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^{10}Be dating reveals early-middle Holocene age of the Drygalski Moraines in central West Greenland

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ABSTRACT

We reconstruct the history of the Greenland Ice Sheet margin on the Nuussuaq Peninsula in central West Greenland through the Holocene using lake sediment analysis and cosmogenic ^{10}Be exposure dating of the prominent Drygalski Moraines. Erratics perched on bedrock outboard of the Drygalski Moraines constrain local deglaciation to $\sim 9.9 \pm 0.6$ ka ($n = 2$). Three Drygalski Moraine crests yield mean ^{10}Be ages of 8.6 ± 0.4 ka ($n = 2$), 8.5 ± 0.2 ka ($n = 3$), and 7.6 ± 0.1 ka ($n = 2$) from outer to inner. Perched erratics between the inner two moraines average 7.8 ± 0.1 ka ($n = 2$) and are consistent with the moraine ages. Sediments from a proglacial lake with a catchment area extending an estimated 2 km beneath (inland of) the present ice sheet terminus constrain an ice sheet minimum extent from 5.4 ka to 0.6 ka. The moraine chronology paired with the lake sediment stratigraphy reveals that the ice margin likely remained within ~ 2 km of its present position from ~ 9.9 to 5.4 ka. This unexpected early Holocene stability, preceded by rapid ice retreat and followed by minimum ice extent between ~ 5.4 and 0.6 ka, contrasts with many records of early Holocene warmth and the Northern Hemisphere summer insolation maximum. We suggest ice margin stability may instead be tied to adjacent ocean temperatures, which reached an optimum in the middle Holocene.

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1. Introduction

Concerns about global climate change involve the response of climatically sensitive regions like the Arctic, including response of the Greenland Ice Sheet (GrIS), to increases in global temperature (Vaughan et al., 2013). The GrIS is estimated to contain the equivalent of ~ 7.4 m of global sea level rise (Morice et al., 2012) and $\sim 10\%$ of the global population lives in low elevation coastal areas, implying high potential for future socio-economic impact should sea level rise continue (Oliver-Smith, 2009). Reconstructing past ice sheet margins is useful for assessing how the GrIS has responded to past climate changes (such as warm and cold times during the

Holocene), as well as for testing ice sheet models used for projections of future sea level rise (Applegate et al., 2012).

Fundamental gaps in our knowledge of GrIS fluctuations throughout the Holocene hamper our ability to assess its response to past climate change. Records of both temperature and ice margin fluctuations throughout the Holocene are increasingly documented, but geomorphic evidence of ice sheet extent during the middle-to-late Holocene is sparse because it is often buried beneath the present extent of the GrIS (Funder et al., 2011). The paucity of moraines preserved from pre-Little Ice Age (LIA; 1200–1900 AD) middle-to-late Holocene glaciation limits our understanding of GrIS margin response during a period of climate transition from warmer to cooler conditions (Kaufman et al., 2004; Marcott et al., 2013).

There are few locations in Greenland that contain ice sheet moraines mapped outboard of the LIA extent that are associated with or dated to the middle or late Holocene (Weidick, 1968;

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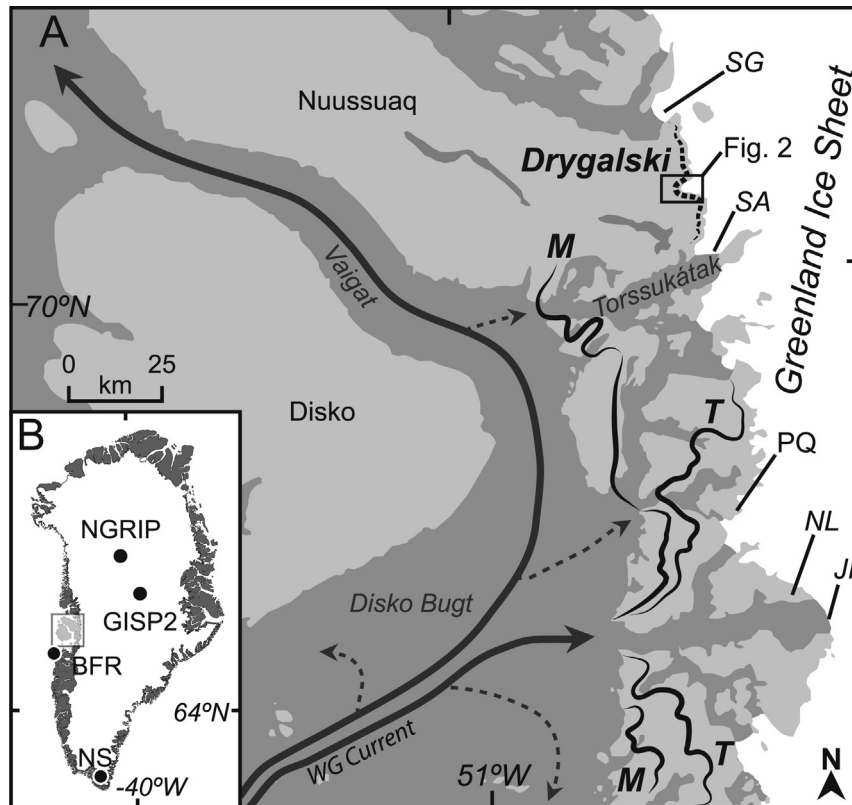


Fig. 1. A) Central West Greenland; thick black lines are Drygalski (dashed) and Fjord Stade [solid; Marrait = M, Tasiussaq = T] Moraines. Sites referred to in the text are: SG = Store Gletscher; SA = Sermeq Avannarleq; PQ = Paaqitsoq; NL = North Lake; JI = Jakobshavn Isbræ. Arrows show West Greenland (WG) Current. Inset (B) shows map of Greenland showing locations of ice cores NGRIP and GISP2, benthic foraminifera record (BFR; [Perner et al. \(2013\)](#)) and ice margin record (NS; [Larsen et al., 2011](#)).

[Bennike and Weidick, 2001](#); [Bennike and Sparrenbom, 2007](#); [Forman et al., 2007](#); [Winsor et al., 2014](#)), one of which is the Drygalski Moraine system in central West Greenland ([Fig. 1](#); [Kelly, 1980](#)). The Drygalski Moraines were first described in the late 1800s by a German group led by Erich von Drygalski ([von Drygalski et al., 1897](#)). The Drygalski Moraines were deposited outboard of LIA moraines, which are interpreted to grade to present day sea level at Store Gletscher to the north and Torssukátak to the south, indicating a maximum age of ~5 ka based on relative sea level curves ([Weidick, 1968](#)). To date there have been no attempts to directly date the Drygalski Moraines. The assignment of the Drygalski Moraines to late Holocene glaciation is important to test because a late Holocene age would make the Drygalski Moraines anomalously young compared to the early Holocene age of moraines present in the Disko Bugt region (e.g., [Young et al., 2013a](#)).

We reconstruct the Holocene GrIS history on inner Nuussuaq using radiocarbon and cosmogenic ^{10}Be exposure dating (hereafter referred to as ^{10}Be dating). The main objective of this study is to directly date the Drygalski Moraines to verify or refute previous estimates that they were deposited during the middle or late Holocene ([Weidick, 1968](#)). Two potential late Holocene moraines may be comparable to the Drygalski Moraines: the Narsarsuaq moraines in southern Greenland (>1.5 ka; [Winsor et al., 2014](#)) and the middle-Holocene moraines dated by [Lane et al. \(2014\)](#) in the Uummanaq Fjord system north of Nuussuaq. Alternatively, the Drygalski Moraines may be analogous to the Ørkendalen (~6.8 ka) or Fjord Stade (Tasiussaq ~8.2 ka; and Marrait ~9.3 ka; [Fig. 1](#)) moraine systems dated south of the Drygalski Moraines in West Greenland ([Levy et al., 2012](#); [Young et al., 2013a](#)). Determining the age of the Drygalski Moraines and assessing the temporal

significance of their deposition offers an opportunity to add to our understanding of the spatial variability of ice margin change during the Holocene.

2. Setting

Nuussuaq (peninsula) is located to the north of Vaigat Strait and Disko Island in central West Greenland. Bedrock at this location consists of Precambrian basement dominated by gneissic lithologies ([Weidick and Bennike, 2007](#)). Nuussuaq is bounded by relatively fast flowing (several kilometers per year), marine-terminating glaciers to the north and south ([Fig. 1](#); [Rignot and Mouginot, 2012](#)). In contrast, the GrIS margin that deposited the Drygalski Moraines is a relatively slow-flowing (10 s of meters per year; [Rignot and Mouginot, 2012](#)) small land-terminating lobe we refer to as the Nuussuaq Lobe (informal name) that lies along the right-lateral flank of the major marine outlet glacier Sermeq Avannarleq. The Nuussuaq Lobe terminus is bordered by a proglacial lake (informally called Newspaper Lake) and is surrounded by the Drygalski Moraines ([Fig. 2](#)).

The Drygalski Moraines include at least four moraine ridges near the present ice margin that are outboard of subdued (only few m in relief), unvegetated historical moraines ([Weidick, 1968](#); [Fig. S1](#)). It is difficult to ascertain the number of discrete Drygalski Moraine crests that were originally deposited due to the present extent of the Nuussuaq Lobe, which currently truncates parts of what may have been previously continuous, and additional, moraine ridges. A number of these moraines have been breached in places by melt-water channels that feed into Newspaper Lake ([Fig. 2](#)). The Drygalski moraines range from ~10 to 30 m in height and include some

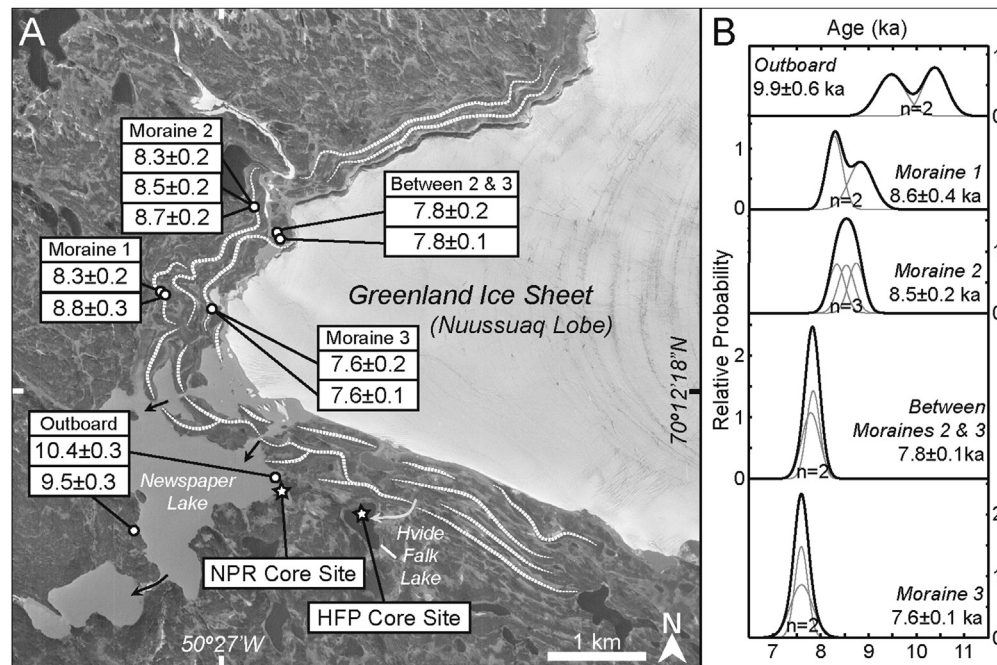


Fig. 2. A) Map with ^{10}Be ages in ka (1985 aerial photograph base; from National Danish Survey and Cadastre of Denmark). Drygalski Moraine crests delineated by dotted white lines and numbered from one to three from outer to inner. Small black arrows show flow in/out of Newspaper Lake; small white arrow is a paleo-channel into Hvide Falk Lake. Sediment core locations shown by white stars. Note non-glacial Hvide Falk Lake is dark in coloration and proglacial Newspaper Lake is light in color due to high suspended sediment load. B) Camel plots with individual (thin gray lines) and summed (thick black lines) Gaussian age distributions for ^{10}Be ages ($n = \times$ denotes number of samples). Mean age $\pm 1\sigma$ is displayed in ka for each sample subset.

continuous single ridge segments up to ~1.5 km long. Lichen growth on the moraines appeared to be saturated (Fig. S1). We focused our study on the terminus environment of the Nuussuaq Lobe, and thus restrict our mapping to that region (Fig. 2). However, one can easily discern Drygalski moraine crests in the broader region from shaded-relief digital elevation maps (Fig. S2).

Moraines preserved on western Greenland landscapes beyond the present ice margin and adjacent historical moraines have been recognized for decades (e.g., Weidick, 1968), although they only have been dated precisely in the last 10 or 15 years (see Young and Briner (2015) for a recent review). Because the GrIS was offshore during the Last Glacial Maximum, these moraines delimit advances and/or stillstands during retreat of the GrIS in the latest Pleistocene and Holocene. Perhaps most prominent among these moraines are the Fjord Stade Moraines, which Weidick (1968) traced from ~70° N (Nuussuaq) to ~63° N. The Fjord Stade Moraines have received most attention in the Disko Bugt region, where they were shown to date to ~9.3 and ~8.2 ka (Young et al., 2013a). Funder et al. (2011) display the moraines on a map of Greenland, which reveals their absence north of Nuussuaq. One reason thought to explain the absence of the Fjord Stade Moraines in western Greenland north of Nuussuaq is that this part of Greenland deglaciated prior to ~9.3 ka (e.g., Bennike and Björck, 2002; Briner et al., 2013). However, recent work in the Ummannaq fjord system (the large fjord embayment north of Nuussuaq), based on several ^{10}Be ages suggested that the GrIS experienced an elongated stillstand from ~11 ka to ~6 ka ~50 km beyond Rink Isbræ (Lane et al., 2014). Furthermore, a single ^{10}Be age ~2 km in front of Store Gletscher suggests it deglaciated ~8.7 ka (Roberts et al., 2013). Thus, it remains unclear if the Fjord Stade Moraines extend across Nuussuaq and into the Ummannaq fjord system or not. Given the lack of GrIS chronology on Nuussuaq, it remains an open question if the Drygalski Moraines post-date the Fjord Stade Moraines, as the observations of earlier workers might

suggest, or if the Drygalski Moraines are Fjord-Stade-Moraine equivalents.

3. Materials and methods

We collected samples for ^{10}Be dating and sediment cores from two lakes in summer 2012 to reconstruct the history of the Nuussuaq Lobe and to directly date the deposition of the Drygalski Moraines. Samples were collected for ^{10}Be dating from three separate Drygalski Moraine ridges (Figs. 2 and 3). We also collected samples for ^{10}Be dating from erratic boulders perched on primary bedrock surfaces located beyond ($n = 2$) and between ($n = 2$) the Drygalski Moraines to provide further constraints on moraine ages and deglaciation of the area. In an attempt to better constrain ice sheet retreat, we also use sub-ice topography data from Morlighem et al. (2014) to estimate how far the Newspaper Lake catchment extends beneath the GrIS at present. We used a 40 m topographic contour and basin analysis raster, both generated using the sub-ice topography data in ArcGIS, to delineate the catchment area under the ice sheet.

3.1. ^{10}Be analysis

We used a hand sledge and chisel to collect quartz-rich material from the tops of tall, stable, flat-topped moraine boulders located on clast-supported moraine segments unlikely to have experienced post-depositional modification ($n = 7$). We also collected erratics ($n = 4$) from high, windswept topographic positions on primary bedrock surfaces in order to reduce uncertainty associated with snow or sediment shielding (Fig. 3). We sampled thin (<3 cm), top surface pieces of flat areas, away from corners and edges. Boulder heights ranged from 0.3 m to 2 m (Table S1). Latitude, longitude and elevation for the samples were determined using a handheld GPS



Fig. 3. Example photographs of boulders sampled for ^{10}Be dating. *12GRO-5 and 12GRO-18*: Samples taken outboard of the Drygalski Moraines. *12GRO-7 and 12GRO-8*: Boulders from outermost Moraine (Moraine 1). *12GRO-9 and 12GRO-10*: Boulders from middle moraine (Moraine 2). *12GRO-13*: Erratic between middle and innermost moraines (Moraine 2 and Moraine 3). *12GRO-16*: Boulder from innermost moraine (Moraine 3).

with approximately $\pm 5\text{--}10$ m vertical accuracy. Topographic shielding was measured in the field with a clinometer and was insignificant for all but one sample. Sample elevations ranged from 363 to 447 m and are well above marine limit, which is estimated to be < 40 m in adjacent fjords (Weidick and Bennike, 2007).

Samples were processed at the University at Buffalo Cosmogenic Nuclide Laboratory and $^{10}\text{Be}/^9\text{Be}$ ratios were measured by accelerator mass spectrometry at Lawrence Livermore National Laboratory. The ^{10}Be ages (Table S1) were calculated using the CRONUS-Earth online exposure age calculator (Balco et al., 2008; version 2.2.1; <http://hess.ess.washington.edu/>). We adopted a locally-constrained production rate (Young et al., 2013b) with the Lal/Stone constant-production scaling scheme to calculate ^{10}Be ages (Lal, 1991; Stone, 2000; Table S2 details ^{10}Be ages calculated with alternative scaling schemes).

3.2. Lake sediment analysis

To capture the broader history of Nuussuaq Lobe margin position through time, we recovered a 1.11-m-long sediment core (NPR-4) from proglacial Newspaper Lake (70.19649° N, 50.44080° W, ~ 326 masl; Fig. 4). Newspaper Lake's upper catchment boundary lies ~ 2 km to the east of the present GRIS margin as estimated from sub-ice topography data (Fig. 5). We also recovered a 1.02-m-long sediment core (HFP-2) from Hvide Falk Lake (informal name; 70.79542° N, 50.41917° W, ~ 397 masl; Fig. 4), a non-glacial lake that would have received glacially derived sediment only when the ice margin was located at the outermost Drygalski Moraine (Fig. 2).

Bathymetry data for Newspaper Lake were collected with a dual beam depth transducer and Garmin GPSMAP 400 GPS device to determine locations most plausible for penetration down to

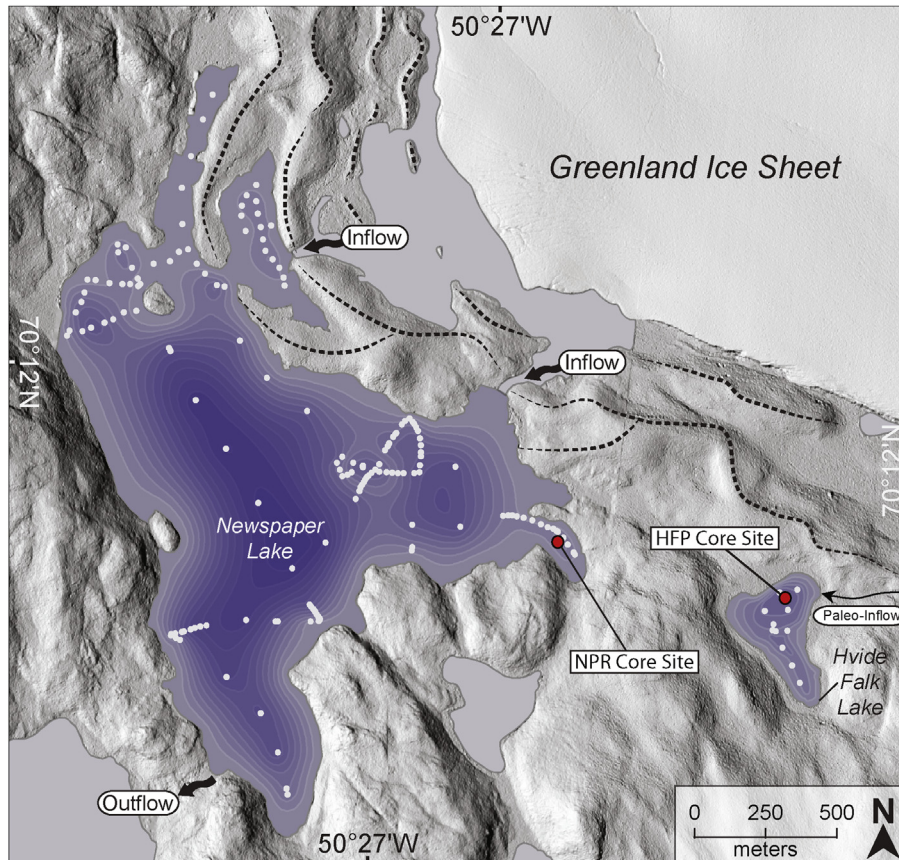


Fig. 4. Bathymetry maps for Newspaper Lake and Hvide Falk Lake superimposed on a hillshade of a digital surface model (<http://www.pgc.umn.edu/elevation/stereo/sets/m>). Bathymetric contours are 5 m each and bathymetry measurement locations are illustrated by white circles. Red circles show coring locations for NPR-4 and HFP-2. Thick black arrows indicate direction of inflows and outflows for Newspaper Lake. The thin black arrow shows a paleo-inflow channel to Hvide Falk Lake that would have been active when the ice margin extent was at the outermost Drygalski Moraine, or perhaps some distance inboard. Drygalski Moraine crests are highlighted with dashed black lines. Grey areas outlined in black are bodies of water where bathymetry data are not available. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deglacial material. We target distal sub-basins with relatively low sedimentation rates for core collection in proglacial lakes because high sedimentation rates and energy of sediment deposition in central basins during the LIA can be prohibitive for coring to deglacial sediment units. A handheld GPS and a tape measure were used to determine locations and depths of Hvide Falk Lake. Geosoft Oasis montaj and ArcGIS were used to create bathymetry maps (Fig. 4). The water depths of HFP-2 and NPR-4 coring locations are 26.3 m and 9.8 m, respectively. Sediment was collected with a Universal Percussion Corer (<http://www.aquaticresearch.com/>) fitted with 71-mm-diameter polycarbonate core barrels. Zorbital was used to stabilize the sediment–water interface before transport to the University at Buffalo where cores were split, photographed and analyzed (Tomkins et al., 2008).

Sediment was analyzed using magnetic susceptibility (MS) and loss-on-ignition (LOI) in order to determine organic vs. minerogenic content. The LOI technique removes organic carbon from sediment during a 2.5 h burn at 550 °C (Smith, 2003). These methods have been used successfully in previous research to determine glacial vs. non-glacial sediment sources (Prueher and Rea, 1998; Young et al., 2011), which are typically sharp in proglacial-threshold lakes (Briner et al., 2010). MS was measured at 0.5 cm intervals for all cores using a Barington MS2 system. Both cores were subsampled for LOI at intervals of 0.5 cm with the exception of the bottom minerogenic unit of NPR-4, which was subsampled at 5 cm increments.

Five radiocarbon ages were acquired from the NPR-4 core and one age was acquired to establish a basal age for HFP-2. Aquatic macrofossils were isolated from surrounding sediment using deionized water washes through sieves. Samples were then freeze-dried before transport to the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at Woods Hole Oceanographic Institution. Aquatic macrofossils were used in order to avoid dating potentially old terrestrial material washed in from the surrounding landscape. A hard-water effect is possible but unlikely to be significant because the catchment is dominated by an acid gneiss terrain similar to that of the Kangerlussuaq area for which Bennike et al. (2010) suggested that there was only a small hard-water effect (between ~100 and 200 ^{14}C yrs). In addition, since the study area is above marine limit, it is unlikely that radiocarbon ages were affected by old carbon sourced from marine water or surrounding marine sediments. Radiocarbon ages were calibrated using CALIB v 7.0 (Stuiver et al., 2013) and the IntCal13 calibration curve (Reimer et al., 2013) and are reported as the median of the 2σ range \pm half of the 2σ range.

Sub-ice topography data from Morlighem et al. (2014) were used to constrain the distance that ice would need to retreat to no longer supply meltwater to Newspaper Lake. The mass conservation algorithm was used to calculate ice thickness close to the margin of the ice sheet instead of the potentially less-accurate kriging method that was used for other slow moving sectors of the ice sheet; vertical error of the sub-ice map is approximately

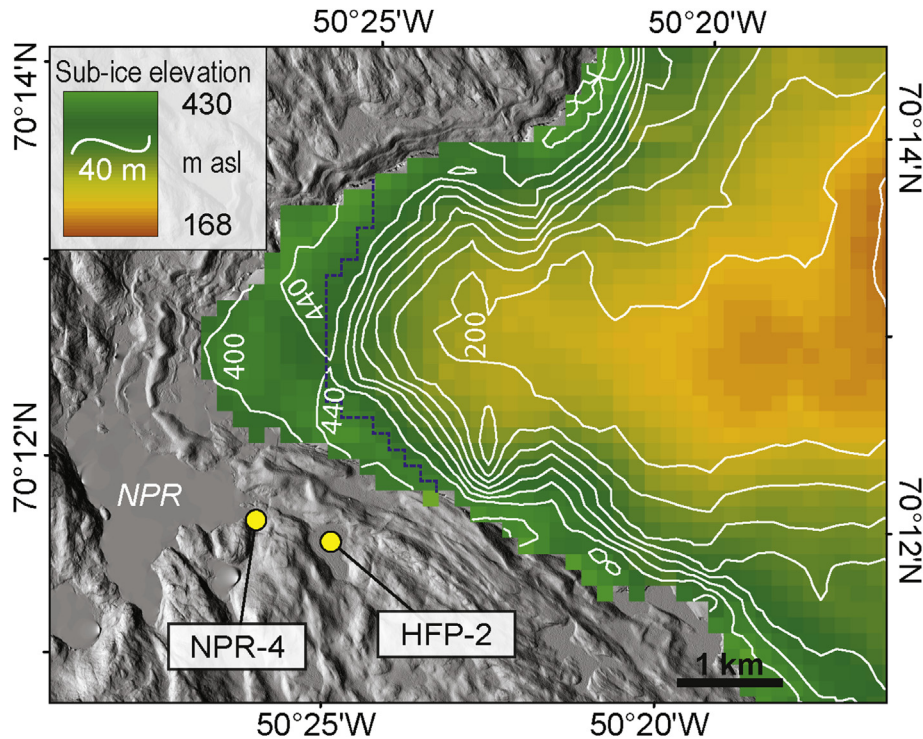


Fig. 5. Map showing sub-ice topography below the Nuussuaq Lobe (Morlighem et al., 2014) and hillshade from digital topographic data of ice-free areas (<http://www.pgc.umn.edu/elevation/stereo>). Sediment core sites denoted by yellow circles. Note Newspaper Lake (NPR) drainage divide ~2 km inboard of the present ice terminus, indicated by the blue dotted line. See text for method used for determining drainage divide location. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

36–50 m in our area (Morlighem et al., 2014).

4. Results

The ^{10}Be ages of two erratic boulders perched on bedrock indicate that deglaciation outboard of the Drygalski Moraine complex occurred at 9.9 ± 0.6 ka ($n = 2$; Fig. 2; Tables S1 and S2). Three moraine crests of the Drygalski Moraine complex have mean ages of 8.6 ± 0.4 ka ($n = 2$), 8.5 ± 0.2 ka ($n = 3$), and 7.6 ± 0.1 ka ($n = 2$), from outer to inner. The ^{10}Be ages from two erratics between the inner two moraines average 7.8 ± 0.1 ka.

The NPR-4 core is composed of a basal unit of minerogenic sediment, a middle unit of organic-rich sediment, and a top unit of minerogenic sediment (Fig. 6). The basal unit has LOI values ranging from 0 to ~1% and MS values ranging from ~200 to ~600 cgs, indicating a high relative abundance of minerogenic material. The middle unit of organic-rich sediment has LOI values ranging from ~2 to ~15% and MS values near zero cgs, indicating a low relative abundance of minerogenic material. The top unit of minerogenic sediment has LOI values ~1% and MS values ~125 cgs, indicating minerogenic material, but less relative abundance than in the basal unit. Macrofossils yielded five stratigraphically consistent radiocarbon ages throughout the organic-rich sediment unit (Fig. 6; Table S3). Two samples from the bottom contact of the organic-rich sediment unit are 5390 ± 80 and 5450 ± 130 cal yr BP, and a sample from the upper contact of the unit is 600 ± 60 cal yr BP. The sediment in the HFP-2 core is dominated by organic-rich, non-glacial material (Fig. 6). One four-cm-thick minerogenic graded bed punctuates the organic-rich sediments and indicates the occurrence of a mass wasting event. Macrofossils from 8.5 cm above the base of the core are 7400 ± 80 cal yr BP (Fig. 6; Table S3).

5. Interpretation

The ^{10}Be ages of the erratics beyond the Drygalski Moraines constrain local deglaciation to ~9.9 ka. The ^{10}Be ages of all three moraine crests consistently date to the early-to-middle Holocene, and are not 5 ka or younger. Although the HFP-2 sediment core did not penetrate deglacial sediments (Fig. 6), the 7.4 ka age from low within the sediment core nonetheless provides a minimum constraint on the deposition of the Drygalski Moraines, and agrees with the ^{10}Be chronology. The radiocarbon chronology of NPR-4 indicates that ice did not retreat out of the lake catchment until ~5.4 ka and later re-entered the lake catchment ~0.6 ka. If the sub-ice elevation model is accurately reflecting the subsurface, it allows us to identify a sill and upper Newspaper Lake catchment boundary about 2 km inland beneath the Nuussuaq Lobe. Combined, the data suggest that the GrIS lingered within about two km of the present ice margin from ~9.9 ka to ~5.4 ka and was at its smallest Holocene extent from ~5.4 ka to ~0.6 ka. Despite our moraine chronology relying on few boulders per crest, we trust our chronology given the agreement between the ^{10}Be ages from the three moraine crests, the agreement between moraine boulder ^{10}Be ages and the ^{10}Be ages of the erratic between the inner two moraines, and agreement with the lake-sediment radiocarbon constraints. Furthermore, it has been shown previously that cosmogenic nuclide inheritance is minimal in the Disko Bugt region (Corbett et al., 2011).

Our interpretation that the ice margin remained within ~2 km of its present position from ~9.9 to ~5.4 ka hinges on the accuracy of the sub-ice elevation model (Fig. 5). We acknowledge that the 2 km distance from the present ice margin to the catchment boundary of Newspaper Lake is an estimate with uncertainty, but is the best we can estimate given present radar data in this region. Other potential uncertainties with using sub-ice topography for reconstructing past

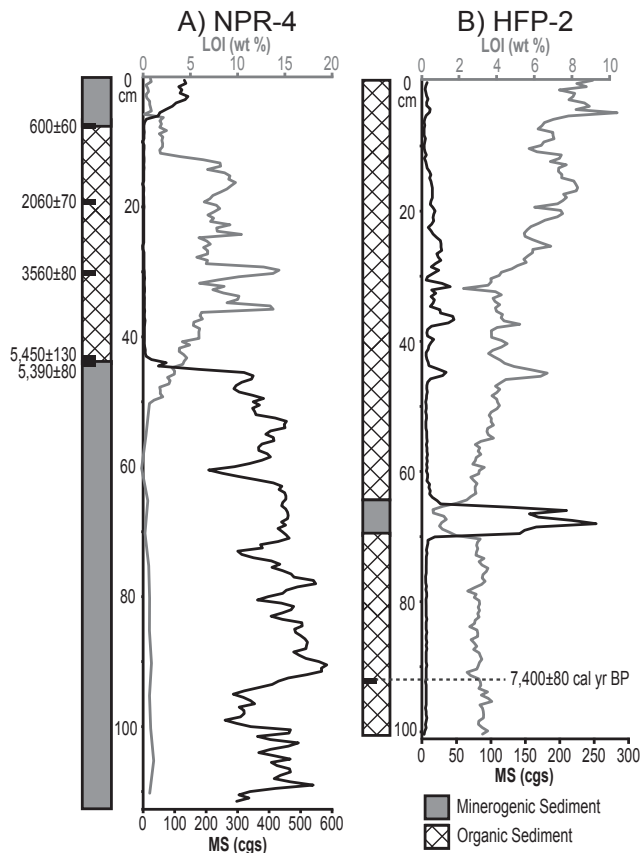


Fig. 6. Sediment core logs from Newspaper Lake and Hvide Falk Lake showing loss-on-ignition (LOI; gray line), magnetic susceptibility (MS; black line) and radiocarbon ages (cal yr BP) reported as the median of the 2σ range \pm one half of the 2σ range. Ages were calibrated using CALIB v 7.0 (Stuiver et al., 2013) and the IntCal13 calibration curve (Reimer et al., 2013). A) NPR-4 sediment core log. B) HFP-2 sediment core log.

ice sheet margins potentially include the effects of isostatic tilting affecting drainage basin geometry, and changes in subglacial drainage such as proglacial lake spillover and meltwater routing. Differential uplift is difficult to constrain for this region because the marine limit pattern is due in part to the spatiotemporal pattern of ice margin retreat. We suggest that differential tilting is a minor effect in the relatively small Newspaper Lake drainage basin given typical crustal rigidity, but cannot rule out that the sill was located more than 2 km away from the lake in the middle Holocene. We also cannot be sure if the ice margin retreated farther inland, eastward of the sill, and that an ice-dammed lake spanned between the ice terminus and the sill, spilling over the sill and into Newspaper Lake. Regardless of these uncertainties, we suggest that the ice margin stayed relatively close (within a few kilometers) to the present ice margin for a surprisingly long amount of time spanning the early and middle Holocene.

6. Discussion

Determining that the Drygalski Moraines were deposited from ~ 8.6 to ~ 7.6 ka eliminates one of the few moraine systems on Greenland previously thought to date to the middle or late Holocene. The age of the moraines, however, is similar to the Fjord Stade moraines in central West Greenland (Young et al., 2013a) and allows for comparison of this site with relatively fast-flowing outlet glacier margins in the Disko Bugt region. Dating of the Fjord Stade Moraines in the Disko Bugt region indicates: (1) significant re-

advances at fast-flowing, climate-sensitive Jakobshavn Isbræ at 9.3 and 8.2 ka, and (2) smaller-scale advances or stillstands at slower-flowing marine outlet glaciers at the same times (Young et al., 2013a).

The chronology of the Drygalski Moraines is not like that of the Fjord Stade Moraines. The Fjord Stade Moraines consist of two moraines that are located ~ 10 km or more from the current ice margin whereas the Drygalski Moraines consist of four or more moraines located within <1 km of the current ice margin. The inner Drygalski Moraines are overlapped by the current ice margin (Fig. S2) suggesting that the Nuussuaq Lobe continued to deposit moraines during slow net retreat behind the current ice margin position even after ~ 7.6 ka. The heterogeneous response of GrIS is also highlighted by how the Drygalski Moraines represent multiple cycles of advance and retreat and/or stillstands spanning from ~ 8.6 to <7.6 ka, as opposed to the Fjord Stade Moraine record characterized by a more simple sequence of two moraine crests coinciding with the 9.3 and 8.2 ka events. This difference in timing and moraine deposition may be a function of a lagged response of the Nuussuaq Lobe to climate perturbations, such as early Holocene Laurentide Ice Sheet meltwater events (Jennings et al., 2015). If so, the Drygalski Moraines may represent the cumulative effect of climate on the millennial scale as opposed to the discrete climate events archived by the Fjord Stade Moraines in response to decadal-to centennial-scale climate forcing. This may have been due to the slower velocities of the Nuussuaq Lobe versus the very-fast-flowing Jakobshavn Isbræ. Regardless, differences between the spatial and temporal distribution of the Drygalski and Fjord Stade Moraines, both located in central West Greenland, emphasize the complex nature of GrIS response to climate change.

In contrast to significant and rapid retreat of the western GrIS from the continental shelf and into the Uummannaq and Disko Bugt fjord systems between ~ 12 and ~ 10 ka (Kelley et al., 2013; Roberts et al., 2013), the Nuussuaq Lobe subsequently only fluctuated within ~ 2 km of its present ice margin terminus between ~ 9.9 and ~ 5.4 ka (Fig. S3). This was followed by a minimum ice extent between ~ 5.4 and 0.6 ka. Reconstructions of land-terminating ice margins elsewhere in western and southern Greenland also reveal ice margin stability in the early Holocene followed by minimum extent during the latter portion of the Holocene (e.g., Larsen et al., 2011, 2015). In particular, the ice margin at Paakitsoq (80 km south of our field site) was reconstructed to have been relatively stable between ~ 7.9 and 5.4 ka, followed by its minimum extent between 5.4 and 0.24 ka (Carlson et al., 2014; Håkansson et al., 2014). Based on a synthesis of geologic data like ours, Young and Briner (2015) suggested that the minimum extent of the western GrIS was experienced between ~ 4 and ~ 2 ka. This timing is later, but similar to the minimum GrIS extent (7–4 ka) depicted by Larsen et al. (2015). However, both compilations show that in most sectors, the GrIS was steadily retreating, with some pauses during moraine deposition, from ~ 10 to 5 ka.

The surprising stability of the Nuussuaq Lobe between ~ 9.9 and ~ 5.4 ka may relate to the complex pattern registered within Holocene climate records from across Greenland. While isotope records from central GrIS ice cores generally follow high-latitude summertime insolation and indicate an early-Holocene thermal maximum followed by steady cooling in the subsequent Holocene (e.g., Vinther et al., 2006), other records, primarily from coastal areas around Greenland (e.g. Axford et al., 2013; Perner et al., 2013; Jennings et al., 2014), reveal a middle-Holocene thermal maximum (Fig. 7). Increased meltwater discharge into Baffin Bay and the North Atlantic Ocean from thinning ice sheets during the early Holocene (e.g., Jennings et al., 2015) has been invoked to explain the delayed timing of the Holocene thermal maximum in parts of Greenland (e.g., Kaplan and Wolfe, 2006; Renssen et al., 2009).

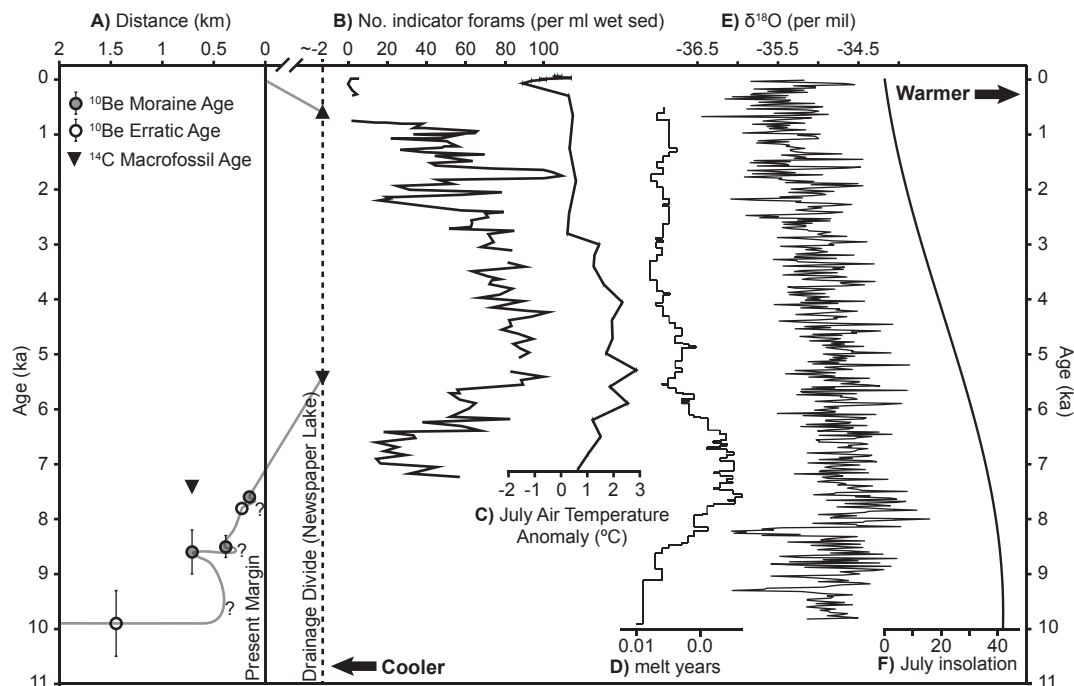


Fig. 7. A) Mean $^{10}\text{Be} \pm 1\sigma$ and ^{14}C ages $\pm 2\sigma$ plotted vs. distance from the present ice margin. White circles are erratic ^{10}Be ages, gray circles are moraine boulder ^{10}Be ages and black triangles are ^{14}C ages from macrofossils in lake sediments (some small error bars are captured within symbol). The drainage divide ~2 km inland of the present ice margin (black vertical line) denoted by dotted vertical line. See Supplemental Fig. S1 for broader time-distance history. B) Number of calcareous Atlantic water foraminifera (per ml of wet sediment; Perner et al., 2013). C) Midge-based July air temperature anomaly (Axford et al., 2013). D) Melt years in GISP2 ice core (1000 year running mean, Alley and Anandakrishnan, 1995). E) NGRIP ice core $\delta^{18}\text{O}$ (Vinther et al., 2006). F) Northern hemisphere July insolation values (Berger and Loutre, 1991).

Recent Holocene climate records from offshore of central West Greenland reveal oceanic thermal optimum conditions occurring from ~5.5 to ~3 ka. For example, Perner et al. (2013) used foraminifera assemblages to conclude that the most “thermal optimum-like” conditions in Disko Bugt occurred from 5.5 to 3.5 ka. In addition, Briner et al. (2014) dated large populations of marine bivalve ages to show that western Greenland fjords were most open from ~5 to ~2 ka, indicating warmest oceanic conditions, smallest

ice extent, or both. The findings of Perner et al. (2013) and Briner et al. (2014) are compatible with the notion that the Nuussuaq Lobe was at its minimum during the oceanic thermal optimum in western Greenland, at least on the millennial time scale.

That our land-based ice margin chronology may have been influenced by the adjacent ocean may not seem initially intuitive. However, our study site is along the right-lateral flank of Sermeq Avannarleq, and thus its history is likely tied to its terminal

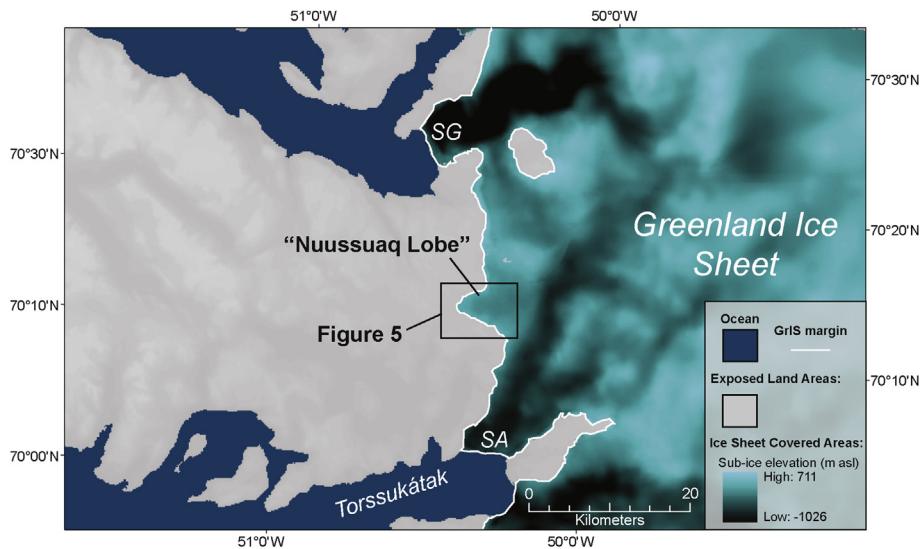


Fig. 8. Sub-ice topography data (Morlighem et al., 2014) showing low-topography areas associated with marine-terminating, high-velocity outlet glaciers (Rignot and Mouginot, 2012) to the north and south of the Nuussuaq Lobe. Sermeq Avannarleq (SA) is the marine-terminating outlet glacier to the south and appears to be more topographically connected to the Nuussuaq Lobe than Store Gletscher (SG) to the north. Radiocarbon constraints from the NPR-4 sediment core constrain minimum ice sheet extent to a period that coincides with local peak oceanic thermal conditions (Perner et al., 2013) suggesting that the Nuussuaq Lobe may be affected by the behavior of the adjacent marine terminating glaciers.

behavior. The relationship between marine-terminating ice sheet margin behavior and that of adjacent land-terminating margins is difficult to quantify, but the compatibility between our ice margin chronology and oceanic records suggests that there may be some influence (i.e. drawdown) from the major marine-terminating outlet glaciers to the north (Store Gletscher) and south (Sermeq Avannarleq) (Fig. 8). The influence of marine-glacier terminus changes on nearby land-terminating margins is apparent at Jakobshavn Isbræ (Csatho et al., 2008), where significant retreat of the marine terminus has led to substantial retreat of adjacent land-based ice margins.

7. Conclusions

The Drygalski Moraines were deposited ~8.6 to ~7.6 ka, not during the late Holocene as previously suggested. Thus, the Drygalski Moraines appear to overlap in age with the Fjord Stade Moraines in Disko Bugt. Furthermore, the decreasing distance between the present GrIS margin and the Fjord Stade Moraines as one moves northward supports the notion that the Fjord Stade Moraines are absent in western Greenland north of Nuussuaq due to the earlier timing of deglaciation. The difference in the number and ages of Drygalski (Nuussuaq) and Fjord Stade Moraine (Disko Bugt region) crests reveals a heterogeneous response of the GrIS to past climate change. The potential lagged response of relatively low-velocity sectors of the GrIS to abrupt climate change implies that the GrIS may respond heterogeneously to ongoing and future climate change as well. The relative stability of the GrIS margin at Nuussuaq from ~9.9 to ~5.4 ka following significant and rapid retreat and preceding its minimum extent is at odds with the pattern of GrIS margin change from many locations elsewhere in western Greenland. Climate proxy records suggest that coastal West Greenland experienced a different Holocene climate history than interior Greenland, and ocean conditions may have significantly influenced the history of the Nuussuaq Lobe. Minimum ice margin position of the Nuussuaq Lobe after 5.4 ka might be attributed to when relatively warm currents overcame the influence of cool conditions from GrIS meltwater produced during the early-middle Holocene. Our chronology supports previous work that suggests ice sheet meltwater may have buffered warming and inhibited ice sheet retreat in some places into the middle Holocene.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.quascirev.2015.08.034>.

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