JOURNAL OF QUATERNARY SCIENCE (2017) 32(1) 80–90 ISSN 0267-8179. DOI: 10.1002/jqs.2925

JQS Journal of Quaternary Science QRA Quaternary Research Association

Deglaciation of Boknafjorden, south-western Norway

DALE J. GUMP,[1] JASON P. BRINER,[1]* JAN MANGERUD[2] and JOHN INGE SVENDSEN[2]
[1]Department of Geology, University at Buffalo, 126 Cooke Hall, Buffalo, NY 14260, USA
[2]Department of Earth Science, University of Bergen, PO 7803, N-5020, Norway, and Bjerknes Centre for Climate Research, Bergen, Norway

Received 29 June 2016; Revised 28 October 2016; Accepted 7 November 2016

ABSTRACT: We present 30 ^{10}Be ages from glacial erratic boulders to constrain the deglaciation of the Scandinavian Ice Sheet in the Boknafjorden region, south-western Norway. The southern part of the island Karmøy, located at the mouth of this fjord system, became free of glacier ice before 16 ka, probably because of the sudden break up of the Norwegian Channel Ice Stream at 20–18 ka. The ice sheet margin then stabilized at the fjord mouth until a second retreat phase commenced at or slightly before 16 ka. A calving bay developed in Boknafjorden after 16 ka, and in the course of the next millennium the ice front retreated to the inner fjord branches. In contrast, a major outlet glacier that filled the Hardangerfjorden farther to the north did not start to retreat from the fjord mouth until after 15 ka, probably in response to the Bølling warming. Thus, not only did Boknafjorden experience major retreat before Bølling warmth, but there was a variable response of south-western fjord glaciers in Norway consistent with prior observations of non-climatic forcing of marine-terminating outlet glaciers. Copyright © 2017 John Wiley & Sons, Ltd.

KEYWORDS: Beryllium-10 dating; Boknafjorden; deglaciation; Norway; Scandinavian Ice Sheet.

Introduction

Non-climatic controls on ice sheet change can lead to non-linear ice sheet response to climatic forcing and result in complex patterns of ice sheet deglaciation (e.g. Kessler *et al.*, 2008; Stokes *et al.*, 2014). Reconstructions of ice sheet change during the Last Glacial Maximum (LGM; ~26–19 ka, Clark *et al.*, 2009) and the subsequent deglaciation provide insight into the spatial variability of ice sheet response to pronounced changes in global atmospheric and oceanic conditions (e.g. Dyke *et al.*, 2002; Hughes *et al.*, 2016). The Scandinavian Ice Sheet bordered the North Atlantic Ocean and is a valuable target for understanding mechanisms that modulate ice loss for ice sheets that border oceans. Two large-scale reconstructions of the Scandinavian Ice Sheet retreat during the last deglaciation highlight spatial and temporal gaps in the geochronology constraining ice margin change that encourage detailed study in some sectors (Hughes *et al.*, 2016; Stroeven *et al.*, 2016).

The Scandinavian Ice Sheet nucleated from glaciers that formed in the Scandinavian mountains (Mangerud *et al.*, 2011). At its maximum extent, this ice sheet coalesced with the neighboring British–Irish Ice Sheet and the Barents–Kara and Svalbard Ice Sheets forming the larger Eurasian Ice Sheet complex (Svendsen *et al.*, 2004; Hughes *et al.*, 2016). As climate warmed following the LGM, the Scandinavian Ice Sheet decoupled from the surrounding sectors of the Eurasian Ice Sheet and retreated towards its continental origin, albeit asynchronously (Hughes *et al.*, 2016).

The configuration of the south-western Scandinavian Ice Sheet during late phases of the LGM was characterized by the Norwegian Channel Ice Stream that flowed parallel with the coast of mainland Norway along the Norwegian Channel (Fig. 1; Sejrup *et al.*, 2000, 2003; Ottesen *et al.*, 2005, 2016), and the subsequent break-up of the ice stream was followed by landward retreat of mainland ice through fjords and on land (Mangerud *et al*, 2013, 2016; Briner *et al.*, 2014). The early collapse of the Norwegian Channel Ice Stream (~20–18 ka) left areas near the mouth of Boknafjorden (Fig. 2) ice free much earlier than elsewhere in Norway (Svendsen *et al.*, 2015), with one exception being the island Andøya in northern Norway (Vorren *et al.*, 2013; Fig. 1). Yet the configuration and chronology of the deglaciation of the Boknafjorden region is only loosely constrained by previous work that for the most part relied on radiocarbon ages from lake basins (e.g. Anundsen, 1985; Paus, 1988). In this study we build on the recent work in the outermost Boknafjorden area by Svendsen *et al.* (2015) and near the Younger Dryas moraines around the innermost areas of Boknafjorden by Briner *et al.* (2014; Fig. 2) with the aim to improve understanding of the temporal pattern of deglaciation of the entire Boknafjorden region and adjacent areas to the north. Realizing that during ice-margin retreat the ice surface would have thinned upstream of the ice sheet margin, we therefore dated erratics from summits along Boknafjorden in an attempt to constrain the timing of when they first protruded through the ice surface. These data are in turn used to reconstruct the ice sheet profile during deglaciation.

Methods

We dated 25 samples from perched erratic boulders from seven sites in the Boknafjorden region and an additional five samples that were collected from large boulders sitting on a moraine ridge (Fig. 2). All samples were taken by using a rock saw combined with hammer and chisel (Fig. 3). The samples were collected in groups of three to five samples per site in the outer and middle Boknafjord region (Fig. 2). The dated samples are ~2-cm-thick slabs that were cut from the top of the boulders, primarily from flat surfaces and away from edges and corners. A clinometer was used to measure topographic shielding and a handheld GPS was used to determine sample location and elevation. Sample elevations were cross-checked using topographic maps with 1-m contours (www.norgeskart.no). All samples were collected above the local marine limit (<50 m a.s.l.) (Thomsen, 1982; Anundsen, 1985; Helle, 2008) to avoid any shielding from seawater before isostatic uplift.

*Correspondence to: J. Briner, as above.
E-mail: jbriner@buffalo.edu

Copyright © 2017 John Wiley & Sons, Ltd.

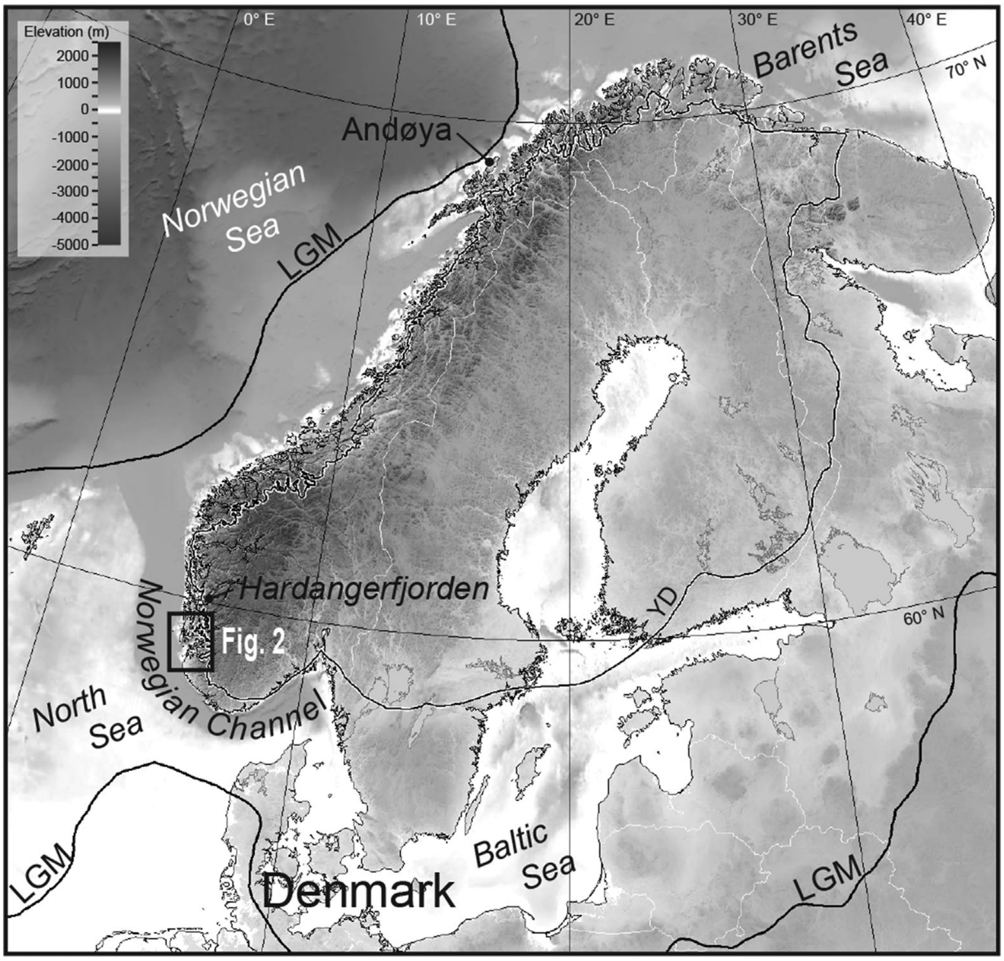

Figure 1. Scandinavia showing extent of the Scandinavian Ice Sheet during the Last Glacial Maximum (LGM) and the Younger Dryas (YD). The study area bordering the Norwegian Channel in south-western Norway is indicated by the box showing the location of Fig. 2. Modified from Mangerud *et al.* (2011).

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 (Nishiizumi *et al.*, 2007; Young *et al.*, 2013a). Beryllium ratios were measured by accelerator mass spectrometry (AMS) at Lawrence Livermore National Laboratory and normalized to standard 07KNSTD3110 with a reported ratio of 2.85×10^{-12} (Nishiizumi *et al.*, 2007; Rood *et al.*, 2010). Procedural blank ratios were 1.53×10^{-15}, 1.93×10^{-15}, 1.96×10^{-15} and 3.35×10^{-15}, equating to an average background correction of 2.36% of the sample total (Table 1). One-sigma analytical uncertainties on background-corrected samples range from 1.84 to 8.72% and average 2.53%.

Age calculations were made with the CRONUS-Earth online exposure age calculator (Balco *et al.*, 2008 version 2.2.1; hess.ess.washington.edu/) using a locally derived production rate (Goehring *et al.*, 2012a,b) with Lm scaling (Balco *et al.*, 2008). In Table 1 we also list ages using the 'Arctic' production rate (Young *et al.*, 2013b). The hard crystalline lithologies of south-west Norway, as well as the presence of glacial striations in multiple locations, suggest corrections for postglacial weathering and erosion is unnecessary. All samples are corrected for air pressure variations based on the present-day elevation above sea level. Given the low marine limit in the field areas of middle and outer Boknafjorden (20–40 m a.s.l.), we do not make corrections for isostatic adjustment of site elevations. Corrections for isostatic rebound on this scale would increase the calculated ages by $<\sim 1\%$, that is a maximum 150–200 years for the innermost samples that experienced the most ($\sim$50 m) relative uplift since deposition. Individual sample ^{10}Be ages are presented with their AMS analytical uncertainty only; we use the standard deviation to represent uncertainty when averaging groups of individual ^{10}Be ages (Table 1). When we consider the clustering of sample ^{10}Be ages, we present the average of all ^{10}Be ages from a sample site, and if there are outliers (defined as single ages >2 sigma of the others), we report the average of the reduced sample collection.

Most radiocarbon ages are cited from the DATED database that includes published ages related to the last glaciation and deglaciation of Scandinavia (Hughes *et al.*, 2016). These and other samples referred to in this study are re-calibrated using IntCal13 (Reimer *et al.*, 2013). For marine samples, we used $\Delta R = 0$, which is close to the present-day reservoir age in this area (Mangerud *et al.*, 2006) and also close to Lateglacial values (Bondevik *et al.*, 2006).

Results and interpretations

Ryvarden, Mølstrevåg

Of our eight sampling sites, the farthest north is located in Ryvarden area (marked 'R' in Fig. 2), a low-lying coastal region ($\sim$65 m a.s.l.) close to the mouth of Bømlafjorden, which is the seaward extension of the large Hardangerfjorden (Fig. 2). Here we dated three erratic boulders that were all perched on exposed bedrock surfaces. The samples (14NOR-2, 14NOR-52 and 14NOR-53) yielded ages of 15.7 ± 0.3, 14.7 ± 0.3 and 14.4 ± 0.3 ka, respectively, with an average ^{10}Be age of 15.0 ± 0.7 ka (Table 1; Figs 2 and 4).

Storasund, northern Karmøy

The $\sim$30-km-long island of Karmøy lies between Bømlafjorden and the mouth of Boknafjorden (Fig. 2). The marine limit

Copyright © 2017 John Wiley & Sons, Ltd.

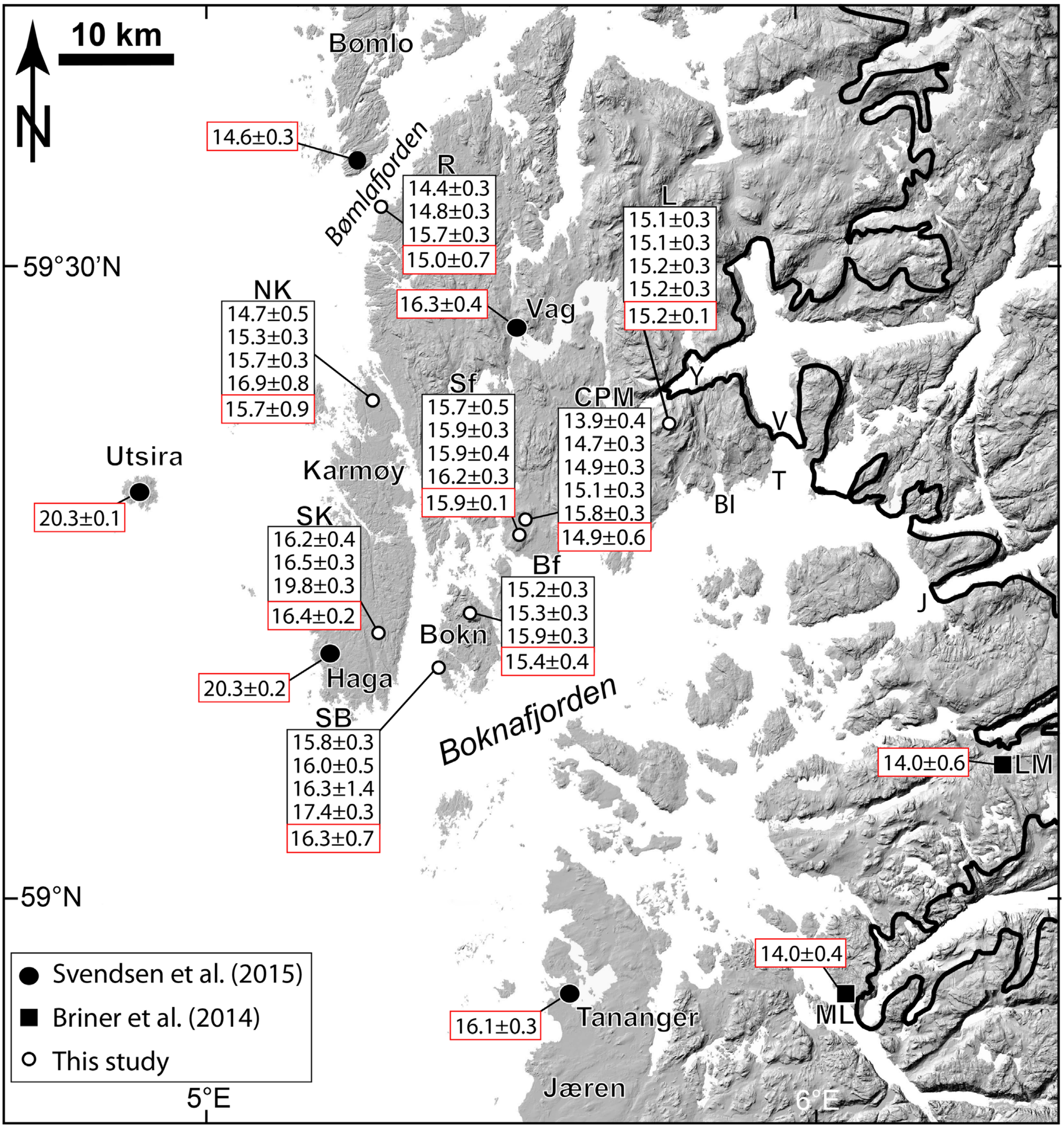

Figure 2. Boknafjorden region showing locations with published and new (this study) ^{10}Be ages and the Younger Dryas ice extent (thick black line). Averages appear in red boxes. Sites with ^{10}Be ages from this study are: NK, northern Karmøy; SK, southern Karmøy; R, Ryvarden; SB, southern Bokn; Bf, Boknafjellet; Sf, Sandviksfjellet; CPM, Cleng Peerson Moraine; L, Lammanuten. Abbreviations of sites with ^{10}Be ages from prior studies are: LM, Leiken Moraine; L, Lysefjorden; ML, mouth of Lysefjorden. Sites with relevant radiocarbon ages are: Y, Yrkjefjorden; V, Vindafjorden; J, Jøsenfjorden; BI, Borgøy Island; T, Tveit.

is probably about 16–17 m a.s.l. on the southern tip of the island (Svean, 2016), rising to ~23 m a.s.l. in the north (Austad and Erichsen, 1987). We sampled from two restricted areas on the island, one in the north and one in the south. From Storasund on northern Karmøy we dated four erratic boulders. Samples 14NOR-3 and 14NOR-4, which are granitic boulders, perched directly on the local bedrock of gneiss and schist, yielded ages of 14.7 ± 0.5 and 16.8 ± 0.8 ka, respectively. The two other samples, 14NOR-5 and 14NOR-7, are large granitic boulders sitting in a pasture on a small plain. They yielded nearly similar ages of 15.3 ± 0.3 and 15.7 ± 0.3 ka, respectively (Fig. 2). The average age of all four samples from northern Karmøy is 15.7 ± 0.9 ka (Table 1 and Fig. 4).

Stiklebotn, Karmøy

Three samples from the south-eastern part of Karmøy were dated. All three samples were collected from boulders that were perched directly on bedrock on top of a plateau ~80 m a.s.l. to the south of lake Stiklevatn. The dated samples, 14NOR-9, 14NOR-10 and 14NOR-11, yielded ages

Copyright © 2017 John Wiley & Sons, Ltd.

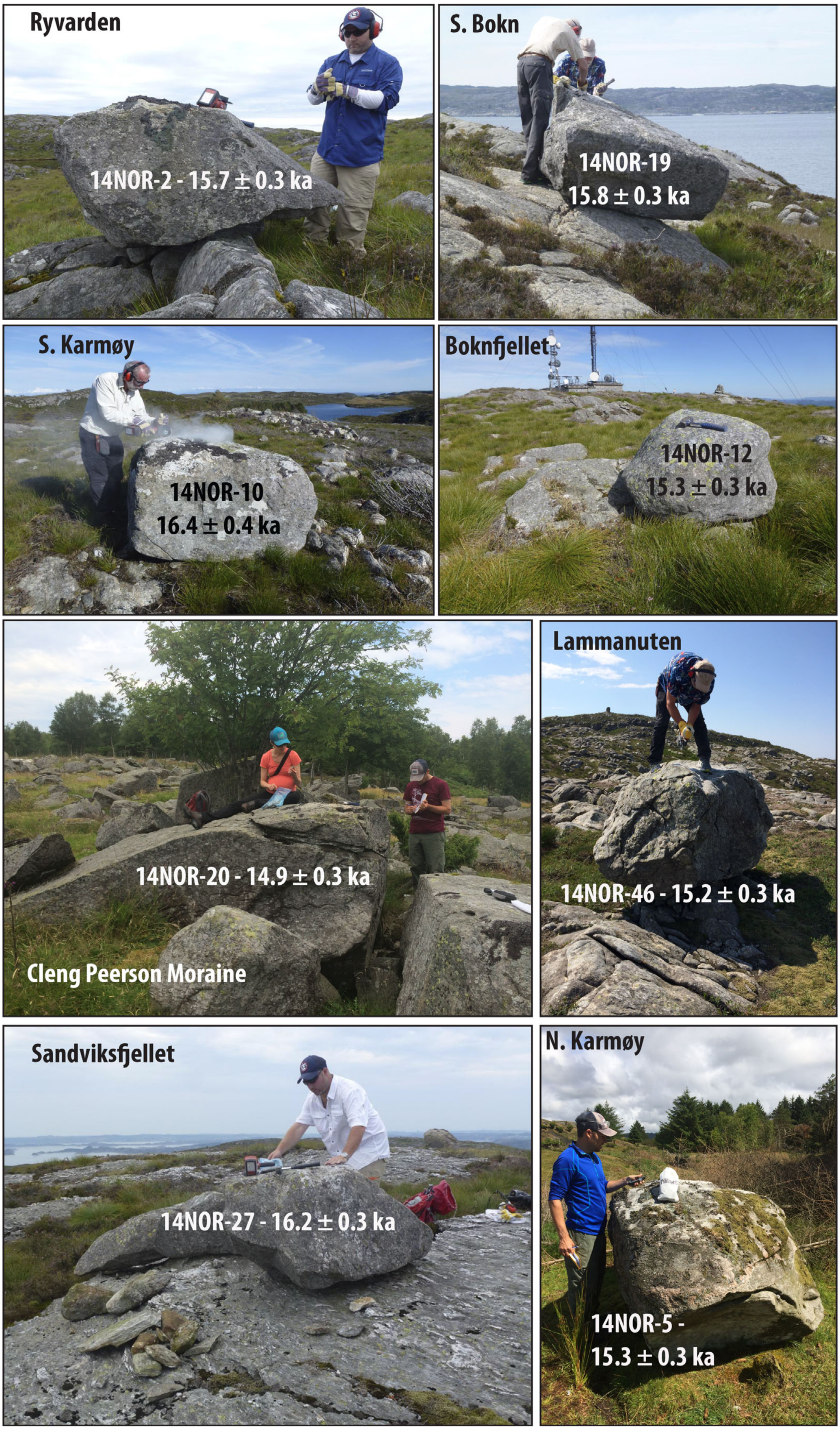

Figure 3. Photographs of selected samples and their ^{10}Be ages to provide a visual context for typical sample settings in this study.

of 16.2 ± 0.4, 16.5 ± 0.4 and 19.8 ± 0.3 ka, respectively. The average age for all three boulders is 17.5 ± 2.0 ka, and the average of the youngest two is 16.4 ± 0.2 ka (see Discussion; Table 1 and Fig. 4).

Bokn

Bordering the north side of Boknafjorden, east of southern Karmøy, is the ~12-km-long island of Bokn (Fig. 2). We dated four erratic boulders from the lowland on south-western

Copyright © 2017 John Wiley & Sons, Ltd.

Table 1. ^{10}Be sample data and ages.

Sample	Boulder height (m)	Boulder dimension (m)	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Sample thickness (cm)	Topographic shielding factor	^{10}Be concentration (at. g^{-1})	^{10}Be age (ka)	^{10}Be age (ka)* (Arctic)
Ryvarden										
14NOR-2	1.2	1.5 × 1.5	59.542892	5.252955	63	1.5	1.000	73 490 ± 1340	15.7 ± 0.3	16.2 ± 0.3
14NOR-52	1.2	2.0 × 2.5	59.542065	5.255194	69	1.0	1.000	68 232 ± 1299	14.8 ± 0.3	15.2 ± 0.3
14NOR-53	0.6	1.2 × 1.2	59.541294	5.250267	60	1.0	1.000	65 888 ± 1350	14.4 ± 0.3	15.0 ± 0.3
									15.0 ± 0.7	**15.5 ± 0.7**
North Karmøy										
14NOR-3	1.5	1.5 × 1.5	59.391308	5.260775	27	2.0	0.999	64 417 ± 2370	14.7 ± 0.5	15.2 ± 0.6
14NOR-4	0.5	1.0 × 1.0	59.390672	5.260714	41	1.0	1.000	75 483 ± 3537	16.9 ± 0.8	17.5 ± 0.8
14NOR-5	1.2	2.0 × 2.0	59.390875	5.258725	27	2.0	1.000	68 105 ± 1242	15.3 ± 0.3	15.8 ± 0.3
14NOR-7	1.2	1.5 × 1.5	59.390214	5.256700	28	2.0	1.000	68 938 ± 1397	15.7 ± 0.3	16.3 ± 0.3
									15.7 ± 0.9	**16.2 ± 1.0**
South Karmøy – Stiklebotn										
14NOR-10	1.2	1.7 × 1.5	59.199449	5.282492	78	2.0	1.000	75 994 ± 1778	16.5 ± 0.4	17.0 ± 0.4
14NOR-11	0.4	0.5 × 0.5	59.199594	5.28177	78	2.0	1.000	91 237 ± 1498	19.8 ± 0.3	20.4 ± 0.3
14NOR-9	1.0	1.2 × 2.0	59.201700	5.283430	84	3.0	1.000	74 772 ± 1831	16.2 ± 0.4	16.8 ± 0.4
									17.5 ± 2.0	**18.1 ± 2.0**
Boknfjellet										
14NOR-12	1.3	1.3 × 1.3	59.218904	5.429401	286	2.0	1.000	86 458 ± 1844	15.3 ± 0.3	15.8 ± 0.3
14NOR-13	1.2	2.0 × 1.5	59.219771	5.428367	285	2.0	1.000	90 918 ± 1788	15.9 ± 0.3	16.4 ± 0.3
14NOR-14	0.5	1.0 × 1.0	59.219593	5.427794	285	1.0	1.000	86 056 ± 1589	15.2 ± 0.3	15.7 ± 0.3
									15.4 ± 0.4	**16.0 ± 0.4**
South Bokn										
14NOR-15	0.6	1.5 × 1.5	59.175612	5.383928	64	1.0	1.000	72 742 ± 2166	16.0 ± 0.5	16.5 ± 0.5
14NOR-17	1.0	2.0 × 2.0	59.175839	5.383096	53	2.0	0.999	77 888 ± 1516	17.4 ± 0.3	18.0 ± 0.3
14NOR-18	0.4	1.0 × 1.5	59.174793	5.383574	62	1.0	1.000	74 464 ± 6494	16.3 ± 1.4	16.8 ± 1.4
14NOR-19	0.4	1.0 × 1.0	59.175052	5.383542	54	2.0	0.996	70 299 ± 1365	15.8 ± 0.3	16.3 ± 0.3
									16.3 ± 0.7	**16.9 ± 0.7**
Cleng Peerson										
14NOR-20	1.3	2.0 × 3.0	59.300926	5.511976	49	1.0	1.000	67 059 ± 1589	14.9 ± 0.3	15.4 ± 0.4
14NOR-21	2.5	3.0 × 3.0	59.300727	5.512094	48	2.5	1.000	71 866 ± 1311	15.8 ± 0.3	16.3 ± 0.3
14NOR-22	2.3	4.0 × 3.0	59.298978	5.511777	43	2.5	1.000	66 993 ± 1410	15.1 ± 0.3	15.6 ± 0.3
14NOR-23	3.0	8.0 × 5.0	59.298889	5.511916	43	2.0	1.000	62 507 ± 2010	13.9 ± 0.4	14.4 ± 0.5
14NOR-24	1.0	2.0 × 1.0	59.298647	5.511158	42	2.5	1.000	66 239 ± 1208	14.7 ± 0.3	15.2 ± 0.3
									14.9 ± 0.6	**15.4 ± 0.6**
Sandvikfjellet										
14NOR-26	3.0	8.0 × 5.0	59.285367	5.497384	183	2.0	1.000	83 452 ± 2368	15.7 ± 0.5	16.3 ± 0.5
14NOR-27	0.8	1.2 × 1.0	59.285000	5.497428	181	1.0	1.000	83 454 ± 1781	16.2 ± 0.3	16.7 ± 0.4
14NOR-28	1.7	1.5 × 1.5	59.286162	5.499575	169	1.3	1.000	80 228 ± 1589	15.9 ± 0.3	16.4 ± 0.3
14NOR-29	1.8	4.0 × 3.0	59.286810	5.501113	159	2.0	1.000	80 015 ± 2250	15.9 ± 0.4	16.5 ± 0.5
									15.9 ± 0.1	**16.5 ± 0.1**
Lammanuten										
14NOR-43	2.0	3.0 × 1.5	59.38209	5.72757	611	2.0	1.000	118 594 ± 2160	15.2 ± 0.3	15.7 ± 0.3
14NOR-46	1.5	1.0 × 2.0	59.38467	5.73015	610	1.0	0.999	120 179 ± 2187	15.2 ± 0.3	15.4 ± 0.3
14NOR-47	1.0	1.3 × 1.0	59.38405	5.72886	616	2.0	1.000	118 815 ± 2165	15.1 ± 0.3	15.6 ± 0.3
14NOR-50	1.0	1.3 × 0.75	59.38292	5.72811	623	3.0	1.000	119 343 ± 2170	15.1 ± 0.3	15.7 ± 0.3
									15.2 ± 0.05	**15.7 ± 0.05**

*^{10}Be age calculated using Arctic wide production rate.

Bokn, all resting directly on bedrock and spanning elevations from ~53 to 64 m a.s.l. The ages from these samples are 16.0 ± 0.5 ka (14NOR-15), 17.4 ± 0.3 ka (14NOR-17), 16.3 ± 1.4 ka (14NOR-18) and 15.8 ± 0.3 ka (14NOR-19), and average is 16.3 ± 0.7 ka, or 16.0 ± 0.3 ka excluding the oldest age (Fig. 4). This is almost identical to the mean for the two youngest boulders on south-eastern Karmøy, suggesting that both areas became ice free roughly at the same time.

We also sampled three erratic boulders from the highest summit on the island, Boknafjellet (~285 m a.s.l.), located on the north-eastern section of the island. The ages are 15.3 ± 0.3 ka (14-NOR-12), 15.9 ± 0.3 ka (14NOR-13) and 15.1 ± 0.3 ka (14NOR-14; Fig. 4), with an average of 15.4 ± 0.4 ka (Table 1). At face value, the average age is slightly younger than the age from the southern tip of the island, which is not feasible from a glaciological point of view. The summit of Boknfjellet is a plateau with shallow topographic depressions that contain the erratics. During the Lateglacial these depressions may have contained perennial (or long season) snowfields (the boulder heights are 1.3, 1.2

Copyright © 2017 John Wiley & Sons, Ltd.

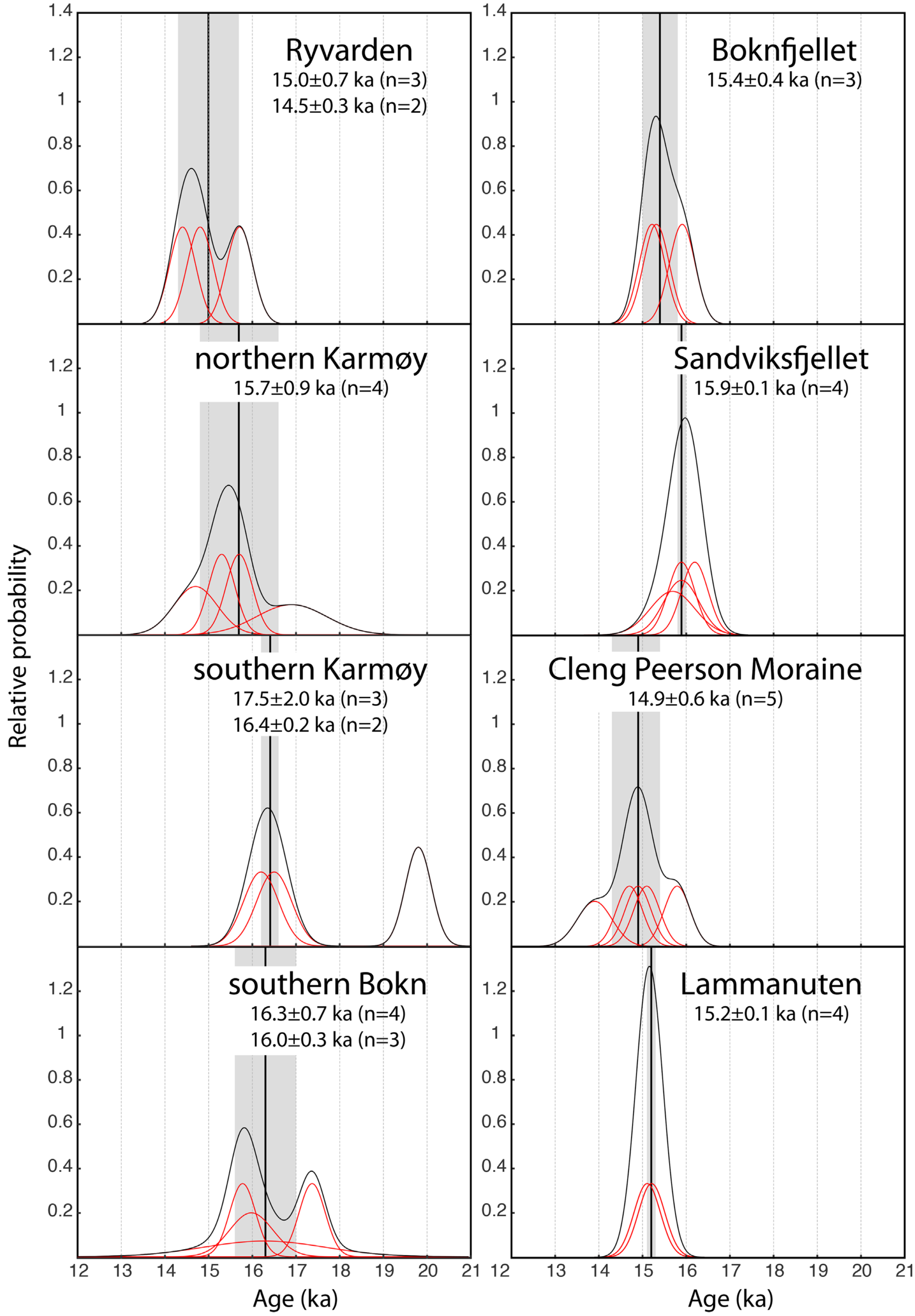

Figure 4. Relative probability plots of ^{10}Be ages from each sample location. Red curves are individual ^{10}Be ages and black curves are summed probabilities of all ^{10}Be ages.

and 0.5 m), probably during the latest Pleistocene. If so, the snowfields may have shielded the boulders, perhaps leading to the slightly younger ages compared to the average age [(16.3 ± 0.7 ka (n = 4), or 16.0 ± 0.3 ka (n = 3)] of those that were collected from the lowland on south-western Bokn.

Sandviksfjellet, Tysvær

Sandviksfjellet is a mountain top (~185 m a.s.l.) bordering the northern shore of Boknafjorden (Fig. 2) where we dated samples from four erratic boulders sitting at the summit. The boulders, which consist of gneiss, are all resting on

Copyright © 2017 John Wiley & Sons, Ltd.

phyllite or schist bedrock without any sediment cover. All ages (14NOR-26–29) from Sandviksfjellet yield similar ages between 15.7 ± 0.5 and 16.1 ± 0.3 ka, and with an average age of 15.9 ± 0.1 ka. It is noteworthy that the average ^{10}Be age on Sandviksfjellet summit is almost identical to the average age from south-western Bokn, suggesting that the deglaciation occurred at the same time.

The Cleng Peerson moraine, Falkeid, Tysvær

A prominent moraine ridge, about 2 km long, comprising clast-supported gneissic boulders lies north of the mid-fjord region of Boknafjorden, about 2 km to the north-east of the aforementioned sampling site on Sandviksfjellet (Fig. 2). The moraine (informally named the Cleng Peerson moraine) is described by Rønnevik (1971), and points to a standstill or re-advance of the ice front. The moraine must have formed after the summit of Sandviksfjellet became ice free because the moraine is draped across the lower eastern (ice-proximal) flanks of the mountain. We dated five large boulders (≥2 × 1 × 1 m in exposed diameter) from the Cleng Peerson Moraine. The ages (from samples 14NOR-20 to 14NOR-24) range from 13.9 ± 0.5 to 15.8 ± 0.3 ka and average 14.9 ± 0.6 ka. The spread in ages could be due to typical factors that influence the ages of moraine boulders, including isotopic inheritance, post-depositional tilting of boulders and analytical uncertainties (Heyman *et al.*, 2011).

Lammanuten, Nedstrand

Samples were collected on the summit (at ~620 m a.s.l.) of the mountain Lammanuten, situated towards the upper reaches of Boknafjorden, and a short distance outside the Younger Dryas ice sheet position near the village Yrkje (Fig. 2) (Anundsen, 1972). This summit contains abundant erratic boulders perched on smaller boulders, cobbles and sculpted bedrock (Fig. 3). We dated four boulders (14NOR-43, -46, -47 and -50) that yield a tight cluster of ages ranging from 15.1 ± 0.3 to 15.2 ± 0.1 ka; together they yield an average age of 15.2 ± 0.1 ka (Table 1 and Fig. 4) that we consider a trustworthy age of the mountain summit deglaciation.

Discussion

^{10}Be production rate choice

The ^{10}Be ages are calculated using a production rate derived from two calibration sites in south-western Norway (Goehring *et al.*, 2012a,b; Table 1). With Lm scaling, this production rate (4.15 ± 0.15 atoms g^{-1} a^{-1}) is the average of values from two independently dated sites, one of which is a Younger Dryas moraine (4.25 ± 0.11 atoms g^{-1} a^{-1}) and the other is a middle Holocene rock avalanche (4.04 ± 0.13 atoms g^{-1} a^{-1}; Goehring *et al.*, 2012b). Stroeven *et al.* (2015) generated a new ^{10}Be production rate at an independently dated site related to a drainage event of the Baltic Sea, and combined this value with a recalculation of four other ^{10}Be production rate values in Scandinavia (Fenton *et al.*, 2011; Goehring *et al.*, 2012a,b). With Lm scaling, the Scandinavian reference ^{10}Be production rate is 4.13 ± 0.11 atoms g^{-1} a^{-1}, which is statistically identical to the rate of Goehring *et al.* (2012a,b). These ^{10}Be production rates from Scandinavia are, however, slightly higher than the findings from other recent studies. For example, the average ^{10}Be production rate from several sites in north-eastern North America (Balco *et al.*, 2009), and an average ^{10}Be production rate from sites spanning the Arctic (Young *et al.*, 2013b), are both ~3.93 atoms g^{-1} a^{-1}, a few per cent lower than the Scandinavia-only value. For comparison, we therefore also present results using the Arctic-wide production rate in Table 1 (Young *et al.*, 2013b). Using the Arctic-wide production rates here would result in a slight shift in ages (~3–4% older).

Initial ice sheet retreat following the break-up of the Norwegian Channel Ice Stream

There are presently two alternative models for the timing of the retreat of the Norwegian Channel Ice Stream from its LGM position on the shelf break to Utsira, an island north-west of the mouth of Boknafjorden (Fig. 2). Dating of basal foraminifera in cores from the Norwegian Channel suggests that the seafloor off the south-western coast of Norway became ice free shortly before ~18.5 cal ka BP (Sejrup *et al.*, 1995). By contrast, recently published ^{10}Be exposure ages from Utsira, which undoubtedly was overridden by the ice stream during the LGM, suggest that deglaciation of the channel may have occurred as early as ~20 ka (Svendsen *et al.*, 2015). Although this age discrepancy is unresolved, both methods contain uncertainties that are not reflected in their standard deviations.

The oldest reported radiocarbon ages from sediment cores in lake basins above the marine limit in southern Karmøy and Utsira are between ~15.5 and ~17 cal ka BP (Paus, 1989, 1990). However, it should be noted that these ages were obtained from sediment horizons that are stratigraphically above relatively thick sequences of inorganic silt and clay (10s of cm) without any radiocarbon ages, and are therefore only minimum ages of deglaciation. The pollen stratigraphy reveals that the lowermost sediments in these basins accumulated during a prolonged cold period (Oldest Dryas) before the onset of the Bølling warming, and it seems clear that sedimentation started well before 16 ka. Recently, during studies of relative sea-level changes, ages of ~18.0 cal ka BP were obtained from radiocarbon dating of foraminifer tests from near the base of marine sediments in cores from two isolation basins located on the southernmost tip of Karmøy (Svean, 2016). Thus, there is evidence to suggest that both Utsira and Karmøy were ice free by ~18.0 cal ka BP. However, one may keep in mind that the uncertain marine reservoir correction represents an additional uncertainty when assessing the reliability of the radiocarbon chronology during the early deglaciation. The marine reservoir correction is highly unlikely to be less than the value we used, but due to slower deepwater turnover during the deglaciation it could be up to several hundred years higher than the present reservoir age (~400 years). Using a higher value results in younger calibrated radiocarbon ages. In the case that the marine reservoir correction during the initial deglaciation is relatively high due to slower deepwater turnover than during the Allerød–Younger Dryas, which is likely, then ice recession may have occurred later.

Svendsen *et al.* (2015) obtained three consistent ^{10}Be ages ~20 ka (20.1 ± 0.4, 20.4 ± 0.6 and 22.3 ± 0.7 ka) from near the farmstead Haga (Fig. 2), only ~3 km to the north-west of the core sites on southern Karmøy mentioned above (Svean, 2016). The samples from the Haga site were collected from glacially transported erratics resting on barren bedrock surfaces. The ages yielded similarly old ages as those from Utsira, and this led Svendsen *et al.* (2015) to suggest a similar age for the deglaciation in both areas. These new radiocarbon ages have created an element of doubt as to whether the existing exposure ages are providing trustworthy ages of the deglaciation or if they are too old due to inheritance (see Briner *et al.*, 2016). To test the consistency of these old

Copyright © 2017 John Wiley & Sons, Ltd.

^{10}Be ages from southern Karmøy, we dated three additional erratic boulders in the Stiklebotn area, ~6 km to the east of the Haga site. As presented above, only one of the samples (14NOR-11) from the Stiklebotn area yielded an equally old age (19.8 ± 0.3 ka) to those from Haga, whereas the other two yield ages more than 3000 years younger (16.2 ± 0.4 and 16.5 ± 0.4 ka). Because of the potential problem with inheritance in these most ice-distal sites in the field area, we in general tend to place more confidence on the young ages, especially when the spread of ages from a sampling site is large. More dating is necessary to constrain the timing of the initial deglaciation, but we consider 16 ka as a safe minimum age for the ice sheet retreat from southern Karmøy. As mentioned above, new radiocarbon dates of foraminifer tests from sediment cores that were retrieved from two lake basins located a few kilometers farther to the south suggest that deglaciation occurred as early as 18 ka (Svean, 2016).

Deglaciation history of Boknafjorden

Our new ages for the deglaciation of outer Boknafjorden are generally self-consistent, particularly the ages from southern Bokn of 16.3 ± 0.7 ka ($n = 4$) and from the summit of Sandviksfjellet, farther upfjord, of 15.9 ± 0.1 ($n = 4$). There is some independent age control from this area from a sediment core that was retrieved from lake Sandvikvatnet, near our sampling site on the mountain Sandviksfjellet (Fig. 2). Based on the pollen stratigraphy, Paus (1988) concluded that lacustrine sedimentation started well before the Bølling interstadial, perhaps as early as ~17 cal ka BP. However, the basal ^{14}C ages were obtained from bulk sediments with low organic content and may overestimate the true age. The most reliable radiocarbon age from the core site is ~14.6 cal ka BP, obtained 50 cm above the base of the core. The ^{10}Be dating results from Sandviksfjellet and Bokn are consistent with existing ^{10}Be ages (16.1 ± 0.3 ka, $n = 3$) that were obtained from erratics on Tananger near the city of Stavanger on the opposite shore of the fjord (Svendsen *et al.*, 2015; Fig. 2). In view of the consistent ^{10}Be ages from Bokn, Sandviksfjellet and Tananger, we conclude that deglaciation in all areas occurred ~16 ka. A major deglaciation event at around this time is also substantiated by AMS radiocarbon ages of plant remains from cored lacustrine sediments on Jæren, somewhat farther south of the fjord (Knudsen, 2006). Finally, thick sequences (up to several hundred meters) of glaciomarine sediments around the mouth of Boknafjorden that accumulated before 13.5 cal ka BP (Bøe *et al.*, 2000) are consistent with a prolonged period of ice stability during deglaciation (Svendsen *et al.*, 2015; Ottesen *et al.*, 2016). Thus, we find it plausible that ~16 ka marks the end of a prolonged halt or re-advance of the ice front position at the mouth of Boknafjorden.

Farther upfjord, our ^{10}Be chronology suggests slightly younger ages for deglaciation. The mountain summit of Lammanuten, located ~30 km upfjord of Bokn, appears to have been deglaciated ~15.2 ± 0.1 ka, nearly a thousand years later than the mouth of Boknafjorden. This site is located just outside the Younger Dryas ice sheet margin that was located in the fjord branch at Yrkje on the northern side of the mountain Lammanuten (Anundsen, 1972). Anundsen (1977) provided radiocarbon ages from whale bones and shells in raised marine deposits from three localities along the northern shores of inner Boknafjorden, *i.e.* a short distance outside the Younger Dryas moraine. The ages indicate that deglaciation took place before ~14.6 cal ka BP (at Borgøy Island), ~13.9 cal ka BP (at Tveit) and at ~13.5 cal ka BP (at the mouth of Vindafjorden, Fig. 2). Beyond the Younger Dryas ice limit in Yrkjefjorden (Fig. 2), the oldest basal ^{14}C age (of bulk sediments) from a series of lakes and bogs is ~15.1 cal ka BP, an age that is substantiated by pollen analysis (Anundsen, 1985; Braaten and Hermansen, 1985; Fig. 2).

Our ages show that Boknafjorden was deglaciated several hundred years before the ice front started to recede from the mouth of Hardangerfjorden which seems to have taken place at the onset of the Bølling interstadial. This is consistent with southerly directions of the youngest striations indicating ice flow towards Boknafjorden and the existence of a calving embayment in this fjord during deglaciation (see Rønnevik, 1971). These young striae are cross-cutting older (presumably LGM) westerly striations.

The landscape between the coast and the Younger Dryas moraines is generally barren of moraines. One exception is the Cleng Peerson Moraine, which dates to 14.9 ± 0.6 ka. Although we are uncertain if this moraine represents a standstill or re-advance, it nonetheless provides a dated ice margin within the Boknafjorden system that can be traced a few kilometers (Rønnevik, 1971). The age is similar to the deglaciation age of Lammanuten at 15.2 ± 0.1 ka, and because the two ages overlap, we are unable to determine if Lammanuten was a nunatak at the time of Cleng Peerson moraine formation or not. That said, in general we do not see older ages at higher elevation sampling sites than lower elevations. If the ice sheet profile was thin and flat during deglaciation we would expect that the mountain summits along Boknafjorden protruded through the ice surfaces earlier than they did. We therefore conclude that either the ice sheet surface profile gradient was rather steep, or that deglaciation occurred rapidly and earlier deglaciation of summits is not detectable by our dating methods (Fig. 5).

At the head of Boknafjorden, where the wide and deep sound separates into a series of narrower tributary fjords, lies the Younger Dryas moraine belt (Fig. 2; Andersen, 1954). Briner *et al.* (2014) ^{10}Be dated most of the moraine belt to the Younger Dryas period, but a crest from the outermost part of the moraine belt (named the Leiken Moraine) was dated to ~14 ka, suggesting an Older Dryas age (Fig. 2). The ^{10}Be age of the Leiken Moraine is similar to erratics that were dated slightly beyond the Younger Dryas moraine belt at the mouth of Lysefjorden that yielded a similar age of ~14 ka. Blystad and Anundsen (1983) dated bivalves from raised marine deposits to 13.7 ± 0.3 cal ka BP, and basal gyttja in a lake-sediment core from an area beyond the Younger Dryas moraine belt at Jøsenfjorden to 13.6 ± 0.3 cal ka BP (Fig. 2). These results collectively suggest that the retreating ice front had reached the location of the Younger Dryas moraine belt by ~14 ka, i.e. about 2000 years before the inner ridges were formed along this moraine belt.

Ice sheet retreat from the mouth of Hardangerfjorden

Our chronology from Ryvarden at the mouth of Bømlafjorden is consistent with previous work. Radiocarbon ages from southern Bømlo on the opposite shore of Bømlafjorden indicate that the area became ice free by ~14.6cal ka BP (Karlsen, 2009), which is bolstered by ^{10}Be ages on erratics from southern Bømlo that average 14.6 ± 0.3 ka ($n = 5$) (Mangerud *et al.*, 2013). Our average ^{10}Be age of 15.0 ± 0.7 ka ($n = 3$) at Ryvarden on the opposite side of Bømlafjorden supports these previous findings. These results collectively suggest the mouth of Bømlafjorden deglaciated ~15 ka or shortly after (Fig. 2). This age overlaps with the average age of the samples from Storesund (15.7 ± 0.9 ka, $n = 4$) on northern Karmøy. Radiocarbon ages and pollen stratigraphic

Copyright © 2017 John Wiley & Sons, Ltd.

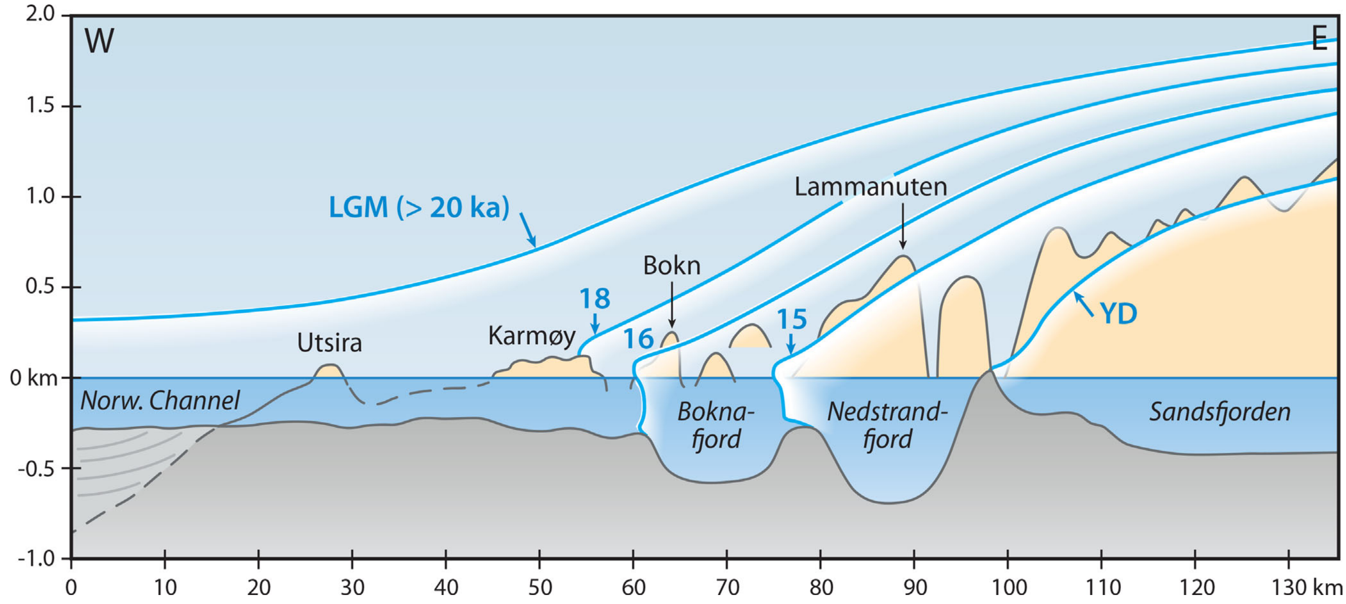

Figure 5. Topographic profile of Boknafjorden region showing generalized fjord bathymetry and adjacent mountain summits; key summits dated in this study are labeled (the diagram contains vertical exaggeration). Ice sheet profiles are shown for key time-slices discussed in the text. Crystalline bedrock is dark grey; the lighter gray to the left is Mesozoic sediments. Location of topographic profile shown in Fig. 6.

data from lacustrine sediments suggest that the Storesund area remained ice covered until the start of the Bølling (Austad and Erichsen, 1987; Svean, 2016). We conclude that the outlet glacier that occupied Hardangerfjorden during the Oldest Dryas reached the northern part of Karmøy, but that the southern end of Karmøy and the mouth of Boknafjorden became ice free significantly earlier. It should be mentioned that Svendsen *et al.* (2015) published three ^{10}Be ages from the site Våg, located on the mainland ~15 km north-east of northern Karmøy, which yield a slightly older average age of 16.3 ± 0.4 ka. If correct, this latter age suggests that deglaciation at Våg occurred as early as at northern Karmøy, which we find unlikely, given that the Våg site is closer to the ice source. The oldest of the three ^{10}Be ages from Våg is from bedrock, which might contain isotopic inheritance, but the two boulder ages are 16.1 ± 0.4 and 15.7 ± 0.5 ka, still statistically older than the ^{10}Be ages from Ryvarden. This discrepancy remains unresolved. Regardless, it seems clear that Hardangerfjorden remained ice-covered longer than Boknafjorden, perhaps because the narrow fjord mouth of Hardangerfjorden did not allow high rates of ice retreat.

The deglaciation of south-western Norway

The available chronology from the Boknafjorden region indicates that the fjord became ice free between ~16.3 ka (Bokn) and ~14.0 ka (Leiken Moraine). Assuming steady retreat between 16.3 ka at southern Bokn and 14 ka at the Older Dryas ice limit allows us to calculate a net retreat rate of ~25 m a^{-1} for the 45- to 50-km-long fjord system outboard of the Younger Dryas/Older Dryas moraines. However, it was certainly not a steady retreat; there may have been long-lasting still-stands and even re-advances that could be in part related to variability in fjord width and depth. Boknafjorden is a large and wide (15–25 km) system of sounds and fjords, and a large volume of ice must have evacuated during this interval. This rate of retreat is much less than reconstructed post-Younger Dryas retreat rates from Hardangerfjorden and Sognefjorden to the north where rates of ~240 and 340 m a^{-1} have been estimated (Mangerud *et al.*, 2013). We consider that retreat generally was faster in the early Holocene due to a warmer climate. By contrast, Stokes *et al.* (2014), who synthesized patterns of fjord glacier retreat in northern Norway during the last deglaciation, point out that fjord depth and width are more important than climate in modulating retreat rate. In fact, Stokes *et al.* (2014) show a statistically significant (albeit weak) correlation with age, revealing generally higher retreat rates earlier during deglaciation (Bølling and pre-Bølling) than during the early Holocene.

Interestingly, the deglaciation of Boknafjorden initiated before the deglaciation of Bømlafjorden and Hardangerfjorden to the north (Mangerud *et al.*, 2013, 2016; Svendsen *et al.*, 2015). For example, southern Bømlo deglaciated ~14.6 ka, around the start of the Bølling, whereas the ice sheet retreated from the mouth of Boknafjorden more than a thousand years earlier, ~16.3 ka (Fig. 6). Furthermore, there is evidence to suggest that Utsira and perhaps the southern tip of Karmøy became ice free even earlier (Svendsen *et al.*, 2015). The uplands surrounding Hardangerfjorden and Sognefjorden are more extensive and higher in elevation than those surrounding the Boknafjorden system, and possibly served as accumulation centers that kept ice relatively extensive for longer than at Boknafjorden. The re-advance of the Scandinavian Ice Sheet during the Younger Dryas was also relatively extensive in the Hardangerfjorden region compared to other sectors of the Scandinavian Ice Sheet (Mangerud *et al.*, 2016), consistent with there being a significant upland accumulation center in this region (Mangerud, 1980).

The evacuation of ice in Boknafjorden initiated before Bølling warming and the fjord was not re-occupied during the Younger Dryas, although the inner tributary fjords were probably deglaciated to some degree during the Allerød and later reoccupied by an ice sheet advance during the Younger Dryas. This is in contrast to the Bømlafjorden–Hardangerfjorden system, which did not deglaciate until the Bølling interstadial. Despite the cool climate of the eastern North Atlantic during Heinrich Stadial 1 (~18–14.7 ka), there must have been a mechanism forcing ice retreat. Indeed, in their compilation, Hughes *et al.* (2016) reveal that the Scandinavian Ice Sheet was reduced to about half its LGM size by the beginning of the

Copyright © 2017 John Wiley & Sons, Ltd.

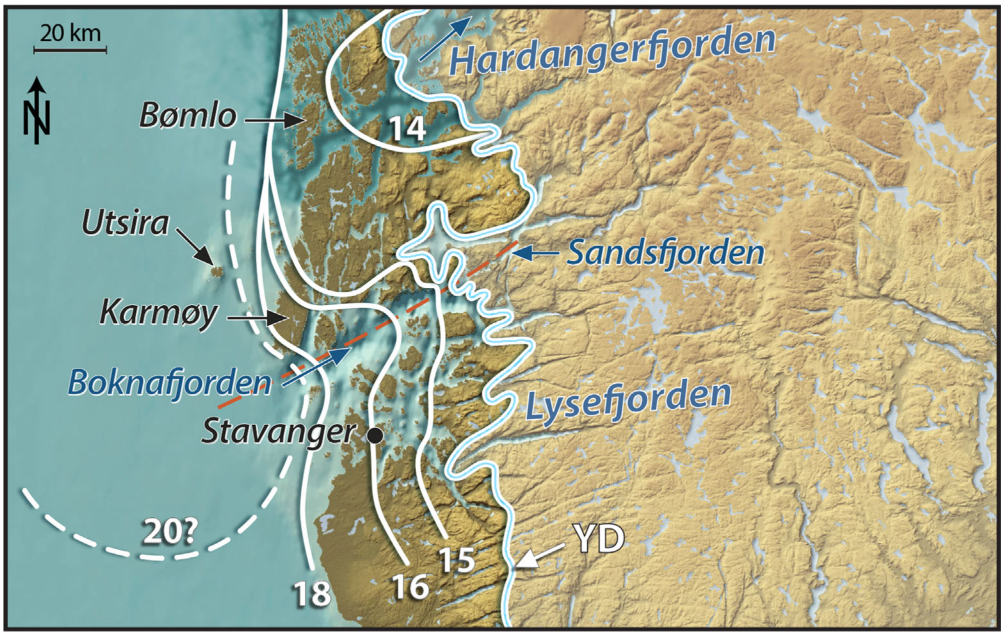

Figure 6. South-western Norway showing deglaciation isochrons reconstructed from our dates and prior literature and the relatively early deglaciation of Boknafjorden compared to Hardangerf-jorden. Red dashed line shows approximate location of topographic profile in Fig. 5.

Bølling. It seems likely that climate forcing mechanisms such as CO_2 rise beginning ~18 ka contributed to the melting of the ice sheet during this interval (Clark *et al.*, 2009; Shakun *et al.*, 2012). Furthermore, despite Northern Hemisphere average temperature increase initiating around the same time that CO_2 increased (Shakun *et al.*, 2012), Hughes *et al.* (2016) show that the Scandinavian Ice Sheet began to shrink before ~18 ka. This suggests that rising northern high latitude summer insolation beginning ~22 ka (Berger and Loutre, 1991) may have initiated ice sheet recession.

Conclusions

Our 30 new ^{10}Be ages improve the chronology of the deglaciation of Boknafjorden and surrounding areas during the last deglaciation. We conclude that Utsira and Karmøy were deglaciated before 16 ka, but recognize the need for continued radiocarbon and ^{10}Be dating from these islands to constrain the pattern and timing of the earliest ice-free terrestrial location in southern Norway. Our ^{10}Be ages from outer and middle Boknafjorden coupled with ^{10}Be ages nearer the fjord head from Briner *et al.* (2014) reveal that deglaciation of Boknafjorden began ~16.3 ka and was completed by ~14 ka. Boknafjorden was mostly ice free while the ice front lingered for more than a thousand years at the mouth of the Bømlafjorden–Hardangerfjorden system to the north. Processes such as sea-level rise, ocean temperature and fjord geometry are key factors that drive calving processes and ice sheet drawdown into over-deepened fjords. Our findings provide further support for non-climatic factors driving the timing and pace of ice sheet retreat in Norwegian fjords (Stokes *et al.*, 2014). The variable ice sheet behavior we identify is an important target for ice sheet models, and will improve data-driven ice sheet reconstructions such as those conducted by Hughes *et al.* (2016) and Stroeven *et al.* (2016).

Acknowledgements. These investigations form part of the research project Eurasian Ice Sheet and Climate Interaction (EISCLIM) financially supported by the Research Council of Norway (grant no. 229788/E10). Financial support was also provided via a Geological Society of America student grant to D.J.G. We would like to thank Sandra Cronauer, Sylvia Choi and Megan Corcoran for assistance in the laboratory; Samuel Kelley, Carolyn Roberts, William Philipps for discussions of these results; Elizabeth Thomas for assistance in the field; and Beata Csatho and Christopher Lowry for editing earlier drafts. We also thank the Editor, Anders Schomacker and an anonymous reviewer for helping to improve the manuscript.

Abbreviations. AMS, accelerator mass spectrometry; LGM, Last Glacial Maximum.

References

Andersen BG. 1954. Randmorener i Sørvest-Norge. *Norsk Geografisk Tidsskrift* **5–6**: 274–339.

Anundsen K. 1972. Glacial chronology in parts of southwestern Norway. *Norges geologiske undersøkelse* **280**: 1–24.

Anundsen K. 1977. Radiocarbon datings and glacial striae from the inner part of Boknfjord area, South Norway. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography* **31**: 41–54 [doi:10.1080/00291957708552010].

Anundsen K. 1985. Changes in shore-level and ice-front position in Late Weichsel and Holocene, southern Norway. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography* **39**: 204–225 [doi:10.1080/00291958508552149].

Austad R, Erichsen C. 1987. *Strandforskyvning på Nord–Karmøy basert på pollen-og diatoméanalyse*. Thesis, University of Bergen.

Balco G, Briner J, Finkel RC *et al.* 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. *Quaternary Geochronology* **4**: 93–107 [DOI: 10.1016/j.quageo.2008.09.001].

Balco G, Stone JO, Lifton NA *et al.* 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quaternary Geochronology* **3**: 174–195 [doi:10.1016/j.quageo.2007.12.001].

Berger A, Loutre MF. 1991. Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews* **10**: 297–317 [DOI: 10.1016/0277-3791(91)90033-Q].

Blystad P, Anundsen K. 1983. Late Weichselian stratigraphy at Hjelmeland, Southwest Norway. *Norsk Geologisk Tidsskrift* **63**: 277–287.

Bøe R, Hovland M, Instanes A *et al.* 2000. Submarine slide scars and mass movements in Karmsundet and Skudenesfjorden, southwestern Norway: morphology and evolution. *Marine Geology* **167**: 147–165 [DOI: 10.1016/S0025-3227(00)00017-7].

Bondevik S, Mangerud J, Birks HH *et al.* 2006. Changes in North Atlantic radiocarbon reservoir ages during the Allerød and Younger Dryas. *Science* **312**: 1514–1517 [DOI: 10.1126/science. 1123300] [Pubmed:16763147].

Braaten AM, Hermansen D. 1985. *En lito-og biostratigrafisk undersøkelse av marine og limniske sedimenter i Yrkje, Nord–Rogaland*. Thesis, University of Bergen.

Copyright © 2017 John Wiley & Sons, Ltd.

Briner JP, Goehring BM, Mangerud J *et al.* 2016. The deep accumulation of ^{10}Be at Utsira, southwestern Norway: implications for cosmogenic nuclide exposure dating in peripheral ice sheet landscapes. *Geophysical Research Letters* **43**: 9121–9129 [doi:10.1002/2016GL070100].

Briner JP, Svendsen JI, Mangerud J *et al.* 2014. A ^{10}Be chronology of south-western Scandinavian Ice Sheet history during the Lateglacial period. *Journal of Quaternary Science* **29**: 370–380 [doi:10.1002/jqs.2710].

Clark PU, Dyke AS, Shakun JD *et al.* 2009. The Last Glacial Maximum. *Science* **325**: 710–714 [doi:10.1126/science.1172873] [Pubmed:19661421].

Dyke AS, Andrews JT, Clark PU *et al.* 2002. The laurentide and innuitian ice sheets during the last glacial maximum. *Quaternary Science Reviews* **21**: 9–31 [DOI: 10.1016/S0277-3791(01)00095-6].

Fenton CR, Hermanns RL, Blikra LH *et al.* 2011. Regional ^{10}Be production rate calibration for the past 12 ka deduced from the radiocarbon-dated Grøtlandsura and Russenes rock avalanches at 69°N, Norway. *Quaternary Geochronology* **6**: 437–452 [DOI: 10.1016/j.quageo.2011.04.005].

Goehring BM, Lohne OS, Mangerud J, *et al.* 2012a. Late glacial and holocene ^{10}Be production rates for western Norway. *Journal of Quaternary Science* **27**: 89–96 [DOI: 10.1002/jqs.1517].

Goehring BM, Lohne OS, Mangerud J, *et al.* 2012b. Erratum: Late glacial and holocene ^{10}Be production rates for western Norway. *Journal of Quaternary Science* **27**: 544–544 [DOI: 10.1002/jqs.2548].

Helle SK. 2008. *Early post-deglaciation shorelines and sea-level changes along Hardangerfjorden and adjacent fjord areas, W Norway*. PhD Thesis, University of Bergen.

Heyman J, Stroeven AP, Harbor JM *et al.* 2011. Too young or too old: evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages. *Earth and Planetary Science Letters* **302**: 71–80 [DOI: 10.1016/j.epsl.2010.11.040].

Hughes ALC, Gyllencreutz R, Lohne ØS *et al.* 2016. The last Eurasian ice sheets – a chronological database and time-slice reconstruction, DATED-1. *Boreas* **45**: 1–45 [doi:10.1111/bor.12142].

Karlsen LC. 2009. Lateglacial vegetation and environment at the mouth of Hardangerfjorden, western Norway. *Boreas* **38**: 315–334 [DOI: 10.1111/j.1502-3885.2008.00062.x].

Kessler MA, Anderson RS, Briner JP. 2008. Fjord insertion into continental margins driven by topographic steering of ice. *Nature Geoscience* **1**: 365–369 [doi:10.1038/ngeo201].

Knudsen CG. 2006. *Glacier dynamics and Lateglacial environmental changes – evidences from SW Norway and Iceland*. PhD Thesis, University of Bergen.

Mangerud J. 1980. Ice-front variations of different parts of the Scandinavian Ice Sheet, 13,000–10,000 years BP. In *Studies in the Lateglacial of North-West Europe*, Lowe JJ, Gray JM, Robinson JE (eds). Pergamon Press: Oxford; 23–30.

Mangerud J, Bondevik S, Gulliksen S *et al.* 2006. Marine ^{14}C reservoir ages for 19th century whales and molluscs from the North Atlantic. *Quaternary Science Reviews* **25**: 3228–3245 [DOI: 10.1016/j.quascirev.2006.03.010].

Mangerud J, Briner JP, Goslar T *et al.* 2016. The Bølling-age Blomvåg Beds, western Norway: implications for the Older Dryas glacial re-advance and the age of the deglaciation. *Boreas* [DOI 10.1111/bor.12208].

Mangerud J, Goehring BM, Lohne ØS *et al.* 2013. Collapse of marine-based outlet glaciers from the Scandinavian Ice Sheet. *Quaternary Science Reviews* **67**: 8–16 [doi:10.1016/j.quascirev.2013.01.024].

Mangerud J, Gyllencreutz R, Lohne Ø *et al.* 2011. Glacial history of Norway. In *Developments in Quaternary Science*, Vol. 15, *Quaternary Glaciations Extent and Chronology*, Ehlers J, Gibbard P, Hughes P (eds). Elsevier: Amsterdam; 279–298.

Nishiizumi K, Imamura M, Caffee MW *et al.* 2007. Absolute calibration of ^{10}Be AMS standards. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **258**: 403–413 [doi:10.1016/j.nimb.2007.01.297].

Ottesen D, Dowdeswell JA, Rise L. 2005. Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: the 2500-km-long Norwegian-Svalbard margin (57°–80°N). *Geological Society of America Bulletin* **117**: 1033–1050 [doi:10.1130/B25577.1].

Ottesen D, Stokes CR, Bøe R *et al.* 2016. Landform assemblages and sedimentary processes along the Norwegian Channel Ice Stream. *Sedimentary Geology* **338**: 115–137 [doi:dx.doi.org/10.1016/j.sedgeo.2016.01.024].

Paus A. 1988. Late Weichselian vegetation, climate, and floral migration at Sandvikvatn, North Rogaland, southwestern Norway. *Boreas* **17**: 113–139 [doi:10.1111/j.1502-3885.1988.tb00128.x].

Paus A. 1989. Late Weichselian vegetation, climate, and floral migration at Liastemmen, North Rogaland, south-western Norway. *Journal of Quaternary Science* **4**: 223–242 [doi:10.1002jqs.3390040304].

Paus A. 1990. Late Weichselian and Early Holocene vegetation, climate, and floral migration at Utsira, north-Rogaland, southwestern Norway. *Norsk Geologisk Tidsskrift* **70**: 135–152.

Reimer PJ, Bard E, Bayliss A *et al.* 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* **55**: 1869–1887 [DOI: 10.2458/azu_js_rc.55.16947].

Rønnevik HK. 1971. *Kvartærgeologi på ytre del av Haugesundshalvøya*. MS Thesis, Department of Geology, University of Bergen.

Rood DH, Hall S, Guilderson TP *et al.* 2010. Challenges and opportunities in high-precision Be-10 measurements at CAMS. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **268**: 730–732 [doi:10.1016/j.nimb.2009.10.016].

Sejrup HP, Aarseth I, Haflidason H *et al.* 1995. Quaternary of the Norwegian Channel: glaciation history and palaeoceanography. *Norsk Geologisk Tidsskrift* **75**: 65–87.

Sejrup HP, Larsen E, Haflidason H *et al.* 2003. Configuration, history and impact of the Norwegian Channel Ice Stream. *Boreas* **32**: 18–36 [doi:10.1080/03009480310001029].

Sejrup HP, Larsen E, Landvik J *et al.* 2000. Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the northern North Sea region. *Quaternary Science Reviews* **19**: 667–685 [doi:10.1016/S0277-3791(99)00016-5].

Shakun JD, Clark PU, He F *et al.* 2012. Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. *Nature* **484**: 49–54 [doi:10.1038/nature10915] [Pubmed:22481357].

Stokes CR, Corner GD, Winsborrow MCM *et al.* 2014. Asynchronous response of marine-terminating outlet glaciers during deglaciation of the Fennoscandian Ice Sheet. *Geology* **42**: 455–458 [doi:10.1130/G35299.1].

Stroeven AP, Hättestrand C, Kleman J *et al.* 2016. Deglaciation of Fennoscandia. *Quaternary Science Reviews* **147**: 91–121 [DOI: 10.1016/j.quascirev.2015.09.016].

Stroeven AP, Heyman J, Fabel D *et al.* 2015. A new Scandinavian reference ^{10}Be production rate. *Quaternary Geochronology* **29**: 104–115 [DOI: 10.1016/j.quageo.2015.06.011].

Svean A. 2016. *Glasiasjonshistorie og strandforskyvning I Boknafjordsområdet i Rogaland*. Master Degree Thesis, Department of Earth Science, University of Bergen.

Svendsen JI, Alexanderson H, Astakhov VI *et al.* 2004. Late Quaternary ice sheet history of northern Eurasia. *Quaternary Science Reviews* **23**: 1229–1271 [DOI: 10.1016/j.quascirev.2003. 12.008].

Svendsen JI, Briner JP, Mangerud J *et al.* 2015. Early break-up of the Norwegian Channel ice stream during the last glacial maximum. *Quaternary Science Reviews* **107**: 231–242 [DOI: 10.1016/j.quascirev.2014.11.001].

Thomsen H. 1982. Late Weichselian shore-level displacement on Nord-Jæren, south-west Norway. *GFF* **103**: 447–468.

Vorren TO, Vorren K-D, Aasheim O *et al.* 2013. Palaeoenvironment in northern Norway between 22.2 and 14.5 cal. ka PB. *Boreas* **42**: 876–895.

Young NE, Briner JP, Rood DH *et al.* 2013a. Age of the Fjord Stade moraines in the Disko Bugt region, western Greenland, and the 9.3 and 8.2 ka cooling events. *Quaternary Science Reviews* **60**: 76–90 [doi:10.1016/j.quascirev.2012.09.028].

Young NE, Schaefer JM, Briner JP *et al.* 2013b. A ^{10}Be production-rate calibration for the Arctic. *Journal of Quaternary Science* **28**: 515–526 [doi:10.1002/jqs.2642].

Copyright © 2017 John Wiley & Sons, Ltd.