An early Neoglacial moraine at Sanddalen, NE Greenland

JASON P. BRINER & OLE BENNIKE

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The Greenland Ice Sheet experienced a minimum ice volume phase in the middle Holocene. The timing and footprint of this minimum ice configuration remain poorly constrained. This minimum configuration, along with ice-sheet recession into and re-growth out of this minimum ice phase, provide critical constraints of the ice sheet's response to Holocene climate forcing. With few exceptions, the late Holocene expansion across the entire ice-sheet perimeter culminated during the last millennium – a period that encompasses the Little Ice Age. Here we focus on a rare moraine in North-East Greenland to which we assign an age of ~4600 ± 400 cal. yr BP via correlation with local sea level curves. Thus, the moraine post-dates the middle Holocene minimum ice phase yet pre-dates the Little Ice Age by thousands of years. The early Neoglacial age of the moraine attests to this sector of the ice sheet reaching modern day ice-margin configuration as early as ~4.6 ka, which is consistent with findings elsewhere in North-East Greenland.

Keywords: Greenland Ice Sheet, Inland Ice, Holocene, Quaternary, climate change

Jason P. Briner [jbriner@buffalo.edu], Department of Earth Sciences, University at Buffalo, Buffalo, NY, USA. Ole Bennike [obe@geus.dk], Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.

The Greenland Ice Sheet has been losing mass every year this century and is significantly contributing to global sea level rise (Mankoff *et al.* 2021). Even at present global temperature, it has been argued that meters of sea level rise from Greenland is inevitable, leaving 'how long will it take' and not 'how much will sea level rise' as the more relevant question (Stokes *et al.* 2025). Characterizing ice-sheet response to past interglacials is one approach for revealing centennial-scale rates of ice-sheet change under a given climate forcing. The Holocene, when the Greenland Ice Sheet became smaller than it is today, provides the most data-constrained interglacial to target in this quest.

Despite ample geologic evidence revealing a minimal size of the Greenland Ice Sheet during the middle Holocene, the minimum size achieved and the spatiotemporal pattern of its recession and regrowth remain poorly constrained (Larsen et al., 2015; Briner *et al.* 2016). The timing of deglaciation around the present-day ice margin constrains the initiation of smaller-than-present interval. This generally occurred around 7000 yr but is spatially variable (Bennike & Björck 2002; Leger *et al.* 2024). Limited data exist to constrain timing of minimum ice, which is generally 6000–3000 yr (Larsen *et al.* 2016). Some evidence points to spatial heterogeneity in the ice sheet's minimum phase, for example it is thought to have occurred 5000–3000 yr in west-central Greenland (e.g., Cronauer *et al.* 2016), 4000–2000 yr in southwestern Greenland (Young & Briner 2015; Larsen *et al.* 2015) but 8000–4000 yr in North-East Greenland (Larsen *et al.* 2018; Smith *et al.* 2023). The timing of when ice reappears near the present-day ice margin constrains the end of the smaller-than-present interval, which is similarly temporally variable. One challenge in further constraining the end of the minimum ice phase is that there are few moraines demarcating the advance towards the present ice configuration because they were removed during the historic maximum extent during the Little Ice Age (~1250–1900 AD; Kjær *et al.* 2022) with few exceptions (Bennike & Sparrenbom 2007). Thus, instead, the timing of ice approaching present margins is usually based on re-worked organic material amenable to radiocarbon dating, such as overrun vegetation or re-worked material (e.g., Briner *et al.* 2014; Kjær *et al.* 2022) or sedimentary sequences in pro-glacial lakes (e.g., Briner *et al.* 2010; Larsen *et al.* 2011) or ice-dammed lakes (e.g., Smith *et al.* 2023).

Here, we explore a previously described candidate for a pre-LIA moraine at Sanddalen, North-East Greenland (Fig. 1), that post-dates the middle Holocene minimum ice phase (Bennike & Weidick 2001). We map glacial outwash terraces that we interpret to be associated with the moraine of interest and extract their elevations using the Arctic DEM. Finally, we relate these outwash terraces to previously dated relative sea level datasets to derive an age estimate for the Sanddalen moraine.

Glacial geomorphology of Sanddalen

Sanddalen lies between the major distributary outlets of the NE Greenland Ice Stream (Fig. 1). To the south lies Storstrømmen, which bifurcates into southern and northern ocean-calving margins. To the north of Sanddalen lie Zachariae Isstrøm and Nioghalvfjerdsfjorden. At Sanddalen, a smaller outlet glacier is one among a few glaciers draped across a north-south strip of rolling terrain that exists directly downflow of an over-deepening, that when ice free, would contain an inland sound (Morlighem *et al.* 2017). The present ice margin fronts a zone of fresh, unvegetated moraines, the historical moraines deposited during the Little Ice Age. The north terminus of Storstrømmen ended in a floating tongue that extended 24 km beyond the present glacier (2024) margin. Post-Little-Ice-Age recession elsewhere in the region is not as significant, and at Sanddalen it is merely a few 10s of meters. It can be challenging to map the Little Ice Age ice extent around Sanddalen,

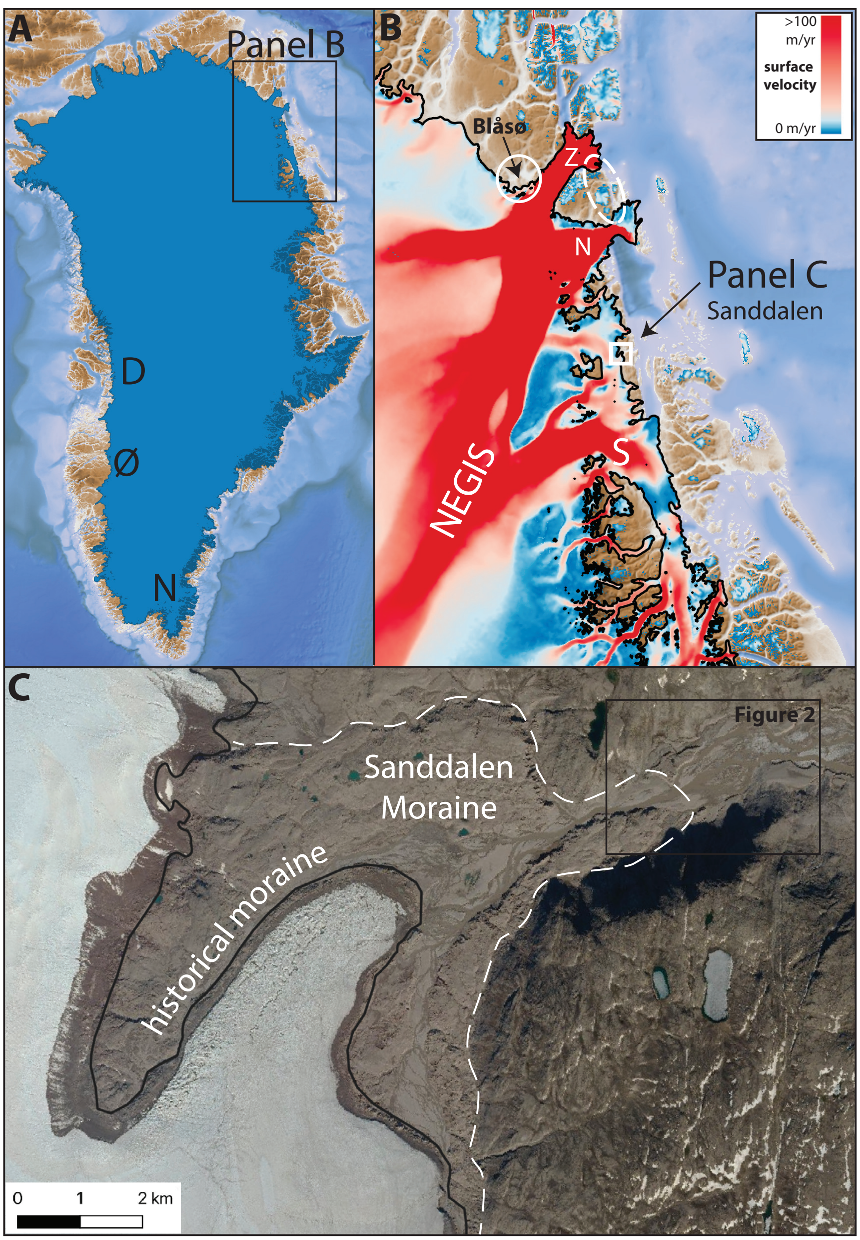

Fig. 1. A. Map of Greenland showing locations discussed in the text; D: Drygalski Moraines; Ø: Ørkendalen; N: Narsarsuak. **B**. NE Greenland showing sites mentioned in text; Z= Zachariae Isstrøm; N= Nioghalvfjerdsbrae; S=Storstrømmen. White circles are sites of relative sea-level curves from Bennike & Weidick (2001) that are discussed in the text. Color represents surface velocity; red: high velocity (Gardner *et al.* 2019). **C**. Satellite image of the historical moraine and the drift sheet of the Sanddalen Moraine at Sanddalen, NE Greenland.

however, because there is a second unvegetated drift sheet that extends farther than the Little Ice Age drift sheet (Fig. 1).

Bennike & Weidick (2001) described the drift as largely unvegetated, ice-cored hummocky moraine covering ~15 km^2 and containing shell fragments up to 200 m a.s.l.. which we herein informally name the 'Sanddalen Moraine'. Between the down-valley drift limit (end moraine) and the sea is a narrow valley with small remnants of outwash terraces above the modern river plain preserved on the northern and southern sides of the modern braid plain (Fig. 2). Where the Sanddalen Moraine crosses the valley bottom, it appears connected with an outwash terrace. Based on mapping the surface geomorphology using the Arctic DEM product (Porter *et al.* 2023), it appears that the terrace is an outwash head that grades directly to the Sanddalen Moraine, and if so, reveals that the deposition of the outwash terraces and the moraine were contemporaneous (Fig. 2). The terrace elevations can be plotted in longitudinal profile, as can the modern river. The profiles of the terraces and river closely parallel each other, with the terraces consistently lying 15 to 18 meters higher than the modern river, including at the present-day coastline fan-delta (Fig. 3).

The relative sea level at the time of the last deglaciation at Sanddalen can be estimated from a raised marine delta that formed at the base of a now-headless glacial meltwater channel. During the last deglaciation, while an ice lobe filled the lower valley, it fed a meltwater channel that spilled southward across a topographic divide, down a ~4-km-long channel ending at a marine delta with a surface that is ~35

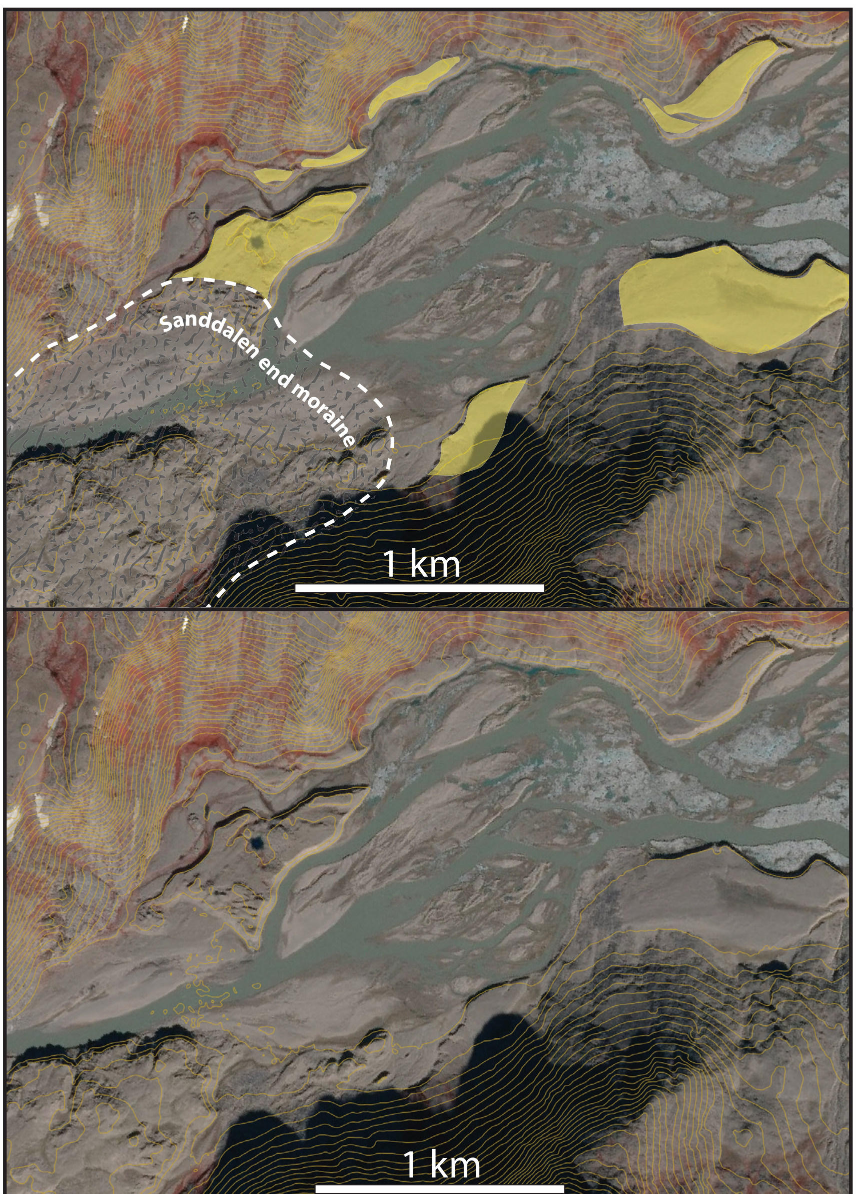

Fig. 2. Top: Sanddalen end moraine and mapped outwash terrace remnants (shown in yellow) the north and south sides of the modern braid plane sourced from the present ice-margin at Sanddalen. Bottom: Uninterpreted image. Contour spacing is 10 m and is used here to clarify topography. North is up in both images. Base image is a mosaic from Sentinel2 (10 m resolution) and Spot (1.6 m resolution) imagery. Map location shown in Figure 1.

m above sea level. This elevation is slightly lower than the marine limit recorded from a location ~10 km south of Sanddalen of 40 m, which connects to other areas with similar marine limit values around the present ice margin to form a 40 m isobase trending north-northeast (Bennike & Weidick 2001).

Age of the Sanddalen Moraine

Bennike & Weidick (2001) obtained six radiocarbon ages from bivalves re-worked into the Sanddalen Moraine. Their ages, ranging from 6100–5500 cal. yr BP, provide a maximum age for the moraine of ~5500 cal. yr BP. Relative sea-level curves allow for dating of events not otherwise directly dated if their relation to sea level is known (e.g., Mangerud *et al.* 2019). Bennike & Weidick (2001) constructed several relative sea level curves for the terminus areas of Zachariae Isstrøm and Nioghalvfjerdsfjorden. These relative sea level histories are constrained by radiocarbon ages of uplifted marine sediments not always with a direct tie to sea level and thus are not based on sea level index points. Nevertheless, the curves are drawn to

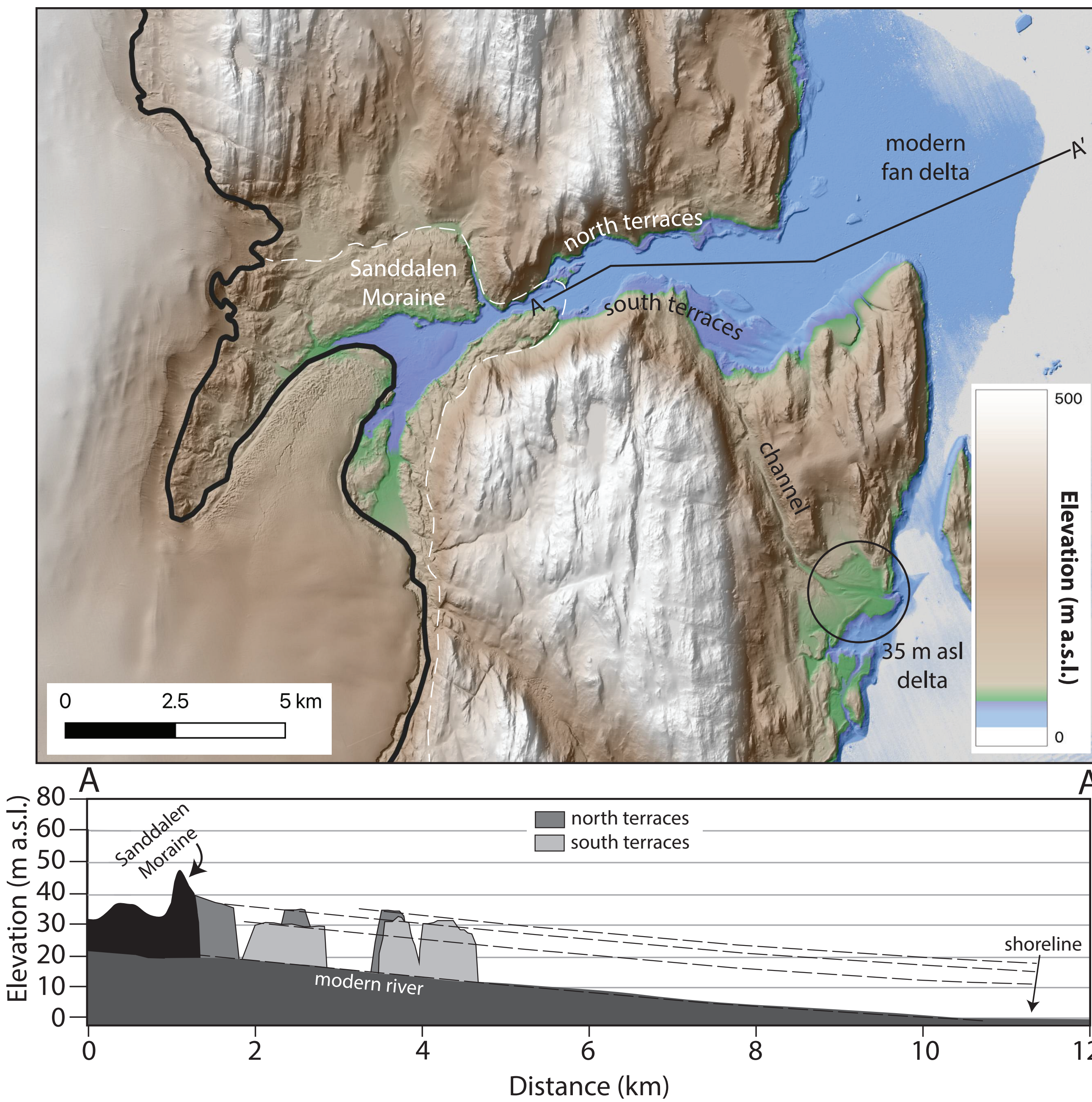

Fig. 3. Map showing elevation of Sanddalen region, location of Sandalen Moraine and terraces in the outflow valley between the glacier at Sanddalen and the sea. Bottom shows topographic profiles of the modern river and raised outwash terraces.

encompass the radiocarbon ages from raised marine material and thus provide useful approximations for the shape and history of relative sea level. Bennike & Weidick (2001) also provide nine radiocarbon ages from uplifted marine sediments closer to Sanddalen, ranging in elevation from 2 to 40 m a.s.l., but did not formulate them into a relative sea level curve. We also do not use these ages to formulate a relative sea level curve, but plot them alongside the curves from Blåsø and Nioghalvfjerdsfjorden (Fig. 1), which reveals a close correspondence and indicates that the relative sea level curves from farther north generally apply to the Sanddalen region (Fig. 4).

Collectively, the relative sea level histories can be used to constrain the age of the 35 m a.s.l. delta and the outwash terraces between the Sanddalen Moraine and the coast. Using the relative sea level curve from inner Nioghalvfjerdsfjorden that lies along the same 40 m isobase but from slightly north of Sanddalen (Bennike & Weidick 2001), we estimate the 35 m a.s.l. delta to be ~7000 cal. yr BP. When considering the other relative sea level histories from Bennike & Weidick (2001), the age could be as young as ~6500 cal. yr BP. The Sanddalen Moraine outwash terraces, which lie 15–18 m a.s.l., intercepts the inner Blåsø sea level curve from 5000 to 4200 cal. yr BP, with an average intercept age of 4600±400 cal yr. BP (Fig. 4). Radiocarbon ages from raised marine fauna at Sanddalen support the use of the Blåsø relative sea level curve (radiocarbon ages have been recalibrated using Marine20; Heaton *et al.* 2020). Using the broader collection of relative sea level curves, the age could be as young as ~3500 cal. yr BP. Such an age assignment of ~4600 ± 400 cal. yr BP for the Sanddalen Moraine is consistent with its maximum age based on the reworked bivalves of ~5500 cal. yr BP.

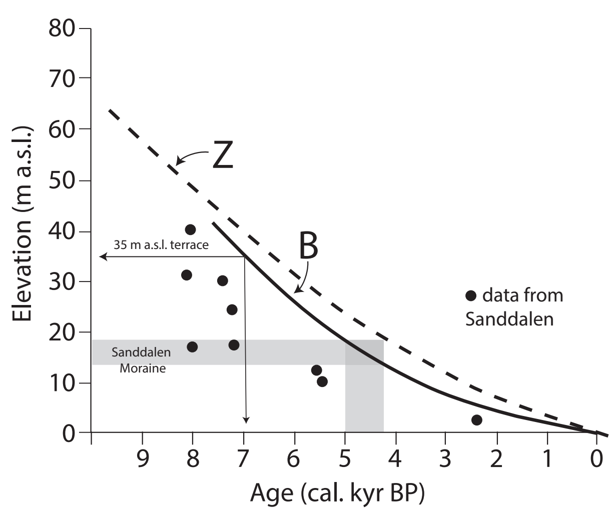

Fig. 4. Relative sea level curves (B: Blåsø; Z: from near the Zachariae Isstrøm terminus) from Bennike & Weidick (2001); locations of sites where these curves are derived is shown in Fig. 1. Black data points are radiocarbon dated marine samples in the Sanddalen area (from Bennike & Weidick 2001). Gray shading demarcates the elevation range of outwash terraces that grade to the Sanddalen Moraine.

Discussion

The proposed ~4600-year-old Sanddalen Moraine would be the oldest Neoglacial moraine yet identified from the Greenland Ice Sheet. Several moraines previously thought to be Neoglacial have since been directly dated to be from the last deglaciation. These include the Drygalski Moraines near Disko Bugt thought to be ~3000 yr old (Weidick 1968; Kelly 1980). They have since been dated to ~8600–7600 yr with ^{10}Be dating (Cronauer *et al.* 2016). The Ørkendalen Moraine System east of Kangerlussuaq, suggested by Forman *et al.* (2007) to contain a 2000-year-old moraine, have since been more directly dated with ^{10}Be dating to ~6800 yr (Levy *et al.* 2012). The Narsarsuaq moraines, South Greenland, remain the exception. Radiocarbon dated lake sediments and direct ^{10}Be dating consistently date the moraines to ~1500 yr (Bennike *et al.* 2007; Winsor *et al.* 2014; Larsen *et al.* 2016). In west central Greenland, directly dated local glacier moraines have ages between ~1500 and ~1000 yr, not too dissimilar in age from the Narsarsuaq moraines (e.g., Young *et al.* 2015; Schweinsberg *et al.* 2019).

Evidence that the Greenland Ice Sheet reached the approximate location of the present margin as early as ~4600 cal. yr BP is consistent with other findings in North-East Greenland. Bennike & Weidick (2001) presented radiocarbon ages from the inner and central parts of Nioghalvfjerdsfjorden (up-valley from the present terminus) based on mollusc shells, bones of marine mammals and driftwood from raised marine deposits adjacent to the fjord. The ages range from ~7700–4400 cal. yr BP, revealing a smaller-than-present ice configuration spanning that interval. The older end of this age range (a close constraint for deglaciation timing) was later bolstered by ^{10}Be dating deglaciation in this region, first by Larsen *et al.* (2018) who reported ages of ~9.3 ± 0.4 ka, and later by Roberts *et al.* (2024) who reported an age range of 9.0 to 8.2 ka; these ages supported earlier radiocarbon ages that provided minimum constraints on deglaciation of ~9700–7700 cal yr BP (Bennike & Weidick 2001). Smith *et al.* (2023) reconstructed the Holocene dynamics of the Nioghalvfjerdsfjorden ice shelf via radiocarbon dating raised glaciomarine sediments and sediment core analysis from Blåsø, a large epishelf lake up-valley of the present grounding line. Their reconstructions suggest that the ice shelf experienced a minimum phase between 8.5 and 4.4 cal. ka BP leaving open marine conditions where

Nioghalvfjerdsbræ currently resides. The ice shelf reformed at Blåsø after 4.4 cal. ka BP, reaching a thickness similar to present by 4.0 cal. ka BP. The history of the ice margin at Sanddalen is highly consistent with the findings of Smith *et al.* (2023).

The 35 m a.s.l. ice-fed delta down-valley from the present ice margin at Sanddalen is suggestive of an ice advance farther down valley than the advance that deposited the Sanddalen Moraine. The elevation is ~5 m lower than the local marine limit, which is dated to ~8000 cal. yr BP (Bennike & Weidick 2001). The estimated age of ~7400 cal. yr BP (7475 yr before today) is similar to a mode of moraine deposition in areas around Baffin Bay (Young *et al.* 2021) and may be related. Regardless, if a glacier around the present margin existed ~7400 cal. yr BP, and then again ~4300 yr BP, it constrains the smaller-than-present ice phase to between these two ages.

There is some surging glacier behavior in northern Greenland (Hill *et al.* 2017; Andersen *et al.* 2025), and it is possible that the Sanddalen Moraine is the result of a surge, hence its unusual occurrence. Andersen *et al.* (2025) suggest that Storstrømmen is one of the largest surging glaciers in the world, and its surge lengths in the 20th century were ~10 km. We thus infer that a surge of the glacier at Sanddalen, if any, would likely have been initiated from a position relatively nearby, likely much less than 10 km away. Surge or no surge, we suggest that the Greenland Ice Sheet had attained a near-present-day ice configuration following a period of reduced size by ~4600 cal. yr BP.

Conclusion

The NE Greenland Ice Sheet margin experienced a minimum ice phase between ~7400 and 4600 cal. yr BP. The Sanddalen Moraine provides evidence for expansion of ice slightly beyond the present-day ice configuration ~4600 cal. yr BP, the earliest moraine yet identified that post-dates the Holocene minimum ice phase. It is possible that a surge is partly the reason why the ice margin may have been so extensive at this time. Even so, such a surge would likely have initiated from a baseline position near-present-day ice configuration at ~4600 cal. yr BP. The timing of when NE Greenland Ice Stream outlets experienced a minimum ice phase from ~7.7 to ~4.3 cal. ka BP differs from the ice-sheet minimum phase elsewhere, for example ~5.0–3.0 cal. ka BP in central-west Greenland (Larsen *et al*. 2015; Young *et al*. 2015; Cronauer *et al*. 2016). Such spatiotemporal variability likely stems from both differing climate-forcing and ice-sheet behavior, and should be the focus of future investigations.

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