Collapse of marine-based outlet glaciers from the Scandinavian Ice Sheet

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A B S T R A C T

We present a reconstruction of the timing and retreat rates of more than 2000 m thick Younger Dryas (YD) fjord glaciers in western Norway using a detailed chronology of 10Be exposure ages from lateral moraines and 14C dated end moraines. A primary conclusion is that ice margins retreated up the 120–170 km long fjords at mean rates of 240–340 m yr −1 during the early Holocene. We further show that part of the south-western sector of the Scandinavian Ice Sheet collapsed in two distinct steps. The first step occurred between 19.5 and 18.5 ka BP as break up of the Norwegian Channel Ice Stream, which drained the ice sheet during the Last Glacial Maximum (LGM). The second step was the rapid retreat up the fjords mentioned above, dated to 11.6–11.1 ka BP. During the intervening ~7000 years no net retreat occurred despite oscillations of the ice margin. This stepwise ice margin retreat strongly contrasts with the more monotonic decay of the ice sheet as a whole, indicating that water depths set the pace for climate-triggered ice margin retreat in this part of the ice sheet. Calving and melting of marine margins has dominated mass-loss from modern ice sheets in recent decades; however, the mechanisms and long-term (100–1000 yr) rate of ice-front retreat is less certain and empirical examples such as those given here may help in developing better numerical models.

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1. Introduction

Following the Last Glacial Maximum (LGM) the western margin of the Scandinavian Ice Sheet was characterised by fjord-filling outlet glaciers that drained large sectors of the ice sheet (Mangerud et al., 2011). In particular, outlet glaciers filling Hardangerfjorden and Sognefjorden (Figs. 1 and 2) were more than 2000 m thick and 120–170 km long and grounded on shallow bedrock sills during the Younger Dryas (YD, ~12.8–11.6 cal ka BP). These outlet glaciers were similar to the present-day Jakobshavn Isbrae (Fig. S1) (Vieli and Nick, 2011) draining the Greenland Ice Sheet as well as Thwaites Glacier (Holt et al., 2006) and Pine Island Glacier (Vaughan et al., 2006) in West Antarctica. Processes occurring at such margins remain a limitation in the modelling and understanding of ice sheet and sea-level response to climate warming – both for the past and the future (Alley et al., 2008). The main objective with this paper is to present a spatio-temporal reconstruction of the collapse of the Hardangerfjorden and Sognefjorden outlet glaciers that can be used to test and improve numerical models.

Retreat rates of Hardangerfjorden and Sognefjorden outlet glaciers have not been calculated before, except for the outer part of Hardangerfjorden (Romundset et al., 2010), mainly due to a lack of accurate and precise dates. Moraines mapped across the mouth of both fjords (Fig. 2) have been attributed to the YD extent (Aarseth and Mangerud, 1974). This interpretation has been questioned in recent papers that conclude Hardangerfjorden became permanently ice free during the Allerød interstadial, i.e. before the YD (e.g. Helle et al., 1997; Helle, 2004; Bakke et al., 2005). However, the latter hypothesis was not based on reliable dates and is inconsistent with numerous 14C dates from shell fragments in tills and glacial melt-water sediments found in well-dated lake cores (Mangerud, 2000; Lohne et al., 2012). Additionally, the observations and dates presented here support the YD age of the fjord-mouth moraines and a subsequent deglaciation of the fjord.
We also present a compilation that details ice-margin retreat from the LGM position to the mountainous areas of central ice accumulation. During the LGM the flow lines along these fjords crossed the shallow fjord entrance before joining the Norwegian Channel Ice Stream (Fig. 1). We present a time-distance diagram along such a flow line, including response to well-known climate excursions such as the Bølling to YD.

2. Methods

2.1. $^{10}$Be exposure dating

Samples were collected from the top-most surfaces of large boulders using a hammer and chisel; sample location was determined using a hand-held GPS unit. Elevations were determined using a barometric altimeter crosschecked against topographic maps and the GPS determined elevation. Shielding of cosmic rays by the surrounding topography was estimated using a hand-held inclinometer.

Chemical processing was carried out in the Lamont-Doherty Earth Observatory Cosmogenic Nuclide Laboratory following standard beryllium isolation methods (Licciardi, 2000). Each sample was spiked with a low-level Be-carrier ($^{10}$Be/$^{9}$Be $\sim 10^{-10}$). All $^{10}$Be/$^{9}$Be ratios were measured at the Lawrence-Livermore National Laboratory Center for Accelerator Mass Spectrometry relative to the 07KNSTD3110 standard with a ratio of 2.85 $\times$ 10$^{-12}$ (Nishiizumi et al., 2007) and corrected for background $^{10}$Be/$^{9}$Be given by the procedural blanks, residual boron contamination, and machine background. All $^{10}$Be concentrations are reported relative to the renormalization presented in Nishiizumi et al. (2007).

$^{10}$Be exposure ages were determined using the scaling scheme of Lal (1991) recast in terms of atmospheric pressure by Stone (2000) and a variable geomagnetic field (Balco et al., 2008). We employ a modified version of the MATLAB code developed for the CRONUS-Earth web-based calculator, version 2.2 (Balco et al., 2008). Air pressure changes with elevation are calculated following the standard atmosphere equation. All sites experienced post-glacial isostatic rebound and therefore experienced time dependent $^{10}$Be production rates as they passed through different elevations (air pressure). We correct for isostatic rebound by using relative sea-level curves determined for the four sites in this study (Lohne et al., 2007; Romundset et al., 2010). We assume a sea level high latitude $^{10}$Be spallation production rate of 4.15 $\pm$ 0.15 atoms g$^{-1}$ yr$^{-1}$ presented in Goehring et al. (2012a, 2012b). Production of $^{10}$Be by muons is absolutely determined following Heisinger et al. (2002a, 2002b).

We have assumed zero erosion of the boulder surfaces from the sites Os, Nordlifjell, and Bømlo; however, some boulder surfaces from Halsnøy showed evidence for up to $\sim$ 1.6 cm of erosion since $\sim$ 11.6 ka BP in the form of differential quartz vein relief. We incorporate this weathering rate in determinations of the $^{10}$Be exposure ages for the Halsnøy samples. Resulting $^{10}$Be exposure ages are shown in Table 1. All ages reported below are shown with their corresponding $1\sigma$ analytical uncertainties. Means of exposure ages reported below are arithmetic means and standard deviations with additional uncertainty from the $^{10}$Be production rate combined in quadrature.

2.2. Calibration of $^{14}$C ages

All $^{14}$C dates, including those previously published, have been calibrated with the software OxCal v4.1 (Bronk Ramsey, 2009) and the INTCAL09/MARINE09 data sets (Reimer et al., 2009). Marine...
samples were calibrated assuming a $\Delta R$ value of $0 \pm 0$ yr, repre-
senting a marine reservoir age of 400 yr (Table 2), which is close to
modern values (Mangerud et al., 2006), however the reservoir age
was up to 600 years during the middle YD (Bondevik et al., 2006).
In order to avoid the larger uncertainty with marine samples we have
used only dates from terrestrial plant material for calculations of
retreat rates, but note that marine samples provide similar but less
precise ages.

### 2.3. Shoreline dating

A shoreline diagram for the Hardangerfjorden area (Fig. 3) has
been constructed by combining two well-dated relative sea-level
curves obtained by the isolation basin method from the island
Sotra (Lohne et al., 2007) and for the mid-Hardangerfjorden area
(Romundset et al., 2010) close to Ljones (Fig. 2), supported by
a third curve from Bomlo (Kaland, 1984; Vasskog, 2006) and
2.4. Ice surface profiles and ice-volume estimates

We follow the perfect-plastic ice approximation (Paterson, 1994) to reconstruct the ice surface profile along Hardangerfjorden. We calculate the sum of basal and lateral shear stresses using the elevation difference between the Nordfjell lateral moraine and contemporaneous sea level and the distance of 37 km along the flow line from Nordfjell to the ice margin at Halsnøy. The resulting shear stress is 76.1 kPa. The reconstructed ice surface (Fig. 4) closely follows the lateral moraine in areas previously mapped by Folkestad (1972).

YD ice volume in the Hardangerfjorden and Sognefjorden area is determined by delimiting the catchment area as the ice-divide to the east (Vorren, 1977; Solid and Torp, 1984), the end moraines in the west, and the watershed limits towards the north and south. Ice surface elevations follow the predictions above for Hardangerfjorden and the reconstruction of Fareth (1987) north of Sognefjorden. Between these areas we partly interpolated and partly used the reconstruction of Hamborg and Mangerud (1981). A reference DEM was constructed from the Norwegian cadastral service N50 DEM (50 m resolution) on land, and OLEX data offshore. Volumes were calculated using the terrain modelling software "IVS Fledermaus".

We also present estimates of the temporal evolution of entire Eurasian Ice Sheet area by using the time synchronous ice margin reconstructions of the DATED Project (Gyllencreutz et al., 2007) and estimate the area of the ice sheet every 1000 years (Fig. 5). The volume of the entire YD Scandinavian Ice Sheet is estimated using the formula (Paterson, 1994)

$$\log V = 1.23(\log A - 1)$$  \hspace{1cm} (1)

where $V$ is ice sheet volume and $A$ is the ice sheet area.

3. Results and discussion

3.1. Extent and thickness of the Younger Dryas (YD) glacier

Several existing $^{14}$C ages from shells in till proximal to the YD moraine, locally named the Herdla-Halsnøy Moraine (Fig. 2), demonstrate that the ice margin retreated up-fjord during the Allerød Interstadial and re-advanced during the Younger Dryas (Mangerud, 2000). Here we present the first $^{14}$C ages of shell fragments from till located within the end moraine at the island of Halsnøy (Table 2). A 50 m wide and 2 m high section at the beach in Eidsvikva on the proximal side of the moraine ridge, consisted of a massive, strongly compacted, bluish unsorted diamicton with ~60% clay and silt with boulders up to 50 cm. The diamicton is confidently interpreted as a till. A second section at Tofte, created along a new road segment that cut across the main moraine ridge, is several hundred metres long and 2-4 m high. This section also revealed a uniform, massive and compacted clayey diamicton with large boulders (Fig. 52). Given the large section, the interpretation of the diamicton as a till was very clear. All samples from the two sections yielded Allerød-YD ages, confirming the YD age of the moraine.

If a lateral moraine at ~900 m a.s.l. on the mountain Nordfjell on the south-east side of Hardangerfjorden indeed correlates with the moraine at Halsnøy, it provides an estimate of the ice surface elevation at the end of the YD (Fig. 2; Folkestad, 1972). The moraine

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Table 2

<table>
<thead>
<tr>
<th>Field sample no.</th>
<th>Material dated</th>
<th>Laboratory number</th>
<th>$^{14}$C age ± 1σ (a BP)</th>
<th>Calibrated age BP ± 1σ</th>
<th>Calibrated age BP ± 0.5%</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tofte, 59.7940 N, 5.7318 E</td>
<td>Mya truncata</td>
<td>Poz-15809</td>
<td>11 750 ± 60</td>
<td>13 226 ± 63</td>
<td>13 347–13 108</td>
<td>Fragment in till</td>
</tr>
<tr>
<td>Eidsvika, 59.7911 N, 5.6681 E</td>
<td>Mya truncata</td>
<td>Poz-15810</td>
<td>12 590 ± 60</td>
<td>14 050 ± 136</td>
<td>14 464–13 807</td>
<td>Fragment in till</td>
</tr>
</tbody>
</table>

*(Δ$^{14}$C value of 0 ± 0.1)

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is 2 km long consisting of 1–3 m high ridges and is very distinct against the barren bedrock of the mountain slope above. We used 10Be exposure dating of large boulders (Fig. S3) resting on the moraine to establish its depositional age. Given the low profile and sandy-gravelly matrix, we find it unlikely that the selected boulders ever had significant changes in orientation. Four large boulders yield consistent ages with a mean of 11.67 ± 0.63 ka. A single boulder (NFJ08-06) yielded an age of 15.40 ± 0.39 ka, which we consider as an outlier due to inheritance because it is more than two standard deviations from the grand mean (Table 1). The mean exposure age is in excellent agreement with the radiocarbon derived and 10Be ages for the Halsnøy Moraine. For example, two groups of exposure ages from the Halsnøy Moraine give means of 11.87 ± 0.46 ka and 12.51 ± 0.45 ka (grand mean of 12.19 ± 0.52 ka). We conclude that the Nordli moraine was formed contemporaneously with the Halsnøy Moraine and thus provides an unambiguous elevation of the ice surface at the end of the YD (Fig. 4B). Note that to avoid circularity we do not include the exposure ages from the Halsnøy Moraine in the following discussion of the absolute timing of deglaciation as these ages were part of the population used to determine the 10Be production rate used here (Goehring et al., 2012a, 2012b). However, this does not affect their role in demonstrating the correlation of the Nordli moraine with the end moraine at Halsnøy. Our YD age interpretation of the lateral moraine is further supported by five boulders resting on the bedrock summit less than 50 m above the moraine, which yield an appreciably older mean age of 14.2 ± 0.8 ka (Table 1, Fig. 4A), consistent with the known timing of up-fjord ice retreat during the early Allerød (Mangerud, 2000). Follestad (1972) mapped lateral moraine segments between Nordli moraine and the Halsnøy Moraine that closely follows the ice surface reconstruction presented here.

Fig. 4. Ice surface profiles and 10Be ages along Hardangerfjorden. A) Individual 10Be exposure dates (•) with mean ages (heavy diamonds). Boulders located outside the Eidfjord-Osa Moraine are marked green (Table S1). B) Profile of the bathymetry along the deep trough of Hardangerfjorden (modified from Aarseth (2004b)). Post-glacial sediments are not shown. Pale yellow colour shows the mean altitude along the fjord, whereas some higher summits are indicated with stars. The ice surface is shown during three stages: 1) the YD glacial maximum (Halsnøy) with dashed red line schematically showing lateral moraines mapped by Follestad (1972), 2) during recession a schematic profile (dashed) based on that of the present-day Jakobshavn Isbrae, and 3) the Eidfjord-Osa Moraine. C) Time-distance curve illustrating the ice-margin retreat. Red bars show mean calibrated 14C ages for Halsnøy and Eidfjord. Blue crosses show calibrated individual 14C ages (95% confidence interval) of terrestrial plant macros for mid-fjord area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Two step ice-margin retreat. A) Time-distance curve illustrating the position of the ice margin (black line) along the Norwegian Channel and Sognefjorden. Key dated sites are LGM (King et al., 1998), Troll (Sejrup et al., 2009), coastal areas (Mangerud et al., 2011), and the YD and Eidfjord-Osa Moraines. Red line with corresponding red scale shows the decrease in total area of the Eurasian (mainly Scandinavian) Ice Sheet through the same time interval. B) Curves on the same age scale as in A, slightly modified from Hafflidaun et al. (1995), showing abundance of N. pachyderma (s) in the Troll Core monitoring changing sea-surface temperatures in the North Sea (red curve; warmer towards right), and δ18O from the GRIP core (blue curve). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Dating the ice margin retreat

Here we present a reconstruction of ice margin retreat following the YD. The most precise and accurate age for the start of retreat
from the Halsnøy Moraine position is obtained from the stratigraphy of a small basin just distal to the moraine. Supply of glacial silt to the basin was limited to times when the ice margin was within ~400 m of the moraine because a bedrock threshold redirected the melt-water away from the basin when the margin had retreated 400 m. The age of the transition from glacial silt to organic sediments is calculated to occur at 11.6 ± 0.1 cal ka BP from a sequence of 15°C dates of terrestrial plant macrofossils (Lohne et al., 2012).

Deglaciation of the mid-fjord region occurred ~11.3 cal ka BP derived from several 14°C ages of terrestrial plant macrofossils in basal lacustrine sediments (Fig. 4C), in addition to similar dates from marine shells (Romundset et al., 2010).

Near the fjord head, the Eidfjord-Osa Moraine is mapped in the valleys and on adjacent mountains (Fig. 2) (Anundsen and Simonsen, 1967). Initial deglaciation and the subsequent readvance forming the Eidfjord-Osa Moraine has been dated using three approaches. The highest glacio-marine deltas, located immediately distal to the moraine (at Ulvik, Fig. 2) are found at 11.1 °C dates of terrestrial plant macrofossils (Anundsen and Simonsen, 1967). The delta surface is irregular and is interpreted as being formed by overriding ice. A flat terrace near the proximal edge, as well as a channel bisecting the terrace, is incised into the irregular delta surface at 101–113 m a.s.l. (Anundsen and Simonsen, 1967). The delta surface is irregular and is interpreted as being formed by overriding ice. A flat terrace near the proximal edge, as well as a channel bisecting the terrace, is incised into the irregular delta surface at 101–103 m a.s.l. We consider these two features to be formed by melt-water channels just prior to final glacier retreat from the delta and according to our shoreline diagram their age are 10.9 ± 0.1 cal ka BP. The latter age is supported by a 14°C date (9680 ± 90 BP, T-886) from a wood fragment (juniperus) found in the distal part of the delta (Rye, 1970). The calibrated age is 10.8–11.2 cal ka BP (95% significance level).

Four boulders (most >1.5 m high, Fig. S3) perched on a narrow, well-defined lateral moraine (Fig. S5) related to the Eidfjord-Osa Moraine yield a mean age of 10.83 ± 0.26 ka (samples OS08-07 to -10, Table 1). Five boulders (OSA08-01 to -05) collected from a correlated moraine zone at Langvatnet 2 km to the south yield a mean age of 11.32 ± 0.22 ka. Additionally five samples (OSA08-11 to 15, marked green in Fig. 4A) resting on bedrock distal to the moraines were sampled. We expected exposure ages of this group to be slightly older than the samples from the moraine proper; however, the mean age of 11.01 ± 0.31 ka lies between those of the two moraines. The ages of the three groups are not significantly different at a 68% significance level and we therefore consider all samples together, yielding a mean exposure age of 11.07 ± 0.31 ka. The tight exposure age distribution supports the assumption of short duration (about 200 years according to the shoreline diagram) of the period between the first deglaciation and deposition of the Eidfjord-Osa Moraine. Strictly, exposure ages are calculated relative to the year of collection (2008 AD in this case) and therefore ~60 years should be subtracted to facilitate comparison with calibrated radiocarbon ages. Thus the mean exposure age for the Eidfjord-Osa Moraine is 11.01 ± 0.31 ka BP, overlapping with the radiocarbon age from the delta and the results from our shoreline based age. We therefore confidently correlate the Eidfjord-Osa Moraines with the ice-marginal delta as being deposited synchronously. The ages are plotted in the time–distance diagram in Fig. 4C, where we use the ages of 11.1 ± 0.1 cal ka for the first deglaciation and 10.9 ± 0.1 cal ka BP for the retreat from the Eidfjord-Osa Moraine, both ages obtained from the shoreline diagram.

The ice margin chronology obtained for Hardangerfjorden can also be applied to the longer and deeper Sognefjorden (Fig. 2) to the north. The YD moraine is mapped continuously between and across the two fjords (Aarseth and Mangerud, 1974). The continuation of the Eidfjord-Osa Moraine can be traced almost continuously to the head of Sognefjorden (Vorren and Mangerud, 2008), with the correlation supported by radiocarbon dating of basal lake sediments (Vorren, 1973; Bergstrøm, 1975) as well as similar shoreline elevations in the heads of the two fjords.

3.3. Retreat rates of the fjord outlet glaciers and involved processes

Using the chronology given above, retreat from the YD position to the fjord heads lasted only 500 ± 140 years, yielding mean retreat rates of 240 ± 70 and 340 ± 70 m yr⁻¹ for Hardangerfjorden (~120 km) and Sognefjorden (~170 km long), respectively. Small ice marginal deposits reflect temporary standstills of the ice margin, for example at Ljones (Fig. 2) (Aarseth, 2004a) and suggest that retreat was not monotonic, yet there is no evidence for major halts or re-advances. Ice volume in the drainage area during the YD was ~16 000 km³, corresponding to 4 cm sea level equivalent. In comparison the volume of the entire YD Scandinavian Ice Sheet was ~6 m (see Section 2.4).

The early Holocene retreat rates presented here are 2–6 times higher than those reported during the early Holocene for Jakobshavn Isbrae in western Greenland (~100 m yr⁻¹) (Young et al., 2011), Helheim Glacier in southeastern Greenland (80 m yr⁻¹) (Hughes et al., 2012) and an outlet glacier of the Laurentide Ice Sheet (~60 m yr⁻¹) (Briner et al., 2009). Our results though are of the same magnitude as the recent retreat rates of thin, floating outlet glaciers of the Greenland Ice Sheet (Howat and Eddy, 2011). The steep slope of the ice margin and the presence of shell-bearing tills on Halsnøy (Fig. S2) demonstrate that the YD glacier was grounded on islands and sills across the fjord mouth (Fig. 4). It is estimated that it resided there for 170 ± 120 years (Lohne et al., 2012). Accordingly the glacier front must have been protected from basal seawater incursion at this position. Deglaciation during the early Holocene coincided with rapidly rising eustatic sea level (Clark et al., 2004). However, the local relative sea level is observed to be continuously falling during this interval due to rapid glacioisostatic uplift (Romundset et al., 2010). Rising sea level was therefore not a driver of ice-margin retreat.

We argue that initial thinning and retreat of the glacier was driven by surface melting due to rapidly increasing air temperatures at the onset of the Holocene. Retreat from the sill at Halsnøy led to a floating ice front that in turn reinforced calving because the bed slope opposed the ice surface slope (Fig. 4; Schoof, 2007). Initial retreat then allowed for additional basal melting by incursion of seawater beneath the floating front (Holland et al., 2008). Simultaneously, glacial striae and ice-marginal deltas in tributary valley mouths show that final ice flow directions were oriented from the adjacent uplands into the fjords (Aarseth and Mangerud, 1974; Holtedahl, 1975; Hamborg and Mangerud, 1981). Thus ice persisted on the adjacent uplands while the fjords were ice-free, supporting our interpretation that rapid retreat along the deep fjords was amplified by calving after initially having been triggered by warming at the beginning of the Holocene.

The highest YD lateral moraine along Hardangerfjorden (970 m a.s.l.) provides an estimate of the equilibrium line altitude (ELA) of about 870 m a.s.l. when corrected for Holocene emergence. This is ~630 m lower than the current ELA of ~1500 m a.s.l. for the nearby Folgefonna Ice Cap (Fig. 2; Andreassen et al., 2005). Greenland Ice Core records suggest that an abrupt rise of several degrees in temperature occurred over only a few decades at the YD/Holocene boundary (Simonsen et al., 2011). Biological and chemical proxies indicate that in western Norway the mean July temperature on land increased by 4–5 °C and slightly more in the adjacent sea (Birks et al., 2005), although possibly over a somewhat longer time period. The precipitation pattern during the YD is
poorly known, but if we for simplicity postulate that precipitation was similar to present day conditions, which is supported by model experiments (Renssen and Isarin, 2001), a temperature rise of 4–5 °C would elevate the ELA to or above the present day ELA. Glacier margins of the ice cap Hardangerjokulen near the fjord head (marked H in Fig. 2) are currently located >1100 m a.s.l. We therefore argue that if the ice margin had retreated at a speed in equilibrium with the climate, it would have retreated from the YD position to the head of the fjords within decades. Retreat rates in the fjord were determined, and thus limited, by the physical processes of surface and submarine melting and calving, but also by the flow of ice from higher areas towards the fjord. Regardless, fjord retreat rate was much faster than the melting of ice on land. Nevertheless, the export of ice and water did not keep pace with the retreat rate was much faster than the melting of ice on land. Nevertheless, the export of ice and water did not keep pace with the rapid warming at the YD termination and we therefore argue that the retreat rates presented here are close to a maximum possible retreat rate for similar fjord glaciers.

The fast up-fjord retreat may suggest that the sill at Halsnøy constitutes a “tipping-point” for ice margin retreat. Curiously, the margin had retreated well up-fjord during the mild Allerød interstadial, but was yet able to re-advance to the sill again during the cold YD (Mangerud, 2000; Mangerud et al., 2011), indicating that the sill in itself does not represent an absolute tipping-point for irreversible glacier retreat. However, as demonstrated here, the sill did in fact become a tipping-point for ice-margin stability in the interplay between warmer climate and topography at the onset of the Holocene. We note that the YD moraine is located near the fjord-heads north of Sognefjorden (Fig. 1) demonstrating that these fjords became much earlier ice-free than Hardangerfjorden and Sognefjorden and thus that the balance between topography and climate was different in these fjords (Mangerud, 1980).

3.4. Retreat rates from the LGM to the ice divide

In the Hardangerfjorden–Sognefjorden region discussed here, ice flow directions were approximately due west during the LGM, and turned northwards as ice flow merged into the Norwegian Channel Ice Stream (Sejrup et al., 2009). We present a time–distance diagram (Fig. 5A) that is constructed along Sognefjorden as ice flow directions were simpler than at the mouth of Hardangerjorden; and because the Troll core is closer to Sognefjorden than Hardangerfjorden (Fig. 1). However, we consider the diagram to be representative for the entire coast between Hardangerjorden and Sognefjorden. We summarize the general ice-margin history below.

Radiocarbon dating of foraminifera in marine sediment cores indicates that the ice-margin retreated from the LGM position at ~ 19.5 cal ka BP (King et al., 1998) and reached the well-dated Troll Core site by ~18.5 cal ka BP (Sejrup et al., 2009), yielding a retreat rate of about 190 m yr⁻¹. This is slightly slower than the retreat rate (310 m yr⁻¹) from the shelf edge outside Andfjorden, North Norway (Vorren and Plassen, 2002). Little evidence for ice margin oscillation exists for the region between the LGM position and the Troll site.

Initial deglaciation of the coast is dated to the start of the Bølling, about 14.6 ka BP, from the site Blomvåg, located west of Herdla (Fig. 2). However, the dated sediments were covered by a basal till (Mangerud, 1977), indicating that the ice margin re-advanced across the outermost coast during the later Older Dryas re-advance (Fig. 5). Here we present a new estimate of final deglaciation timing of the outermost coast at the mouth of Hardangerfjorden, which is derived from ten 10Be exposure ages of boulders resting directly on bedrock (Fig. S3) from the northern and southern tips of the island Bømlo (Fig. 2, Table 1). The mean age of all ten boulders is 14.8 ± 0.9 ka BP, consistent with basal 14C ages of terrestrial plant macros from a lake on Bømlo (Karlsen, 2009). Our results suggest that Bømlo was not overrun by the Older Dryas re-advance, but the age uncertainty is too large to provide unambiguous answers to this question.

Following the Older Dryas, the ice margin retreated well up-fjord (~40 km) during the Allerød. The ice margin then re-advanced during the late Allerød and the YD, which is well documented in Hardangerfjorden (Mangerud, 2000; Lohne et al., 2007). In Fig. 5A we adopt the curve from a recent synthesis (Mangerud et al., 2011) for the period 14.6–11.7 cal ka BP.

The time–distance curve in Fig. 5A shows that more than 400 km of net ice-margin retreat occurred in two phases lasting only 1000 and 500 years respectively, separated by a 7000 year period between 18.5 and 11.6 cal ka BP. During this period, the ice margin fluctuated considerably but there was little or no net retreat (Fig. 5A). Initial retreat in the Norwegian Channel may have been triggered by global sea-level rise and/or sub-surface temperate water inflow as proposed by Lekens et al. (2005) or directly by the first warming at northern latitudes at ~19 cal ka BP (Shakun et al., 2012). The second phase, i.e. the break-up of glaciers in the fjords, was initiated by warming at the start of the Holocene, but strongly reinforced by the up-fjord increasing water depths and related calving of the floating ice-margin.

The period (14.6–11.6 cal ka) with little net retreat encompasses the Bølling at ~14.6 cal ka BP, which is classically considered the start of warmth in northwest Europe and is seen as a period with distinct ice margin retreat in other sectors of the Scandinavian Ice Sheet (Mangerud et al., 2011). Concurrent step-wise temperature rise is observed in the Norwegian Channel and the Greenland Ice Core records (Hafldason et al., 1995) (Fig. 5B), along with rapid sea-level rise during Melt-Water Pulse 1a (Deschamps et al., 2012). During most of the period 14.6 to 11.6 cal ka the ice margin in south-western Norway was grounded near the coast in shallow water and on numerous islands. Conversely, the ice margin during the two main phases of retreat was located in the Norwegian Channel or the fjords. Overall, the two-step retreat in this sector of the Scandinavian Ice Sheet differs strongly from the more monotonic, mainly climate driven decay of the ice sheet as a whole (Fig. 5A). We add that although there was almost no net ice margin retreat during the period 14.6–11.6, oscillations of the ice margin with retreat during the Bølling and Allerød and re-advances during the Older Dryas and YD, correlate well with climate events seen in the Greenland Ice Core and foraminifera in Troll Core records (Hafldason et al., 1995) (Fig. 5B) indicating climatically mediated advance/retreat during this period.

4. Conclusions

We have presented a 3-dimensional reconstruction of the outlet glacier filling Hardangerfjorden of western Norway during Younger Dryas. Between 11.6 ± 0.1 and 11.1 ± 0.1 cal ka BP the ice front in Hardangerfjorden and the adjacent Sognefjorden retreated at mean rates of 240 ± 70 and 340 ± 70 m per year, respectively. The fjord bathymetry and ice surface profiles of these large western Norwegian fjords are very similar to those of Jakobshavn Isbræ, Greenland, Pine Island Glacier, Antarctica, and other modern ice sheet outlet glaciers, potentially providing rates of future ice sheet collapse.

Ice margin retreat in the fjords was initiated and partly driven by the warming at the YD/Holocene boundary, but calving of the floating ice front ultimately controlled rapid retreat. Melting of ice in the upland was slower. Yet, the ice margin retreat in the fjord should have been even faster to keep up with the abrupt climate warming.
The southwestern sector of the Scandinavian Ice Sheet retreated from its LGM maximum to near the central area of ice accumulation in two main phases lasting only 1000 (19.5–18.5 ka BP) and 500 years (11.6–11.1 ka BP). During the 7000 years between the two main retreat phases, the ice margin displayed considerable fluctuations, but overall little or no net retreat occurred.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2013.01.024.

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Supplementary figures for the paper:


Fig. S1. A) Profile along the deep trough of Hardangerfjorden with the YD ice profile, as given in Fig. 4. As a comparison similar profiles (dashed) are given for the present-day (2007) fastest flowing outlet glacier on Greenland (Jakobshavn Isbræ, >10 km yr⁻¹), and its host fjord (Thomas et al., 2009) (dashed and darker grey). B) Profile along Sognefjorden (Aarseth, 1997). Postglacial sediments are not shown.

Fig. S2. Part of the section in shell-bearing till at Tofte located on top of the Herdla-Halsnøy Moraine at the island of Halsnøy. The YD-Allerød ages of the shell fragments (Table 2) demonstrate that the moraine was formed by the YD re-advance.
Fig. S3. Examples of $^{10}$Be-dated boulders from the different sites:
A. Boulder at northern Bømlo (sample BØ08-03). Note the North Sea in the background.
B. The largest boulder on southern Bømlo (sample BØ08-09). Photo towards north-east.
C. Boulder on the Nordlifjell lateral moraine; Sample NF08-6. The Hardangerfjorden can be seen about 900 m below the sampling site.
D. Boulder at the summit of Nordlifjell; i.e. slightly above the lateral moraine. Sample NFJ08-2.
E. Boulder on bedrock distal to the Eidfjord-Osa Moraine. Sample OSA08-15.
F. Boulder on the lateral moraine in Osa (Fig. S6). Sample OSA08-7.
**Fig. S4.** Probability density plots of $^{10}$Be ages from the dated ice marginal positions. Heavy black line is the summed probability based on all individual sample probability densities (thin gray lines). The vertical dashed line is the arithmetic mean. Values in parentheses represent uncertainty when the analytical and uncertainty on the $^{10}$Be production rate are combined in quadrature. Resulting distributions for Bømlo and Osa are highly normal, whereas the two sites on Nordlifjell display slightly more scatter, which might be due to high elevation, lateral moraine setting and fewer examined samples.

**Fig. S5.** The part of the Eidfjord-Osa lateral moraine where samples OSA08-7 to -10 were collected. Ice was flowing towards the viewer on the left side of the moraines. Note the many large boulders, especially on the left of the two parallel ridges. Some of the dated boulders distal to the moraines were collected on the mountain in the very upper right corner of the photo.