arktos (2018) 4:17
https://doi.org/10.1007/s41063-018-0051-1

ORIGINAL ARTICLE

^{10}Be dating the last deglaciation of Bjørnøya, Svalbard

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Received: 3 November 2017 / Accepted: 29 May 2018

Abstract
The retreat of the Barents Sea Ice Sheet was a major event in the last deglaciation of the Arctic. Numerous studies document the fine details of the seafloor that reveal a highly dynamic ice sheet somewhat analogous to the West Antarctic Ice Sheet. Despite detailed records of the Barents Sea Ice Sheet's dynamics, comparatively few studies have provided chronological control that constrains its history of final collapse. We report cosmogenic ^{10}Be exposure ages from 14 glacial erratics, nine moraine boulders and one bedrock surface from southern Bjørnøya, an island situated in the Barents Sea between Svalbard and Norway. 17 of 24 samples average 12.4 ± 0.5 ka with no significant relationship between age and elevation. We interpret the ages to represent the time when Bjørnøya, and the shallow Spitsbergenbanken upon which it sits, became finally deglaciated following break up of the Barents Sea Ice Sheet. The timing of deglaciation, overlapping with the early Younger Dryas, suggests that Younger Dryas climate change did not reverse overall glacier recession, although we cannot rule out a stillstand or re-advance during the early Younger Dryas.

Keywords Bjørnøya · Cosmogenic ^{10}Be exposure dating · Barents Sea Ice Sheet · Deglaciation

Introduction

Information derived about the past response of ice sheets to climate change can lead to an improved understanding of future ice sheet stability and sea level change. The behavior of contemporary ice sheets in the face of ongoing rapid climate change is complex, and ice sheet dynamics ensure that the relationship between climate forcing and ice sheet response is not simple [1, 19]. Past ice sheets prone to collapse are of particular importance, and for this reason the configuration and history of the Barents Sea Ice Sheet (Fig. 1) has been the focus of many studies (e.g., [8, 15, 16, 24, 40). In addition, because the marine-based Barents Sea Ice Sheet is often likened to the West Antarctic Ice Sheet, many studies have focused on its dynamics (e.g., [13, 30, 29, 43).

During the Last Glacial Maximum the margin of the Barents Sea Ice Sheet was located along the western and northern continental shelf break; ice flowed over or merged with ice domes on Svalbard, and converged with ice flowing from Scandinavia (Fig. 2; e.g., [16, 43]). It is thought that the ice sheet started to thin between 26 and 20.5 ka in high elevation regions of northwestern Svalbard [10, 14]. The recent synthesis of Hughes et al. [15] depicts the marine ice margin initiating retreat from the shelf break around 20 ka in the major troughs that drained the ice sheet (Fig. 2). Subsequent retreat progressed until the Barents Sea Ice Sheet had mostly retreated out of the central Barents Sea between ~15 and 14 ka, and back to terrestrial centers between 14 and 12 ka [Hughes et al. 15].

Despite the overall configuration and timing of deglaciation of the Barents Sea Ice Sheet being generally known, there are relatively few locations in the Barents Sea with absolute ages of ice margin retreat. The Barents Sea floor contains deep troughs and shallow banks, but there are no islands in the central Barents Sea, leaving ^{14}C ages from marine sediment cores being the best option for chronology. However, an opportunity exists to constrain the timing of ice retreat from the western Barents Sea at Bjørnøya, a remote island between Norway and the Svalbard archipelago (Fig. 1), using cosmogenic ^{10}Be exposure dating.

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Published online: 13 June 2018

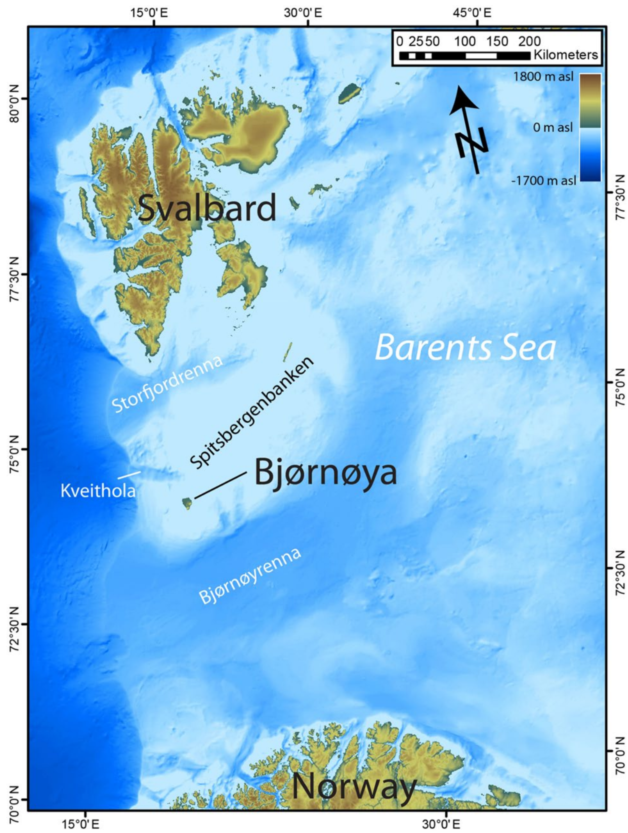

Fig. 1 Map of the western Barents Sea showing Svalbard and other important places mentioned in the text. Bathymetric data from IBCAO Version 3.0 [17]

Bjørnøya lies along the shallow Spitsbergenbanken (water depth 30–80 m) and near the mouths of the Bjørnøyrenna and Storfjordennna glacial trough systems that drained the Barents Sea Ice Sheet via the massive Bjørnøya and smaller Storfjorden paleo-ice streams (e.g., [21, 24, 29, 43]). In this paper, we report 24 ^{10}Be exposure ages from Bjørnøya that constrain the final deglaciation of the Barents Sea Ice Sheet along southern Spitsbergenbanken.

Setting

Bjørnøya (178 km^2; Fig. 3) has relatively subdued and low-lying topography in the north and more relief in its eastern and southern portions, with some summit elevations reaching 360 m asl (Antarcticfjellet), 421 m asl (Alfredfjellet), and 536 m asl (Myseryfjellet). Bjørnøya is situated at the oceanographic polar front where cold, relatively fresh Arctic Water masses meet warm and saline Atlantic water [41]. At present, the North Atlantic Current splits into branches west and south of Svalbard: the West Spitsbergen Current travels northward along western Svalbard, and the Nordkapp Current enters into the Barents Sea and eventually into the Arctic Ocean. Weather observations have occurred on Bjørnøya since 1910 AD; the mean annual temperature is − 1.7 °C, average winter snow depth is 10 cm, and mean annual precipitation is 371 mm (1960–1990, eKlima.met.no). The bedrock geology of the island consists of sedimentary formations, including carbonate, sandstone, shale and conglomerate dating from the Late Proterozoic to Mesozoic [45].

To date, the most comprehensive study of the glacial history of Bjørnøya is that of Salvigsen and Slettemark [36], who documented thin patches of till, erratics of local provenance, and glacial erosional features indicative of outward radiating ice flow from central Bjørnøya. There is no evidence for isostatic uplift on Bjørnøya, and thus it appears that the island is beyond the zero meter isobase [24, 36]. Salvigsen and Slettemark [36] concluded that Bjørnøya was covered by local ice only, and not by the Barents Sea Ice Sheet. Landvik et al. [24] suggested the alternative that the erosional imprint represents a final phase of ice cover (e.g., during final deglaciation), and that the island could have been covered by Barents Sea ice earlier (e.g., during the Last Glacial Maximum; cf Landvik et al. [23]).

In terms of chronology, the best constraint to date for the deglaciation of Bjørnøya itself is a ^{14}C age obtained by Wohlfarth et al. [44] from a macrofossil in basal lake sediments in north-central Bjørnøya of 9795 ± 90 ^{14}C year BP (11,195 ± 400 cal year BP; mid-point ± 2σ age range). Offshore, there is additional chronology that is useful for constraining the deglaciation of Bjørnøya. The ice stream occupying Storfjordrenna began to retreat prior to 19.4 cal ka, and perhaps between 21.2 and 19.8 cal ka [18, 32]. The major ice stream occupying Bjørnøyrenna began its final deglaciation ~ 16.6 cal ka following a readvance [35]. A comparatively smaller trough, Kveithola, exists off north-eastern Bjørnøya, where ^{14}C ages from marine sediment cores constrain deglaciation to prior to 14.2 cal ka [34]. Rüther et al. [34] interpreted ice-rafted sediments dating to between 14.2 and 13.9 cal ka to be sourced from ice over Spitsbergenbanken, after which marine evidence for proximal ice is absent.

Methods

We collected 23 samples from boulders for ^{10}Be dating in the southern part of Bjørnøya (Figs. 3, 4). One additional sample was collected from a glacially-sculpted bedrock surface (AEM-8). Most boulders stand 1–3 m above the land surface, although several are less than one meter above the surface. We collected samples for ^{10}Be dating from three main areas from a range of elevations throughout southern Bjørnøya (Figs. 3, 4). The first area is west of Ellasjøen; the samples AEM and IEM are taken on small bouldery

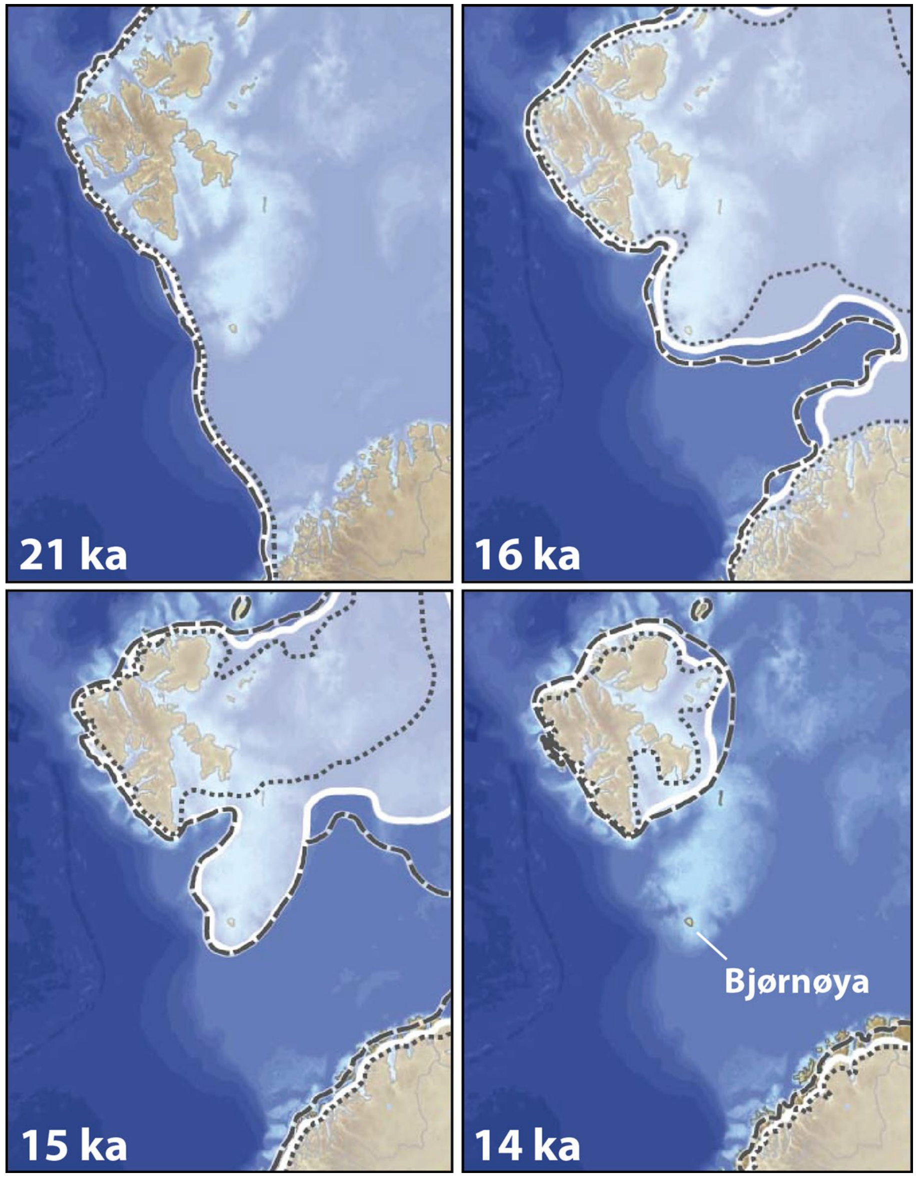

Fig. 2 Maps showing the deglaciation of the western Barents Sea modified from Hughes et al. [15]

end moraines between 17 and 54 m asl. Samples were also collected from the ridges surrounding Ellasjøen; Landnørdingsvika lies between 59 and 139 m asl, and the Skurven ridge ranges from 121 to 153 m asl. The third sampling area is located on summits Alfredfjellet (at 293 m asl) and Antarcticafjellet (at 340–351 m asl).

Samples were collected with a saw, hammer and chisel. Sample thickness was measured in the field and was between 1.6 and 4.1 cm. Sample elevation and position was recorded with a barometrically corrected GPS that was adjusted to known altitudes several times during the day; topographic shielding was calculated with a clinometer. Given low average winter snow depth, we calculate ages with no snow shielding. We also note from past experience collecting samples in the Arctic during the spring that boulders protruding above the ground are usually windswept and not covered by snow. Boulder surfaces may have experienced surface erosion and weathering since deposition. Boulder surface erosion would vary according to lithology (the ^{10}Be ages are mostly from sandstone lithologies, but sourced from different formations). We are not aware of studies on erosion rates of these lithologies and, therefore, report ages assuming zero boulder surface erosion. When we calculate the ^{10}Be ages using a nominal Arctic rock surface erosion rate of 1 mm kyear^{-1}, [4] the ages become 0.3–2.0% (average 1.1%) younger.

Physical and chemical processing of rock samples for ^{10}Be analysis took place at the University at Buffalo Cosmogenic Nuclide Laboratory following a modified version of previously described procedures [7, 20]. Approximately 225 µg of ^{9}Be carrier was added during sample preparation; beryllium ratios were measured by accelerator mass

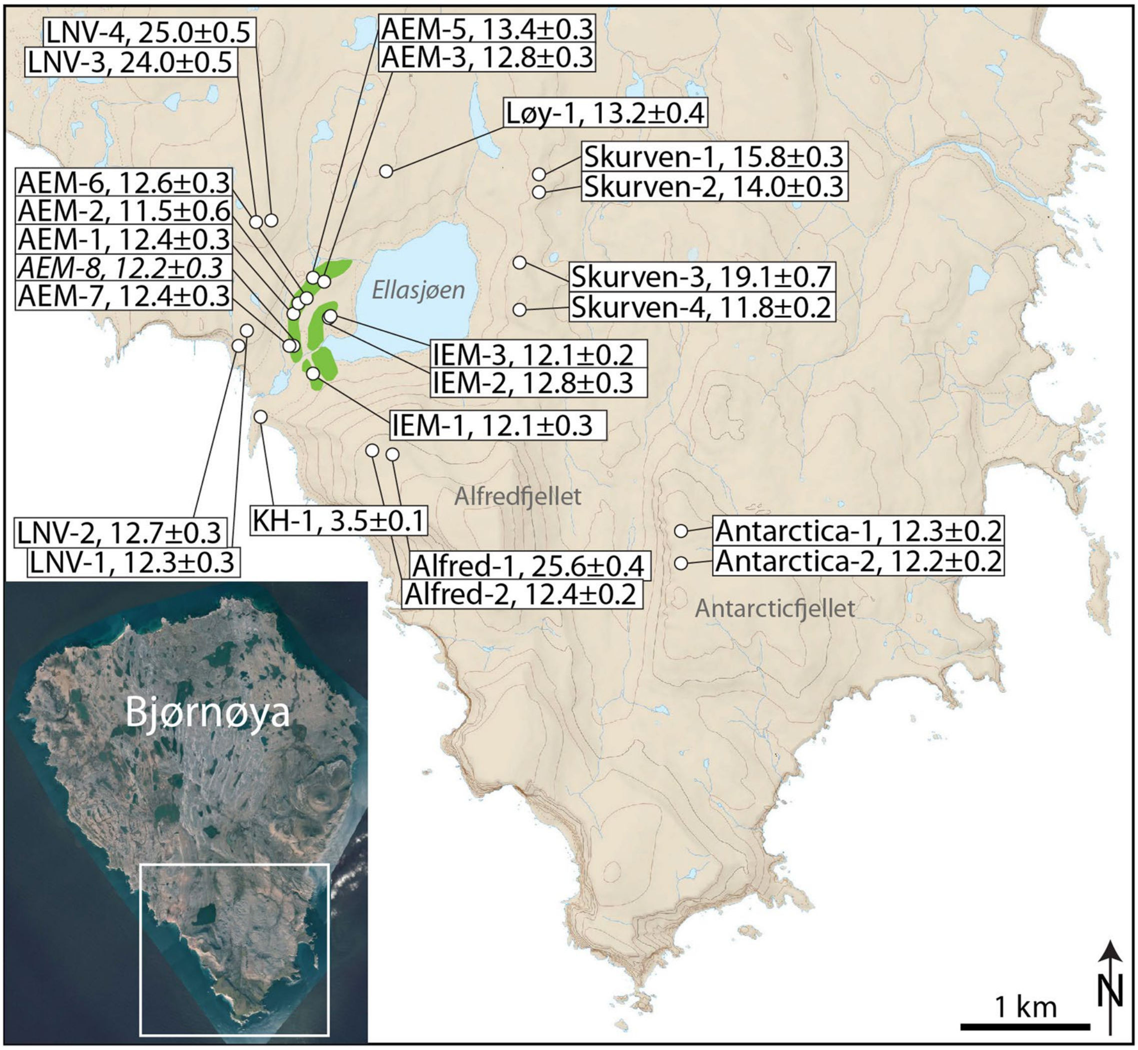

Fig. 3 Map of southern Bjørnøya (inset shows all of Bjørnøya) showing sample ID and ^{10}Be age. Italic (sample AEM-8) designates bedrock sample. Sample details reported in Table 1. Moraines west of Ellasjøen depicted in green (samples IEM and AEM). Location of Bjørnøya shown in Fig. 1. Basemap (and inset) from toposvalbard.npolar.no; contour interval is 50 m

spectrometry at Lawrence Livermore National Laboratory and normalized to standard 07KNSTD3110 with a reported ratio of 2.85×10^{12} [28, 33]. Procedural blank ratios were 1.44×10^{-15}, 2.99×10^{-15}, and 4.17×10^{-15}, equating to an average background correction of 2.12% of the sample total (except for sample KH-1, age 3.5 ± 0.1 ka, the background correction is 10.9%). One-sigma analytical uncertainties on background-corrected samples range from 1.63 to 5.55% and average 2.39%.

The individual ^{10}Be ages are reported in Table 1. The ^{10}Be ages were calculated via the CRONUS-Earth online exposure age calculator [3, version 3, http://hess.ess.washington.edu/] using a production rate for the Arctic (3.93 ± 0.15 atoms g year^{-1} using Lm scaling; Young et al. [46]) and the Lm scaling scheme [3, 22, 38]. Ages in Table 1 are also reported using the LSDn scaling scheme [25; see Table 1 for details].

Results and interpretation

The ^{10}Be ages of glacially transported sandstone and conglomerate boulders are from elevations spanning from 17 to 350 m asl and range from 3.5 to 25.6 ka (Table 1; Fig. 5). Notable features of the dataset are an anomalously young erratic (KH-1; 3.5 ± 0.1 ka), a cluster of erratic ages that average 12.4 ± 0.5 ka ($n = 16$), and six older erratics that range from 14.0 to 25.6 ka (Fig. 5). The bedrock sample (AEM-8) yields a ^{10}Be age of 12.2 ± 0.3 ka (Table 1). When

Table 1 ^{10}Be ages of samples from Bjørnøya, Svalbard

Sample	Latitude (°N)	Longitude (°E)	Elevation (m asl)	Lithology[a]	Thickness (cm)	Shielding correction	Quartz (g)	^{9}Be carrier (g)[b]	$^{10}Be \pm 1\ \sigma$ (atoms g^{-1})	^{10}Be age (a)[c]	^{10}Be age (a)[d]
Løy-1	74.3925	19.0110	107	Conglomerate (Rødvika)	3.3	1.000	28.931	0.607	59597 ± 1862	13200 ± 400	13200 ± 400
Antarctica-1	74.3653	19.0796	340	Grey sandstone (Rødvika)	2.1	0.998	28.042	0.608	74378 ± 1402	12300 ± 200	12500 ± 200
Antarctica-2	74.3638	19.0761	351	Grey sandstone (Rødvika)	2.3	1.000	27.019	0.608	74327 ± 1420	12200 ± 200	12400 ± 200
Alfred-1	74.3737	19.0060	293	Grey sandstone (Rødvika)	2.8	1.000	18.099	0.611	146179 ± 2385	25600 ± 400	26100 ± 400
Alfred-2	74.3739	19.0043	293	Grey sandstone (Rødvika)	3.3	1.000	32.429	0.608	70867 ± 1339	12400 ± 200	12600 ± 200
LNV-1	74.3817	18.9719	58	Yellow–redbrown sandstone (Nordkapp)	3.2	0.998	34.662	0.615	55177 ± 1335	12300 ± 300	12300 ± 300
LNV-2	74.3824	18.9739	72	Yellow–brown sandstone (Landnørdingsvika)	1.6	1.000	23.041	0.608	58472 ± 1265	12700 ± 300	12700 ± 300
LNV-3	74.3897	18.9780	137	Yellow–redbrown sandstone (Nordkapp)	3.3	1.000	35.050	0.609	116435 ± 2186	24000 ± 500	24200 ± 500
LNV-4	74.3897	18.9798	139	White sandstone (Nordkapp)	1.9	1.000	22.081	0.608	122987 ± 2319	25000 ± 500	25200 ± 500
KH-1	74.3765	18.9753	28	White carbonaceous sandstone (Kapp Hanna)	2.5	0.961	39.562	0.607	14614 ± 524	3500 ± 100	3400 ± 100
Skurven-1	74.3912	19.0492	121	Sandstone (Rødvika)	3.3	1.000	20.007	0.607	75532 ± 1433	15800 ± 300	15900 ± 300
Skurven-2	74.3906	19.0495	121	Yellow–brown sandstone (Landnørdingsvika)	3.7	1.000	27.050	0.608	66766 ± 1300	14000 ± 300	14100 ± 300
Skurven-3	74.3856	19.0432	148	Yellowish sandstone (Nordkapp)	3.4	0.856	23.196	0.608	80371 ± 2776	19100 ± 700	19200 ± 700
Skurven-4	74.3829	19.0415	153	Grey sandstone (Rødvika)	3.9	1.000	25.038	0.608	58244 ± 1151	11800 ± 200	11900 ± 200
AEM-1	74.3840	18.9857	44	Sandstone (Landnørdingsvika)	1.8	0.995	38.225	0.610	54295 ± 1196	12400 ± 300	12400 ± 300
AEM-2	74.3845	18.9878	47	Sandstone (Landnørdingsvika)	3.9	0.999	33.882	0.609	51178 ± 2842	11500 ± 600	11500 ± 600
AEM-3	74.3856	18.9934	54	Sandstone (Rødvika)	3.5	0.999	38.480	0.609	56381 ± 1110	12800 ± 300	12700 ± 300
AEM-5	74.3857	18.9921	53	Sandstone (Nordkapp)	1.7	1.000	36.836	0.610	59432 ± 1337	13400 ± 300	13400 ± 300

Table 1 (continued)

Sample	Latitude (°N)	Longitude (°E)	Elevation (m asl)	Lithology[a]	Thickness (cm)	Shielding correction	Quartz (g)	^{9}Be carrier (g)[b]	^{10}Be ± 1 σ (atoms g^{-1})	^{10}Be age (a)[c]	^{10}Be age (a)[d]
AEM-6	74.3848	18.9893	53	conglomerate (Kapp Kåre)	3.5	1.000	39.078	0.610	56393 ± 1192	12600 ± 300	12500 ± 300
AEM-7	74.3812	18.9837	26	Sandstone (Nordkapp)	4.0	0.999	34.689	0.611	53347 ± 1384	12400 ± 300	12300 ± 300
AEM-8	74.3812	18.9837	25	Bedrock: sandstone (Rødvika)	3.4	0.999	31.376	0.611	52029 ± 1260	12200 ± 300	12100 ± 300
IEM-1	74.3799	18.9893	17	Sandstone (Nordkapp)	2.4	0.989	37.177	0.609	51335 ± 1064	12100 ± 300	12000 ± 200
IEM-2	74.3832	18.9938	38	Sandstone (Nordkapp)	3.4	0.993	39.463	0.608	55616 ± 1382	12800 ± 300	12700 ± 300
IEM-3	74.3832	18.9940	38	Sandstone (Rødvika)	4.1	1.000	39.438	0.610	52550 ± 1015	12100 ± 200	12100 ± 200

A rock density of 2.65 g/cm^3 was used in age calculations. Samples were collected in 2013. Age calculations were made in October, 2017

[a] All samples erratics except sample AEM-8, which is bedrock

[b] Samples were spiked with Be carrier with a concentration of 372.5 ± 3.5 ppm

[c] CRONUS v3, Arctic production rate of Young et al. [46], using Lm scaling

[d] CRONUS v3, Arctic production rate of Young et al. [46], using LSDn scaling

including bedrock surface erosion, the age cluster becomes 12.3 ± 0.5 ka.

We interpret the mode in erratic ages at 12.4 ka as the timing of deglaciation of Bjørnøya. Because there is no significant relationship between age and elevation, we suggest that the entire island may have become deglaciated at approximately the same time. For example, the two erratics from Antarcticafjellet, at 340 and 351 m asl, are 12.3 ± 0.2 and 12.2 ± 0.2 ka, respectively, and one erratic from Alfredfjellet at 293 m asl is 12.4 ± 0.2 ka. The ages from the bouldery moraines at low elevation to the west of Ellasjøen (AEM and IEM samples) range from 13.4 ± 0.3 to 11.5 ± 0.6 ka and average 12.5 ± 0.5 ka. The bedrock surface near these moraines dates to 12.2 ± 0.3 ka, the same age as the other boulders across Bjørnøya, suggesting that ice cover over the low-elevation portions of the island was warm-based and erosive, which is supported by the observations of Salvigsen and Slettemark [36].

There are six samples that pre-date the cluster of ages at 12.4 ± 0.5 ka, at ~ 14 ka, ~ 16 ka, one at ~ 19 ka and three between ~ 24 and ~ 26 ka. We attribute these older ages as being influenced by inheritance, a common feature in ^{10}Be age datasets of glacial boulders from the high latitudes (e.g., [6, 10, 12]). The high elevations of Bjørnøya lack geomorphic evidence of erosive ice, and Salvigsen and Slettemark [36] suggested that the mountain summits potentially rose above a local ice cap surface. There has been much progress in recent years that has led to a new model of an ice sheet's imprint on the landscape [23]; this model of glaciation includes ice cover in landscapes that do not show evidence of erosive ice. This new view is consistent with cosmogenic ^{10}Be exposure age datasets containing inheritance to varying degrees depending on where in the glacial erosion regime they are from. In addition, this view is compatible with ice overriding Bjørnøya, and a portion of the ^{10}Be age dataset being influenced by inheritance.

Discussion

The pattern of deglaciation in the Barents Sea reveals that ice retreat initiated in the major troughs, followed by ice retreat from shallow banks and finally by ice margins receding into landscapes with extant glaciers [13, 15]. Without a higher spatial concentration of age constraints in the western Barents Sea, it is difficult to know what the ice configuration was as it receded onto Bjørnøya. Rüther et al. [34] also used marine sediment stratigraphy and provenance from Kveithola to depict ice margin recession to an isolated ice cap mantling southern Spitsbergenbanken. Rüther et al. [34] depicted Bjørnøya as becoming ice free sometime during the Allerød (~ 14–13 ka). Hughes et al. [15], on the other hand, depicted Bjørnøya becoming ice free earlier, between 15

Fig. 4 Photographs of selected boulders sampled for ^{10}Be dating on Bjørnøya (locations shown in Fig. 2; ages found in Table 1)

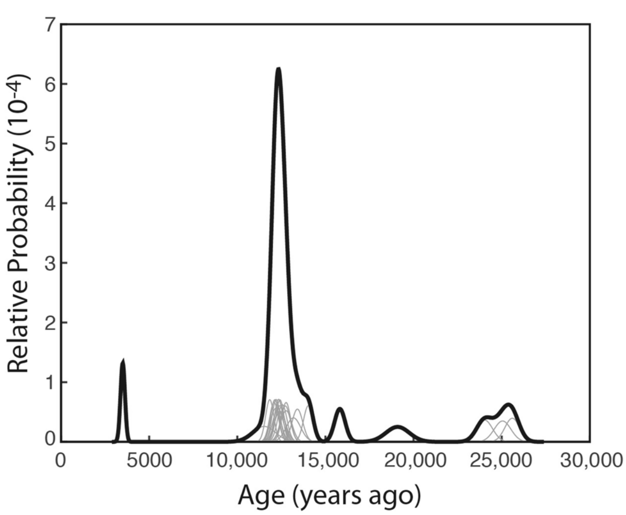

Fig. 5 The distribution of ^{10}Be ages on Bjørnøya; thin lines represent each individual ^{10}Be age and bold line is the summed probability of all ^{10}Be ages

and 14 ka. We suppose it is possible that Bjørnøya deglaciated between 15 and 14 ka and subsequently re-grew and, therefore, we are dating the timing of final deglaciation. Although we cannot rule this out, we point out that the age control from near Bjørnøya was previously too sparse to lend very high confidence in a 15–14 ka age for deglaciation. In any case, like Rüther et al. [34], Hughes et al. [15] reconstructed ice lingering over Spitsbergenbanken longer than in adjacent areas of the Barents Sea. The direct chronology that we obtained for the final deglaciation of Bjørnøya of 12.4 ± 0.5 ka is younger by one to two thousand years than these previous reconstructions. This suggests that ice lingered on Spitsbergenbanken, and possibly in other shallow portions of the Barents Sea, for longer than what is shown by Hughes et al. [15]. This is consistent with the reconstruction of Hogan et al. [13] in the northern Barents Sea, which similarly depicts ice remaining in shallow portions of the Barents Sea until ~ 13.5 to ~ 11.5 ka, although their ice extents are based on relatively few age constraints.

The timing of deglaciation of Bjørnøya, overlapping with the early portion of the Younger Dryas period (12.9–11.7 ka) provides some insight about Younger Dryas climate change in this region. It suggests that there was not a strong glacier response during the Younger Dryas. Indeed, the fact that ice finally disappeared during the Younger Dryas counters against it being a period of summertime cooling favorable for ice growth. This contrasts with advances during Younger Dryas farther south, in western Norway [26]. On the other hand, our finding is compatible with the lack of a glacier advance beyond the present ice extent in western Spitsbergen [27], and elsewhere in the Arctic (e.g., Pendleton et al. [31]).

Before making firm conclusions about the timing of ice recession in comparison to the Younger Dryas period, however, we must consider the average ^{10}Be age using other possible production rates. The average age calculated using the production rate of Borchers et al. [5; based on two calibration sites each in the northern and southern hemispheres, reported value using Lm scaling is 4.00 atoms g year^{-1}] is 12.0 ± 0.6 ka, and using the Scandinavia-wide production rate from Stroeven et al. ([39]; based on four calibration sites in Sweden and Norway; reported value using Lm scaling is 4.13 ± 0.11 atoms g year^{-1}) is 12.1 ± 0.6 ka. We prefer the average ^{10}Be age using the Baffin Bay rate of Young et al. [46; based on two sites on Greenland and one on Baffin Island] because it is indistinguishable from the average of four sites from Norway (two from Goehring et al. [11] and two from Fenton et al. [9]), and in addition it is indistinguishable from the northeastern North America production rate [2]. Regardless, we cannot rule out that Bjørnøya deglaciated just prior to the Younger Dryas nor at the end of the Younger Dryas, although we find it more likely given all age calculations and uncertainties, that the island likely deglaciated as late as the middle Younger Dryas, and as early as the beginning of the Younger Dryas. There is some evidence from northern Norway for glacier advance during the Allerød and retreat during the middle Younger Dryas [37, 42]. We speculate that this could also be a possibility for the ice cap covering Bjørnøya, given the presence of small moraines, which may delimit a stillstand or re-advance that occurred within the Younger Dryas.

Conclusions

Our best estimate for the age of final deglaciation of Bjørnøya is 12.4 ± 0.5 ka, which overlaps with the Younger Dryas. Given current uncertainties, we cannot rule out that Bjørnøya deglaciated prior to, or even after, the Younger Dryas. This timing of deglaciation for the entire island from low to high elevation suggests that ice lingered over the shallow Spitsbergenbanken in the western Barents Sea later than prior work depicts. The significance of the final collapse of ice in the Barents Sea and the opening of a new gateway between Atlantic and Arctic ocean basins could have important ramifications for the climate system. Additional ^{10}Be ages from other southern and eastern islands within the Svalbard archipelago could help to further constrain the timing of the final demise of the Barents Sea Ice Sheet.

Acknowledgements We thank William d'Andrea, Katja Baum, Willem van der Bilt, Alexander Hovland, Henriika Kivilä and Torgeir Røthe for help during fieldwork, Joseph Tulenko for help with figure 1, and Susan Zimmerman and the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory for assistance with ^{10}Be/^{9}Be measurements.

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