10Be surface exposure dating of the deglaciation of northernmost Norway and Finland

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During the Last Glacial Maximum, the coast of Finnmark county, northern Norway, was covered by the Scandinavian Ice Sheet (SIS), which coalesced with the Barents Sea Ice Sheet (BSIS) off the coast. The region is thus important for our understanding of the dynamic interactions between the BSIS and the SIS, yet it remains one of the least dated regions covered by the SIS. To improve the chronological constraints, we present 23 new ^{10}Be ages from eight localities in northernmost Norway and Finland, and discuss implications for the pattern and timing of ice sheet retreat in the region. The samples were collected along a 240 km-long north-south transect ranging from the outer coast of Nordkinn peninsula (Norway) to Lake Inarijärvi (Finland). The new exposure ages indicate deglaciation of the outer coast at ~14.5 ka. From there, the ice retreated southward until it reached the Main sub-stage moraine complex just north of the Norwegian-Finnish border during the Younger Dryas. South of the Main sub-stage moraines the deglaciation appears to have become more rapid, eventually reaching Inari, at the southern end of our transect, around 10.4±1.4 ka.

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The coast of Finnmark (northern Norway) forms the northernmost edge of mainland Europe. During the Last Glacial Maximum (LGM) this region was covered by the Scandinavian Ice Sheet (SIS), which coalesced with the Barents Sea Ice Sheet (BSIS) to the north (e.g. Svendsen *et al.* 2004; Andreassen *et al.* 2008; Hughes *et al.* 2016; Stroeven *et al.* 2016). At this time, the entire Barents Sea continental shelf was ice covered with ice margins situated at the shelf edge and ice drainage dominated by the Bjørnøyrenna ice stream (Vorren & Laberg 1996; Winsborrow *et al.* 2010).

The first sign of deglaciation was a significant retreat in the southern Barents Sea (Winsborrow *et al.* 2010), possibly before 18.6±0.1 cal. ka BP (Junttila *et al.* 2010). At this stage, the Barents Sea and the Scandinavian ice sheets had already started to separate (Junttila *et al.* 2010; Rüther *et al.* 2011). However, the Finnmark coast remained glaciated and coast-parallel ice streams were active (Winsborrow *et al.* 2010). It took until ~15 cal. ka BP before the nearshore coastal waters in western Finnmark were deglaciated (Junttila *et al.* 2010, based on radiocarbon-dated deglacial sediments).

On land, marine macrofossils from basal sediments in lake cores from Rolvsøya, Magerøya and outer Nordkinn (Fig. 1) have been dated to 14.2, 13.6 and 14.4 cal. ka BP, respectively, providing minimum-limiting ages for the deglaciation on the outer coast (Romundset *et al.* 2011). Romundset *et al.* (2011) suggested that, as these lakes are situated below the marine limit, they closely constrain deglaciation, and that the outer coast became ice-free shortly after the beginning of the Bølling warm period, around 14.6 cal. ka BP. This contrasts with recent deglaciation reconstructions by Hughes *et al*. (2016) and Stroeven *et al.* (2016), which both place deglaciation of the outer coast between 15 and 16 ka.

The regional glacial geomorphology of Finnmark was mapped by Sollid *et al.* (1973). They identified multiple retreat stages with corresponding end moraines. The most prominent of these is the Main sub-stage moraine, a largely continuous end moraine complex attributed to Younger Dryas advances and dated to 12.2±1.2 ka near Kirkenes (recalibrated from Romundset *et al.* 2017). Older end moraines have also been identified but these only constitute discontinuous ice-marginal deposits, which were correlated based on their cross-cutting relationships with palaeo-shore lines of regional extent. The most prominent of these older moraine systems defines the Outer Porsanger sub-stage (Sollid *et al.* 1973), recently dated to approximately 14.3±1.5 ka on eastern Varangerhalvøya by Romundset *et al.* (2017, recalibrated).

Heavily streamlined terrain has been identified both onshore (e.g. Sollid *et al.* 1973; Kleman *et al.* 1997; Winsborrow *et al.* 2010) and offshore (e.g. Winsborrow *et al.* 2010; Rüther *et al.* 2011), indicating a highly dynamic ice sheet. The region is important for our understanding of the interactions between the BSIS and the SIS, and by extension for our understanding of the dynamic relationship between land-based and shelf-based ice sheets. However, despite several recent studies adding surface exposure ages from various parts of Finnmark and northernmost Finland (Fjellanger *et al.* 2006; Stroeven *et al.* 2011; Cuzzone *et al.* 2016, Romundset *et al.* 2017), relatively few numerical ages exist from the region compared to other sectors of the SIS (Hughes *et al.* 2016; Stroeven *et al.* 2016). Improvements to the chronology of ice sheet retreat following the Last Glacial Maximum could provide important constraints for quantifying ice sheet behavior, glacial-isostatic adjustments (GIA), and palaeoclimate (i.e. Tarasov *et al*. 2012; Love *et al.* 2016; Patton *et al*. 2016, 2017).

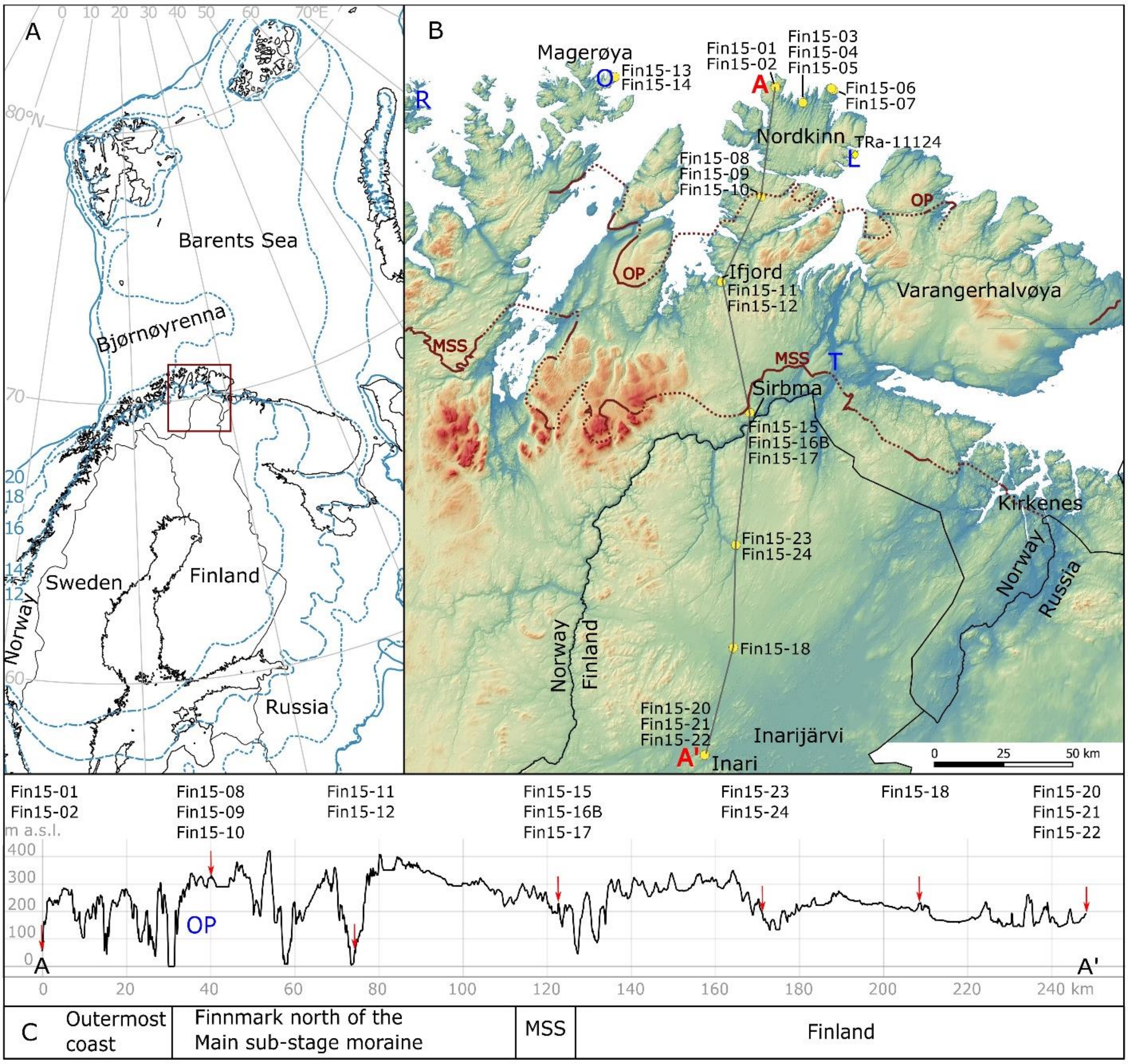

Fig. 1. A. Overview map over northern Fennoscandia and the Barents Sea. The ice extents at 20, 18, 16, 14 and 12 ka are indicated in blue (based on Hughes *et al.* 2016). B. Map over the study region. The sample locations are indicated in yellow and the end points of the N-S transect, A and A', are indicated in red. The positions of the Outer Porsanger stage (OP) and Main sub-stage (MSS), redrawn from Sollid *et al.* (1973), are indicated in brown. Solid lines are used where the suggested ice margins coincide with end moraines mapped by the Geological Survey of Norway (ND_Løsmasser 3.0, available from https://www.ngu.no/emne/datasett-og-nedlasting). R = Rolvsøya; O = Opnan; L = Losvik; T = Tana Bru. C. Topographic profile along transect A-A' indicated in B. The positions of the sample sites are indicated by red arrows. Sample sites that do not fall on the transect are excluded.

Cosmogenic surface exposure dating has made it possible to directly date the deglaciation of an area, estimate erosion rates, and reconstruct the thermal regime of palaeo-ice-sheets (e.g. Gosse & Phillips 2001; Stroeven *et al.* 2002, 2016; Briner *et al.* 2006; Kelly *et al.* 2008; Licciardi & Pierce 2008; Dunai 2010; Margreth *et al.* 2016). In this study, we present ^{10}Be surface exposure ages from erratic boulders and glacially eroded bedrock outcrops from eight localities in northernmost Norway and Finland. The sites are situated along a 240 km N-S transect starting just below the marine limit at the outer coast (Fig. 1). By the time of our field campaign, in 2015, a parallel sampling campaign by Romundset and others had already collected surface exposure samples from end moraines attributed to two of the regionally identified deglaciation sub-stages, the Outer Porsanger sub-stage and the Main sub-stage (Younger Dryas) (later presented in Romundset *et al.* 2017). To complement that study we, therefore, focused on the areas outside of the moraine system, taking samples proximal, in-between, and distal to these moraine systems. This approach meant that we lacked distinct ice-marginal landforms that could be followed over large distances, and, rather than focusing on specific landforms, we prioritized dating a larger number of sites. Although this approach allowed us to attain an approximately even spatial distribution of sample localities along our transect, it also meant that for most individual sites the small number of samples made it more difficult to identify outliers. We augment these new ages with a review of previously reported deglaciation ages from the region.

The objectives of the study are to (i) date the deglaciation of the outer coast of Finnmark, the area where the ice-front first retreated onto land in this region, (ii) reconstruct deglaciation along a N-S transect ranging from the outer coast of Nordkinn peninsula to Lake Inarijärvi in northern Finland, and (iii) present the first geological ^{10}Be samples measured at the National Laboratory for Age Determination, Trondheim.

Study area

Apart from a site on Magerøya, all the studied sites lie along a transect spanning 69-71ºN (Fig. 1). The landscape in the region is dominated by rounded mountain plateaus, rarely exceeding 500 m above sea level (m a.s.l.), dissected by valleys and fjords. The proximity of the North Atlantic Current ensures a relatively temperate present-day climate. None of the Norwegian sites we investigated (Fig. 1) are currently forested, although for the more southerly sites forest is found nearby in less exposed settings. In contrast, all our Finnish sites are forested.

Methods

Surface exposure dating

Fieldwork was done in June 2015 when samples for ^{10}Be dating were collected at eight localities (Fig. 1). The sample sites were selected with the aim of dating the deglaciation of the outer coast, and obtaining an approximately equal sampling density along the N-S transect. A total of nine samples were collected from the outer coasts of Nordkinn peninsula and Magerøya. In addition, 15 samples were obtained along the transect. For each site where at least three ages were judged reliable, an error-weighted mean age was calculated following Taylor (1997). To estimate the uncertainty of each of these mean ages, we used either the mean uncertainty of the included ages, or the standard error (based on the deviation from the weighted mean rather than the arithmetic mean), whichever gave the highest uncertainty. This approach results in a reasonable and conservative estimate of the uncertainty, but it does not give a true standard deviation for the ages.

The rock samples were collected from the surfaces of erratic boulders and glacially abraded bedrock outcrops using a rock saw and hammer and chisel. Only boulders resting on apparently stable surfaces were selected and steep slopes were avoided to minimize the effect of post-depositional movements (Fig. 2). Where possible, the samples were collected from large and reasonably flat surfaces (maximum dip of a sampled surface is 21°). Sample locations were recorded using a handheld GPS. As the available digital elevation models over the study area have a

Fig 2. Selection of boulder and bedrock outcrops sampled in this study. A. Fin15-01. B. Fin15-03. C. Fin15-10. D. Fin15-11. E. Fin15-15. F. Fin15-21. See Table 1 for boulder heights.

higher vertical precision than the GPS used, altitudes were retrieved from the Norwegian Mapping Authority and the National Land Survey of Finland (Elevation model 2 m and 10 m, 03/2015). Samples were preferentially taken above the marine limit, and samples taken below the marine limit are considered minimum ages and are indicated both in the text and in Table 1. The topographic shielding at each sampling location was measured with a clinometer and compass, and was calculated using an online topographic shielding calculator (http://stoneage.ice-d.org/math/skyline/skyline_in.html, calculated in 2017). In total 24 samples were taken, of which 23 were analyzed (Fig. 1).

Initial sample preparation was completed at the Geological Survey of Norway, where the 23 selected samples were crushed to a grain size of 250-400 µm and a Frantz magnetic separator was used to separate the non-magnetic grains from the magnetic grains. Crushed samples then underwent quartz isolation and purification at the Institute of Geological Sciences, University of Bern using the method of Akçar *et al.* (2017), which is a modified version of the technique introduced by Kohl & Nishiizumi (1992). Extraction of beryllium from clean quartz, and subsequent preparation of targets for AMS analysis, was also done at University of Bern, following procedures from Akçar *et al*. (2017). The samples were processed in batches of 10 where each batch included 2-3 procedural ^{10}Be blank samples, resulting in a total of seven blanks for this study. Beryllium isotope ratios of samples and procedural blanks were measured at the 1 MV AMS at the National Laboratory for Age Determination, Trondheim (Nadeau *et al.* 2015; Seiler *et al.* 2018) using the 01-5-1 standard material from Nishiizumi *et al.* (2007). The measured ^{10}Be concentrations have been converted into apparent exposure ages using the CRONUScalc v.2.1 Web interface (Marrero *et al.* 2016; using the SA scaling based on Lifton *et al.* 2014 and production rates from Borchers *et al.* 2016). All ages were calculated using erosion rates of 0 mm ka^{-1} and 1±0.5 mm ka^{-1} and the results are presented in Table 1. For the ages presented in the text, the 1±0.5 mm ka^{-1} erosion rate was used for all samples except those collected from massive quartz such as quartz veins or quartz nodules (Fin15-01, Fin15-07, Fin15-11 and Fin15-12), for which zero erosion was assumed. The 1±0.5 mm ka^{-1} erosion rate was estimated based on observations of quartz veins and quartz nodules protruding ~1 cm from the surrounding rocks in the study area. Snow shielding and vegetation shielding were assumed to be negligible. This assumption is probably reasonable for the Norwegian samples (Fin15-01 – Fin15-17), which were in general taken in highly wind exposed settings, but is more questionable for the Finnish samples (Fin15-18 – Fin15-24) which were sheltered in a low-density boreal forest and may have experienced a substantial, but unknown, amount of snow shielding. The rock density was assumed to be 2.65 g cm^{-3} for all samples.

No correction for isostatic rebound was made. To estimate the potential error due to this omission the samples were also calibrated using the iceTEA web application (Jones *et al*. 2019), which correct for isostatic movements. For this calibration experiment we selected a GIA model correction, an ICE-6G ice model and LSD scaling.

To enable comparisons with our samples, cosmogenic surface exposure ages reported by Fjellanger *et al.* (2006), Cuzzone *et al.* (2016) and Romundset *et al.* (2017) were recalculated using the CRONUScalc v.2.0 Web interface. For these samples we also use a rock density of 2.65 g cm^{-3}, assume zero shielding from snow and vegetation, and calculate the new ages using a 1±0.5 mm ka^{-1} erosion rate. Among the previously published data sets, only exposure ages having a clear geomorphological or geological relationship to the deglaciation were included. Samples taken below the marine limit (n = 4, Romundset *et al.* 2017) were excluded, unless they were the only ages from a site, in which case they were treated as minimum ages (n = 5, Cuzzone *et al.* 2016). Samples from preserved block-fields (n = 7, Fjellanger *et al.* 2006) were excluded. In addition, two samples which gave clear pre-LGM ages, (47±5 ka, Fjellanger *et al.* (2006) and 170±22 ka, Romundset *et al.* (2017)), were excluded.

AMS radiocarbon dating

A single mollusc shell was found at Losvik, western Nordkinn, and radiocarbon dated at Trondheim radiocarbon laboratory. The result was calibrated using the Marine13 calibration curve (Reimer *et al.* 2013) using a Delta-R value of 72±18 ^{14}C years, based on the weighted mean of five bivalve samples from North Norway and the Barents Sea (Mangerud & Gulliksen 1975; Mangerud *et al.* 2006). All ages from radiocarbon dating are calculated using this procedure.

Results

Twenty-three new ^{10}Be-samples were measured together with procedural blanks. ^{10}Be/^{9}Be ratios of the procedural blanks (n = 7) range from 1.845±0.653 to 4.227±1.058 (×10^{-15}), with an average value of 3.169±0.804 (×10^{-15}). The ^{10}Be/^{9}Be ratios in the samples were measured between 1.286±0.078 and 7.229±0.216 (×10^{-13}) and were converted to ^{10}Be concentrations (Table 1). These dates are the first geological ^{10}Be samples with previously unknown ages measured at the National Laboratory for Age Determination, Trondheim.

In the text, we report exposure ages with 1σ external uncertainties. Two samples yielded ages that are inconsistent with the timing of regional deglaciation (Fin15-07, 52.5±4.4 ka and Fin15-18, 35.7±3.3 ka). Another sample gave a somewhat reasonable age, but as only a small amount of beryllium remained after pre-treatment, analytical uncertainties approached 50% (Fin15-16B). These three samples are included in Table 1 but were not used to reconstruct the timing of deglaciation. The remaining samples are discussed in more detail for each separate area below.

Outermost coast

Seven samples, from six erratic boulders and one bedrock surface, were collected from the outer coast of Nordkinn peninsula (Table 1). In addition, two samples from the outer coast of Magerøya were obtained. One sample from Nordkinn gave an age of 52.5±4.4 ka (Fin15-07), indicating inherited ^{10}Be from previous exposure periods. This sample was therefore excluded from further analysis.

Out of the six remaining samples, Fin15-02, with an age of 19.5±1.8 ka, is more than 2 standard deviations older than the mean age of the five other samples and is considered an outlier. Another sample, Fin15-06 dating to 13.6±1.3 ka, was taken 8 m below the marine limit (gravel- to cobble-dominated beach ridges extending to 49 m a.s.l.), and thus experienced a period with water shielding. If these two samples are also excluded, the weighted mean of the four remaining samples becomes 14.5±1.4 ka, which we consider the best estimate of the timing of deglaciation at the outer coast of Nordkinn (Figs. 3, 4). If the age of Fin15-06 is assumed to date its emergence above sea level, it would imply a relative uplift of roughly 8 m in 900 years, consistent with the Lateglacial uplift rate suggested for Nordkinn by Romundset *et al.* (2011).

At Losvik, situated on the eastern coast of Nordkinn peninsula (70.866 °N, 28.412 °E), a raised delta at 9 m a.s.l. contains mollusc-bearing delta foresets. A sample from 3 m a.s.l. included whole valves of *Hiatella arctica*, and radiocarbon dating yielded an age of 13.5±0.08 cal. ka BP (TRa-11124: ^{14}C age 12124±47 BP, δ^{13}C 3.8±0.5‰). This date is a close maximum-limiting age for abandonment of the delta, as well as a minimum-limiting constraint for the age of the local marine limit at ~20 m a.s.l. In a similar valley farther west, Opnan on Magerøya, two ^{10}Be samples from the crest of a washed end moraine extending from 35 m a.s.l. to present sea level, yielded ages of 13.7±1.3 and 14.7±1.3 ka. The moraine is boulder-rich and delineates a former tidewater glacier in Opnan valley. We interpret these ages as close minimum-limiting constraints for the age of the moraine and for the ~35 m a.s.l. shoreline in this area (Sollid *et al.* 1973).

Finnmark north of the Main sub-stage moraines

On central Nordkinn three erratic boulders were sampled (Fin15-08, Fin15-09 and Fin15-10) and gave ages ranging from 16.6±1.5 to 13.8±1.2 ka with a weighted average of 14.9±1.4 ka. Sollid *et al.* (1973) suggested that the ice margin during the Outer Porsanger sub-stage was situated approximately at the sampled site, however, as no ice-marginal deposits delineating the position of the SIS during this stage have been identified on Nordkinn, its exact relation to the sampled site is unknown (Fig. 3).

Approximately 30 km south, at a small bedrock hill at Ifjord, two samples (Fin15-11, Fin15-12) were taken from a glacially abraded bedrock surface at 59 m a.s.l. and from an erratic boulder at 61 m a.s.l., respectively. These gave ages of 12.2±1.1 and 11.5±1.1 ka. As we estimate the marine limit in the area to ~67 m a.s.l., based on the highest coastal landforms (beach ridges) observed in the near surroundings, it is likely that these samples were situated below sea level for an unknown duration.

South of the Main sub-stage moraines

The southernmost part of the transect includes one site in Norway (Sirbma) and all the Finnish localities. A total of nine samples were taken from erratic boulders at four sites along the transect in this area. Two of these samples were excluded from the reconstruction due to inheritance (Fin15-18 yielded an apparent age of 35.7±3.3 ka) and low beryllium retrieval (Fin15-16B).

The northernmost samples in this area (Fin15-15, Fin15-17) come from Sirbma, just inside the Main sub-stage end moraine zone. These samples were collected adjacent to a low local moraine situated on a bedrock ridge. They were both taken from erratic boulders resting on bedrock and in a highly exposed position where neither snow shielding nor shielding from vegetation is likely to be a significant problem (e.g. Fig. 2E). They yielded ages of 12.6±1.2 and 14.0±1.3 ka, respectively.

The moraine at Sirbma delineates a former glacier margin that is traceable into an adjacent valley to the west and demarcates a recessional ice margin which postdates ice sheet withdrawal from prominent ice-contact deltas near Tana Bru that are assumed to be of Younger Dryas age. The sampled moraine is thus from the southern limit of the ice-marginal landforms and deposits comprising the Main sub-stage ice margin.

Farther south, Fin15-23 and Fin15-24, both sampled from erratic boulders, gave ages of 13.2±1.3 and 12.6±1.4 ka, respectively, whereas the three southernmost samples (Fin15-20, Fin15-21 and Fin15-22), collected from erratic boulders on top of a drumlin, gave well-clustered ages of 9.9±1.2, 10.6±1.7 and 10.8±1.2 ka.

Evaluation of uncertainties

Cosmogenic nuclide production can be temporally reduced by local and episodic shielding effects, such as snow cover, soil and vegetation (e.g. moss, forest), which causes an underestimation of the true age of a sampled surface. The Norwegian samples in this study are all in exposed positions without significant vegetation shielding today (Fin15-01 – Fin15-17; Fig. 2A-2E). Although some of the sites could have been periodically forested during the Holocene, the effect of vegetation shielding on these sites would most likely be small. Snow shielding could be more important, but here too the wind-exposed positions of most of the sampled boulders and bedrock surfaces would likely limit the influence. In contrast, all the Finnish samples were taken in what is today a low-density forest and it is reasonable to suppose that these areas have been forested for much of their exposure duration (Fin15-18 – Fin15-24; Fig. 2F). Plug *et al.* (2007) modelled the attenuation of cosmic rays by vegetation in an Acadian forest and found it to be only ~2.25%. We expect that the attenuation in our sparsely forested study area would be even lower. However, the forest could potentially also have an indirect effect by reducing the strongest winter winds and thus protecting the snow on top of the sampled boulders. The Finnish meteorological institute has collected observations of the snow depth at Inari Ivalo airport (40 km southeast of our southernmost site) between 1960-01-01 and 1999-12-31, and found an average of 215 days with snow cover per year, and an average snow thickness of 27.5 cm. Such a snow cover would result in a ~5% underestimation of the sample ages (snow shielding estimated using the iceTEA web application by Jones *et al*. 2019), similar to previous snow shielding estimates from the region (3-4%, Stroeven *et al.* 2011). However, even though the Finnish samples are in somewhat sheltered positions (e.g. Fig. 2F), we would expect the actual snow cover on top of large boulders to be thinner than at the observation site, and to have large spatial and temporal variation. Due to the large uncertainties in our vegetation and snow cover estimates, we have not attempted a correction, but note it as a potential problem, especially for the Finnish sites.

Six samples were taken below the marine limit (Table 1). One of those, Fin15-07, was excluded as an outlier, but for the remaining five we also have to consider water shielding. We therefore consider these samples as minimum ages for deglaciation, and exclude them when calculating site averages. The Lateglacial relative sea level history of the area is not known in detail, but Romundset *et al.* (2011) suggested a rapid Lateglacial rebound following the deglaciation of the Barents Sea. Three of the samples, Fin15-06 from the Nordkinn coast and Fin15-11 and Fin15-12 from Ifjord, were taken less than 10 m below the marine limit and are thus expected to have experienced only a relatively brief period of water shielding. The two samples from Magerøya (Fin15-13 and Fin15-14), taken 15-20 m below the local Marine Limit, could have experienced more substantive water shielding. However, we interpret them as deposited by a later readvance of the local cirque glacier, in which case the duration of water shielding would have been limited.

No correction for isostatic rebound was applied for any of the samples. Experiments with altitude corrections using the iceTEA web application (Jones *et al*. 2019) on all the acceptable samples (all but Fin15-07, Fin15-16B and Fin15-18) indicated that this may lead to an average underestimation of the true ages by ~4 % (510 years), with a maximum offset of 1180 years for Fin15-02. No obvious geographic trend was seen in the offset. As the iceTEA calibration uses a different set of assumptions (e.g. no erosion, LSD scaling) than the calibration we used, the results are not directly transferable to our ages, but they give a reasonable estimate on the potential errors.

Deglaciation chronology

Outermost coast

The new ages date the onset of deglaciation along the outer Nordkinn coast to 14.5±1.4 ka (n = 4, based on samples with ages ranging from 15.0 to 13.8 ka), supporting deglaciation during the Bølling chronozone as suggested by Romundset *et al.* 2011. As the ice sheet retreated on land, ice marginal withdrawal most likely became more geographically variable, with tidewater glaciers occupying some valleys, e.g. the Losvik and Opnan valleys (Fig. 1), for a period following the initial withdrawal of the SIS from the outer coast (Fig. 5).

Finnmark north of the Main sub-stage moraines

Outer Porsanger sub-stage. The Outer Porsanger sub-stage is the most laterally traceable ice-marginal position distal to the Main sub-stage moraine complex in Finnmark (Sollid *et al.* 1973). Our central Nordkinn samples (Fin15-08, Fin15-09 and Fin15-10), which give a weighted average of 14.9±1.4 ka (n = 3, ranging from 16.6 to 13.8 ka), are situated near the estimated ice position for the Outer Porsanger sub-stage (Sollid *et al.* 1973), but may pre- or post-date it. This age is a few

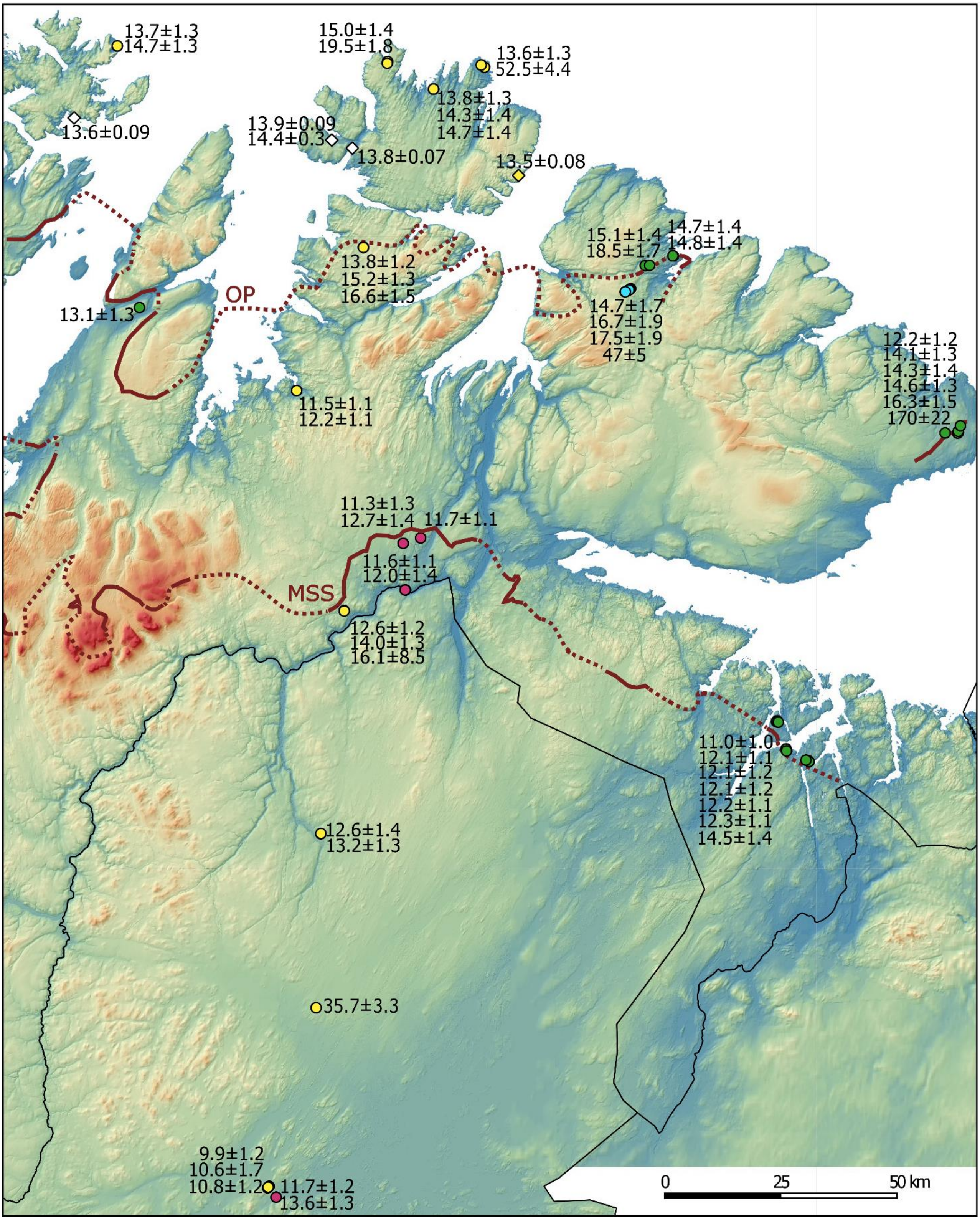

Fig. 3. Deglaciation ages (ka) from the studied region. Circles indicate cosmogenic exposure ages whereas rhombuses mark radiocarbon dated sites. Yellow = This study; Red = Cuzzone *et al.* (2016); Blue = Fjellanger *et al.* (2006); Green = Romundset *et al.* (2017); White = Romundset *et al.* (2011). OP = Outer Porsanger stage; MSS = Main sub-stage.

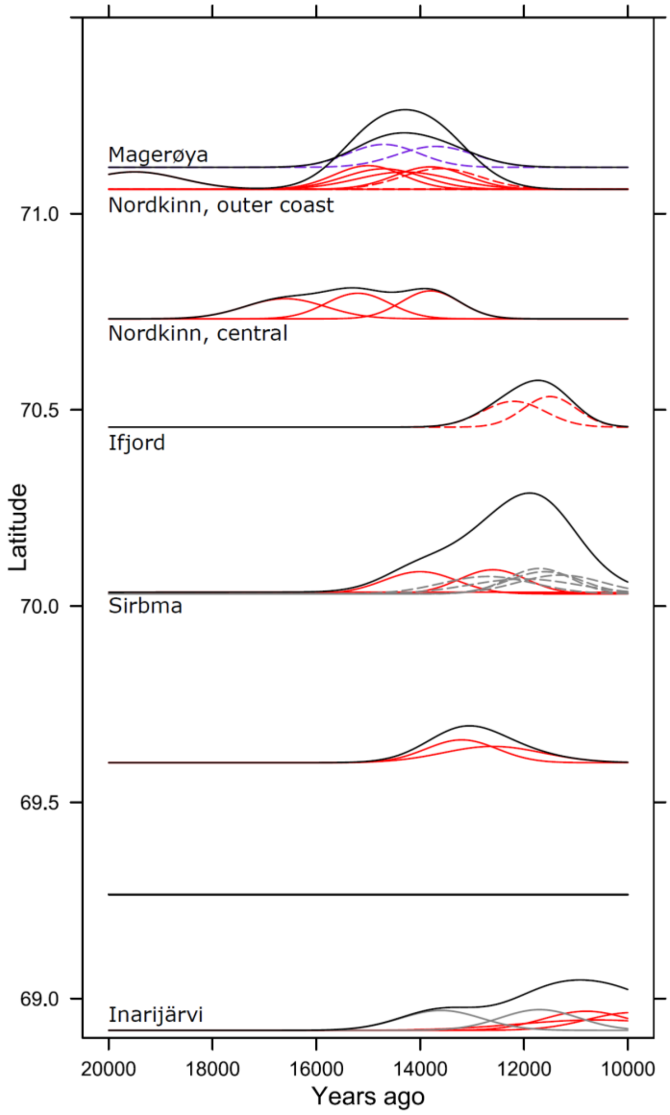

Fig. 4. Probability density plots for the exposure ages. The ages from each site are plotted so that their baseline, that is zero-probability, falls at the latitude for each site. Red and violet curves indicate exposure ages from this study. Red curves are from samples taken along the N-S transect, whereas the samples from Magerøya are indicated in violet. In addition, the samples from Cuzzone *et al.* (2016, recalculated) have been added to the nearest of our sites (grey lines). Samples taken below the marine limit have been indicated by dashed lines. The uncertainties only include internal errors (see Table 1 for details on each sample). A cumulative curve for all the ages from each site is shown in black.

hundred years older than our best estimate for the deglaciation age at the outer coast of Nordkinn (Fig. 5). As the age ranges overlap (Fig. 4), this apparent age reversal may be the result of a rapid deglaciation together with the large uncertainties associated with ^{10}Be-ages. Alternatively, it may reflect actual deglaciation behaviour, with a thinning ice sheet exposing the higher elevation areas at a time when the fjords and outer coast were still glaciated.

Landforms attributed to the Outer Porsanger sub-stage have previously been dated on Varanger peninsula (Fjellanger *et al.* 2006; Romundset *et al.* 2017) where ^{10}Be-samples gave a weighted mean age of 14.3±1.5 ka (n = 5, range from 16.3 to 12.2 ka) in the east and 15.6±1.6 (n = 7, range from 18.5 to 14.7 ka) in the west. However, as four of the seven ^{10}Be ages from the western part of Varanger peninsula cluster in the younger end of the age range, Romundset *et al.* (2017) argue that the older ages suffer from inheritance and that the true deglaciation age is in the younger end of the age range. This interpretation would align the deglaciation age with our ages from central Nordkinn, suggesting contemporaneous ice sheet retreat from the peninsulas of northern Finnmark during the Bølling chronozone.

Central Finnmark. In central Finnmark two samples at Ifjord (Fin15-11 and Fin15-12; Fig. 2D) gave ages of 12.2±1.1 and 11.5±1.1 ka, which is spuriously young considering that the site is situated distal to the Younger Dryas aged Main sub-stage end moraine zone (Figs. 3, 4, 5). The samples are from a small bedrock hill at an elevation of a few meters below the marine limit (~67 m a.s.l.) that, by the time of the formation of the Younger Dryas shoreline (locally estimated to ~54 m a.s.l.) would have formed a low skerry in a fjord head setting. A possible explanation for the young ages could thus involve shielding by pervasive and possibly landfast sea ice during the Younger Dryas.

Main sub-stage

A well-developed end-moraine complex situated between our Ifjord and Sirbma sites defines the Younger Dryas ice margin in southern Finnmark. Here, Sollid *et al.* (1973) identified two deglaciation sub-stages, the Gaissa sub-stage and the Main sub-stage. The Main sub-stage was originally dated based on its morphological relationship to the Main Line, a distinct Younger Dryas shoreline generally characterized by marked bedrock-terraces, especially in western Finnmark (Marthinussen 1960; Sollid *et al.* 1973). More recently Romundset *et al.* (2017) presented cosmogenic surface exposure ages of landforms associated with the Main sub-stage near Kirkenes, which dated the ice margin there to 12.2±1.2 ka (n = 7, range from 11.0 to 14.5 ka; Fig. 3).

Our Sirbma samples (Fin15-15 and Fin15-17) were taken from a recessional moraine just south of this moraine complex and could thus be expected to date the retreat from the end moraine. In addition, Cuzzone *et al.* (2016) reported five exposure ages from nearby sites with a weighted average age of 11.8±1.2 ka (n = 5, range from 11.3 to 12.7 ka, Fig. 4), consistent with the deglaciation age at Kirkenes. However, although the geomorphological context of Cuzzone *et al.'s* (2016) samples was not described, they were collected at 50-65 m a.s.l., below the local marine limit of ~70 m. They, therefore, experienced a period of water shielding and should be considered minimum ages. The two Sirbma samples, at 12.6±1.2 and 14.0±1.3 ka, may thus give a more reliable age estimate.

South of the Main sub-stage moraines

Finland. Our two northernmost samples from Finland (Fin15-23 and Fin15-24) give ages of 13.2±1.3 and 12.6±1.4 ka, consistent with the deglaciation age we estimated for Sirbma 48 km farther north, but older than the nearby ages presented by Cuzzone *et al.* (2016).

Our three southernmost samples (Fin15-20, Fin15-21 and Fin15-22), were taken from the top of a drumlin near Inari. This drumlin is part of a larger streamlined area with a SW-NE direction, placing our Inari samples on a flow-line ending west of Romundset *et al.*'s (2017) samples from Kirkenes. The Inari samples give well-clustered ages with a weighted average of 10.4±1.4 ka (range from 9.9 to 10.8 ka), which we consider our best estimate of the deglaciation age. This would then suggest an ice-margin retreat rate of ~80 m a^{-1} between the Main sub-stage moraine at Kirkenes and Inari (Fig. 5). However, Cuzzone *et al.* (2016) also sampled near our Inari site and report two exposure ages (Fin-54 and Fin-56) with recalibrated ages of 11.7±1.2 and 13.6±1.3 ka, respectively. Their ages might thus indicate an earlier deglaciation, and thus a faster deglaciation rate, but, as the samples lack geomorphological information and the ages show less agreement, we consider them less reliable (Fig. 4).

We conclude that the current distribution of deglacial ages from this region makes it difficult to precisely reconstruct deglaciation on a millennial scale. Nonetheless, our results clearly show a pattern of north-south ice sheet retreat, spanning some 240 km, over the period ~14.5–10.4 ka (Fig. 5).

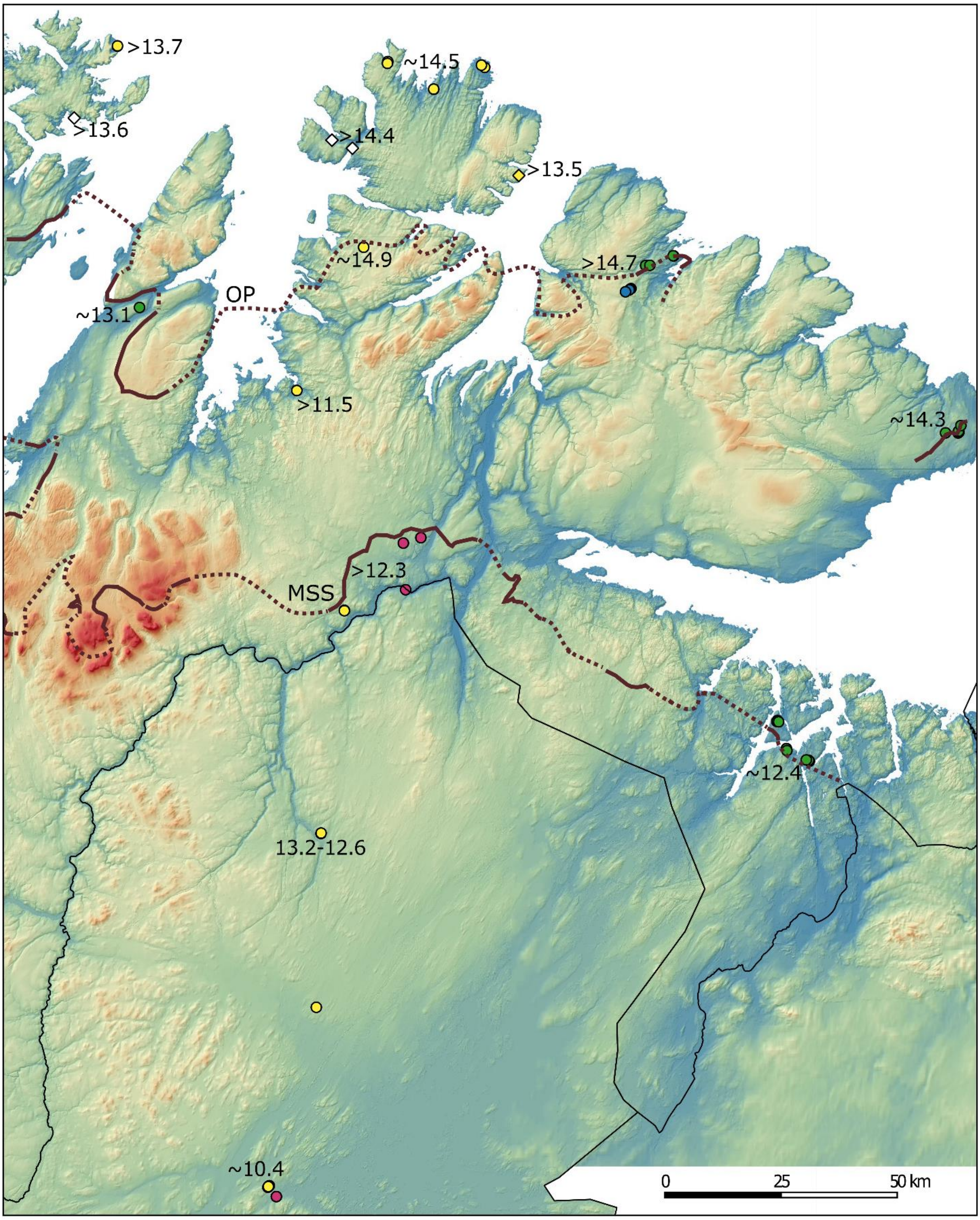

Fig. 5. Overview map over the studied region with our best estimates for the deglaciation age (ka) at each site indicated. Based on the deglaciation ages shown in Fig. 3. OP = Outer Porsanger stage; MSS = Main sub-stage.

Conclusions

- In this study we present 23 new cosmogenic surface exposure ages (^{10}Be) from eight localities in northernmost Norway and Finland, thereby improving the age constraints for the deglaciation in this sparsely dated region.
- For the outer coast, our results indicate initial ice sheet retreat at 14.5±1.4 ka, consistent with earlier estimates of a deglaciation of the outer coast during the early Bølling chronozone. From there the ice front retreated southwards and inland, eventually reaching Lake Inarijärvi in northern Finland around 10.4±1.4 ka.

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Author contributions. JA and EAL planned the project and carried out the fieldwork together with TL. JA prepared the samples under NA's guidance whereas MS performed the ^{10}Be measurements and calculated the ^{10}Be concentrations. All authors contributed to the interpretations of the data. JA wrote most of the manuscript but with substantial input from all the authors.

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