins register multiple rapid glacier advances, especially during the last few millennia (e.g. Levy *et al.*, 2014; Schweinsberg *et al.*, 2018).

## GIC proglacial lake sedimentology and stratigraphy

All lakes included in the following summary are documented in Table 1. Idealised sediment logs (Figs. 3–6) provide a macrostratigraphic framework and a basis for comparison between studies.

### North Greenland

In Sifs Valley, two phases of Holocene valley glacier advance are identified in the morphosedimentary assemblage (Möller *et al.*, 2010). The first (9.6–6.3 cal kaBP) is recorded by glacial and glaciofluvial sediments, and the second (6.3–5.1 cal kaBP) by 4.5 m of glaciolacustrine fines from a former ice-dammed lake. Now exposed in section, these are laminated, normally graded fine silt beds (5–30 mm thick), with interbedded fine sand and clay (both ~2–5 mm thick). Coarse sand and clasts (up to 1 cm), either as dropstones or gravel stringers, indicate ice-rafted debris and disturbance from underflows (Möller *et al.*, 2010). Parts of the sequence are varved – one of the few varved deposits identified in GIC lakes (see also Wagner and Melles, 2002). These rhythmites are not discussed further in the original study, but their occurrence is significant because they represent quiescent lake conditions and will contain insights into seasonal environmental conditions. Unlike the other studies reviewed here, which are based on core sequences from present-day lakes, the Sifs sediments are obtained from a former lake site and are thus not displayed in Fig. 3.

Macrosedimentology, X-radiographs, and geochemical analyses of five proglacial lakes from Finderup Land (Lakes T2–T8,

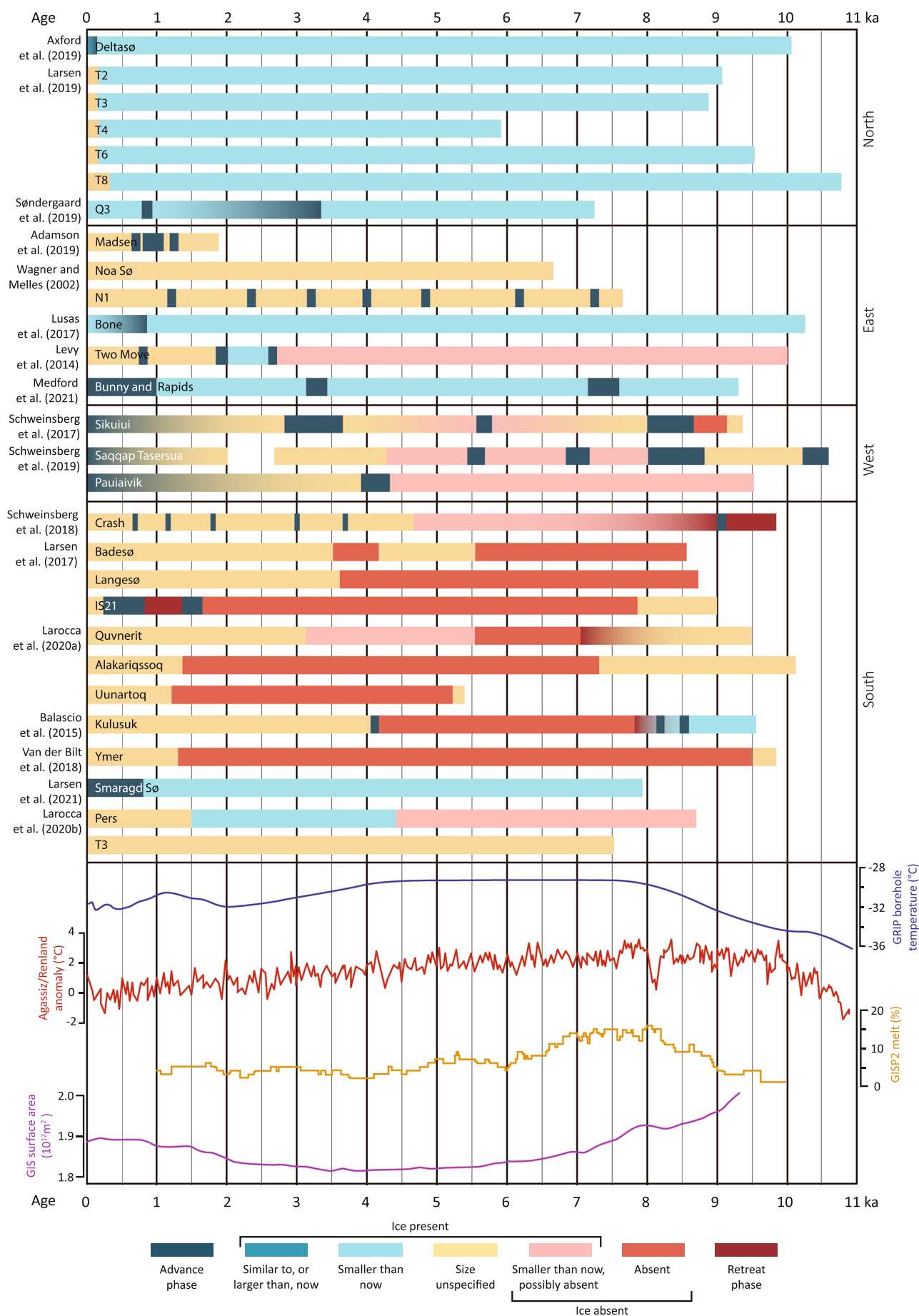
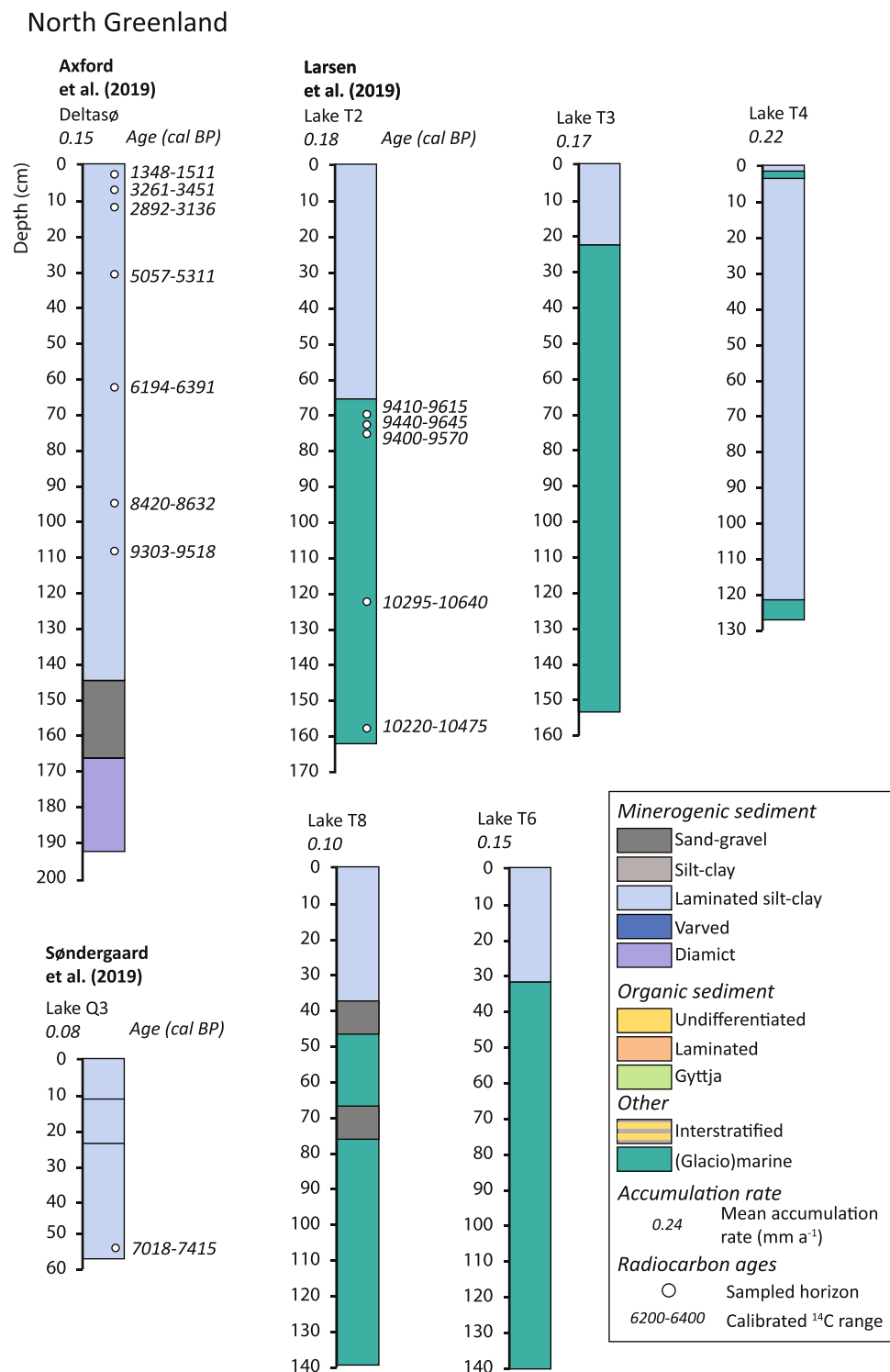


FIGURE 2. Continued.

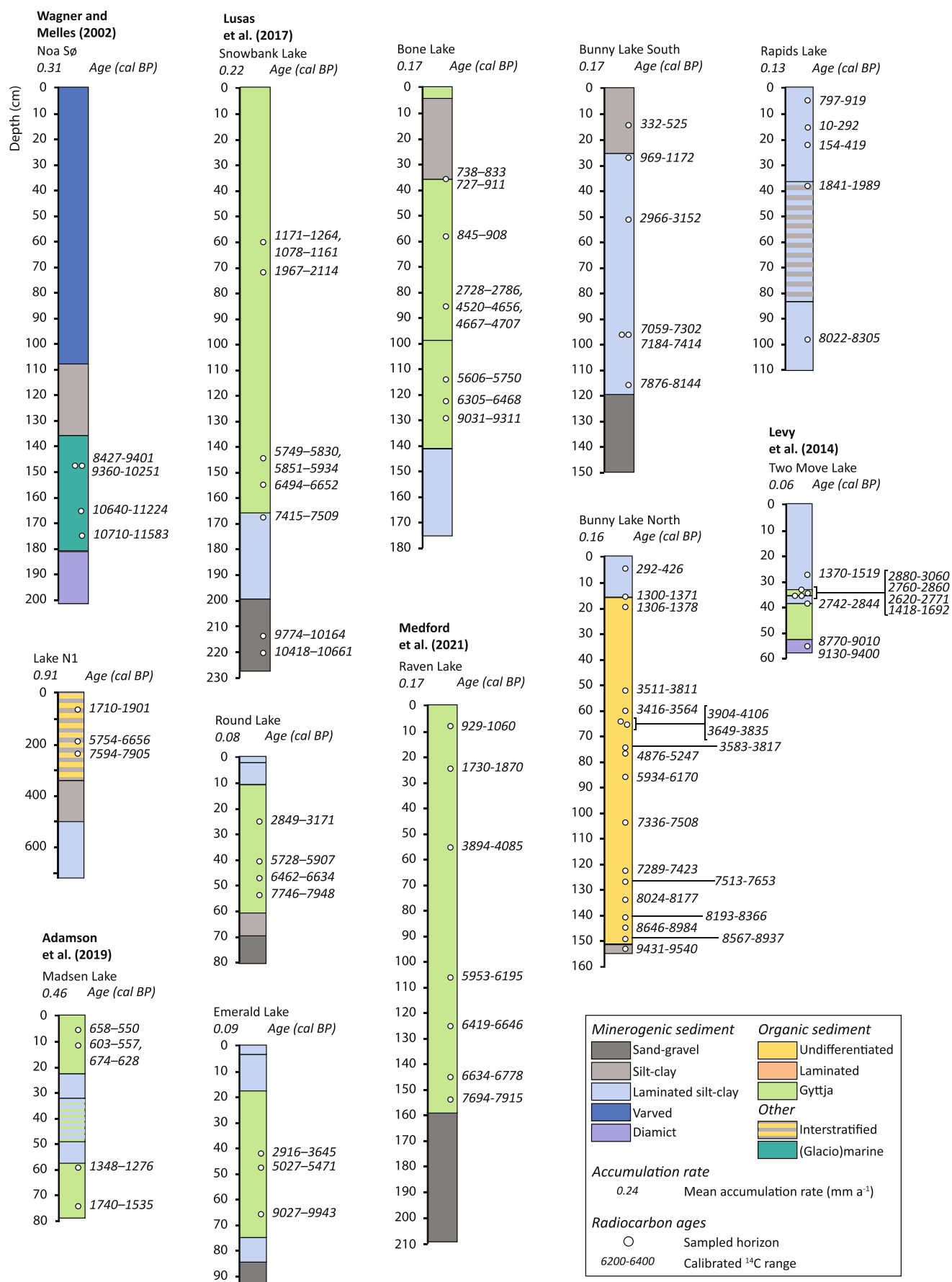




**Figure 3.** Summary of Greenlandic ice cap proglacial lake sedimentology and radiocarbon ages, presented as calibrated age ranges, from the studied lakes in North Greenland. Commas separate multiple age ranges for a single sample. <sup>210</sup>Pb ages are not included. Macrostratigraphy follows the sedimentological and stratigraphic descriptions in the original publications. Average accumulation rate is displayed above each log. [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

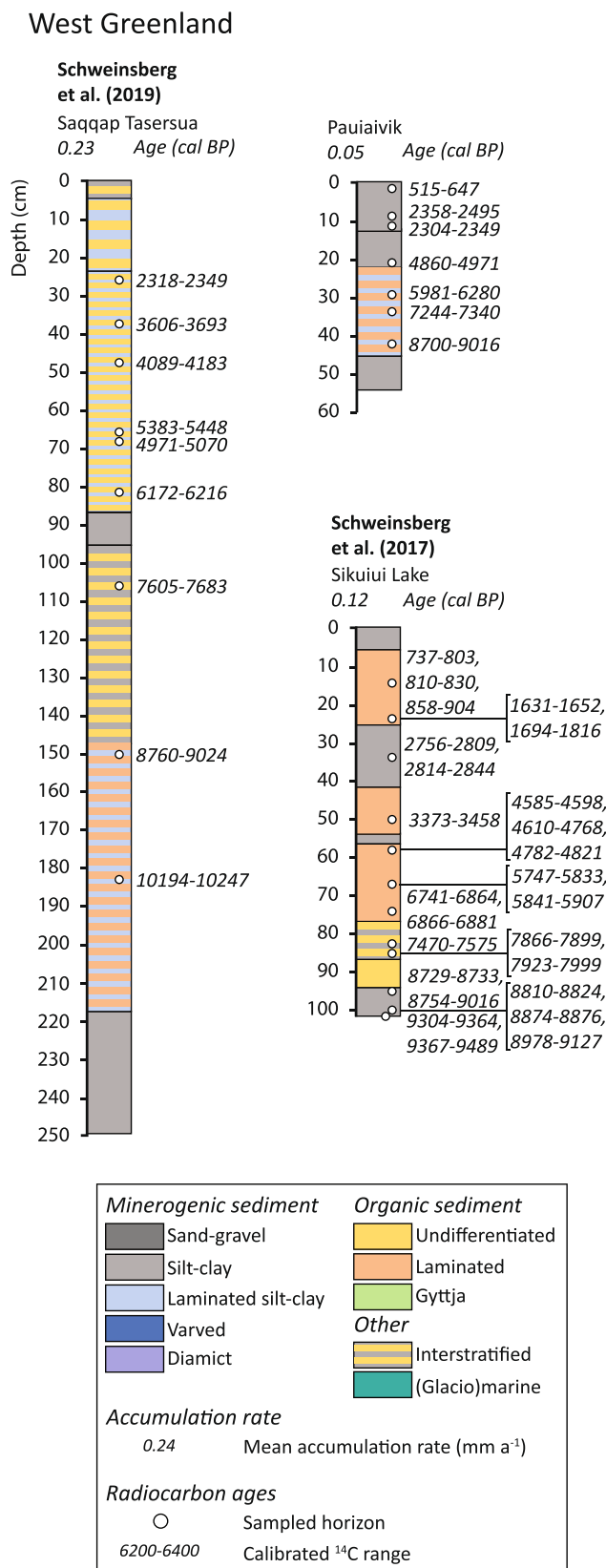
**Figure 2.** Summary of Holocene climate conditions and GIC glacial activity derived from lake records examined in this review. Glacier activity is defined following the original interpretations, and categorised by ice mass size relative to the present day. Advance and retreat phases are indicated when highlighted in the original studies. Selected Greenlandic Holocene climate proxies include: GRIP borehole temperature (Dahl-Jensen *et al.*, 1998), Agassiz Ice Cap and Renland Ice Cap temperature anomaly (Vinther *et al.*, 2009), GISP 2 melt percentage (Alley and Anandakrishnan 1995) and Greenland Ice Sheet surface area (Larsen *et al.*, 2015). [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

## East Greenland



**Figure 4.** Summary of Greenlandic ice cap proglacial lake sedimentology and radiocarbon ages, presented as calibrated age ranges, from the studied lakes in East Greenland. Commas separate multiple age ranges for a single sample. <sup>210</sup>Pb ages are not included. Macrostratigraphy follows the sedimentological and stratigraphic descriptions in the original publications. Average accumulation rate is displayed above each log. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]





**Figure 5.** Summary of Greenlandic ice cap proglacial lake sedimentology and radiocarbon ages, presented as calibrated age ranges, from the studied lakes in West Greenland. Commas separate multiple age ranges for a single sample. <sup>210</sup>Pb ages are not included. Macrostratigraphy follows the sedimentological and stratigraphic descriptions in the original publications. Average accumulation rate is displayed above each log. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

Fig. 3) show that ice caps survived the HTM and advanced later in the Holocene, evidenced by persistent minerogenic silt and clay, variable MS and elemental values, and overall low LOI (<4%) (Larsen *et al.*, 2019). On the western coast, lacustrine sediments and moss kill dates also indicate that Lake Q3 (Fig. 3, 59 cm, mean accumulation rate 0.08 mm a<sup>-1</sup>) received minerogenic sediment from the GrIS and/or Qaanaaq Ice Cap through the HTM (Søndergaard *et al.*, 2019). This is recorded as laminated silty clay units with no visible organic matter (Fig. 3).

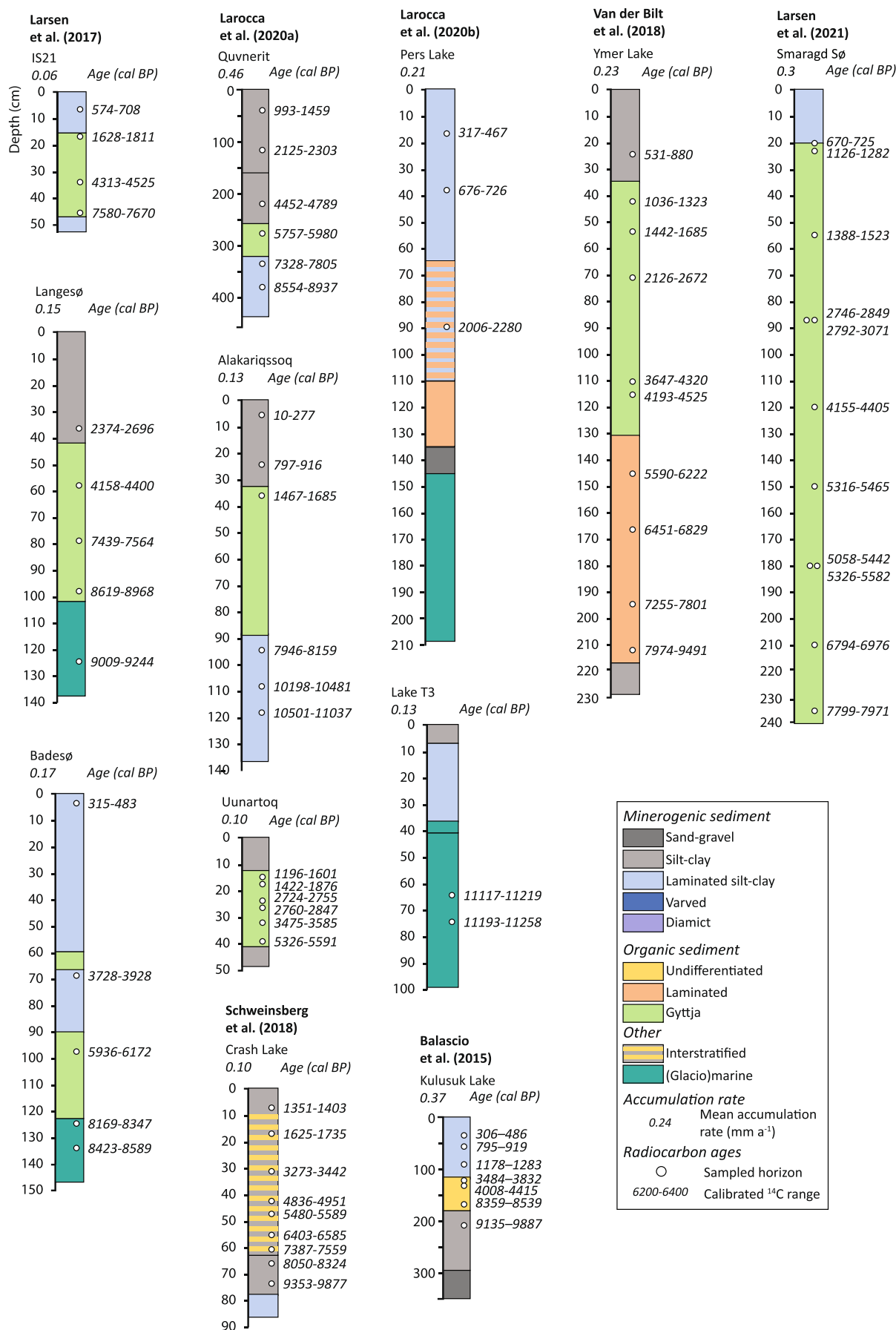
Sedimentological and geochemical excursions are not discussed in detail at Finderup Land or Lake Q3, but a similar glacial history is observed at nearby Deltasø (192 cm, 0.15 mm a<sup>-1</sup>) where several catchment signatures have been identified. Here, basal diamict is overlain by a sand unit with elevated Ca and Sr and very low LOI values (<1%), used to indicate a GrIS source area. The sequence is capped by 145 cm of laminated glaciolacustrine fines with elevated and covarying MS and Ti (Axford *et al.*, 2019; Fig. 3). Organic content remains steady throughout the lacustrine unit (LOI typically 3–15%), though BioSiO<sub>2</sub> exhibits submillennial variability (~3–12%). Rare elements (e.g. Zr, Y, Tb and Ta) shown in the XRF principal components analysis (PCA) after 5.8 cal kaBP are thought to derive from windblown material, providing insights into aeolian trajectories. While North Ice Cap is considered to have survived the HTM, its meltwater did not flow into Deltasø until an advance at 1850AD—consistent with an increasing sedimentation rate towards the core top (Axford *et al.*, 2019).

### East Greenland

At Madsen Lake, combined sedimentological and geochemical analysis of a short sequence (80 cm long, 0.46 mm a<sup>-1</sup>) of interstratified laminated gyttja and minerogenic sediment (Fig. 4), suggests that Slettebreen Ice Cap varied in size over the last two millennia. At the core top, interstratified gyttja and clastic sediments reflect the current conditions where ice persists in a much retracted, high altitude, position. Throughout the sequence, laminations vary in thickness, likely reflecting changes in sediment inputs, water depth and stratification. Short-lived sedimentological and geochemical fluctuations are also thought to reflect variations in meltwater flows and enhanced lake ice cover during known climatic cold phases. Two phases of enhanced glacier activity are identified in the macrostratigraphy and characterised by high DBD, MS, Ti and Ca, and low TOC values. The third phase, which was otherwise muted in its sedimentary signature, and absent entirely from the geomorphological record, was identified using cluster analysis of high-resolution XRD data, highlighting the value of these approaches to examine fine-scale environmental changes that cannot be identified in the visual stratigraphy (Adamson *et al.*, 2019).

Farther south, two proglacial records from Ymer Ø (Fig. 1) show rapid early Holocene retreat of a local ice cap (Wagner and Møller, 2002). Noa Sø (201 cm, 0.30 mm a<sup>-1</sup>) transitions from basal subaqueously deposited diamict to marine muds and is capped by 108 cm of varved glaciolacustrine clay and silt, indicative of ice distal quiescent lake conditions (Fig. 4). As is the case in Sifs Valley (Møller *et al.*, 2010), the Ymer Ø varves are not examined in detail, but would provide valuable seasonal palaeoenvironmental data. At neighbouring N1 (704 cm, 0.91 mm a<sup>-1</sup>), basal laminated glaciogenic silt and sand (240 cm, low organic matter and carbonate content, and high MS) are overlain by 500 cm of interstratified clastic-organic sediments indicating that local glaciers were present throughout the Holocene, but

## South Greenland



**Figure 6.** Summary of Greenlandic ice cap proglacial lake sedimentology and radiocarbon ages, presented as calibrated age ranges, from the studied lakes in South Greenland. Commas separate multiple age ranges for a single sample. <sup>210</sup>Pb ages are not included. Macrostratigraphy follows the sedimentological and stratigraphic descriptions in the original publications. Average accumulation rate is displayed above each log. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

fluctuated in size, likely in response to precipitation changes. Pollen, TOC and biogeochemistry suggest an early Holocene climate warmer than the present day from ~9 to 5 ka, followed by climatic cooling and reduced biological productivity towards the LIA (Wagner and Melles, 2002). Today, low MS values and high organic content are consistent with ice cap position outside of the lake catchment, but not melted entirely.

Four lake records close to Istorvet Ice Cap, Liverpool Land, also suggest that the ice was smaller than at present, but likely absent, for large parts of the Holocene (Lowell *et al.*, 2013; Lusas *et al.*, 2017). Snowbank Lake, a control lake, has not received glacial sediment since local deglaciation (228 cm,  $0.217 \text{ mm a}^{-1}$ ). Bone, Round and Emerald lakes (82–174 cm long,  $0.08\text{--}0.17 \text{ mm a}^{-1}$ ) all contain a similar stratigraphy of basal minerogenic units (sands and gravels, and silts and clays, Fig. 4), with high MS values and low LOI (<15%). These are overlain by laminated gyttja with high LOI (up to 30% at Emerald Lake, 50% at Snowbank). LOI variations between the neighbouring sites are attributed to lake characteristics such as bathymetry and water chemistry. The authors also highlight that, despite the high organic content – amongst the highest of the reviewed GIC lakes – there is a sustained, substantial clastic sediment input, even during ice-free periods. For example, silt horizons up to 2 mm thick within the gyttja at Snowbank and Bone lakes are evident in the MS readings, and common during climatic warm phases. Their fine grain size makes an aeolian source more likely than precipitation-induced runoff events. Above the gyttja, thin section analysis at Bone Lake reveals 170 millimetre-scale couplets. While these closely resemble varves, they are not thought to be annually resolved due to the elapsed timeframe in the age–depth model. Some of the couplets are exceptionally well-preserved and contain up to ~30 sub-millimetre-scale laminations, demonstrating intricate seasonal sedimentation patterns, though these have not yet been discussed in more detail.

A shorter sequence from Two Move Lake (60 cm,  $0.06 \text{ mm a}^{-1}$ ) has one of the lowest average accumulation rates in this region (Table 1). Sediments transition from basal diamict, to laminated gyttja with high LOI (20–30%). MS, organic matter and biogenic silica indicators suggest that Bregne Ice Cap was small or possibly absent from 10 cal kaBP until advance at ~2.6 and 1.9 cal kaBP. Minerogenic grains within the gyttja are considered a product of catchment runoff and not glacier activity due to (1) their distinctive MS values and (2) the overall low accumulation rate, and therefore limited primary glacial inputs, in this part of the core (Levy *et al.*, 2014). Likely source areas for these grains were considered to be either nearby high-altitude terrain, sourced during cool phases with enhanced snowcover, or from the exposure of different bedrock lithologies during ice retreat. The top of the core contains laminated silts (1–5 mm thick) displaying ~230 clay–silt couplets. As observed at Bone Lake (Lusas *et al.*, 2017), these are not thought to be annually resolved. Thin section analysis revealed pellets of fine sands, embedded within the silty clay laminae. These were not examined further in the original study but may represent the aggregation and rainout of clastic sediment from lake ice, thus documenting changing air temperatures and lake ice cover (Tomkins *et al.*, 2009).

Farther inland and at a higher elevation, lacustrine evidence shows that Renland Ice Cap survived the HTM (Fig. 4) (Medford *et al.*, 2021). Raven Lake (210 cm,  $0.17 \text{ mm a}^{-1}$ ), a control lake, ceased to receive glacial meltwater in the early Holocene (12.7–11.5 ka), marked by an abrupt shift from basal sands (LOI ~0%) to organic-rich sediments (LOI 30%) (Fig. 4). In Rapids Lake (107 cm,  $0.13 \text{ mm a}^{-1}$ ), basal sand and clayey silt is overlain by finely laminated (1 mm) silt with distinct clay

horizons. The uppermost silty clay unit contains massive clay layers that correspond to MS peaks. Twelve of these clay/silt layers are also seen in nearby Bunny Lake, where they are set within an organic-rich silt unit (LOI ~30% in Bunny Lake South) and thought to represent minor glacial advances. The uppermost silt and clay unit at Bunny Lake (high MS and LOI <10%) contains intermittent sand–silt horizons. These could reflect mass wasting events, or alternatively, reworking of sediment during lake level low-stands potentially caused by reduced summer temperatures or temporary ice dam removal and rerouting of meltwater away from the lake (Medford *et al.*, 2021).

## West Greenland

Saqqap Tasersua (Fig. 5), at the southern margin of Qangattaq Ice Cap, is amongst the oldest included in this review (10.8 ka), with one of the highest average accumulation rates ( $249.5 \text{ cm}$ ,  $0.23 \text{ mm a}^{-1}$ ), making it one of the most expanded full-Holocene sequences (Table 1). Interstratified units of laminated and massive organic and minerogenic sediment (Fig. 5) show multiple phases of ice advance, though ice was smaller than at present and likely absent through the mid-Holocene (Schweinsberg *et al.*, 2019). A mineral-rich horizon within otherwise organic-rich deposits at ~7 ka is considered in the context of glacier surging and mass wasting, but is instead thought to originate from the growth of multiple outlets.

Sikuiui Lake (99.5 cm,  $0.11 \text{ mm a}^{-1}$ ), at the eastern margin of Qangattaq Ice Cap (Schweinsberg *et al.*, 2017), records a similar though less complex macrostratigraphy of interstratified clastic–organic units (Fig. 5). Increased clastic inputs at 8.8–8.0 ka represent a phase of cooling and glacier readvance. Glaciers receded at ~7.5–5.0 ka (HTM) but consistent XRF PC1 scores and a thin clastic horizon indicates that ice did not disappear entirely. Consistent with this stratigraphy, branched glycerol dialkyl tetraethers (brGDGTs) and hydrogen isotope ratios of leaf waxes, used to reconstruct summer temperatures and lake water  $\delta^2\text{H}$ , respectively (Thomas *et al.*, 2018), suggest a warmer and wetter early Holocene that was punctuated by a phase of cool, dry summers from 9 to 8 ka.

Nearby Pauiaivik Lake (56.5 cm,  $0.05 \text{ mm a}^{-1}$ ) is fed by meltwater from Sermikassak Ice Cap. Unlike Sikuiui Lake and Saqqap Tasersua, it is thought that glacial input to Pauiaivik ceased from ~9.5 to 4.3 ka (Schweinsberg *et al.*, 2019; Fig. 5). This is reflected in the macrostratigraphy, where basal massive silts are overlain by interstratified laminated silt and organics (LOI ~9–35%). X-ray analysis of the uppermost units reveals faint laminations (Fig. 5), though these have not been further examined. The authors highlight the importance of glacier-, catchment- and lake-specific processes (e.g. glacier sensitivity, catchment size, sediment reworking and redox conditions) in determining sedimentological variations between these lakes, despite their geographical proximity and common glacier source area in the case of Sikuiui Lake and Saqqap Tasersua (Schweinsberg *et al.*, 2019).

## South Greenland

At Crash Lake (88.5 cm,  $0.10 \text{ mm a}^{-1}$ ), fine-scale sedimentology is not discussed in detail, but interstratified organic–clastic deposits indicate that GICs receded and were smaller than the present day in the mid-Holocene (Fig. 6). Low LOI values throughout the sequence (<6%) suggest persistent ice cover through the HTM (Schweinsberg *et al.*, 2018). The macrostratigraphy of Lake T3 (100 cm,  $0.13 \text{ mm a}^{-1}$ ) (Fig. 6), and low LOI values (typically <4%), also reflect sustained GIC meltwater input for the duration of lake sedimentation (Larocca

*et al.*, 2020b). In contrast, slightly more organic-rich sediments (LOI 6.0–6.5%) in nearby Pers Lake (180 cm,  $0.21 \text{ mm a}^{-1}$ ) (Figs. 1 and 6) are used alongside ELA reconstructions to suggest that GICs were not present in the catchment, and possibly melted entirely, until 4.3 ka (Larocca *et al.*, 2020b). After that, interstratified organics and laminated silts (LOI typically 4–5%) and silty clays (LOI <3%) mark the onset of periodic and permanent meltwater inputs, respectively.

Farther north, laminated gyttja with low Ti and LOI values (~4–10%) in Badesø (147 cm,  $0.17 \text{ mm a}^{-1}$ ), Langesø (134 cm,  $0.15 \text{ mm a}^{-1}$ ) and Lake IS21 (55 cm,  $0.06 \text{ mm a}^{-1}$ ), are also used to indicate that ice was reduced in size, or absent during the mid-Holocene (Larsen *et al.*, 2017; Figs. 2 and 6). Altitude drove the timing of neoglacial advance in these lake basins, where higher elevation glaciers (1370 m asl) regrew at ~5.5 cal kaBP, several millennia earlier than their lower elevation neighbours, at ~3.6 cal kaBP (1170 m asl) and ~1.6 cal kaBP (1000 m asl). These lake basins are set amidst steep-sided, debris-mantled slopes. The authors note the significance of mass wasting and paraglacial sediment reworking as a source of clastic lacustrine sediment input but suggest that the thin soil cover in these catchments rendered non-glacial sources unlikely, even despite the low LOI % values.

In southernmost Greenland, sediment from lakes Quvnerit (437 cm,  $0.46 \text{ mm a}^{-1}$ ), Alakariqssoq (135 cm,  $0.13 \text{ mm a}^{-1}$ ) and Uunartoq (50 cm,  $0.10 \text{ mm a}^{-1}$ ), also suggest mid-Holocene glacier retreat or disappearance (Larocca *et al.*, 2020a). Early Holocene laminated glaciogenic deposits (LOI up to 6% in Alakariqssoq) are overlain by massive to faintly laminated gyttja. LOI varies from 4–6% at Quvnerit up to 20% in Alakariqssoq. Uppermost units of sands, silts and clays with low LOI (1.5–9%), high MS and Ti values, record late Holocene glacier regrowth (Table 1, Figs. 2 and 6). Variations in the timing of advance are attributed to the larger ice mass and greater precipitation inputs to the Quvnerit catchment, demonstrating the significance of local catchment context.

Kulusuk Lake has one of the longest and most expanded sequences in this part of Greenland (350 cm,  $0.37 \text{ mm a}^{-1}$ ) (Balascio *et al.*, 2015). Basal gravelly sand and clayey silt reflect ice presence in the catchment until ~8.7 ka (Figs. 2 and 6). Sharply reduced XRF PC1 scores and higher LOI (12–19%), suggest that glaciers were at their minimum Holocene extent, and likely melted entirely, from 7.8 to 4.1 ka. MS excursions during that period are thought to reflect reworked material from the catchment, and not increased glacier activity. Other than these inputs, the authors indicate that the low-angle slopes and proximity to the ice margin means that the potential for non-glacial inputs to Kulusuk Lake is relatively low. A sharply increased accumulation rate (up to  $0.8 \text{ mm a}^{-1}$ ) in the uppermost laminated minerogenic unit marks the onset of neoglaciation at 4.1 ka.

At Smaragd Sø (240 cm,  $0.30 \text{ mm a}^{-1}$ ) basal laminated gyttja, with low MS, Ti, Si and K values, was deposited when ice had retreated out of the catchment from ~7.9 to 0.7 cal kaBP (Larsen *et al.*, 2021) (Figs. 2 and 6). Overlying laminated silt and clay and associated increases in Ti, K and Si, reflect glacier readvance. Importantly, aerial photographs indicate that ice had left the catchment once again by 1933CE, but this is not expressed in the lake sediments (Fig. 6). In topographic settings such as this, where ice exists outside of the lake catchment, small-scale oscillations are not captured in the macrostratigraphy.

Like many lakes in this part of Greenland, sediments at Ymer Lake (228 cm,  $0.23 \text{ mm a}^{-1}$ ) also show that ice was absent for much of the Holocene (van der Bilt *et al.*, 2018) (Fig. 6). Following early Holocene glacier retreat, a coarse sand layer is attributed to a glacial lake outburst flood (GLOF) in the upper

catchment. The subsequent stratigraphy is dominated by organic-rich sediment from 9.5–1.2 cal kaBP. Laminated organic material from 9.5–5.0 cal kaBP contains sustained fine-grained clastic inputs, revealed via XRF and XRD analyses to be windblown, comminuted silt. The overlying gyttja has sharply increased organic and Fe/Ti values, as the onset of the Neoglacial brings coarse, sand-sized minerogenic grains, linked to prolonged seasonal lake ice cover and avalanching. From ~1.2 cal kaBP, renewed minerogenic sediments with high Ca, DBD and MS indicators record a rapid transition to renewed glacier growth and downstream meltwater delivery. More recent analysis at Ymer Lake (Møller *et al.*, 2020) shows that microbial communities are tightly clustered along lithological units, effectively tracking Holocene climate transitions. They are also strongly correlated to clastic sediment inputs (identified through Ti values), organic content (LOI), and lake level changes, demonstrating their value for palaeoenvironmental reconstruction, provided that their analysis is set within a clear sedimentological and/or geochemical framework (Møller *et al.*, 2020).

## GIC proglacial lake geochemical analysis of catchment processes

In the reviewed GIC studies, XRF analysis is by far the most widely used geochemical analytical tool and is summarised briefly here to aid further discussion (see below). Elemental data support microstratigraphic analysis by providing signals of ice margin fluctuations within a catchment, as well as binary signals of thickening/downwasting and advance/retreat across topographic boundaries (e.g. Lusas *et al.*, 2017; Medford *et al.*, 2021). It has been used extensively in proglacial lake studies, including at the GrIS margins (e.g. Larsen *et al.*, 2017; Levy *et al.*, 2017; Bjørk *et al.*, 2018). Importantly in the context of this review, elemental shifts have also been used to constrain short-lived or catchment-specific events and processes in GIC forelands, and fingerprinting of exotic grains. The detected elements inherently vary by catchment. The most commonly examined elements and their interpretations are collated in Table 2. Two approaches to data analysis are typically used in the GIC basins, often in tandem.

*Approach 1: A single or small set of elements or elemental ratios that co-vary with macrostratigraphic changes.* Ti is the most commonly used indicator of glacially derived minerogenic sediment (e.g. Larsen *et al.*, 2017, 2019; Levy *et al.*, 2017; Adamson *et al.*, 2019; Axford *et al.*, 2019; Søndergaard *et al.*, 2019; Larocca *et al.*, 2020a, b; Lasher *et al.*, 2020). It has been used in conjunction with other prevalent elements (e.g. Ca, K, Si and Sr) to identify shifts in glacier activity, marine influence (Larsen *et al.*, 2017, 2019) and sediment provenance (van der Bilt *et al.*, 2018), or alongside trace elements (e.g. Ta, Tb, Y and Zr) as indicators of exotic, aeolian inputs (Axford *et al.*, 2019). In some studies, geochemical signatures of short-lived sedimentological perturbations have been used to examine centennial-scale glacier oscillations (e.g. Medford *et al.*, 2021) and stochastic events such as mass wasting, high precipitation in-wash, or outburst floods (e.g. van der Bilt *et al.*, 2018). In instances where XRF reaches the limits of its capabilities to differentiate depositional phases, XRD, which establishes mineralogical composition, has also been used to discern catchment sediment sources (van der Bilt *et al.*, 2018; Adamson *et al.*, 2019).

**Table 2.** Summary table of geochemical parameters used in GIC lake sediment analyses, and examples of their corresponding palaeoenvironmental interpretations

Element(s)	Environmental interpretations	Examples in GIC lake studies
<b>Individual elements</b>		
Ti	Indicative of glacially derived sediment. Higher values are linked to climate deterioration and increased glacier activity/area, and typically inversely correlated to organic indicators (e.g. LOI, TOC).	Larsen <i>et al.</i> , 2017, 2019; Adamson <i>et al.</i> , 2019; Axford <i>et al.</i> , 2019; Søndergaard <i>et al.</i> , 2019; Larocca, <i>et al.</i> , 2020b
Ca	Indicative of glacially derived minerogenic sediment reflecting increased glacial activity due to climatic deterioration. Used to detect changes in sediment provenance (in this example, from the GrIS), especially in catchments with spatially variable lithologies.	van der Bilt <i>et al.</i> , 2018; Adamson <i>et al.</i> , 2019; Axford <i>et al.</i> , 2019; Larocca, <i>et al.</i> , 2020b Axford <i>et al.</i> , 2019
Sr	Higher values correlated with periods of enhanced glacial activity. Co-varies with Ca. Can be used to detect changes in sediment provenance (in this example, from the GrIS), especially in catchments with spatially variable lithologies.	Adamson <i>et al.</i> , 2019 Axford <i>et al.</i> , 2019
K Si	Used alongside Ti to indicate meltwater influx to the lake basin, where higher values correspond to phases of increased meltwater and mineral sediment inputs.	Larsen <i>et al.</i> , 2021
S	Enriched values are indicative of glaciomarine influence. Values decrease in freshwater lacustrine settings.	Larocca, <i>et al.</i> , 2020b
<b>Elemental ratios</b>		
Mn/Fe	Used to indicate lake bed anoxia. Higher values are linked to oxidising conditions.	Adamson <i>et al.</i> , 2019
Fe/Ti	Fe/Ti values are correlated to redox potential of the lake bed through changes in ice cover, grain size coarsening, and/or increased frequency of mass wasting events.	van der Bilt <i>et al.</i> , 2018
Ti/Al	Indicative of detrital mineral sediment, where higher values are associated with increased glacial activity.	Adamson <i>et al.</i> , 2019
Ca/Fe Sr/Ca	Used to examine transitions from marine, brackish, and freshwater lacustrine conditions. Higher values are indicative of stronger marine influence.	Larsen <i>et al.</i> , 2017, 2019, 2021
Rb/Sr	An indicator of catchment chemical weathering, where values are negatively correlated to glaciogenic sediment inputs due to increased supply of Sr from glacial erosion against nonresponsive Rb.	Adamson <i>et al.</i> , 2019
<b>Principal component analysis (PCA)</b>		
<i>Examples of typical elemental groups used for PCA. The resulting PC1 scores are used as a proxy for glacier size/activity, and the principal driver of signal variance, where higher values indicate increased glacier activity.</i>		
Si, Ca, Mn, Fe, Rb, Sr, Ti, K/Ti, Ca/Fe, Sr/Ca		Larsen <i>et al.</i> , 2017
Ti, Si, Ca, Al, Fe, K, Mn, Rb, Sr plus MS, LOI, and density		Larocca, <i>et al.</i> , 2020a
K, Ca, Ti, Mn, Fe, Zn, Rb, Sr		Balascio <i>et al.</i> , 2015
Si, K/Ti, Ca, Mn, Fe, Rb, Sr plus MS, LOI and density		Schweinsberg <i>et al.</i> , 2018, 2019
K/Ti used to dampen fluctuations due to water content		
Zn, Si, K, Ca, Ti, Mn, Fe, Zn, Rb		Schweinsberg <i>et al.</i> , 2017
<b>Elemental suites</b>		
Ta, Tb, Y, Zr	Aeolian input from areas of exotic lithologies.	Axford <i>et al.</i> , 2019
Ca, K, Si, Mn, Sr	Rock forming elements used to indicate entrainment of minerogenic sediment, reflecting increased glacial activity/area related to inferred climate deterioration.	Axford <i>et al.</i> , 2019

GIC: Greenlandic ice cap; GrIS: Greenland Ice Sheet; PCA: principal component analysis.

**Approach 2: PCA of a suite of elements** that are represented in the catchment geology; co-vary with stratigraphy, MS or LOI; and/or display high signal-to-noise ratios. The leading mode of variance (PCA axis 1) is used as an indicator of ice presence or absence (e.g. Balascio *et al.*, 2015; Schweinsberg *et al.*, 2017, 2018, 2019; van der Bilt *et al.*, 2018; Adamson *et al.*, 2019; Axford *et al.*, 2019), though this approach could mask smaller-scale ice margin fluctuations if considered in isolation. The number and variety of elements used within the PCA varies considerably between studies (Table 2). In some, all detectable elements are utilised (Axford *et al.*, 2019), while in others, a targeted selection is used based on their high signal-to-noise ratios (Schweinsberg

*et al.*, 2017, 2018, 2019), abundance in bedrock and lake sediment (Adamson *et al.*, 2019; Larocca, *et al.*, 2020a, b) and correlation with the leading mode of variance (Balascio *et al.*, 2015).

## Discussion: catchment changes and their imprints on GIC proglacial lake records

In addition to climate-driven glacier mass balance changes, the GIC lakes reviewed here record a range of glacier characteristics, catchment processes and lake conditions (Table 3, Fig. 7). In some cases, these have modified the mass

**Table 3.** A summary of key catchment-wide and in-lake conditions and processes identified in the reviewed GIC studies and discussed in the text, and their impact on proglacial lake sediment archives. These are represented schematically in Fig. 7

Catchment process or characteristic	Impact on sediment input to proglacial lakes
Percentage glacial cover and size of proglacial zone	<ul style="list-style-type: none"> <li>• Sediment supply and availability</li> <li>• Distribution, storage, and accessibility of sediment across foreland</li> </ul>
Topography (e.g. slopes, proglacial geomorphology)	<ul style="list-style-type: none"> <li>• Mass movement and colluvial inputs to proglacial zone</li> <li>• Distribution, storage and accessibility of sediment across foreland</li> <li>• Influences meltwater routing to the lake basin due to topographic and/or geomorphological boundaries</li> </ul>
Landscape stability and vegetation cover	<ul style="list-style-type: none"> <li>• Mobility of glacial, fluvial, and colluvial material</li> <li>• Influences frequency and magnitude of sediment movement</li> </ul>
Deflation	<ul style="list-style-type: none"> <li>• Mobilisation of fine-grained sediments</li> <li>• Influences frequency and magnitude of sediment movement</li> <li>• Inputs of nutrients (N and P)</li> </ul>
Surface runoff including flood events	<ul style="list-style-type: none"> <li>• Coarse-grained sediment movement</li> <li>• Influences frequency and magnitude of sediment movement</li> </ul>
Lake process or characteristic	Impact on sediment input and the sedimentary record
Ice margin proximity: ice marginal/proximal	<ul style="list-style-type: none"> <li>• Grain size decreases with distance from the ice margin</li> <li>• Ice-calving events and deposition of ice-rafted debris</li> </ul>
Ice margin proximity: ice distal	<ul style="list-style-type: none"> <li>• Grain size decreases with distance from the ice margin</li> <li>• 'Conveyance loss' or dilution of glacial signals, and potential for enhanced catchment inputs</li> <li>• Quiescent conditions conducive to fine sediment structure formation and preservation, including fine laminations and varves</li> </ul>
Lake ice cover	<ul style="list-style-type: none"> <li>• Influences sediment routing into the lake (e.g. surface runoff)</li> <li>• Enhanced lake ice cover can lead to greater inputs of windblown grains</li> </ul>
Water residence time	<ul style="list-style-type: none"> <li>• Longer residence times facilitate settling of the finest clays to lake bed and therefore increases the potential for higher resolution archives</li> </ul>
Stratification or mixing of the water column	<ul style="list-style-type: none"> <li>• Overturning, oxygenation</li> <li>• Influences the formation of seasonal layers (varves)</li> </ul>
Inputs of comminuted sediment	<ul style="list-style-type: none"> <li>• Can lead to obscuration of the water column and reduced organic productivity</li> <li>• Inputs of nutrients (N and P)</li> </ul>
Lake bathymetry and lake-level change	<ul style="list-style-type: none"> <li>• Influences spatial continuity of the sedimentary record</li> <li>• Low water levels, proximity to inflows and slumping of sediment leads to reworking of sediment at the lake bed</li> <li>• Influences the formation of seasonal layers (varves)</li> </ul>

GIC: Greenlandic ice cap.

balance signal, but in many have also provided an additional layer of palaeoenvironmental information. This is especially valuable in rapidly changing Greenlandic forelands where short-lived or localised events are not routinely captured in the geomorphological or macrosedimentological record and can thus be overlooked. The following discussion examines the ways that these drivers are manifest in GIC proglacial lakes, our ability to isolate these signals analytically, and how they can enhance palaeoenvironmental reconstructions.

## Glacier behaviour and characteristics

### Macrostratigraphic indicators of glacier advance and retreat

The GIC sites contain typical Quaternary proglacial lake successions of clastic and organic units, reflecting glacially and non-glacially dominated conditions, respectively (Figs. 3–6). Average GIC lake sedimentation rates (Table 1) range from 0.914 mm a<sup>-1</sup> (Lake N1) to as low as 0.054 mm a<sup>-1</sup> (Pauiaivik), consistent with modern accumulation rates in Icefall Lake (0.19–0.42 mm a<sup>-1</sup>, Hasholt *et al.*, 2000). We acknowledge, as discussed in many studies, that accumulation rates varied considerably, and in some basins increased by an order of magnitude during phases of enhanced glacier activity.

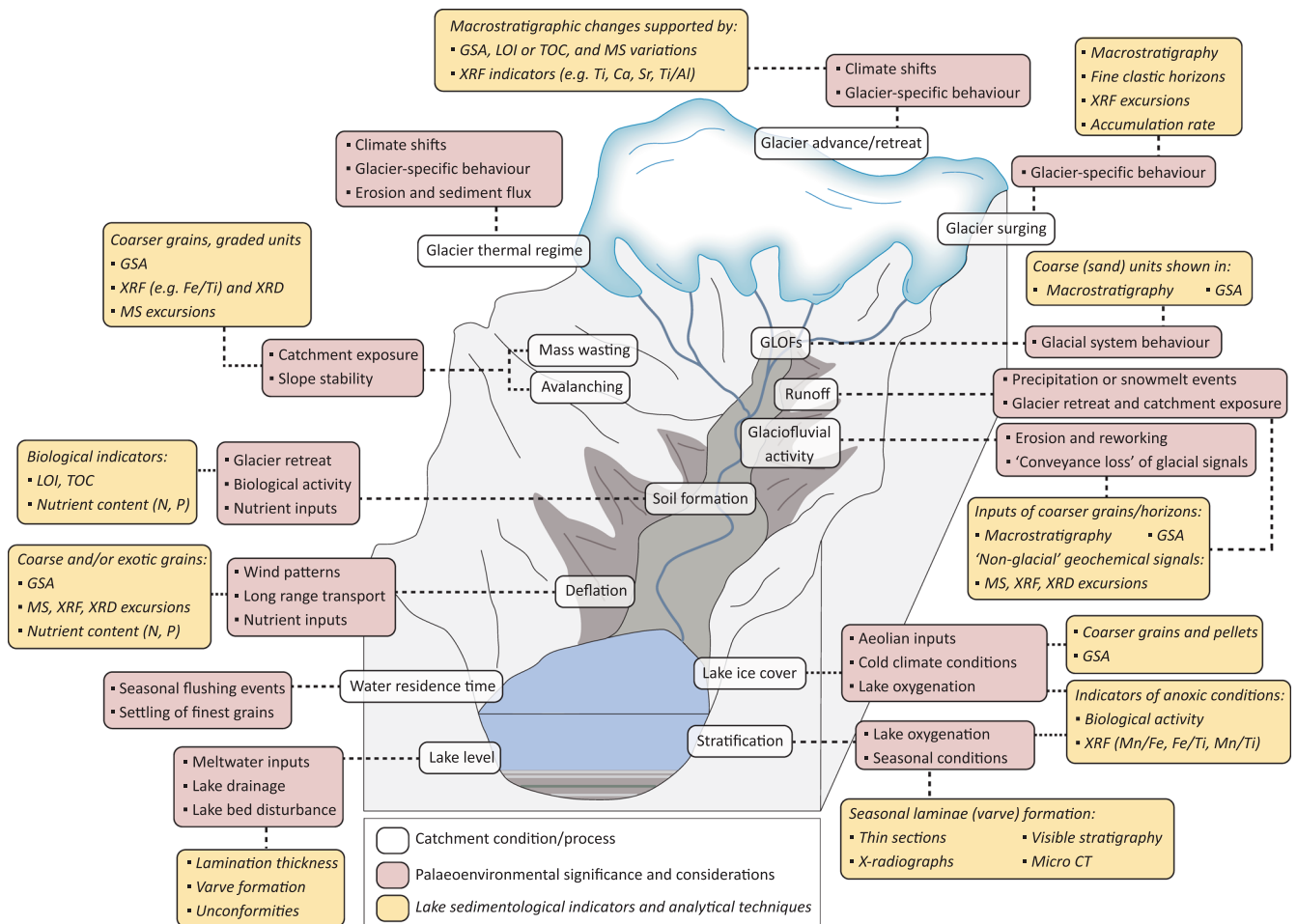
In the GIC records, macrostratigraphic shifts are almost always accompanied by high-amplitude geochemical variations (Balascio *et al.*, 2015; Levy *et al.*, 2017; Schweinsberg *et al.*, 2019; Medford *et al.*, 2021). Thick organic units are

present in many basins, where they are often attributed to ice disappearance from the catchment. Organic deposits are frequently referred to as gyttja, despite large variations in the reported organic content (as LOI %) from as little as ~4–6% (Larsen *et al.*, 2017; Larocca *et al.*, 2020a) to ~30% (Lusas *et al.*, 2017). Definitions vary, but gyttja *sensu stricto* is considered to contain >12% organic matter (see Łachacz and Nitkiewicz, 2021). Where LOI values are especially low, but the GIC is thought to have receded, the source of clastic material is not always addressed. These discrepancies have implications for meaningful comparisons between records, especially where interpretations lean heavily on LOI values, and greater standardisation is needed in this regard.

### Smaller-scale indicators of glacier behaviour

Beyond macrostratigraphic indicators of ice advance/retreat, detailed mineral sediment analyses have also been used to investigate other aspects of glacier behaviour. At Saqqap Tasersua, Schweinsberg *et al.* (2019) note a major increase in XRF PC1 scores without an accompanying sedimentological shift. The authors posit either a significant change in glacier behaviour, such as surging, or a mass movement event depositing large volumes of clastic sediment. Due to limited evidence of surging in the Qangattaq Ice Cap region, and limited sedimentological grading, the growth of multiple large outlets is considered a more likely driver of the observed stratigraphy. We know from monitoring studies that glaciers





**Figure 7.** Schematic diagram of catchment processes and sediment sources discussed in Greenlandic ice cap studies (white boxes), their palaeoenvironmental significance (pink boxes), sedimentary signatures and typical analytical methods used to identify them (yellow boxes). GSA: grain size analysis, LOI: loss on ignition, TOC: total organic carbon, MS: magnetic susceptibility, XRF: X-ray fluorescence, XRD: X-ray diffraction. [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

can undergo rapid, short-term, mass balance changes that transform catchment hydrology and sediment flux over decadal to subannual timescales (e.g. Knight *et al.*, 2000), including surge-type behaviour. It raises valuable questions for other locations where surge activity is likely, of which there are many in Greenland (see Sevestre and Benn, 2015), regarding how these signals are recorded and identified in glaciolacustrine sediments.

#### Ice thickness and thermal regime

Many of the GICs examined here are likely polythermal, with some high-latitude, cold-based exceptions, such as North Ice Cap (Axford *et al.*, 2019). Changes in basal thermal conditions in response to climate change and associated thickening/downwasting, can transform glacier erosive capacity and downstream sediment transfer. At Deltasø, Axford *et al.* (2019) note the low suspended sediment concentrations in modern-day meltwater channels draining North Ice Cap, due to its cold-based, non-erosive regime. At some sites, low clastic sediment accumulation rates in the palaeorecord are therefore not necessarily indicative of glacier absence and may instead reflect glacier thermal characteristics. In such cases, low-magnitude sedimentological and geochemical perturbations could indicate sizeable glacial and environmental change. Where lake conditions are favourable (see below), thermal regime shifts would surely register in the GIC

lacustrine archives, but reliably isolating these signals from background glacial and catchment inputs, as well as lake conditions, has not yet been examined.

In many of the GIC studies, a focus on reconstructing ice marginal position means that glacier thickness and hypsometry, including their links with thermal regime, are less frequently discussed, not least due to the inherent scarcity of ice thickness indicators, especially in ice cap interiors. Nonetheless, a consideration of glacier geometry, and its impacts on subglacial erosion and sediment production can enhance our palaeoenvironmental reconstructions. As well as constraining the ice marginal position (e.g. Bone Lake, Lusas *et al.* 2017), sedimentological and geochemical fingerprints from threshold lakes have also been used by Medford *et al.* (2021) to reconstruct ice thickness and subsequent meltwater routing of Renland Ice Cap. This study, amongst others reviewed here, highlights the influence of topography on the real and perceived sensitivity of lake records and their (a)synchronicity (Larsen *et al.*, 2021; Medford *et al.*, 2021). At some sites, lakes lie in topographically sensitive locations where a few hundred metres of glacier retreat causes ice to exit the catchment and meltwater inputs to cease, causing a rapid change in lake sedimentology (e.g. Medford *et al.*, 2021). In such locations, ice may have persisted outside of the catchment, but with meltwater routed elsewhere such that glacier fluctuations beyond the drainage basin are not captured in the lacustrine record (Larsen *et al.*, 2021). At others,

prolonged retreat or downwasting in the catchment means that meltwater flow is sustained and lake sediment transitions are more protracted (e.g. Adamson *et al.*, 2019). Topographic setting therefore dictates, to some extent, the interpretational limits of the lacustrine archive. This exemplifies the necessity of careful site selection, the use of multiple lakes where feasible, coupled with clear catchment and process understanding, to maximise glacial and palaeoenvironmental reconstructions (Larsen *et al.*, 2021, Medford *et al.*, 2021).

### *Catchment characteristics and sediment sources*

Modern summer suspended sediment yields from Greenlandic glacierised catchments are typically 84–1500 t km<sup>-2</sup> yr<sup>-1</sup>, compared with 1–56 t km<sup>-2</sup> yr<sup>-1</sup> in ice-free basins (Hasholt *et al.*, 2000). In these transient landscapes, with vast volumes of material stored and released periodically, multiple parameters influence sediment reworking and transfer to proglacial lake basins, in the present day and during the Holocene (Knight *et al.*, 2000; Hasholt and Mernild, 2006; Table 3). This includes topography and land surface stability (Knight *et al.*, 2000; Hasholt and Mernild, 2006), proglacial geomorphology (Knight *et al.*, 2000), vegetation cover (Anderson *et al.*, 2018; Stevenson *et al.*, 2021; Wojcik *et al.*, 2021), aeolian processes (Adamson *et al.*, 2014; Stevenson *et al.*, 2021), and glaciofluvial and surface runoff (Hasholt *et al.*, 2000). These have the potential to obscure the incoming glacial signal, not least because with increasing distance from the ice margin the potential for ‘conveyance loss’ of the primary glacial sediment signal increases, as has been suggested for modern Greenlandic proglacial lakes (Hasholt *et al.*, 2000; Hasholt and Mernild, 2006). What is more, distinguishing ‘primary’ glacial signals from secondary (para-glacial) reworked material can be challenging, especially in catchments with uniform bedrock lithology where sediments produced over multiple glacier advance–retreat phases are physically and geochemically similar. However, several studies reviewed here show that with careful analysis catchment processes can be identified.

### *Catchment runoff, slope processes and sediment reworking*

In some basins, catchment sediment inputs are considered minimal in instances where soil cover is thin (e.g. Langesø and Badesø, Larsen *et al.*, 2017, and Smaragd Sø, Larsen *et al.*, 2021) or slope angle is relatively low (e.g. Kulusuk Lake, Balascio *et al.*, 2015). However, GIC lakes on Disko Island (Table 1) show that even in regions with limited or patchy soils, post-LIA warming has prompted large changes in lake conditions due to soil organic matter cycling and glaciofluvial erosion (Stevenson *et al.*, 2021). Catchment glacier cover, soil and vegetation type are considered to be closely tied to water quality and lake biological activity and can determine lake system response to perturbation (Anderson *et al.*, 2018; Stevenson *et al.*, 2021). In particular, changes in meltwater regime and land surface exposure since the LIA have transformed lake sediment inputs and nutrient levels, promoting algal growth (Stevenson *et al.*, 2021). These processes also undoubtedly influenced catchment sediment transfer during Holocene warm phases. Their signatures in proglacial lakes, and corresponding palaeoenvironmental implications should not be overlooked, and are discussed further below.

Runoff-derived, reworked mineral grains embedded in organic-rich horizons were successfully differentiated from glacial sediments using MS values in Two Move (Levy

*et al.*, 2014) and Kulusuk lakes (Balascio *et al.*, 2015). XRF and XRD signatures have also been used to resolve catchment vs glacial inputs. At Madsen Lake, mineral fingerprinting using cluster analysis isolated late Holocene glacier activity from ‘background’ sedimentation, considerably extending the morphosedimentary record to identify a minor phase of enhanced glacier activity (Adamson *et al.*, 2019). In Ymer Lake, a period of increased avalanching was identified via coarse grain sizes and accompanying LOI and Fe/Ti excursions and linked to cool Neoglacial conditions (van der Bilt *et al.*, 2018). A later phase of snowmelt-driven flood events was also identified via distinctive particle size distributions. In the same lake, a GLOF event in the upper catchment was identified as a discrete sand horizon, elucidating glacial retreat and gorge incision during early Holocene deglaciation.

### *Catchment-derived and far-travelled aeolian inputs*

In addition to runoff, aeolian dust is a major component of labile glacial forelands, abundant in comminuted sediment stored within glacial and glaciofluvial landforms (Knight *et al.*, 2000; Bullard and Mockford *et al.*, 2018; Stevenson *et al.*, 2021). On Disko Island, Stevenson *et al.* (2021) highlight the importance of windblown material for lake N and P inputs, and thus lake chemistry. At Deltasø, far-travelled deflated sediment is shown through exotic elemental indicators (e.g. Ta, Tb and Y, Axford *et al.*, 2019). Windblown material in Ymer Lake is identified through grain size analysis and linked to changing wind patterns and enhanced lake ice cover which facilitates coarse sediment transport across lake surfaces (van der Bilt *et al.*, 2018). Prolonged ice cover, especially during the coldest or driest parts of the Holocene, would increase the potential for aeolian inputs (Adamson *et al.*, 2019). What is more, pellets of fine sand identified in Two Move Lake (Levy *et al.*, 2014) may represent rain out of material from a frozen lake surface, though this was not explored in the original study. In contrast to cold-climate indicators, aeolian inputs to Snowbank and Round lakes, identified through MS excursions and grain size, correspond to known warm conditions (Lusas *et al.*, 2017).

The examples discussed above demonstrate that even if catchment sediment contributions are small, when constrained via appropriate sedimentological or geochemical methods, they offer insights into local land surface processes (runoff, flooding, avalanching) that can be tied to regional climatic conditions (wind patterns, aridity, temperature).

### *Lake conditions*

Understanding lake physical and biogeochemical conditions have proven valuable in the GIC studies because: (1) these conditions can temper the incoming climate/glacial signal, in some instances producing contrasting stratigraphies even within neighbouring basins fed by the same GIC (e.g. Lusas *et al.*, 2017; Schweinsberg *et al.*, 2017, 2019); (2) lake size can determine the formation and preservation of fine-scale (sub-millimetre), high-temporal resolution sedimentary structures such as varves; and (3) when effectively identified in the sedimentological and geochemical records, they have enhanced the understanding of in-lake (e.g. water level, stratification) and catchment-wide (e.g. glacier proximity, fluvial inputs) processes and conditions.

### *Lake size and its impacts on microstratigraphy*

Lake level variation, and its impacts on water residence time and water column stratification, has not been widely discussed

in the GIC studies, but in some basins likely fluctuated considerably over the Holocene, primarily in response to glacier growth and decay. However, some studies have identified changes in lake level linked to climate patterns (Thomas *et al.*, 2018), meltwater rerouting (Medford *et al.*, 2021) and seasonal melt inputs (e.g. Stevenson *et al.*, 2021).

At Icefall and Kuutuaq lakes, modern-day residence times vary in the order of months (5–15 days and 20–60 days, respectively), meaning that the finest clays are unlikely to be captured in the sedimentary record (Hasholt *et al.*, 2000). At Sikuiui Lake (summer residence time ~60 days) there is evidence of strong flushing of lake waters by spring snowmelt and summer rain (Schweinsberg *et al.*, 2017), likely hindering seasonal stratification and deposition of fines.

The vast majority of the GIC cores examined here are from small (<0.5 km<sup>2</sup>) shallow basins that are unlikely to support long-term lake stratification. It is unsurprising, therefore, that only two sequences, from two of the largest lakes (Noa Sø and Sifs) contain annually laminated sediments (varves) (Wagner and Melles, 2002; Möller *et al.*, 2010). Several other sites contain laminated units (Figs. 5 and 6), and fine-grained couplets are reported at Two Move Lake (Levy *et al.*, 2014) and Bone Lake (Lusas *et al.*, 2017), but these are not considered true varves and were not examined further in the original studies. At Kuutuaq and Icefall lakes, no significant relationships were found between modern varve thickness and air temperature, and by extension short-term glacier behaviour (Hasholt *et al.*, 2000), highlighting the important contribution of a climatic controls on lacustrine sedimentation patterns (varved or otherwise), in addition to climate-driven macrostratigraphic variation. Fine laminae are therefore especially important from an analytical perspective because they record palaeoenvironmental processes and conditions at an unrivalled resolution. Several GIC sites have successfully identified these horizons using X-radiographs (Lusas *et al.*, 2017; Schweinsberg *et al.*, 2017), CT scanning (van der Bilt *et al.*, 2018), and thin section micromorphology (Levy *et al.*, 2014), to reveal considerable 'hidden' microstratigraphic detail, but they have not always been analysed fully.

Finally, in some topographic settings small changes in ice-marginal position have caused rapid transitions between high-energy, high-sedimentation, ice-proximal regimes and quiescent organic sedimentation (e.g. Lusas *et al.*, 2017; Axford *et al.*, 2019). In these cases, ice-distal, low-energy, stratified lake conditions that favour the formation and preservation of delicate laminae may be short lived or unattainable (Palmer *et al.*, 2019; Zolitschka *et al.*, 2015). What is more, post-depositional sediment disturbance has been documented in the GIC lakes via fluvial reworking, slumping of delta foresets, and wind currents in especially shallow lakes (e.g. Hasholt *et al.*, 2000; van der Bilt, 2018; Medford *et al.*, 2021). It is possible, therefore, that fine laminations exist in other basins, at least intermittently, but have not been identified, especially where the sedimentation rate is low and they are not apparent in the visual stratigraphy.

#### Lake biogeochemistry

Glacial meltwater influences lake chemistry through nutrient release, turbidity of the water column, and resulting productivity (Anderson *et al.*, 2018; Schweinsberg *et al.*, 2018; McFarlin *et al.*, 2019; Stevenson *et al.*, 2021). These processes, coupled with broader catchment palaeoenvironmental change, can be identified in the sedimentary record. For example, geochemical variations paired with sedimentological indicators are widely used to examine changes in lake

conditions (see Table 3), including marine influence (Ca/Fe and Sr/Ca, Larsen *et al.*, 2017), lake stratification and anoxia (Mn/Fe, Adamson *et al.*, 2019).

Though not yet widely applied in GIC studies, biomarker analysis and DNA sequencing have been used to examine the interplay between regional climate drivers, GIC behaviour and lake conditions. At Sikuiui Lake, brGDGTs have constrained regional temperatures, aridity and moisture sources as well as local conditions (Thomas *et al.*, 2018). At Ymer Lake, large variations between microbial populations in adjacent basins, despite identical climate drivers, highlight the importance of local conditions for biological processes and the resulting palaeorecord. Two key in-lake parameters were found to strongly influence microbial communities. First, lake depth, also discussed above from a sedimentological perspective, can influence redox conditions (shown by LOI, Fe/Ti and Mn/Ti values). Second, minerogenic sediment inputs were found to strongly control microbial activity (Møller *et al.*, 2020), where increased water turbidity stifles biological productivity (Anderson *et al.*, 2018 and McFarlin *et al.*, 2019). The lakes examined here highlight the fact that biogeochemical techniques, when paired with sedimentological analyses, provide opportunities to examine the interplay between climate and earth surface processes, and lake conditions.

## Conclusions and future considerations

Quaternary proglacial lake sequences have been increasingly used to examine the behaviour of GICs. Many existing studies, due to their primary objectives, focus on macrostratigraphic changes driven by climate-conditioned glacier advance–retreat. In contrast, comparatively little attention has been paid to microstratigraphic variations in clastic sediments that can be indicative of catchment-wide and in-lake conditions. These signals are important because they capture landscape processes and local palaeoenvironmental changes that are not typically preserved in other glacial morphosedimentary records.

This review has synthesised sedimentological and geochemical data from over 30 published GIC proglacial lake sequences to examine: (1) the ways that catchment-specific and in-lake conditions are registered in GIC proglacial sediments; and (2) our ability to use detailed sedimentological and geochemical analyses to isolate and understand these signals to enhance palaeoenvironmental reconstructions. From this, we collate existing insights into Holocene GIC catchment behaviour and implications for palaeoclimatic interpretations, as well as opportunities and considerations for expanding this approach in future analyses.

The GIC records showcase the wealth of catchment-derived signals that are embedded within the broader macrostratigraphy and can be successfully used to augment palaeoenvironmental reconstructions, including links to local and regional climate evolution.

First, glacier behaviour such as surging and downwasting has been tested through the use of sediment accumulation rates, grain size and elemental geochemistry. In some settings, it has been possible to tie these sedimentological characteristics to changes in meltwater drainage routing and to substantiate the contrasting behaviour of neighbouring outlet glaciers.

Second, there are clear imprints of catchment processes within many of the GIC lakes, most notably mass wasting, aeolian transportation and wind patterns, snowmelt and runoff. To identify these signatures, studies have combined detailed sedimentological descriptions with specific focus on

the mineral sediment component, including through the use of thin-section micromorphology, CT scanning, and X-radiographs; a clear consideration of catchment context, such as topography and proximity to reconstructed ice margins; and targeted geochemical (XRF, XRD) and MS analyses for sediment provenancing. Several GIC studies demonstrate that catchment processes identified in the microstratigraphy correspond to the palaeoclimatic conditions evident in independent proxy archives, and therefore provide opportunities to interrogate the links between climatic shifts and catchment response.

Finally, lake conditions, including water depth and stratification can influence the production and preservation of the sedimentary record, including the formation of high-resolution laminations and varves. Where such structures have been identified, they are often diagnostic of specific sedimentological and climatic conditions. This includes seasonal variations in lake ice cover and by extension, air temperature, but these archives have not yet been examined in depth in the GIC basins.

It is likely that many GIC lakes contain an array of sedimentological detail that has not yet been fully explored, often because it is not apparent in the visual stratigraphy. Given the small sample size in the GIC lakes, it is not yet feasible to make broader-scale links to Holocene climate patterns. However, the approaches synthesised here, if more widely applied, provide exciting opportunities for future analyses of catchment response to palaeoenvironmental change, not only in Greenland but in glaciated catchments elsewhere.

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