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Late Holocene glacier activity at inner Hornsund and Scottbreen, southern Svalbard

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ABSTRACT: New ^{10}Be dating on two late Holocene maximum moraines on the Treskelen Peninsula and at Scottbreen, Svalbard, improve constraints on the timing and character of Holocene glacial activity in this region. Average moraine ages of 1.9 ± 0.3 ka ($n = 4$) on the Treskelen Peninsula and 1.7 ± 0.1 ka ($n = 5$) on Scottbreen indicate the timing of a glacial culmination. The age of moraine abandonment at Treskelen and Scottbreen correlates with snowline lowering and glacier expansion between ~2.0 and 1.5 ka observed elsewhere on Svalbard. Both Scottbreen and the glaciers near Treskelen have surged in the instrumental record, like many glaciers across Svalbard. Yet, the age relation between our possible surge-related moraines and other glacier records leads us to hypothesize that on centennial and longer timescales, climate forcing outweighs surge dynamics, which exerts a stronger control on glacier length on centennial timescales at our study sites.

KEYWORDS: ^{10}Be exposure dating; late Holocene; moraines; Svalbard.

Introduction

Climate models forecast severe warmth in Earth's polar regions by 2100 AD, which is expected to significantly impact alpine glaciers due to cryosphere-albedo feedbacks amplifying warming of the Arctic (e.g. Chapin *et al.*, 2005; Stocker *et al.*, 2013). However, the response of glaciers to climate change is complex, which makes their future behavior difficult to predict (e.g. Solomina *et al.*, 2015). By increasing the spatial and temporal resolution of glacier histories in the Arctic, where warming trends are amplified, we can better understand the complex interplay of past climate change as well as glacier advance and retreat, ultimately allowing for better predictions of the cryosphere evolution in the future (Miller *et al.*, 2010).

Glaciers presently cover ~60% of the island of Spitsbergen, Svalbard (Fig. 1; 74°–81°N, 10°–35°E; Hagen *et al.*, 2003). Despite widespread glaciation, the history of glacier change during the Holocene is not well known, particularly following deglaciation from the Last Glacial Maximum (LGM). A widely held view is that glaciers reached their maximum Holocene extent during the Little Ice Age (LIA; 1450–1850 AD; Grove, 1988) (e.g. Werner, 1993; Mangerud and Landvik, 2007). However, the majority of glacial imprints in the landscape are biased towards the youngest events as glacier advances obliterated earlier events (Landvik *et al.*, 2014) and an increasing number of studies indicate that glaciers extended to and/or beyond their LIA limits earlier in the Holocene (e.g. Humlum *et al.*, 2005; Reusche *et al.*, 2014; Røthe *et al.*, 2015).

An issue complicating the ability to reconstruct paleoclimate events from glacier-geological data on Svalbard is the abundance of surge-type glaciers (Hagen *et al.*, 1993). Surging glaciers exhibit abnormal fluctuations in velocity and terminus position caused by internally forced oscillations rather than by surface mass balance changes conditioned by changes in climate (Meier and Post, 1969; Sharp *et al.*, 1988; Benn and Evans, 2010). Therefore, the accepted notion is that surge-associated deposits cannot be used to simply estimate paleoclimate (Yde and Paasche, 2010). However, a paradigm shift has emerged in recent years because it has been proposed that the frequency of surge events is controlled by climate-induced mass balance changes (e.g. Dowdeswell *et al.*, 1995; Sevestre and Benn, 2015; Ingólfsson *et al.*, 2016). In this study we aim to show that late Holocene glacier advances in different sites did not occur unpredictably, but rather near simultaneously.

^{10}Be exposure dating (hereafter referred to as ^{10}Be dating) allows for the ability to precisely determine the age of moraine abandonment (Balco, 2011), and recent advances in this technique have yielded accurate ages for late Holocene moraines (e.g. Young and Briner, 2015). Here, we use ^{10}Be dating in conjunction with geomorphological mapping to date late Holocene moraines in south-western Spitsbergen on the Treskelen Peninsula, inner Hornsund Fjord and Scottbreen, Bellsund (Figs 1 and 2). Our objectives are to: (i) determine if the sites record glacier history before the LIA, and (ii) compare moraine ages to other known glacier records in western Svalbard.

Background

Treskelen Peninsula

Hornsund Fjord (Fig. 2; 76.97°N, 15.70°E) is the southernmost fjord on Spitsbergen and currently 802 km^2 of the 1200-km^2 drainage basin is covered by glaciers (Błaszczyk *et al.*, 2013).

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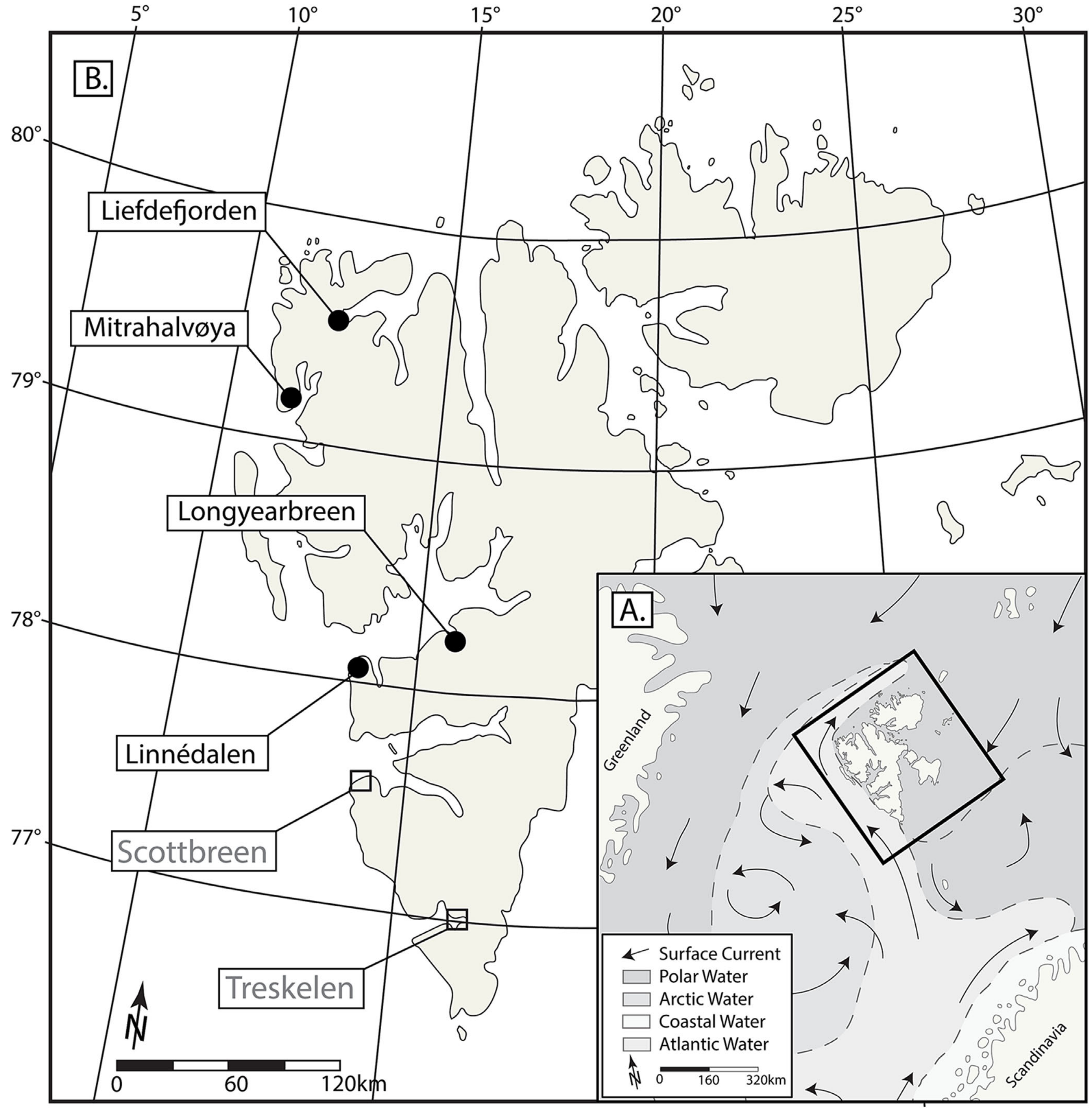

Figure 1. (A) Index map showing modern day surface water masses and surface currents around Svalbard (Hald *et al.*, 2004). (B) Map of Svalbard showing sites discussed in the text (Norwegian Polar Institute; toposvalbard.npolar.no/). Open squares indicate the region of fieldwork and full circles denote the location study sites discussed in Fig. 9.

The overwhelming majority of the fjord's glaciers are valley-type tidewater glaciers. Glaciers in Hornsund have retreated in the observational record at an average rate of $\sim$70 m a^{-1}, which is higher than the average rate of retreat of $\sim$45 m a^{-1} for glaciers elsewhere on Svalbard (Błaszczyk *et al.*, 2013). The most noticeable area of glacier retreat in Hornsund Fjord has been in its eastern extent beginning at the Treskelen Peninsula (Figs 2 and 3), where glaciers have retreated >10 km since 1899 AD (Błaszczyk *et al.*, 2013).

The Treskelen Peninsula (Figs 2 and 3; 77.01°N, 16.23°E) is a 3.5-km-long north–south-trending peninsula that is the largest topographic obstacle to glacier flow in the Hornsund Fjord (Lindner and Marks, 1990). The peninsula leads to a major constriction in fjord width and is where Hornsund reaches its shallowest depths of 40–60 m below sea level (b.s.l.) (Lindner and Marks, 1990; Kowalewski *et al.*, 1991). East of Treskelen at Brepollen the fjord reaches >140 m b.s.l. and is surrounded by large tidewater glaciers including Storbreen, Hornbreen, Svalisbreen and Mendeleevbreen (Fig. 2) (Moskalik *et al.*, 2013). To the west of Treskelen, Hornsund Fjord widens significantly and reaches its greatest depth of 250 m b.s.l. (Kowalewski *et al.*, 1991).

In 1899 AD the tidewater glaciers in Hornsund Fjord were confluent and extended to the Treskelen Peninsula (Kowalewski *et al.*, 1991; Majewski *et al.*, 2009; Błaszczyk *et al.*, 2013). By 1936 AD the ice margin had retreated from Treskelen (Kowalewski *et al.*, 1991; Majewski *et al.*, 2009; Błaszczyk *et al.*, 2013). In 1961 AD ice terminated $\sim$2.5 km east of Treskelen and by 2001 AD glaciers were within $\sim$1 km of their present position (Nordli, 2010; Błaszczyk *et al.*, 2013;

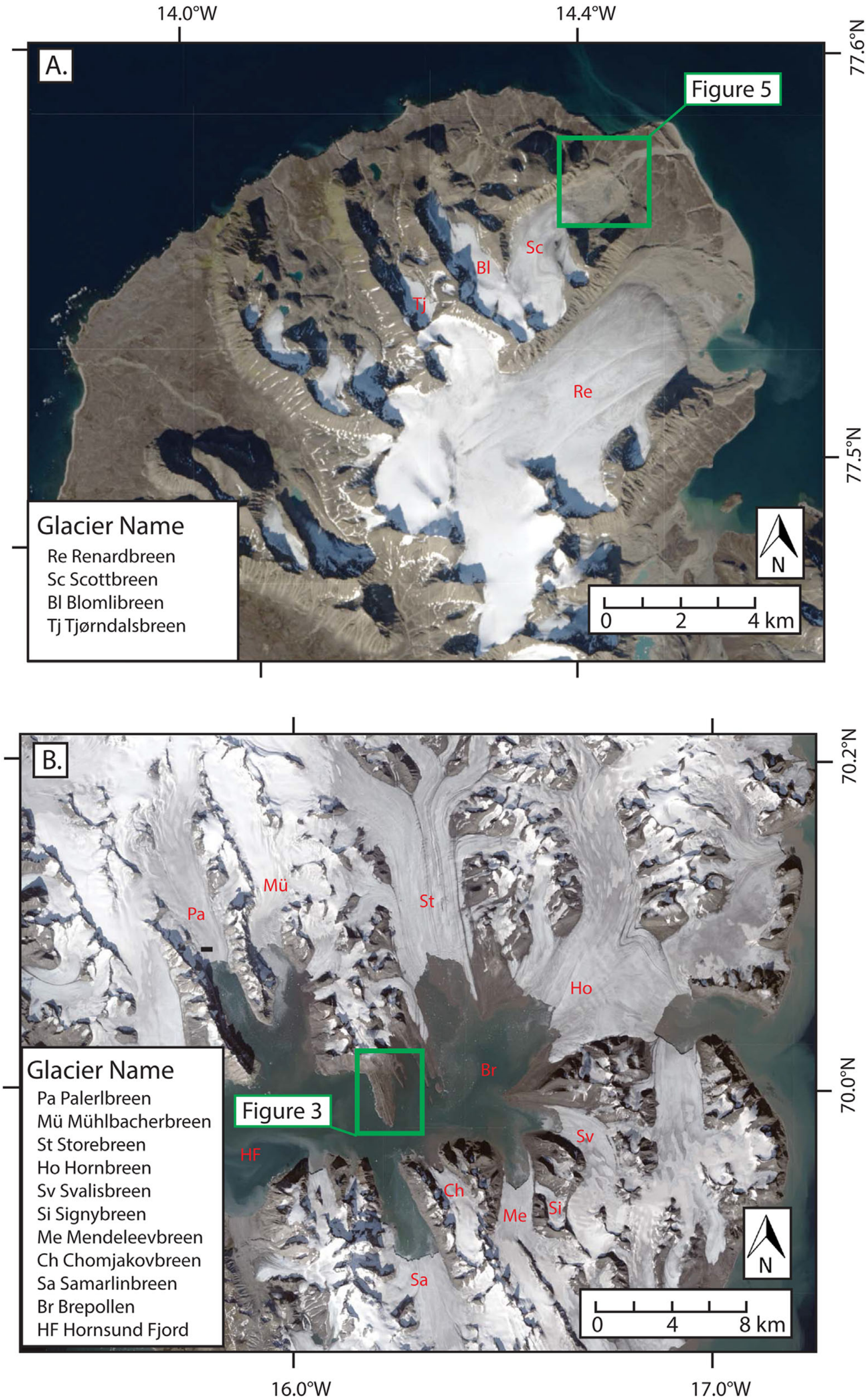

Figure 2. (A) Aerial photograph of Scottbreen, its frontal moraines and the surrounding area. (B) Aerial photograph of Treskelen Peninsula (green box) and the surrounding area (Norwegian Polar Institute; toposvalbard.npolar.no/; taken in 2011).

Moskalik *et al.*, 2013). These tidewater glaciers have been in an overall retreat since 1899 AD, but retreat was interrupted during surge events at Mendeleevbreen, and there is indirect evidence of surge behavior at Storbreen, Svalisbreen and Hornbreen (Błaszczyk *et al.*, 2013).

The major retreat of glaciers in eastern Hornsund Fjord in the 20th century has made the Treskelen Peninsula the subject of numerous Quaternary studies (e.g. Lindner and Marks, 1997). Treskelen is dominated by a bedrock ridge along the center of the peninsula, which reaches over 160 m above sea level (a.s.l.) in the north and divides the landmass into western and eastern geomorphological sectors (Fig. 2). The western and southern side of Treskelen contains marine terraces ranging from 105 to 2 m a.s.l. An 8–12 m a.s.l. terrace is thought to correlate to a nearby terrace dated to 5786 ± 128 cal a BP (Chmal, 1987; Lindner and Marks, 1993), indicating that the western portion of Treskelen, where this terrace is preserved, has been exposed at least since that time. Conversely, eastern and southern Treskelen is draped with young, fresh Holocene moraines (Fig. 3). These moraines

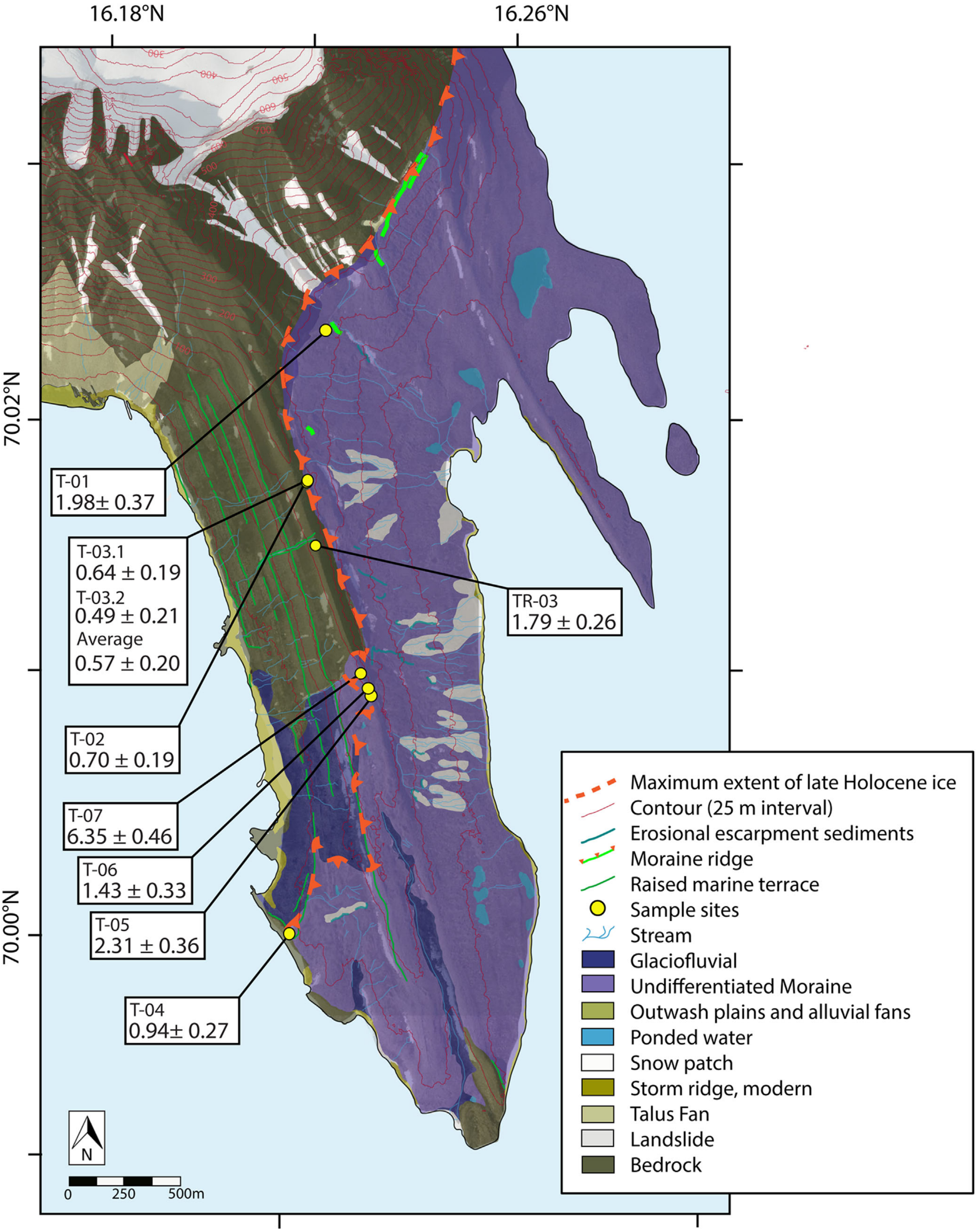

Figure 3. Geomorphologic map of Treskelen Peninsula (underlain with Norwegian Polar Institute aerial photographs s2011_25163_00183; s2011_25163_00184; s2011_25163_00185) showing ^{10}Be ages (ka).

overlay the 8–12 m a.s.l. terrace in southern Treskelen (Fig. 3; Lindner and Marks, 1990).

Published ages on the Holocene moraines on eastern Treskelen are limited to two ages, both from glacier-reworked material. The first is a ^{14}C age of a *Chlamys islandica* shell reworked into the glacial drift yielding an age of 9319 ± 168 cal a BP (Marks and Mekala, 1986; Lindner and Marks, 1993). This suggests that the moraines were abandoned after ~9.3 ka. The second is a piece of glacier-transported driftwood incorporated into the glacial drift at

38 m a.s.l. ^{14}C dated to 747 ± 88 cal a BP. This provides a maximum age of an advance to eastern Treskelen (Grosswald *et al.*, 1967; Marks and Mekala, 1986; Lindner and Marks, 1993).

Despite the lack of age control, there have been numerous published studies of field observations and interpretations of the glacier history of Treskelen (Lindner and Marks, 1997). Some constraints on the timing of late Holocene glacial activity in the broader Hornsund region arise from thermoluminescence ($n = 3$) and ^{14}C ($n = 11$) ages from coastal deposits that span as far as 25 km south-west and 36 km north-west of Treskelen. The ages are interpreted to indicate late Holocene glacier advances between ~3.3 and 2.1 ka BP and after ~0.6 ka BP (Pękala, 1989; Lindner *et al.*, 1991; Lindner and Marks, 1993).

In this study, we use ^{10}Be dating of moraine boulders to determine the age of the Holocene moraines on eastern Treskelen. We re-map the peninsula considering previously published work and new field observations from our 2013 field session, and date moraine boulders (Fig. 4) located on the outer margin of the Holocene drift that covers large areas of eastern and southern Treskelen.

Scottbreen

Scottbreen (Figs 1, 2 and 5; 77.54°N, 14.36°E) is an alpine glacier on the southern coast of Bellsund that has an accumulation zone partly shared with neighboring Blomlibreen. Scottbreen's Holocene moraines over drape a sequence of raised beach terraces of Calypsostranda dated to 13 530 ± 130 cal a BP ($n = 4$) at 57–61 m a.s.l. (Mangerud and Landvik, 2007). About 1 km beyond the 2012 ice margin (Fig. 5), ice-cored frontal and lateral moraines contain quartz-bearing Kapp Lyell diamictites (Fig. 5; Kowallis and Craddock, 1984). Around 1880 AD a surge event was observed and since then Scottbreen has remained in a phase of quiescence (Hagen *et al.*, 1993; Liestøl, 1993). Scottbreen was still adjacent to its Holocene maximum limit in 1936 AD (Fig. 6; Mangerud and Landvik, 2007; Norwegian Polar Institute, aerial images S36-1694 and S36-3189). From 1936 to 2012 AD the glacier underwent a net area change from 5.98 to 4.61 km^2 for a 22.9% net area loss (Zagórski *et al.*, 2013).

The ages of the Holocene moraines at Scottbreen have been considered by two independent groups (Mangerud and Landvik, 2007; Reder and Zagórski, 2007). Reder and Zagórski (2007) attribute the terminal moraine, particularly the north-east sector, to represent two phases of glacial advance. Both phases of advance were suggested to date to the LIA; however, no numerical dating methods have been used to date the moraines. Mangerud and Landvik (2007) suggested that a warm-based ice advance overrode all older deposits during the LIA, referring to an oblique air photograph from 1936 AD that is interpreted to show Scottbreen forming its outermost moraine (Fig. 6, Norwegian Polar Institute, aerial images S36-1694 and S36-3189). Thus, Mangerud and Landvik (2007) concluded that Scottbreen was at its most extensive position since LGM deglaciation during the LIA. At present, there are no direct and absolute ages on the moraine itself, which leaves a gap between the Allerød-aged terraces and the ~1880 AD surge (Liestøl, 1993; Reder, 1996; Mangerud and Landvik, 2007; Zagórski *et al.*, 2012).

Field observations we made in 2014 in conjunction with aerial photographs (Norwegian Polar Institute, photograph s2011_25163_00522_l3) reveal a series of distinctive moraine crests with observable variation in the degree of weathering from the most ice-distal to the most ice-proximal crests. At Scottbreen, our goals are to: (i) delineate moraine crests in the end moraine complex, and (ii) date moraine boulders from the outermost crests using ^{10}Be dating (Fig. 7).

Methods

^{10}Be methodology

Treskelen Peninsula

Eight sandstone boulders were sampled from the Holocene moraines on Treskelen. The sampling protocol followed Akçar *et al.* (2011) and Ivy-Ochs and Kober (2008). One boulder was sampled at two separate locations (T-03.1 and T-03.2) due to its irregular surface (Fig. 3). We sampled boulders from stable, wind-swept portions of moraine, reducing chances of boulder rotation and cover by snow. We sampled the upper several centimeters of boulders with a rock saw, hammer and chisel. A handheld GPS (Garmin Montana 600) with a vertical uncertainty of ±4 m was used to mark the boulder location and elevation (Table 1). A handheld clinometer was used to measure shielding from the surrounding topography and resulting shielding factors range from 0.9255 to 0.9999 (Table 1).

Physical and chemical isolation of quartz took place at the University of Bergen using the methods reported in Kohl and Nishiizumi (1992) and Child *et al.* (2000). The clean quartz fractions were brought to the University of Glasgow's Cosmogenic Isotope Laboratory, located at the Scottish Universities Environmental Research Centre (SUERC), for beryllium chemistry, following procedures modified from Child *et al.* (2000). Accelerator mass spectrometry (AMS) measurements of ^{10}Be/^{9}Be were conducted at the SUERC AMS facility and compared against the NIST SRM4325 standard with an assumed isotope ratio of 3.06×10^{-11} and background-corrected using procedural blanks (Xu *et al.*, 2010). The ^{10}Be surface exposure ages were calculated using the CRONUS-Earth online exposure age calculator version 2.2 (hess.ess.washington.edu; Balco *et al.*, 2008) using the Arctic-wide production rate from Young *et al.* (2013) and with the Lal/Stone scaling scheme (Table 1; Lal, 1991; Stone, 2000). No corrections for changes in air pressure or glacial isostasy were made because these effects are assumed to be negligible in recent millennia.

Scottbreen

We sampled quartz-rich meta-conglomerate boulders on the outermost moraine crests on Scottbreen ($n = 8$) for ^{10}Be dating. The upper several centimeters of boulder surfaces were collected using a drill, blasting caps, hammer and chisel. A Trimble GeoXT and Tempest antenna GPS (with differential corrections made with Trimble Geomatics Software using base-station data from Ny-Ålesund) receiver with a vertical uncertainty of ±0.5 m was used to record sample location and elevation. A handheld clinometer was used to measure shielding from the surrounding topography; correction factors range from 0.9955 to 0.9987 (Table 1).

Physical and chemical processing of samples took place at the University of Buffalo following procedures outlined in Young *et al.* (2011). Ratios of ^{10}Be/^{9}Be were measured at the Lawrence Livermore National Laboratory Center for AMS, were compared against the 07KNSTD standard with a reported ratio of 2.85×10^{-12} (Nishiizumi *et al.*, 2007; Rood *et al.*, 2010) and were background-corrected using procedural blanks (Table 1). ^{10}Be ages were calculated using the CRONUS-Earth online exposure age calculator version 2.2 (hess.ess.washington.edu; Balco *et al.*, 2008), applying the

Figure 4. Photographs of sampled boulders for ^{10}Be dating (locations shown in Fig. 3) on the Treskelen Peninsula with resulting ^{10}Be ages (ka).

Arctic-wide production rate (Young *et al.*, 2013) with the Lal/Stone scaling scheme (Lal, 1991; Stone, 2000). No corrections for snow cover were made on any of the samples based on the assumption that the areas are windswept due to strong katabatic winds; no corrections for surface erosion were made. Also, no corrections for changes in air pressure or glacial isostasy were made because these effects are assumed to be negligible in the last few millennia.

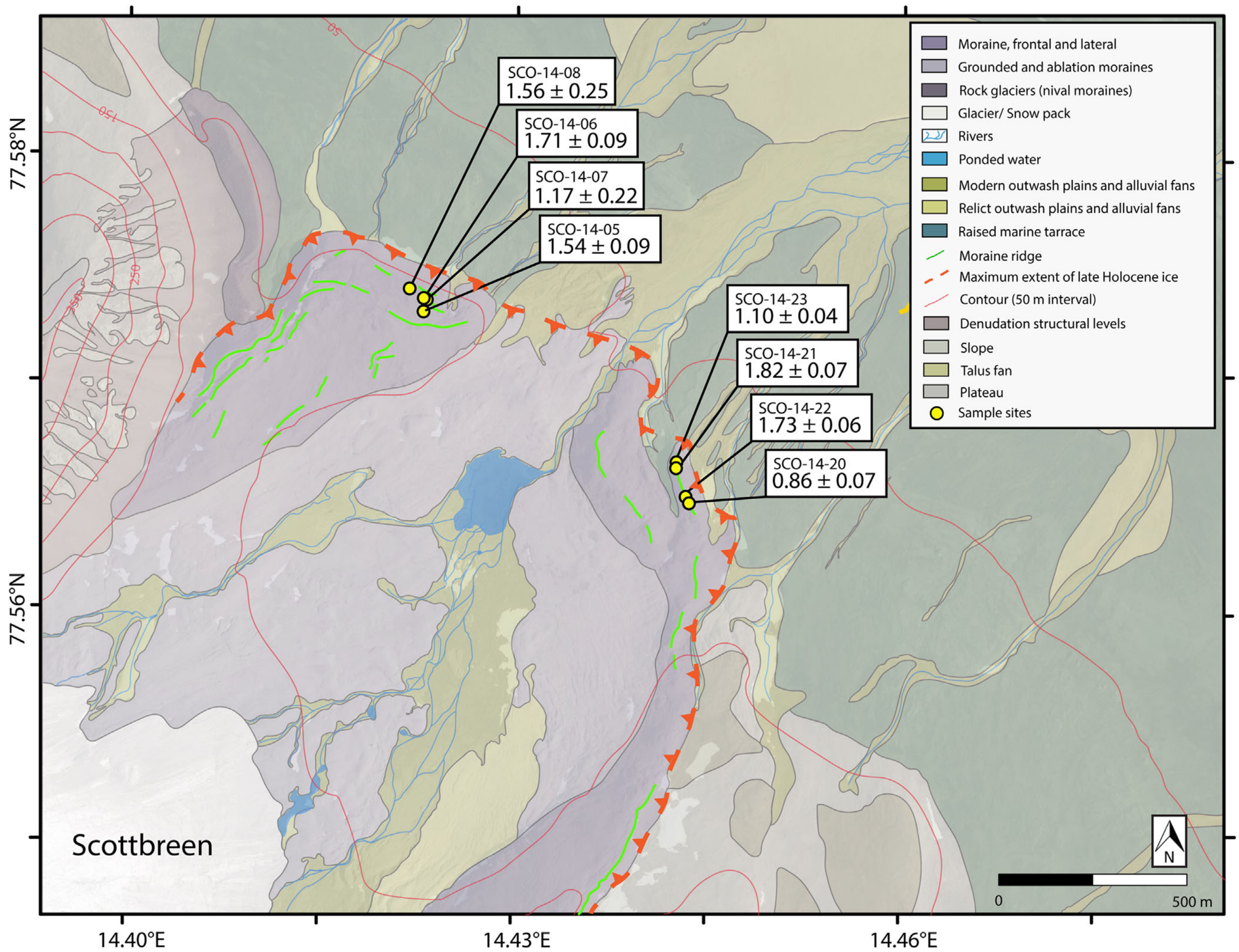

Figure 5. Geomorphologic map of Scottbreen's terminus modified from Zagórski (2002), underlain with Norsk Polar Institute aerial photograph (s2011_25163_00522_l3) showing ^{10}Be ages (ka).

Mapping

The Treskelen Quaternary geological map (Fig. 3) is based on: aerial images from the Norwegian Polar Institute collected in 2011 (Norwegian Polar Institute, photographs s2011_25163_00183; s2011_25163_00184; s2011_25163_00185), selected previous published work (Heintz, 1953; Birkenmajer, 1964; Marks, 1983; Szczęsny *et al.*, 1989a; Lindner and Marks, 1990) and field observations from our summer 2013 fieldwork. The Scottbreen Quaternary geological map (Fig. 5) is based on aerial images (Norwegian Polar Institute, photograph s2011_25163_00522_l3) and previously published work (Szczęsny *et al.*, 1989a; Zagórski, 2002). The goal of both maps is to provide an overview map of the locations of sampled boulders and their relation to moraine crests. The color schemes for the Treskelen and Scottbreen maps are based on Zagórski (2002). We add to the maps the inferred maximum extent of late Holocene ice and sampling locations as well as the location of moraine ridge crests at the Scottbreen site. Quaternary geological mapping of both field areas was performed using ESRI ArcGIS version 10.2.2 and edited in Adobe Illustrator CS6.

Results and interpretations

Treskelen Peninsula

The sampled moraine boulders are from the distal margin of ground moraine. We were unable to differentiate the ground moraine into more than one geomorphic unit. The ^{10}Be ages range from 0.49 ± 0.21 to 6.35 ± 0.46 ka ($n = 9$; Table 1). The two ^{10}Be ages from the same boulder yield ages of 0.64 ± 0.19 (T-03.1) and 0.49 ± 0.21 ka (T-03.2); from here forward we only discuss the average of these two ages, which is 0.57 ± 0.20 ka. The age distribution exhibits a bimodal pattern with clusters at 0.74 ± 0.22 ka ($n = 3$) and 1.88 ± 0.33 ka ($n = 4$), with an outlier of 6.35 ± 0.46 ka ($n = 1$) (Fig. 8).

The samples that comprise the two age clusters show no clear spatial distribution across the peninsula (Fig. 3). The northernmost sample is from the moraine ridge at 81 m a.s.l. and yields an age of 1.98 ± 0.37 ka (T-01). In the northern central portion of the peninsula, samples T-02, T-03.1 and T-03.2 were collected ~1.5 m apart in the center of Treskelen at elevations between 105 and 107 m a.s.l. The samples are situated on a thin till cover deposited on the transition between till-covered bedrock above and moraine below (Figs 3 and 4). The ages are 0.70 ± 0.19 ka (T-02) and 0.57 ± 0.20 ka (average of T-03.1 and T-03.2). To the south, a sandstone cobble at 114 m a.s.l. on weathered bedrock located slightly beyond (~20 m) the Holocene drift limit dates to 1.79 ± 0.26 ka (TR-03; Figs 3 and 4). Sample TR-03 was probably emplaced by a tall glacier front that dropped the cobble slightly beyond the drift limit. The southernmost samples occur in the southern central sector of the peninsula, where a cluster of three sampled boulders date to 2.31 ± 0.36 ka (T-05), 1.43 ± 0.33 ka (T-06) and 6.35 ± 0.46 ka (T-07) at elevations between 96 and

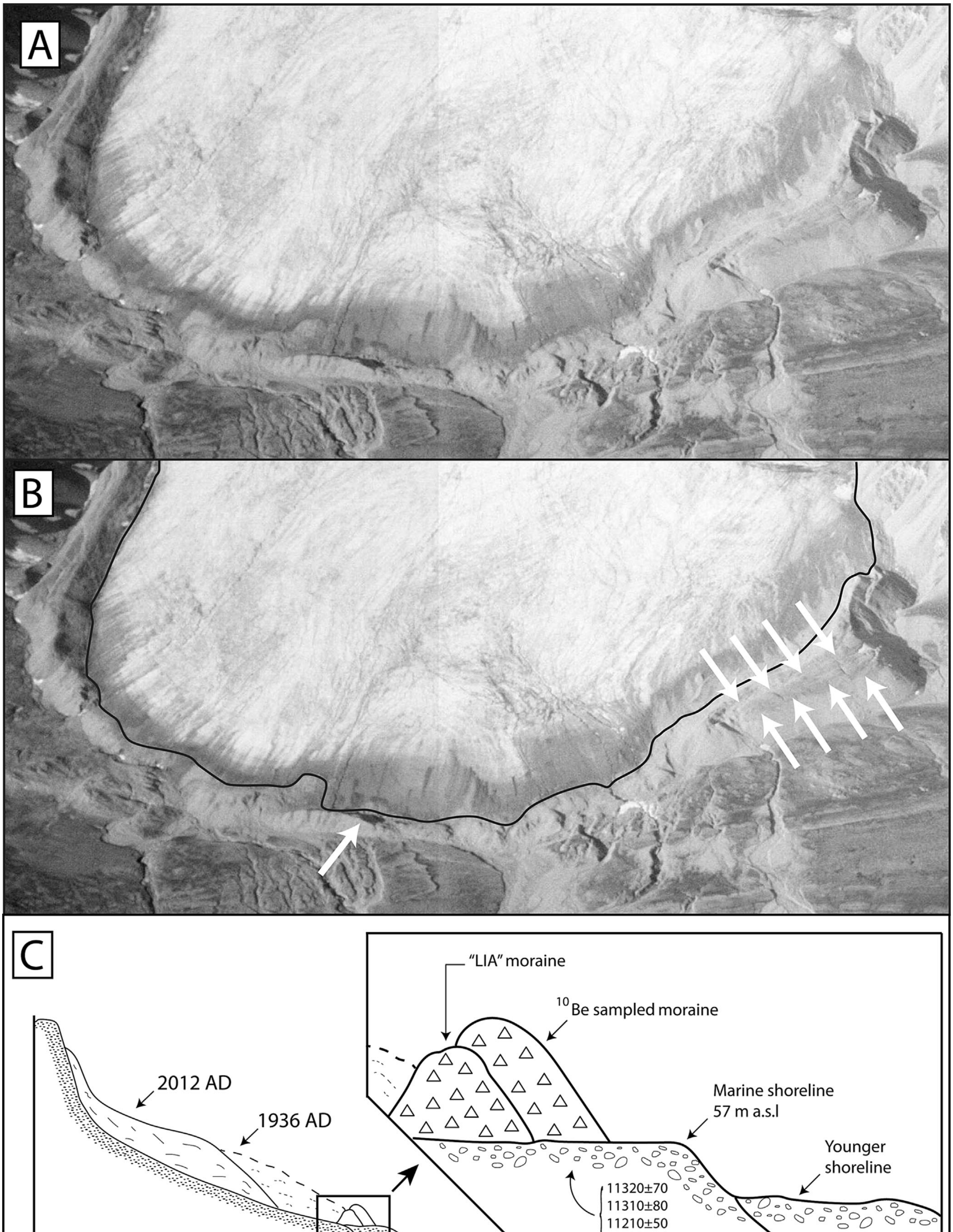

Figure 6. (A) Oblique air photo of Scottbreen's terminus from July 1936 (Norwegian Polar Institute, photograph no. S36-1694). (B) Duplicate image with the black line showing the ice extent in 1936 and white arrows showing the sampled moraines detailed in Fig. 5. (C) Schematic cross-section of Scottbreen modified from Mangerud and Landvik (2007) to add the pre-LIA moraine studied here.

Figure 7. Photographs of sampled boulders for ^{10}Be dating on Scottbreen's Holocene terminal moraine (locations shown in Fig. 5) showing ^{10}Be ages (ka).

Table 1. ^{10}Be data for calculation of cosmogenic nuclide exposure ages.

Sample	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Sample type	Thickness (cm)	Shielding correction	Quartz (g)	^{9}Be carrier (μg)	$^{10}Be \pm 1\sigma$ (atoms g^{-1})	^{10}Be age (ka)
Scottbreen										
SCO-14-05	77.5638	14.4171	112	Tillite boulder	2.0	0.9978	32.006	227.56	7.31E+03 ± 4.26E+02	1.54 ± 0.09
SCO-14-06	77.5640	14.4172	113	Tillite boulder	2.0	0.9978	26.754	226.48	8.31E+03 ± 4.07E+02	1.71 ± 0.09
SCO-14-07	77.5640	14.4175	112	Tillite boulder	2.0	0.9978	28.525	227.30	5.55E+03 ± 1.06E+03	1.17 ± 0.22
SCO-14-08	77.5642	14.4159	113	Tillite boulder	2.0	0.9974	17.464	227.60	7.44E+03 ± 1.17E+03	1.56 ± 0.25
SCO-14-20	77.5603	14.4401	84	Tillite boulder	2.0	0.9986	28.561	226.37	7.54E+03 ± 5.86E+02	0.86 ± 0.07
SCO-14-21	77.5604	14.4397	82	Tillite boulder	2.0	0.9987	45.800	227.34	8.40E+03 ± 3.19E+02	1.82 ± 0.07
SCO-14-22	77.5609	14.4390	77	Tillite boulder	2.0	0.9987	25.409	226.59	8.49E+03 ± 4.74E+02	1.73 ± 0.06
SCO-14-23	77.5611	14.4390	76	Tillite boulder	2.0	0.9987	30.555	227.63	1.10E+04 ± 3.39E+02	1.10 ± 0.04
Treskelen										
T-01	77.0237	16.2204	81	Siltstone boulder	2.4	0.9916	20.296	209.85	9.90E+03 ± 1.80E+03	1.98 ± 0.37
T-02	77.0174	16.2164	107	Siltstone boulder	4.5	0.9938	25.107	211.68	3.50E+03 ± 1.00E+03	0.70 ± 0.19
T-03.1	77.0175	16.2166	105	Siltstone boulder	1.4	0.9601	26.834	211.52	3.20E+03 ± 1.00E+03	0.64 ± 0.19
T-03.2	77.0175	16.2166	105	Siltstone boulder	2.0	0.9712	22.702	209.19	2.50E+03 ± 1.10E+03	0.49 ± 0.21
T-04	76.9986	16.2114	13	Siltstone boulder	3.0	0.9255	23.045	212.02	4.00E+03 ± 1.20E+03	0.94 ± 0.27
T-05	77.0085	16.2274	100	Siltstone boulder	2.9	0.9998	16.638	211.68	1.18E+04 ± 1.90E+03	2.31 ± 0.36
T-06	77.0088	16.2269	96	Siltstone boulder	1.1	0.9999	15.239	211.68	7.40E+05 ± 1.70E+03	1.43 ± 0.33
T-07	77.0094	16.2256	104	Siltstone boulder	1.7	0.9998	21.335	211.02	3.29E+04 ± 2.40E+03	6.35 ± 0.46
TR-03	77.0148	16.2178	114	Siltstone boulder	5.0	0.9993	20.704	211.52	9.20E+03 ± 1.30E+03	1.79 ± 0.26

104 m a.s.l. (Figs 3 and 4). The anomalously old age of 6.35 ± 0.46 ka (Fig. 8) probably represents inheritance due to boulder recycling. The southernmost sample (T-04) yields an age of 0.94 ± 0.27 ka (Figs 3 and 4).

Previously published work does not reveal moraine deposits from separate advances on Treskelen (e.g. Birkenmajer, 1964; Heintz, 1953; Lindner and Marks, 1990; Marks, 1983). Based on our fieldwork and mapping, we also observed no evidence for deposits of visibly different age on Treskelen (Fig. 3). However, our new moraine chronology suggests two modes of ages that represent (i) degradation of a moraine with a single age, (ii) inheritance on a moraine of a single age or (iii) two glacier advances to the same position on Treskelen and the younger advance added new boulders among the boulders deposited during the older advance. In this section, we correlate the two age modes with previously published chronologies from around Svalbard and favor the interpretation that the clusters of ages represent two glacial advances.

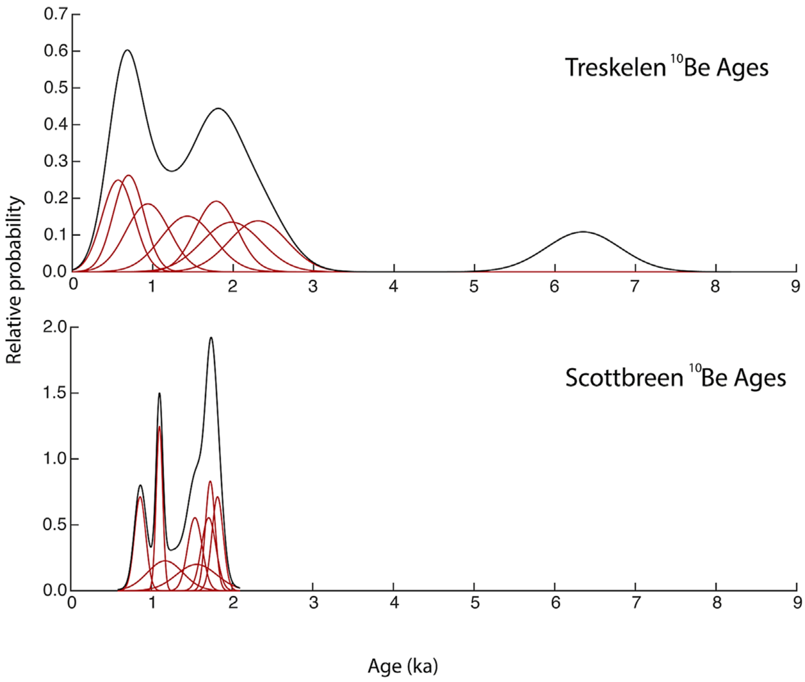

Figure 8. Normal kernel density estimates of ^{10}Be ages on Treskelen Peninsula and Scottbreen.

We interpret the older mode of ^{10}Be ages from Treskelen as the timing of moraine abandonment at 1.9 ± 0.3 ka (n = 4), and the young mode at 0.7 ± 0.2 ka (n = 3) to represent moraine abandonment in the last millennium. The lack of a spatial pattern of ages across Treskelen suggests the ice margin occupied the same portion of the peninsula during both advances, which perhaps is related to Treskelen acting as a topographic pinning point (e.g. Barr and Lovell, 2014). There is no existing chronology from the Treskelen Peninsula indicating pre-LIA, late Holocene glacier activity. However, thermoluminescence (n = 3) and ^{14}C (n = 11) ages from coastal deposits in outer Hornsund Fjord bracket a glacier advance between ~3.3 and 2.1 ka (Lindner and Marks, 1993), which may correlate with our interpretation of moraine abandonment at 1.9 ± 0.3 ka at Treskelen.

The younger mode of ^{10}Be ages of 0.7 ± 0.2 ka may relate to the glacier-transported driftwood incorporated into till on Treskelen, which provides a maximum age for a glacier advance during the LIA of 750 ± 90 cal a BP (Grosswald *et al.*, 1967). In the greater Hornsund region, a glacier advance is constrained between ~0.81 and 0.39 ^{14}C ka BP (Lindner and Marks, 1993). We suggest that the young mode of ^{10}Be ages at 0.74 ± 0.22 ka represents an ice advance on Treskelen during the last millennium that was of comparable magnitude as an earlier advance at or before 1.9 ± 0.3 ka. The pair of glacier advances to the same position on Treskelen may relate to the Treskelen Peninsula acting as a topographic pinning point – because it results in a significant narrowing (and perhaps shallowing) of the fjord – for multiple glacial advances in the late Holocene.

Scottbreen

Based on new field observations, previously published maps (Szczęsny *et al.*, 1989b; Zagórski, 2002) and high-resolution aerial photographs (Norwegian Polar Institute, photograph s2011_25163_00522_l3), we delineated multiple crests in the moraine complex fronting Scottbreen (Figs 5 and 6). Unlike at Treskelen, the morphostratigraphy fronting Scottbreen exhibits many individual moraine crests of varying age. The eight ^{10}Be ages that we obtained from the outermost moraine crest range from 1.82 ± 0.07 to 0.86 ± 0.07 ka, and average 1.44 ± 0.11 ka (Table 1; Figs 7 and 8), all of which pre-date the LIA.

Four of the ^{10}Be ages from the outermost moraine crest east of the outwash plain range from 0.86 ± 0.07 to 1.82 ± 0.07 ka and average 1.38 ± 0.06 ka (n = 4; SCO-14-20, 21, 22, 23). The samples yielding ages of 0.86 ± 0.07 (SCO-14-20) and 1.10 ± 0.04 (SCO-14-23) may be young outliers due to moraine degradation; the samples fall outside of the 3-sigma error of the average of the other ages (Table 1; Fig. 8). Excluding samples SCO-14-20 and SCO-14-23, the outermost moraine averages 1.78 ± 0.07 ka (n = 2; SCO-14-21, 22).

The samples on the outermost moraine crest west of the outwash plain have ^{10}Be ages that range from 1.17 ± 0.22 to 1.71 ± 0.09 ka and average 1.50 ± 0.16 ka (n = 4; SCO-14-05, 06, 07, 08). The sites on either side of the outwash plain are not easily traceable to each other, but due to the similarity in average ages, we assume they are contemporaneous. Comparing the average age clusters of the outer moraine crests, we conclude that the ages are part of a single cluster, indicating that the moraines on either side of the outwash plain probably formed at the same time at 1.7 ± 0.1 ka (n = 5).

The age distribution of samples from the outermost Scottbreen moraines (Figs 5 and 8) indicates that most of the moraine boulders were emplaced before the LIA at ~1.7 ka. An alternative explanation would be that all moraines and moraine boulders were deposited during the LIA, and all eight boulders contain inheritance. We find this unlikely given the clustering of ages at ~1.7 ka. Given the photographic evidence for the Scottbreen terminus residing slightly inboard of the ~1.7-ka moraines in 1936 AD (Norwegian Polar Institute, S36, photographs 1694 and 3189), there is evidence that the end moraine complex represents multiple ice advances, as proposed by Reder and Zagórski (2007). Thus, Scottbreen was almost as extensive during the LIA as it was at ~1.7 ka.

Comparing Scottbreen and Treskelen moraine ages

The average moraine age of the older mode of 1.88 ± 0.33 ka on the Treskelen Peninsula and 1.7 ± 0.1 ka on the outer moraine crest on Scottbreen are within error of each other. Thus, it seems that moraine crests abandoned before the LIA are preserved at both sites. Although some of the merged tidewater glaciers that reached the Treskelen Peninsula and the alpine glacier Scottbreen have vastly different glacier geometries, and most of which are likely to have surged at least once, the moraines were abandoned around the same time before the LIA.

Discussion

Regional late Holocene glacial records

The similar age of moraines of ~1.9 ka at Treskelen and ~1.6 ka at Scottbreen suggests that glaciers across southern Svalbard may have behaved synchronously during the late Holocene (Fig. 9). In this section, we compare these moraine ages with previously published glacier records from the region (Fig. 9).

The Linnédalen region (Fig. 1) provides records of late Holocene glacier activity from two glaciers in the Linnevatnet catchment and the moraines outboard of Linnebreen. The meltwater signal from a small cirque glacier to the west of Linnevatnet, which is virtually absent today, indicates glacier activity during the LIA, but not before ~0.4 cal ka BP (Snyder *et al.*, 2000). Sediment cores from part of Linnevatnet that record the major inflow to the lake, from Linnebreen, reveal a peak in sedimentation at ~2.5 cal ka BP that decreases by ~1.1 cal ka BP, which increases again at ~0.4 cal a BP (Fig. 9; Svendsen *et al.*, 1987; Svendsen and Mangerud, 1997). Finally, moraine boulders from the right lateral pre-LIA moraine (Werner, 1993) fronting Linnebreen yield ^{10}Be ages ranging from 3.6 ± 0.3 to 0.5 ± 0.2 ka and average 1.6 ± 0.2 ka (Fig. 9; Reusche *et al.*, 2014).

At Longyearbreen (Fig. 1), a small valley glacier up-valley from the hamlet of Longyearbyen, a supraglacial meltwater channel eroded into the glacier's bed exposing subglacial sediments ~2 km up-valley of its terminus (Gulley *et al.*, 2009). ^{14}C ages of macrofossils from the sub-glacial sediments range from 1.2 ± 0.1 to 1.8 ± 0.2 cal ka BP (n = 11) and a paleosol in which the macrofossils are rooted dates to 4.6 ± 0.2 cal ka BP (Fig. 9; Humlum *et al.*, 2005). The 1.8–1.1 cal ka BP period represents a time of ice-free conditions at a location 2 km up valley from the present terminus. The time before the earliest age of ~1.8 cal ka BP could be interpreted as a time of ice occupation.

At many sites in central Spitsbergen, recession of cold-based ice caps reveals surface tundra moss preserved in growth position. Miller *et al.* (2017) dated 45 samples of the moss to derive a record of glacier expansion and snowline lowering in the late Holocene. The resulting record indicates ice cap growth episodes at approximately 1.66, 1.47 and 1.23 cal ka BP. Following a ~0.25-kyr hiatus, ice cap

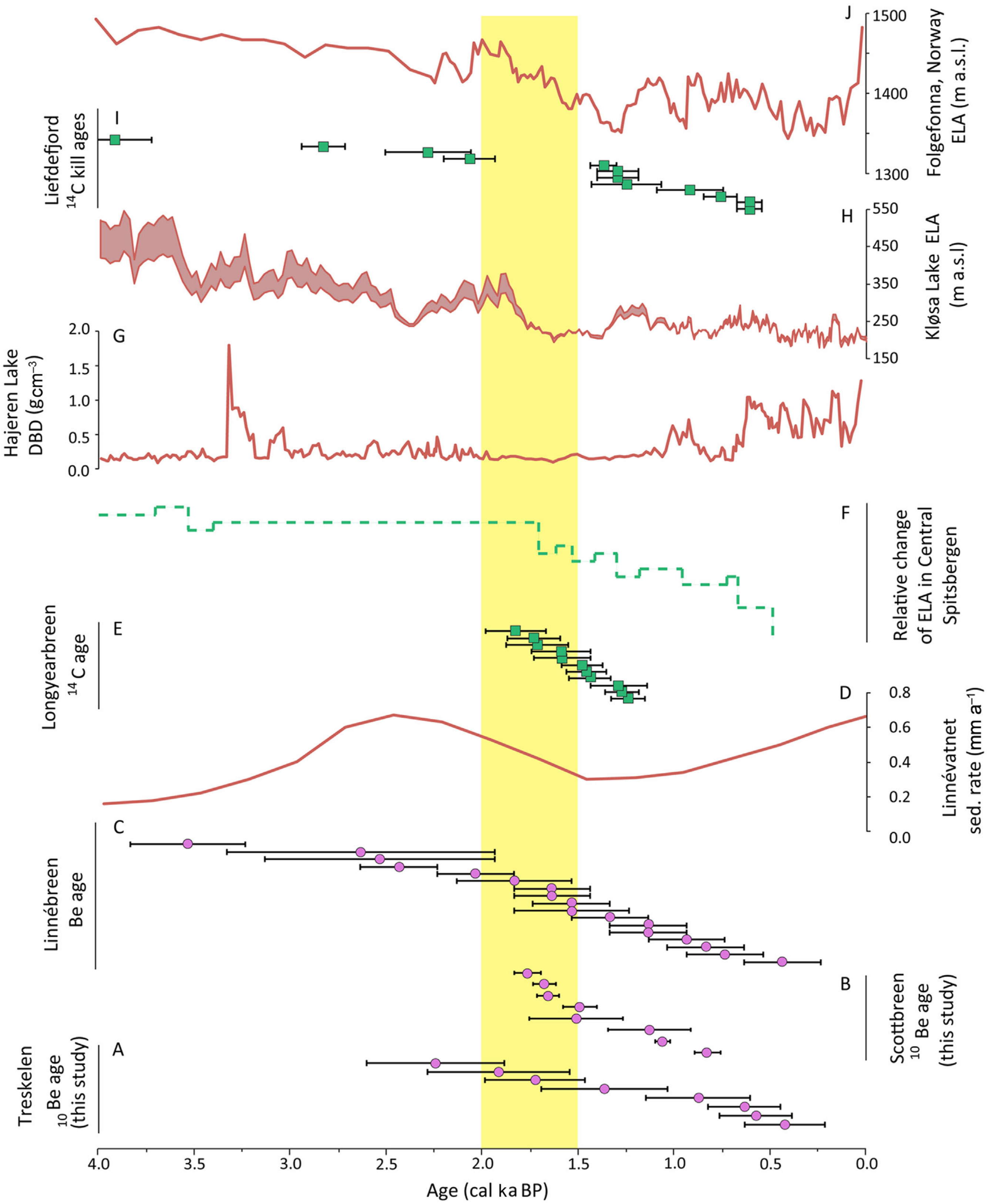

Figure 9. Late Holocene glacier records from on and around Svalbard: (A) ^{10}Be ages from the Treskelen moraine (this study); (B) ^{10}Be ages from the Scottbreen moraine (this study); (C) ^{10}Be ages from the Linnébreen moraine (Reusche *et al.*, 2014); (D) Linnévatnet sedimentation rate (mm $^{a-1}$) (Svendsen and Mangerud, 1997); (E) Longyearbreen ^{14}C ages representing –ree conditions (Humlum *et al.*, 2005); (F) relative change in snowline constructed from ^{14}C kill dates in central Spitsbergen (Miller *et al.*, 2017); (G) Hajeren Lake dry bulk density (DBD; g cm^{-3}) (van der Bilt *et al.*, 2015b); (H) Kløsa Lake equilibrium line elevation (Røthe *et al.*, 2015); (I) Liefdefjord ^{14}C ages representing ice-free conditions (Furrer *et al.*, 1991); and (J) ELA reconstruction of Folgefonna, Norway (Bakke *et al.*, 2005).

expansion began again, marked by advances at ~0.95 cal ka BP, ~0.72 cal ka BP, and the LIA between 0.65 and 0.50 cal ka BP (Fig. 9; Miller *et al.*, 2017). The record of Miller *et al.* (2017) includes evidence for an episode of glacier expansion between ~2 and 1.5 ka, similar to the moraine records that we studied.

In north-eastern Spitsbergen at Mitrahalvøya (Fig. 1), two adjacent lake basins record Holocene glacier fluctuations.

Hajeren Lake receives runoff from two small cirque glaciers (van der Bilt *et al.*, 2015a,b). The lake catchment's dry bulk density record (Fig. 9) is interpreted to indicate glacier advances between 3.4 and 3.2 cal ka BP and after 1.1 cal ka BP (van der Bilt *et al.*, 2015b). Kløsa Lake, ~1 km south-west of Hajeren Lake, receives its dominant sediment supply from Karlbreen. Røthe *et al.* (2015) reconstructed equilibrium line altitudes (ELAs) of Karlbreen since ~4.0 cal ka BP. The ELA reconstruction indicates an overall lowering ELA through the late Holocene, with significant episodes of ELA lowering close to its Holocene maximum extent at approximately 1.70, 0.23 and 0.14 cal ka BP (Fig. 9; Røthe *et al.*, 2015). The period of ELA lowering at ~1.7 cal ka BP may relate to moraine formation at our study sites.

In eastern Liefdefjorden (Fig. 1), moraines that contain numerous buried organic soil horizons are interpreted to be overridden by former glacial advances (Furrer *et al.*, 1991). ^{14}C ages obtained in the soil horizons cluster into two modes between ~2.8 and 2.1 cal ka BP ($n=3$) and between ~1.4 and 0.6 cal ka BP ($n=8$). The ages are interpreted to represent times of reduced glacier extent with glacier advances during times with no ^{14}C ages from ~2.1 to 1.4 cal ka BP and after ~0.6 cal ka BP (Fig. 9; Furrer *et al.*, 1991).

Although reconstructions of late Holocene glacier activity on Svalbard remain unevenly distributed through space and time, some of the published records showing an ice advance before the LIA have similarities with our new moraine ages from Treskelen and Scottbreen. Similarly, glacier ELAs on mainland Norway show similar trends, notably significant ELA lowering between ~2 and ~1.5 ka (e.g. Bakke *et al.*, 2005). Although scattered, the mean ^{10}Be age of moraine boulders at Linnébreen of 1.6 ± 0.2 ka (Reusche *et al.*, 2014) overlaps with the moraine ages at Treskelen at 1.9 ± 0.3 ka ($n=3$) and Scottbreen at 1.7 ± 0.1 ka ($n=5$). Similarly, the ELA reconstruction from Karlbreen (Røthe *et al.*, 2015), snowline lowering data from Miller *et al.* (2017) and the sedimentation rate fluctuation of Linnevatnet (Svendsen and Mangerud, 1997) are compatible with a glacier advance leading to moraine abandonment in the period ~1.9–1.7 ka. Although both our moraine ages and these snowline-lowering reconstructions are at odds with the record from Longyearbreen (Humlum *et al.*, 2005), they may be compatible with the ^{14}C ages from glacier-reworked soils from Liefdefjorden (Furrer *et al.*, 1991). The variation in the timing of late Holocene glacier activity on western Svalbard may relate either to uncertainties in the ^{14}C and ^{10}Be chronologies (e.g. Wolfe *et al.*, 2004; Balco, 2011), or to variable glacier behavior relating to factors such as surging (Meier and Post, 1969), glacier response time, or hypsometric controls on glacier response to climate change (Benn and Evans, 2010).

Implications for surge dynamics

The tidewater glaciers that reached the Treskelen Peninsula and the alpine glacier Scottbreen have documented surge activity (Hagen *et al.*, 1993; Liestøl, 1993; Błaszczyk *et al.*, 2013). Surging glaciers have a complicated response to climate change, and experience advances due to non-climatic factors (Meier and Post, 1969; Yde and Paasche, 2010). However, the highly similar moraine ages, indicating the timing of late Holocene advance culmination, at the Treskelen Peninsula (1.88 ± 0.33 ka) and Scottbreen (1.59 ± 0.13 ka) are within error of each other and of other glacial records around Spitsbergen (Fig. 9). Therefore, we suspect a common regional climatic forcing. Surge cycles on Svalbard have been hypothesized to range from 50 to 500 years, with an active phase of 3–10 years (Dowdeswell and Collin, 1990). On centennial and longer timescales, glacier changes due to climate change may dominate over short-lived glacier changes due to surging activity, much in the way that ice sheet dynamics can lead to short-lived changes in terminus position, while terminus changes are dominated by climate on longer timescales (e.g. Kjeldsen *et al.*, 2015). To know with more certainty if the moraines that we dated reflect regional climate change or non-climatic surging behavior, additional moraine chronologies of glaciers on Svalbard are required.

Conclusions

The glaciers that reached the Treskelen Peninsula and Scottbreen have vastly different glacier geometries but yield similar moraine ^{10}Be ages of 1.9 ± 0.3 ka ($n=4$) on the Treskelen Peninsula and 1.7 ± 0.1 ka ($n=6$) at Scottbreen. The moraines at the Treskelen Peninsula and Scottbreen are within error of each other and of other glacier records on Spitsbergen, suggesting a significant snowline lowering and glacier expansion event between ~2.0 and 1.5 ka. Scottbreen and several glaciers in inner Hornsund are documented to have surged in historical times. Yet, both glaciers deposited late Holocene moraines at about the same time. We suggest that on centennial and longer timescales, climate influences outweigh surging activity, which exerts a stronger control on glacier length on shorter (decadal) timescales. However, more chronologies are needed to test this hypothesis.

Records of early Holocene glacier variability around Svalbard are scarce and unevenly distributed. The three late Holocene moraines so far ^{10}Be dated on Svalbard reveal information about pre-LIA glacier activity. This indicates that, like elsewhere in the Arctic (e.g. Badding *et al.*, 2013; Young and Briner, 2015), pre-LIA late Holocene moraines may be more typical than previously thought, and might well be preserved elsewhere in Svalbard.

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Abbreviations. AMS, accelerator mass spectrometry; ELA, equilibrium line altitude; LGM, Last Glacial Maximum; LIA, Little Ice Age.

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