

Re-advance of the Fennoscandian Ice Sheet during Heinrich Event 1

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Abstract

Five sediment cores, bathymetric and 2D seismic reflection data from Vestfjorden, northern Norway, were studied in order to constrain the timing and extent of a major ice stream draining the northwestern Fennoscandian Ice Sheet during the last deglaciation (15–10 ¹⁴C ka B.P.). The bathymetric and seismic data indicate that Vestfjorden/Trænadjupet was covered by grounded ice reaching the shelf break during the Last Glacial Maximum (LGM). After the LGM break-up and recession towards outer inner Vestfjorden at ~13.6 ¹⁴C ka B.P., the ice re-advanced towards the outer part of Vestfjorden prior to 13.1 ¹⁴C ka B.P. This is inferred from glaciomarine sediments overlain by diamicton at the base of the sediment cores interpreted as basal tills and associated contemporaneous build-up of grounding zone wedges in the central Vestfjorden. This sequence of events is coherent with the late Weichselian ice sheet dynamics both along the western Norwegian continental shelf and in the Barents Sea, possibly indicating a direct response to meltwater injection and accompanied cooling during disruption of the thermohaline circulation associated with Heinrich Event 1. Enhanced supply of suspension load resulted in deposition of laminated sediments at ~13 ¹⁴C ka B.P. reflecting the retreat of the ice stream towards the inner fjord in response to global climate amelioration and increased Atlantic water inflow.

Two additional ice re-advances towards the Norwegian coastline are inferred from distinct input of ice-rafted debris (IRD) with a typical mineralogical fingerprint derived from Neoproterozoic–Early Silurian calcite and dolomite marbles in the ice sheet catchment area. Thus, the re-advances may be concurrent with the Older Dryas (~12.2 ¹⁴C ka B.P., Skarpnes) and Younger Dryas (~10.7 ¹⁴C ka B.P., Tromsø Lyngen) cooling events.

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1. Introduction

The nature and timing of the Late Weichselian glaciation in Fennoscandia has been much debated during the past decades (e.g. Sejrup et al., 1994; Rokoengen and

Frengstad, 1999; Sejrup et al., 2000; Ottesen et al., 2001; Olsen, 2002; Sejrup et al., 2003; Dahlgren and Vorren, 2003; Nygård et al., 2004; Sejrup et al., 2005; Nygård et al., 2005; Ottesen et al., 2005a,b; Hjelstuen et al., 2005; Lekens et al., 2005). Of particular interest are the dynamics and evolution of the fast-flowing ice streams, which are critical for the stability of the Fennoscandian (FIS) and Svalbard–Barents Sea ice sheets (SBIS).

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Along the Norwegian continental shelf, and the western and northern Barents Sea slopes, several fast-flowing ice streams expanded across the shelf to the shelf edge, delivering large quantities of sediment to the marine realm (e.g. Dowdeswell et al., 1996; Laberg et al., 2002; Ó Cofaigh et al., 2003; Sejrup et al., 2003; Lekens et al., 2005; Ottesen et al., 2005a). Ottesen et al. (2005a) show from an extensive set of bathymetric data that ice streams existed in about 20 cross-shelf troughs along the western margin of the FIS and SBIS during the Late Weichselian. The largest of these palaeo-ice streams was the Norwegian Channel Ice Stream draining a substantial part of the FIS during the Last Glacial Maximum (LGM) (Longva and Thorsnes, 1997; Sejrup et al., 2000, 2003, 2005; Nygård et al., 2005). Moreover, the periodic advance of these ice streams to the continental shelf edge, together with associated rapid sediment delivery (Dowdeswell and Siegert, 1999), have triggered large-scale mass-wasting events along the continental slope (Haflidason et al., 2005; Rise et al., 2005; Nygård et al., 2005; Evans et al., 2005).

One of the major drainage routes of the central part of the FIS was the Ofotfjorden–Vestfjorden–Trænadjupet

trough system (Ottesen et al., 2005b) (Fig. 1). The Vestfjorden–Trænadjupet depression was the pathway of an ice-stream, which flowed southwestwards in Vestfjorden, coalesced with other ice masses in the eastern part of Trænadjupet, and then flowed northwestwards transporting huge amounts of glacial debris to the shelf edge and into the deep sea (cf. Laberg et al., 2002; Ottesen et al., 2005b). During the late Weichselian, the ice margin was located at the shelf edge of the Mid-Norwegian shelf (64° N) at ~16 ^{14}C ka B.P. (Dahlgren and Vorren, 2003; Hjelstuen et al., 2005) and probably also after ~15.3 ^{14}C ka B.P. (Rokoengen and Frengstad, 1999). Based on several radiocarbon dates along the west coast of Norway, the ice margin had recessed to the coastal zone of mid-Norway between >13 and 12.5 ^{14}C ka B.P. (e.g. Svendsen and Mangerud, 1987, 1990; Reite, 1994; Andersen et al. 1995; Nygård et al., 2004; Rise et al. 2006).

However, in a time–distance diagram for the margin of the ice sheet in northern Norway, Vorren et al. (1983) and later Vorren and Plassen (2002) and Dahlgren and Vorren (2003) proposed at least four re-advances of the ice sheet during the last deglaciation, which are

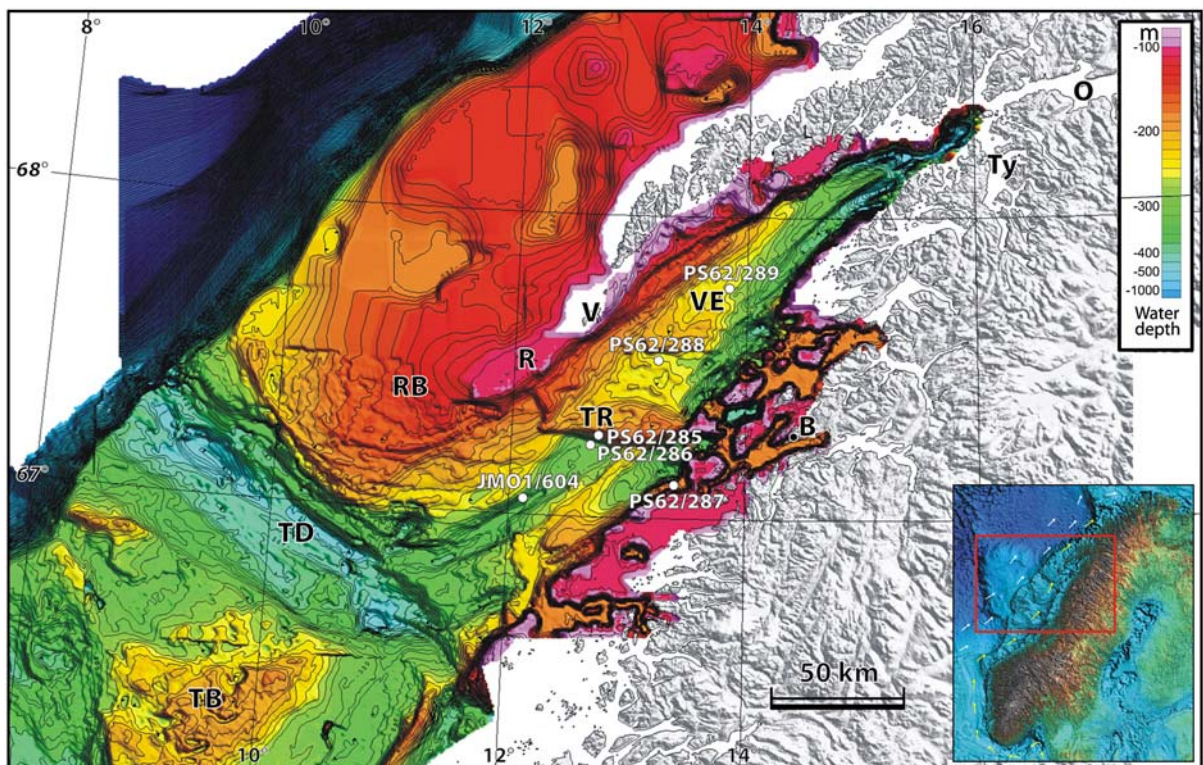


Fig. 1. Bathymetry and location of studied sediment cores in the Vestfjorden. Inset shows the regional bathymetry of the study area on the Norwegian margin and simplified the main surface ocean currents in the Norwegian Sea (white arrows: North Atlantic Current; yellow arrows: Norwegian Coastal Current). TB — Trænabanken, TD — Trænadjupet, RB — Røstbanken, VE — Vestfjorden, R — Røst, V — Værøy, L — Lofoten, B — Bodø, O — Ofotfjorden, Ty — Tysfjorden, TR — Tennholmen Ridge.

consistent with observations from adjacent onshore areas (e.g. Bergström et al. 2005). Recently, Ottesen et al. (2005b) suggested, based on bathymetric and seismic data only, that after the LGM break-up, the ice withdrew rapidly from the shelf edge to Vestfjorden, where the ice stream deposited the Tennholmen Ridge (Figs. 1, 2), a grounding zone wedge (GZW) (McMullen et al., 2006), tentatively dated to between 15 and 13 ^{14}C ka B.P. during a still-stand or a re-advance, and that the inner parts of Vestfjorden may have been deglaciated at ~ 12.5 ^{14}C ka B.P. Yet, both scenarios remain to be confirmed by sedimentary records and several key questions concerning the timing and extent of the palaeo-ice stream in Vestfjorden are unresolved: (1) How many re-advances occurred in the Vestfjorden ice drainage system during the last deglaciation? (2) Are the deglaciation patterns of FIS and SBIS comparable and are they related to the deposition of Heinrich Event (14.6 to ~ 12.8 ^{14}C ka B.P.) in the North Atlantic? (3) What was the extent of the Younger Dryas ice sheet in Vestfjorden?

In this study, we address these questions by reporting results from sedimentary records retrieved during the *RV Polarstern* expedition ARK XVIII/2 in 2001 (Jokat 2003). Together with published high-resolution multi-beam bathymetric data and seismic profiles (Ottesen et al., 2005b), the timing and pattern of the deglacial history of Vestfjorden and its relationship to climate deterioration during Heinrich Event 1 is discussed.

2. Regional setting

Vestfjorden is a wide NE–SW trending trough between the Lofoten islands and the Norwegian mainland (Fig. 1). The trough is approximately 250 km long and represents the seaward continuation of the E–W trending Ofotfjorden, which is up to 550 m deep, 70–80 km long and 5 km wide. The inner, narrow part of Vestfjorden is over-deepened (600 m water depth), but the trough widens and shallows towards the southwest. Off Værøy, 150 km from the coast, the water depth is 200–300 m and the width 50–60 km. The outer Vestfjorden is approximately 70 km wide and the water depth reaches 350–400 m. Vestfjorden apparently terminates where the basin coincides with the wide and slightly deeper, SE–NW trending, Trænadjupet cross-shelf trough (Fig. 1). This depression is approximately 150 km long, 40 km wide in the inner part and ~ 90 km wide at its mouth at the shelf break with a water depth of 200–500 m.

Two major currents dominate the hydrography of Vestfjorden: the Norwegian Atlantic Current (NAC) and the Norwegian Coastal Current (NCC) (Fig. 1, inset).

Strong tides and the bathymetry of the continental shelf affect these currents in the region (Eide, 1979; Mitchelson-Jacob and Sundby, 2001). While the NAC follows the shelf break, the NCC bifurcates and the larger branch moves westwards crossing the Trænadjupet trough before following the west coast of the Lofoten Islands. The smaller branch (10% of the total volume flux) enters Vestfjorden and mixes with fresh surface waters (Geddes and Scott, 1994).

Geologically, Vestfjorden comprises a Mesozoic and Cenozoic sedimentary basin (Rokoengen and Sættem, 1983; Løseth and Tveten, 1996). On the southeastern side, the boundary to crystalline bedrock is marked by a very steep, up to 300 m high, escarpment (Fig. 1; Ottesen et al., 2005b). This is interpreted to be the result of enhanced glacial erosion of the downfaulted Vestfjorden Basin (Rokoengen and Sættem, 1983). The bedrock geology in the study area is dominated by a parautochthonous Precambrian crystalline basement and an overlying, allochthonous Caledonian nappe complex (e.g. Roberts and Gee, 1985; Tull et al., 1985; Melezhik et al., 2002, 2003). Of particular interest for this study are extensive outcrops of calcitic and dolomitic marbles of the Caledonian nappe complex in the Ofotfjorden region (Fig. 1) (Melezhik et al., 2002, 2003).

3. Data acquisition and methods

A geological sampling program at five selected locations (Figs. 1, 2) based on seismic and bathymetric data (Ottesen et al., 2005b) was conducted during *RV Polarstern* cruise ARK XVIII/2 (Jokat, 2003). Five gravity cores were retrieved (Table 1) and stored at temperatures (4 °C) until analysis. The cores were then opened and described lithologically and structurally at the Alfred Wegener Institute (AWI), Bremerhaven, Germany.

3.1. Sedimentological and geochemical analysis

Fall-cone testing was used to measure undrained shear strength. This method, described in Norwegian Standard 8015, is a simple method where a cone of defined shape and load is positioned at the surface of the sediment. After release of the load, the penetration is measured, and the undrained shear strength is determined from a calibration table (Norges Byggstandardiseringsråd, 1988). X-ray photography performed on 1-cm slices of each sediment core was used to improve and/or verify the lithological description as well as to count ice-rafted debris (IRD) (no. >2 mm/ 10 cm^3) (Grobe, 1987). FIELAX GmbH (Bremerhaven, Germany) provided

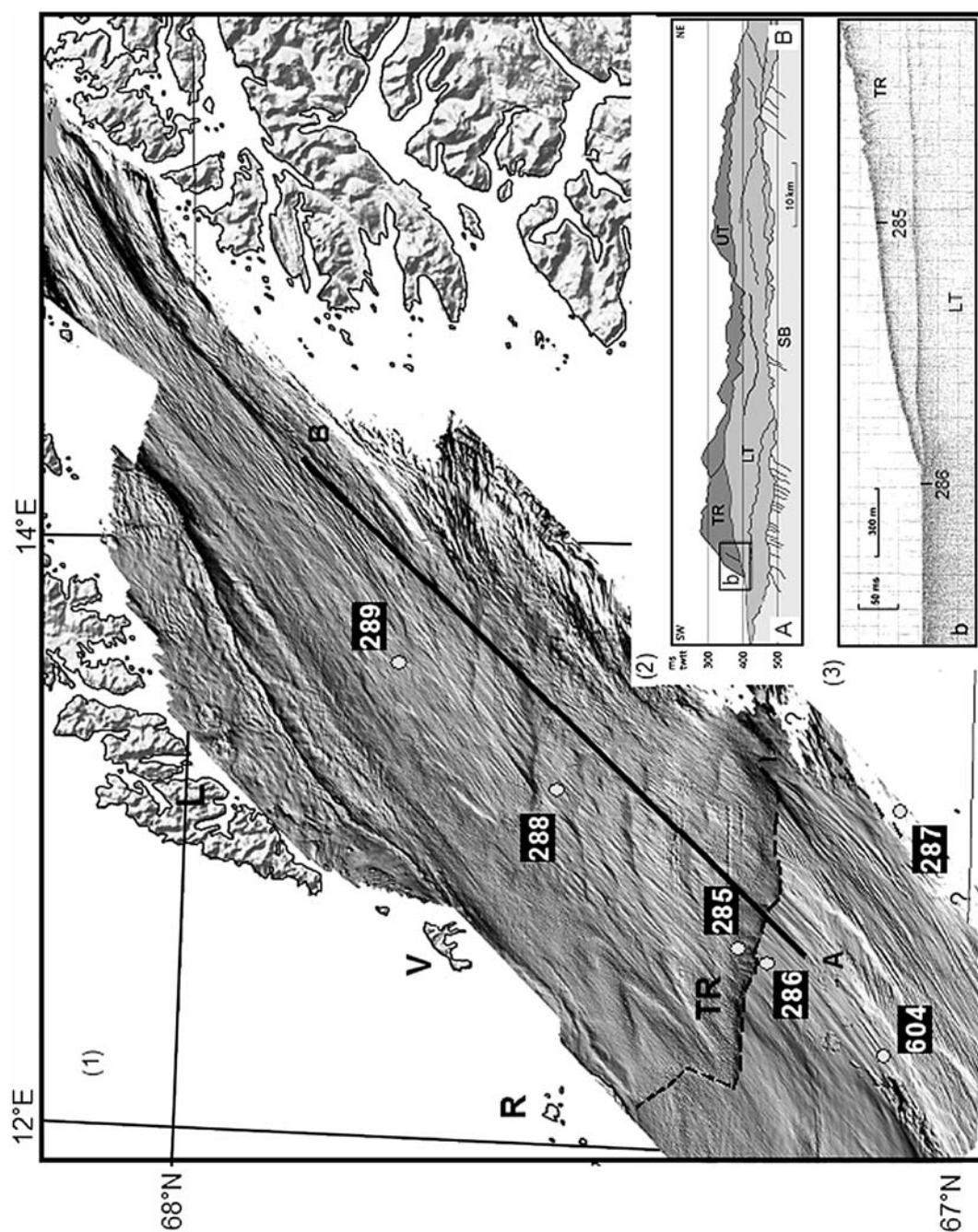


Fig. 2. (1) Sea-floor morphology of Vestfjord from multibeam bathymetry (shaded relief map) and positions of sediment cores (modified after Ottesen et al., 2005b). The dotted line indicates the outer limit of the central moraine ridge, the Tennholmen Ridge (TR). The black line marks the seismic profile shown in inset (2). R — Røst, V — Væroy, L — Lofoten. Black line — seismic profile (see inset). Inset (2): line drawing of seismic (sparker) profile IKU-V4-72. SB — sedimentary bedrock, LT — lower till unit(s), UT — upper till unit. The rectangular marks approximate location of profile in inset (3). Inset (3): seismic (Geopulse boomer) profile NGU0008006 showing the boundary between the upper (UT) and lower till (LT) units. Location of cores PS62/286 and, PS62/285 is displayed.

Table 1
Core locations and recovery

Latitude	Longitude	Sediment core	Water depth (m)	Gear	Penetration (cm)	Recovery (cm)
67°15,103N	12°45,029E	PS62/285–1	266	Gravity core	500	370
67°14,481N	12°44,851E	PS62/286–2	290	Gravity core	n.d.	23
67°14,578N	12°44,861E	PS62/286–3	292	Gravity core	n.d.	46
67°07,372N	13°20,617E	PS62/287–1	239	Gravity core	400	352
67°32,275N	13°20,180E	PS62/288–1	259	Gravity core	600	500
67°45,610N	13°48,325E	PS62/289–1	248	Gravity core	100	100

Multi-Sensor Core Logging (MSCL) data. The data (e.g. magnetic susceptibility) were used for correlation purposes and to assist in establishing a chronological framework for the records. Selected intervals were sampled and sieved (63–125 μm , 125–250 μm , > 250 μm) to collect dateable material (foraminifera, shells) and perform grain size analyses on the coarse fraction. Accelerator Mass Spectrometry (AMS) radiocarbon dates of 12 samples were obtained at the Radiocarbon Laboratory in Uppsala, Sweden and the Leibniz Labor for Radiometric Dating and Isotope Research, Kiel, Germany (Table 2). The ^{14}C dates were $\delta^{13}\text{C}$ -normalized and corrected for

an average global ocean reservoir effect of 400 yr, with a regional delta R -value of 64 ± 35 yr for northern Norway (Stuiver et al., 1986, 1998). All ages are given in radiocarbon years unless otherwise stated.

Total organic carbon (TOC) content was measured at the Geological Survey of Norway (NGU). Details of the measurements were published in Knies et al. (2003). Briefly, TOC was determined using a LECO CS 244 analyzer. The reproducibility of TOC (wt.%) analysis is $\pm 10\%$. Stable carbon isotope ratios of the organic matter ($\delta^{13}\text{C}_{\text{org}}$) were determined on decarbonated (10% HCl) samples using a CHN-HERAEUS elemental analyzer

Table 2
AMS ^{14}C results

Core number	Depth (cm)	^{14}C age (B.P.)	Carbon source	Laboratory	^{14}C age reservoir corrected	2σ maximum cal. age (cal. age, intercepts) minimum cal. age	Age (cal. ka B.P.)	Sedimentation rate (cm (kyr) $^{-1}$)
PS62/285–1	7–8	4750 $\pm$ 45	Bulk foraminifera	TUa-4153	4286	cal. B.P. 5045 (4867) 4805	4867	
PS62/285–1	63–64	6515 $\pm$ 45	Bulk foraminifera	TUa-4152	6051	cal. B.P. 7087 (6928) 6780	6928	27.0
PS62/285–1	170–171	10,085 $\pm$ 50	Bulk foraminifera	KIA-24512	9621	cal. B.P. 11,591 (11,047, 10,988, 10,830) 10,369	10,988	26.3
PS62/285–1	350–351	24,120 $\pm$ 260	Bulk foraminifera	KIA-24513	23,656			
PS62/286–3	2–3	3580 $\pm$ 40	Bulk foraminifera	TUa-4151	3116	cal. B.P. 3524 (3384) 3293	3384	
PS62/286–3	43–46	13,440 $\pm$ 65	<i>Yoldiella</i>	TUa-4150	12,976	cal. B.P. 15,961 (15,510) 14,430	15,510	3.4
PS62/287–1	27–28	5155 $\pm$ 65	Bulk foraminifera	TUa-4149	4691	cal. B.P. 5592 (5454) 5287	5454	
PS62/287–1	184–186	13,530 $\pm$ 65	Bulk foraminifera	TUa-4148	13,066	cal. B.P. 16,069 (15,592) 14,533	15,592	15.6
PS62/288–1	55–56	12,430 $\pm$ 70	Bulk foraminifera	TUa-4147	11,966	cal. B.P. 14,296 (13,835) 13,432	13,835	
PS62/288–1	150–153	13,305 $\pm$ 70	Bulk foraminifera	TUa-4146	12,841	cal. B.P. 15,801 (15,384) 14,227	15,384	61.3
PS62/289–1	3–4	8615 $\pm$ 50	Bulk foraminifera	TUa-4154	8151	cal. B.P. 9576 (8986) 8880	8986	
PS62/289–1	50–51	13,460 $\pm$ 180	<i>Yoldiella</i>	TUa-4155	12,996	cal. B.P. 16,129 (15,528) 14,348	15,528	7.2

A global ocean reservoir correction of about 400 yr with a regional delta R -value of 64 ± 35 for northern Norway has been used. The radiocarbon dates have been calibrated into calendar (cal.) years with the INTCAL-98 data set (Stuiver et al., 1998). TUa, Laboratory of Uppsala, Sweden; KIA, Leibniz Labor für Altersbestimmung, Kiel, Germany.

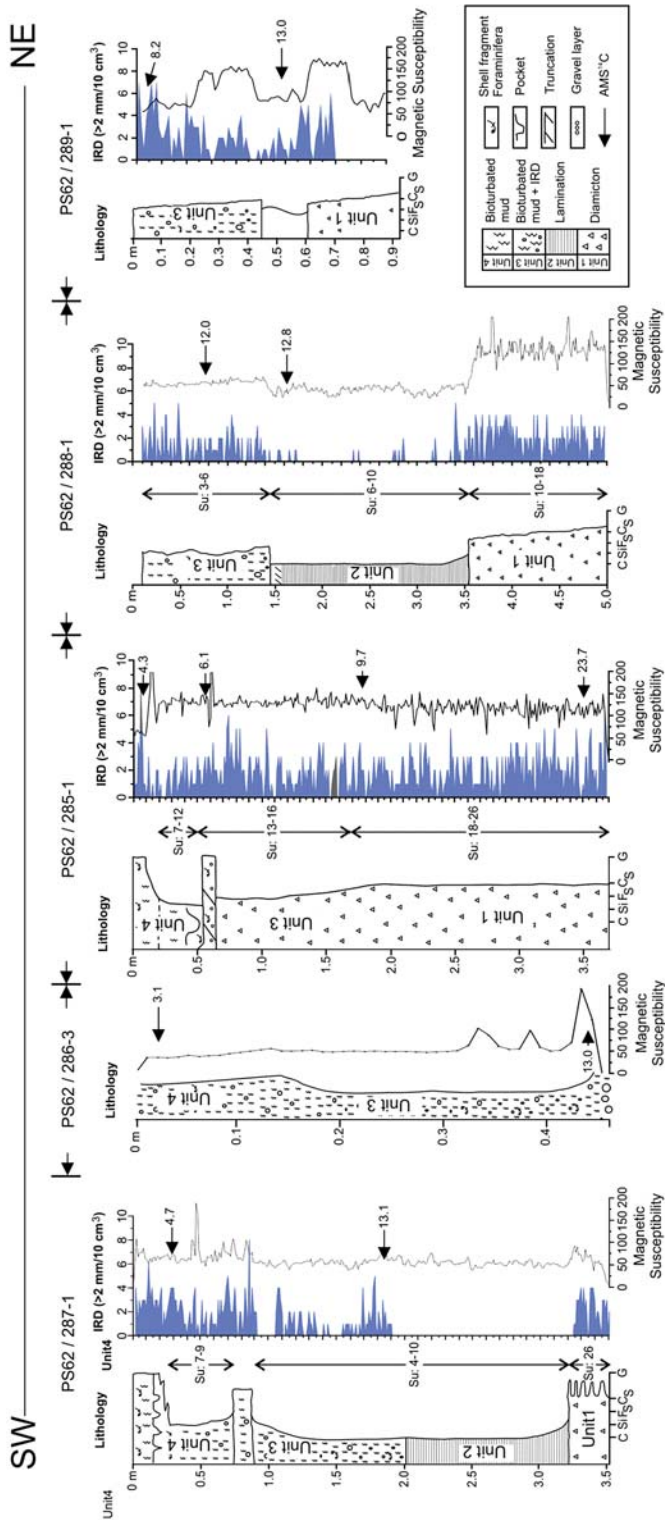


Fig. 3. West-east directed compilation of sedimentological data of sediment cores in the Vestfjorden. Displayed are lithological units, lithostratigraphic units, selected shear strength profiles, magnetic susceptibility and ice-rafted detritus (IRD) content (numbers of particles >2 mm). Reservoir corrected AMS ¹⁴C ages are marked by black arrows. Abbreviations are G = gravel, CS = coarse sand, FS = fine sand, Si = silt, C = clay.

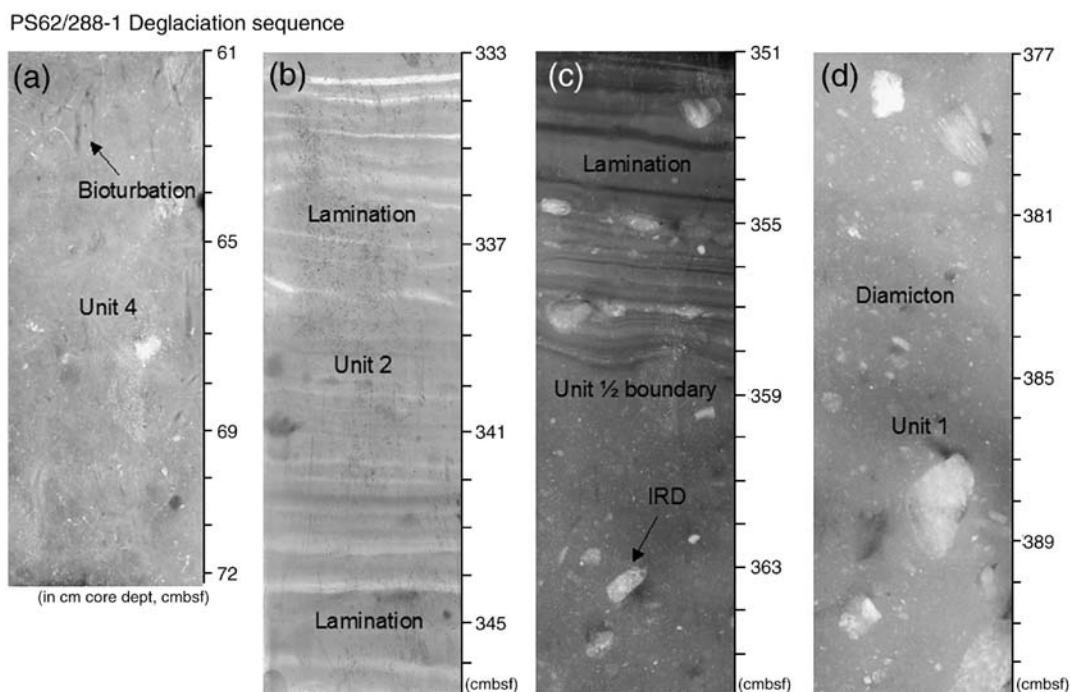


Fig. 4. X-ray photography showing a typical deglaciation sequence in sediment core PS62/288-1. Lithostratigraphic units are indicated in each picture. IRD = ice-rafted detritus.

coupled to a Finnigan MAT Delta E mass spectrometer at Bremen University. The $\delta^{13}\text{C}_{\text{org}}$ results are in per mil notation. The reference material was a laboratory working standard gas. This was then calibrated against the international NBS-19 standard. The reproducibility was $<0.1\text{‰}$.

3.2. Mineralogical studies

X-ray diffraction measurements have been performed at Bremen University, on a Philips X'Pert Pro equipped with a Cu-tube ($\text{K}\alpha$ λ 1.541, 45 kV 40 mA), a fixed divergence slit ($1/4^\circ$ 2θ), a 15 samples changer, a secondary monochromator and the X'Celerator detector system. Sample preparation with the Philips backloading system should provide random distribution of crystallites in the sample. Measurements were done as a continuous scan from 3 to 85° 2θ with a calculated step size of 0.016° 2θ . The calculated time per step was 100 s.

A set of 50 samples of cores 288 and 289 was measured at the NGU on a Philips X'pert MPD with a Cu-tube ($\text{K}\alpha$ λ 1.541, 40 kV, 50 mA), and a variable divergence slit (illumination length 12 mm, Curved Graphite Monochromator, 21 positions sample changer). Samples were also prepared with the Philips backloading system. Step measurements were run from 3 – 70° 2θ

with a scan speed of 0.02° $2\theta/\text{s}$, a step size of 0.04° 2θ (Xe filled mini-proportional detector (PW3011/10). The time per step was 2 s.

Peak identification was done graphically through the Apple MacIntosh Program MacDiff 4.5 (available at <http://servermac.geologie.uni-frankfurt.de/Rainer.html>) (Petschick et al., 1996). Normalization and comparison of measurements of the two different XRD systems were also done with MacDiff. A comparison of detected

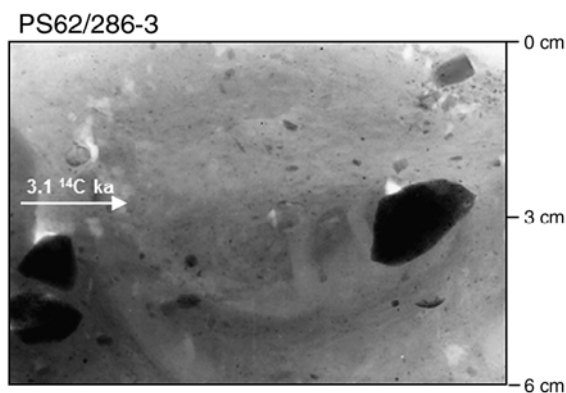


Fig. 5. X-ray photograph of Unit 4 in sediment core PS62/286-3 showing the regular occurrences of dropstones in late Holocene sediments.

intensity of multiple calcite and quartz mineral peaks yielded an overall ratio of 0.75 between NGU and Bremen University.

Integrated intensities for 32 investigated mineral peaks of quartz, feldspars, carbonates, clay minerals and heavy minerals were calculated by MacDiff. Based on this, intensity ratios were calculated. To provide an easy comparison to published data in the region and the subset of samples measured at NGU (Andersen et al., 1996; Vogt, 1997; Vogt et al., 2001; Knies et al., 2003) the fixed divergence of the Bremen University samples was changed to automatic divergence using an algorithm integrated in MacDiff.

4. Results

4.1. Seismo- and lithostratigraphy

The uppermost identified seismic unit (upper till — UT) in Vestfjorden comprises two large and several smaller sea-floor moraine ridges, which are perpendicular to the inferred ice-flow direction (Fig. 2) (Ottesen et al., 2005b). The seismic character of UT is fairly transparent and structureless, and only a few internal reflections are observed. UT can be followed several tens of kilometers northeast of the central main ridge (Fig. 2) with a maximum thickness of ~100 ms (ca. 80 m). The lower till unit

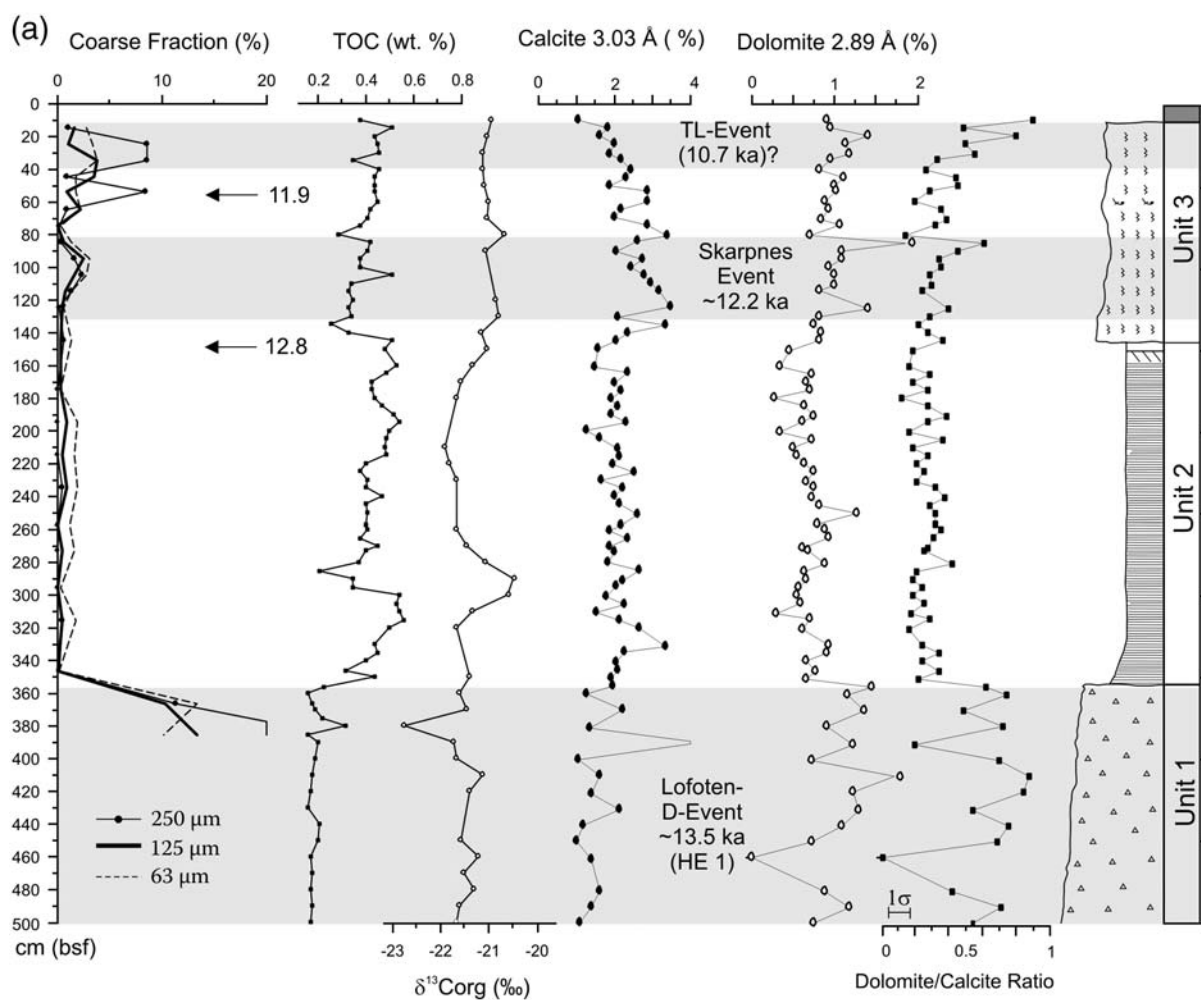


Fig. 6. Compilation of sedimentological and geochemical proxies in (a) sediment core PS62/288–1 and (b) PS62/289–1. TOC = total organic carbon (wt.%), $\delta^{13}\text{C}_{\text{org}}$ = $\delta^{13}\text{C}$ isotopic signature of the organic matter. Carbonate mineral contents were calculated from calibration curves of peak area intensity vs. the full quantitative phase analysis QUAX in Arctic Ocean surface samples and LECO based carbonate content determination (rel. error: 1%; c.f., Vogt, 1997). Calcite content (calculated from the integrated area intensity of the X-ray peak at 3.035 Å) and dolomite/ankerite content (calculated from the integrated area intensity of the 2.889–2.905 Å peaks) and the area intensity ratio of both carbonate mineral peaks are shown. Standard deviation of mineral content determination and the intensity ratio dolomite/ankerite vs. calcite as determined from standard calibration curves are given as error bars in the plots. Lithostratigraphic units and AMS 14C datings are displayed. HE = Heinrich Event 1. See Fig. 3 for references.

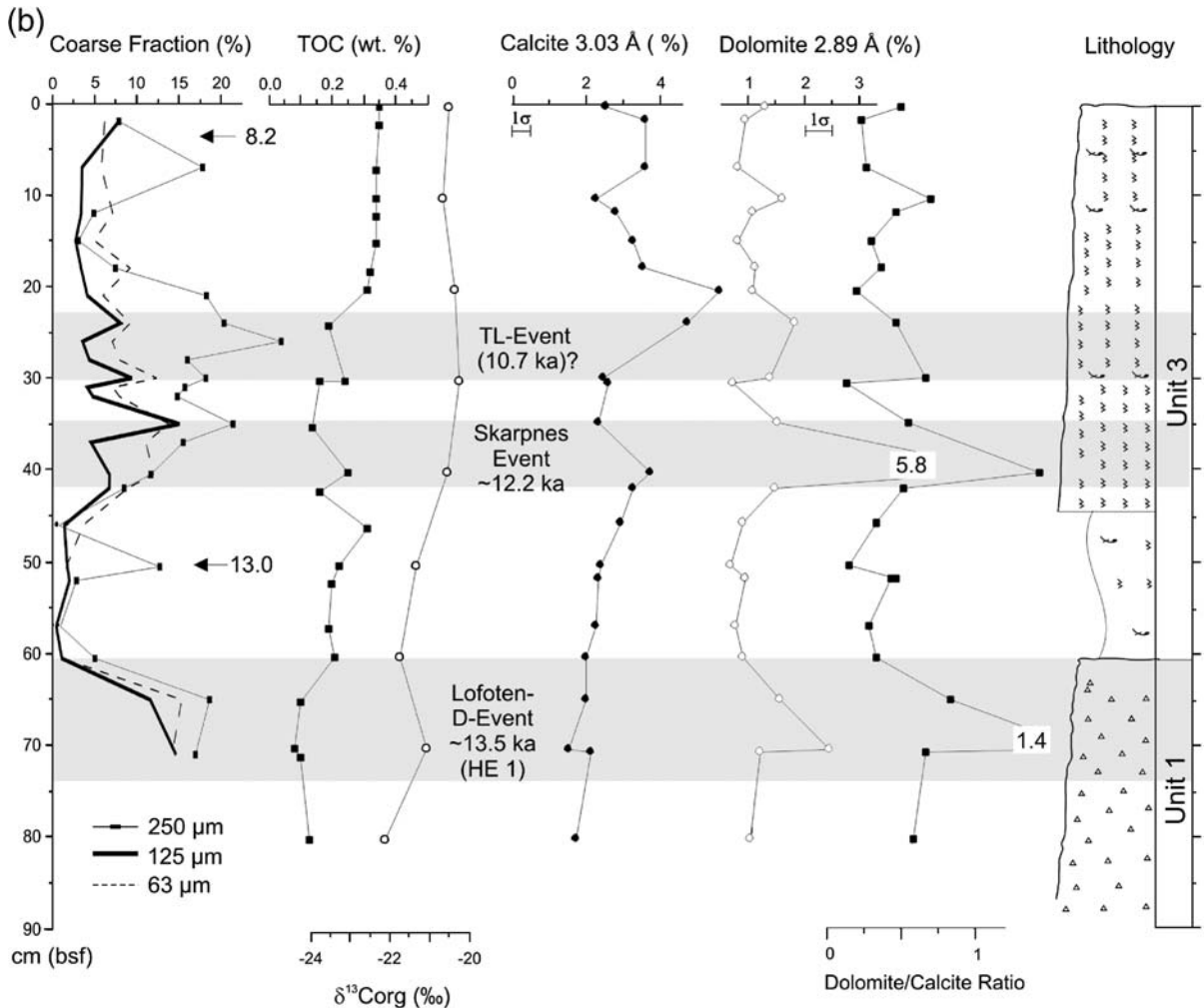


Fig. 6 (continued).

(LT) is structureless and transparent with a few internal reflectors (Fig. 2). A smooth and strong reflector between the upper and lower seismic units is interpreted to represent an erosional surface (Fig. 2; Ottesen et al., 2005b). At most places, glaciomarine/marine sediments covering the upper (inner Vestfjorden) and lower till units (outer Vestfjorden) is too thin to form an identifiable seismic-stratigraphic unit. The most pronounced morphological feature within UT is a huge GZW, the Tennholmen Ridge (TR), which is ~60 km long, ~15 km wide and crosses Vestfjorden in a NW–SE direction (Fig. 2). It is deposited on top of a fluted surface that is visible in front of the ridge (cf. Ottesen et al., 2005b). The GZW strikes almost perpendicular to the fjord axis, and has a well-defined distal boundary towards southwest (Fig. 2).

Visual inspection, X-ray photography, grain size analyses and magnetic susceptibility data have been

used to describe the sediments of the UT unit. Four main lithostratigraphic units have been identified in the cores (Fig. 3): Unit 1 representing deposits of the upper till unit is found at the base of all cores (except PS62/286) and consists of a dark, grey diamicton, which is poorly sorted, entirely homogenous, and characterized by enhanced magnetic susceptibility values ($>100 \cdot 10^6$ SI units) and undrained shear strength values (>10 kPa) (Fig. 3). The highest shear strength values (18–26 kPa) are measured in the lower part of the diamicton in PS62/285 and PS62/287, indicating that the sediments are slightly overconsolidated.

Laminated sediments of Unit 2 overlie the diamicton in two sediment cores (PS62/287, PS62/288). The contact between Unit 1 and Unit 2 is very distinct, but shows no sign of disconformities (Fig. 4). The sediments are soft and very fine-grained with generally high

water contents (up to 70%, data not shown) and very low magnetic susceptibility values ($<50 \cdot 10^6$ SI units) (Fig. 3). Numerous clasts >2 mm occur at the transition to the diamicton (Fig. 4). Microfossils and bioturbation are absent in Unit 2.

The clayey silty mud of Unit 3 is almost homogenous but differs from Unit 1 in being more bioturbated, with scattered matrix-supported clasts and having lower shear strength values (<10 kPa) (Figs. 3, 4). Shell fauna consisting of e.g. *Yoldiella lenticula* are often paired and found in their living position (e.g. PS62/286, 43–46 cm). In three of the records (PS62/285, PS62/286, PS62/289), Unit 3 is resting directly on top of Unit 1.

The uppermost unit Unit 4, found in three of the cores (PS62/285, PS62/286 and PS62/287), consists of moderate to heavily bioturbated silt and clay, and is commonly more finely grained than the underlying units. Nevertheless, matrix-supported scattered dropstones occur in these sediments as well (Fig. 5).

4.2. Sedimentological and geochemical proxies

Sediment cores PS62/288 and PS62/289 from the inner part of Vestfjorden have been studied for several palaeoenvironmental proxies (Fig. 6). The coarse-grained fractions ($>63 \mu\text{m}$, $>125 \mu\text{m}$, $>250 \mu\text{m}$) in both records show a prominent maximum in Unit 1 (basal diamicton). A similar maximum occurs in core PS62/289 at the base of Unit 3, while a prominent sand peak characterizes the top of the core. The more distal core PS62/288 reveals a minor, but distinct peak in the basal Unit 3 similar to core PS62/289. In addition, two additional sand maxima in the same unit are clearly seen, most likely due to a higher temporal resolution in this section of core PS62/288. Parallel to these maxima in both cores occur distinct inputs of detrital dolomite (Fig. 6). The dolomite content – here the sum of the two X-ray diffraction peaks of dolomite ($2.889 \text{ \AA}$) and ankerite ($2.905 \text{ \AA}$) – varies between 0.8 and 5.8 wt.%, while the calcite content ($3.035 \text{ \AA}$) is generally higher, with values between 2 wt.% and more than 5 wt.%. Peak values in dolomite/ankerite and calcite content, and the intensity ratio of both occur in contemporaneous stratigraphic positions of Unit 1 and basal Unit 3 (Fig. 6), while discrepancies are observed in the middle to upper Unit 3, possibly induced by the deposition of calcareous microfossils.

The TOC values vary between 0.1 and 0.5 wt.% with a systematic trend in both records. Unit 1 and basal Unit 3 reveal lower values (<0.2 wt.%), while the laminated, fine-grained sediments of Unit 2 and Unit 4 contain higher contents ($>0.4\%$). The composition of the organic

matter in the records (e.g. PS62/288) remains remarkably unchanged throughout the whole time span. $\delta^{13}\text{C}_{\text{org}}$ values show rather constant values (-21.3% in average) with a low standard deviation (± 0.4) indicative of the predominance of marine organic matter supply (Fig. 6). This is inferred from recent studies in adjacent fjords to the north (cf. Knies et al., 2003) where the marine $\delta^{13}\text{C}_{\text{org}}$ end-member value is -20.3% . Higher proportions of terrestrial organic matter may be supplied during deposition of the basal diamicton (Unit 1, PS62/289), where single spikes of lighter $\delta^{13}\text{C}_{\text{org}}$ values (-23.0%) occur (Fig. 6).

4.3. Chronology and sedimentation rates

The chronology of the sediment cores is based on 12 AMS ^{14}C dates (Table 2). The datings are based on bulk foraminifera and fragments of bivalve shells. All the dates were corrected for a reservoir effect of 464 yr, although we are aware that the reservoir age may be higher for the benthic foraminifera/bivalve shells compared to the planktonic foraminifera and has varied significantly during the last deglaciation in the North Atlantic (Björck et al., 2003; Bondevik et al., 2006). For the Vestfjorden area, however, we have currently no data to confirm this. So far, all the dates show increasing ages with core depth and sedimentation rates were calculated by linear interpolation between the dated levels (Table 2). One date, KIA-24513 ($24,120 \pm 260$) appears too old and was excluded from the age model. It was retrieved from the overconsolidated part of the basal diamicton (Unit 1) in core PS62/285 and has probably been reworked.

The sediments in front of the Tennholmen Ridge (PS62/286) are heavily condensed, with a low sedimentation rate of $2.0\text{--}4.0 \text{ cm/ka}$ between 13.0 and $3.0 \text{ }^{14}\text{C ka B.P.}$ (Table 2). On the ridge crest (PS62/285) and towards the outer coastline (PS62/287), the results reveal relatively high sedimentation rates ($16\text{--}27 \text{ cm/ka}$) between 13.0 and $4.0 \text{ }^{14}\text{C ka B.P.}$ The age model for the innermost cores (PS62/288, PS62/289) implies that sedimentation rates vary from 7 to 61 cm/ka during the deglacial period with highest values (61 cm/ka) during the initial phase ($13\text{--}12 \text{ }^{14}\text{C ka B.P.}$) of the deglaciation.

5. Discussion

5.1. Interpretation of the depositional environment

The morphological indicators of past ice flow in Vestfjorden–Trænadjupet (e.g. mega-scale glacial lineations, drumlins; e.g. Clark, 1994) suggest at least two

phases of activity (Ottesen et al., 2005b). The oldest – possibly from the LGM – is indicated by glacial lineations in the outer part of Vestfjorden and in Trænadjupet (Ottesen et al., 2005b), and may be coupled to deposits within seismic unit LT (Fig. 2). Sediments from this unit were probably recovered in front of the Tennholmen Ridge (PS62/286); however, from available bathymetric data and the resolution of seismic data (Fig. 2) we are currently unable to provide evidence for this assumption. Better data are required for resolving this problem. A very thin sequence of glaciomarine sediments (45 cm) was recovered above large rock fragments (~5–8 cm in diameter) found in the core catcher (Fig. 3). We presume that the fragments represent the erosional surface between seismic units UT and LT, whilst the radiocarbon age directly above (13 ^{14}C ka B.P.) provides a minimum age for the formation of the upper till unit UT.

The youngest phase is associated with the build-up of a large GZW, the Tennholmen Ridge, corresponding to seismic unit UT (Fig. 2). The diamicton (Unit 1) in cores PS62/285, PS 62/287, PS62/288, and PS62/289 was recovered from this unit. In-fjord dipping reflections within the UT may indicate pushing of mainly morainic sediments during an ice sheet advance. The morphology and ubiquity of the diamicton also suggest that UT most likely comprises basal till or ice marginal debris flow deposit. The massive character of the diamicton and shear strength values of 18–26 kPa and low water content (< 40%, data not shown) are indeed very similar to subglacial diamicton with a fluted surface known from different areas in the Barents Sea (e.g. Elverhøi and Solheim, 1983; Elverhøi et al., 1993; Lubinski et al., 1996; Polyak et al., 1997; Kleiber et al., 2000) and from the West Spitsbergen shelf (Svendsen et al., 1996). These parameters do not reflect a glaciomarine ice-drop origin. The parallel peaks in detrital dolomite in cores PS62/288 and PS62/289 (Fig. 6) point to a source within the catchment area of the ice stream. Indeed, the extensive occurrence of Neoproterozoic–Silurian calcite and dolomite marbles in the Ofotfjorden region (Fig. 1) (Melezhik et al., 2002, 2003), where major ice-flow tributaries are inferred to make up the main trunk of the ice drainage system (Ottesen et al., 2005b), may be the geological fingerprint for the coarse-grained and dolomite-rich sections in the Vestfjorden records. Hence, it is suggested that the dolomite peaks in the basal diamicton in PS62/288 and PS62/289 indicate glacial erosion and transport of material from Ofotfjorden deposited as ice marginal deposits in Vestfjorden during a re-advance of the adjacent ice sheet. The fact that the dolomite can be sourced via ice streams draining the Fennoscandian Ice Sheet during the last deglaciation provides additional

evidence for the presence of detrital carbonate-rich IRD peaks in North Atlantic and Nordic Sea sediments from more than one source (Andrews and Tedesco, 1992; Nørgaard-Pedersen et al., 1998; Hemming, 2004). The latter fully agrees with the observation that Palaeozoic carbonate deposits occur in many places surrounding the North Atlantic (Bond et al., 1992), however, have presumably little influence on the fact that elevated detrital carbonate content in IRD-rich sediments of this region (“Heinrich events” see discussion below) is mainly derived from a Hudson Strait source (Andrews and Tedesco, 1992).

The laminated sediments overlying UT have apparently been deposited by suspension settling from melt-water plumes during ice retreat. This is inferred from the fining upward trend from IRD-rich, sandy ice-proximal rhythmites to finer-grained rhythmites above (Fig. 4) and the transition into massive, bioturbated mud of Unit 3, a sequence frequently described from the Barents Sea and the Norwegian Channel Ice Stream during the last deglaciation (e.g. Polyak and Solheim, 1994; Lubinski et al., 1996; Lekens et al., 2005). The absence of macro- and microfossils and the lack of bioturbation traces in the laminated sediments suggest a very high sedimentation rate and an ice-proximal location of the records (e.g. Ó Cofaigh and Dowdeswell, 2001). The consistent age (~13.0 ^{14}C ka B.P.) for the upper boundary of this sequence in central and inner fjord records indicates a rapid retreat of the ice sheet towards the shoreline. The following ice-distal conditions are accompanied by an increase in bioturbation, the occurrence of dropstones and the deposition of homogenous, silty-clay mud (Unit 3). This depositional environment is less influenced by meltwater discharge and the supply of sediments. This supports the colonisation of the sea bottom by macrofauna (Boulton, 1990; Görlich et al., 1987). The abrupt increase in calcite content at the same time (Fig. 6) may indicate a stronger production of calcareous microfossils in more open glaciomarine conditions. However, numerous clasts still indicate the presence of calving icebergs from the nearby ice sheet. Interestingly, diamictic sediments in core PS62/285 deposited both in Unit 1 and Unit 3 (Unit 2 is missing in core PS62/285) possibly indicate that bathymetric steering of water mass exchange on top of the Tennholmen Ridge (as observed today, Mitchelson-Jacob and Sundby, 2001) may have caused strong winnowing and thus outwashing of the fines after retreat of the ice sheet. Unit 4 deposited after ~6.0 ^{14}C ka B.P. resembles postglacial sediments in the Barents Sea (Polyak and Solheim, 1994; Lubinski et al., 1996; Kleiber et al., 2000), characterized by a high

grade of bioturbation and a low sedimentation rates (Table 2). However, numerous clasts in these sediments suggest glaciomarine conditions (Fig. 5), possibly due to coastal erosion by shorefast sea-ice formation and subsequent release of debris during melting.

5.2. Deglaciation pattern in Vestfjorden

The onset of the last deglaciation in Vestfjorden is not documented by our seismo- and lithostratigraphic data sets. Radiocarbon-dated foraminifers in the overconsolidated till upon the Tennholmen Ridge (core PS62/285) gave an age of 23.7 ^{14}C ka B.P. implying that the Trænadjupet–Vestfjorden–Ofotfjorden system was glaciated after 23.7 ^{14}C ka B.P. Dahlgren and Vorren (2003) postulated that the final deglaciation of the Mid-Norwegian outermost shelf occurred around 16.5–16 ^{14}C ka B.P. with a short re-advance close to the shelf break after 15.3 ^{14}C ka B.P. (Rokoengen and Frengstad, 1999). From western Spitsbergen, the southern Barents Sea,

northern Norway and the Norwegian Channel, it is known that the ice sheet retreated from the shelf edge between 15 and 14 ^{14}C ka B.P. (e.g. Jones and Keigwin, 1988; Vorren et al., 1988; Lehman et al., 1991; Sejrup, 1994; Laberg and Vorren, 1996; Svendsen et al., 1996; Sejrup et al., 2000; Vorren and Plassen, 2002; Dahlgren and Vorren, 2003; Nygård et al., 2004) and contributed to a regional meltwater event in the Nordic Seas (e.g. Hebbeln et al., 1994; Koç and Jansen, 1994; Elverhøi et al. 1995; Sarnthein et al., 1995; Dokken and Jansen, 1999; Sarnthein et al., 2001; Bauch et al., 2001; Lekens et al., 2005). This is in good agreement with the dating of ~ 13.6 ^{14}C ka B.P. in glaciomarine sediments overlying basal diamicton of seismic unit LT in the outermost Vestfjorden (core JM 1–604, see Fig. 1 for location) (Laberg et al., in press) and agrees well with our findings in front of the Tennholmen Ridge (>13.0 ^{14}C ka B.P.) representing a minimum age for the deglaciation of the Trænadjupet area. However, the timing contradicts with observations made by Laberg

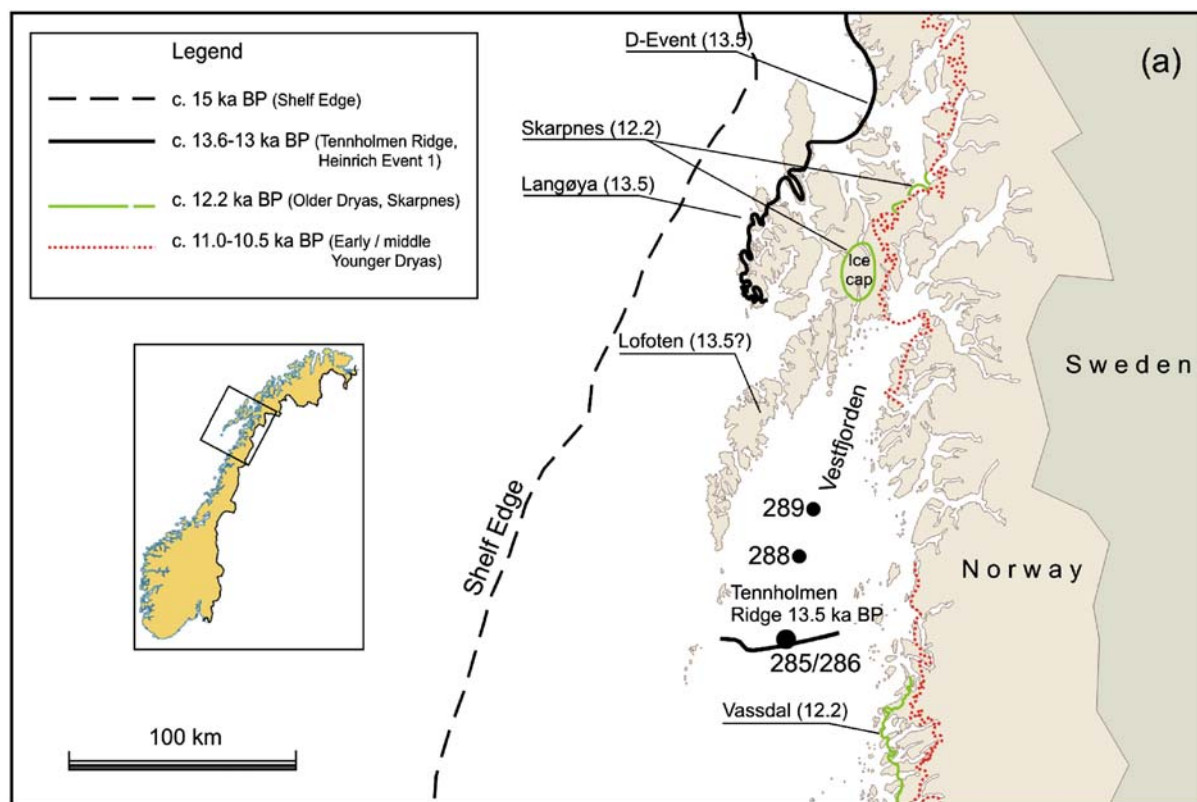


Fig. 7. a) Map with ice sheet extension during the last deglaciation in northern Norway (shelf edge (~ 15 ^{14}C ka), “D-Event”/Tennholmen/Heinrich Event 1, ~ 13.5 ^{14}C ka), Skarpnes Event (Older Dryas, ~ 12.2 ^{14}C ka), Tromsø Lyngen Event (Younger Dryas, ~ 11 – 10 ^{14}C ka) (see Olsen, 2002; Dahlgren and Vorren, 2003; Bargel, 2003; Bergström et al., 2005 and references therein). Core positions in Vestfjorden and outline of the inferred re-advances prior to 13.1 ^{14}C ka are displayed. b) Time–distance glaciation diagram from the Vestfjorden (black line, this study) and Andfjorden (gray line, Vorren and Plassen, 2002) area. Both curves are plotted against reservoir corrected radiocarbon ages. The chronozones are according to Mangerud et al. (1974). Lithostratigraphic units in Vestfjorden are displayed.

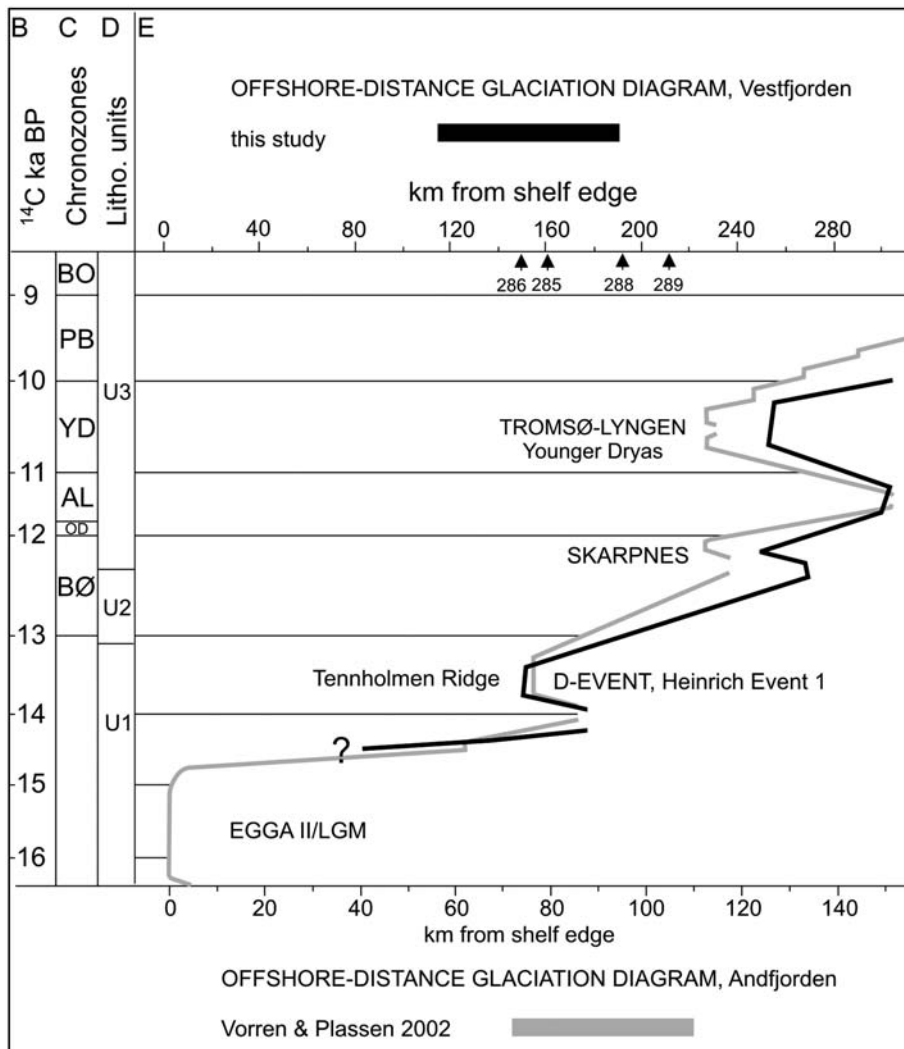


Fig. 7 (continued).

et al. (2002) suggesting that debris flow deposits along the adjacent continental slope prior to 13.2 ^{14}C ka B.P. may be the result of re-mobilisation of basal, deformable till in front of an ice stream located upon the shelf edge. One reason for this discrepancy might be the incompleteness of deglacial sediments along the continental slope (hiatus) (Jan Sverre Laberg, personal communication), however, more core data from the slope are needed to resolve this problem.

According to our model, the re-advance to the Tennholmen Ridge occurred some time between ~ 13.6 and ~ 13.0 ^{14}C ka B.P. The minimum age for the re-advance is constrained by the boundary of the LT unit (~ 13.6 ^{14}C ka B.P.) in front of the Tennholmen Ridge. The radiocarbon ages of 12.8–13.1 ^{14}C ka B.P. in glaciomarine sediments above seismic unit UT provide a

minimum age for the retreat of the grounded ice stream from the outer Vestfjorden. This model is consistent with reconstructions of the adjacent palaeo-ice stream system in Andfjorden (Vorren and Plassen, 2002). After the initial break-up along the shelf break at ~ 15 – 14 ^{14}C ka B.P., a glacial re-advance (“D-Event”) was postulated for the period between 13.8 and 13.2 ^{14}C ka B.P. inferred from IRD maxima and cold, near glacial fauna in cores from the outer and middle basins of Andfjorden (Vorren and Plassen, 2002) (Fig. 7). This is consistent with a distinct cold phase observed on the adjacent Norwegian mainland between 14.2 and 12.8 ^{14}C ka B.P. (Alm, 1993; Vorren and Alm, 1999) and a prominent ice advance on the Mid-Norwegian continental shelf occurring some time between <15 and 13.3 ^{14}C ka B.P. (Nygård et al., 2004). A contemporaneous re-advance may be inferred

from a minimum age of 13.2/13.3 ^{14}C ka B.P. for the retreat of the grounded ice margin in the cross-shelf troughs of the northern Barents Sea (Lubinski et al., 1996; Polyak et al., 1997) and a prominent IRD pulse along the northern Barents Sea continental margin at 13.6 ^{14}C ka B.P. (Kleiber et al., 2000; Knies et al., 2001). This evidence most likely points to a concurrent re-advance of the FIS and SBIS at ~ 13.8 – 13.3 ^{14}C ka B.P., suggesting a connected dynamic of the ice sheets existed during the last deglaciation. A common trigger for the short-term re-advance might have been meltwater injections into the North Atlantic and Nordic Seas associated with Heinrich Event 1 (>12.8 – 14.8 ^{14}C ka B.P.; Sarnthein et al., 2001) as postulated for the ice advance on the Mid-Norwegian continental shelf (Nygård et al., 2004) and the British Ice Sheet at ~ 14 ^{14}C ka B.P. (e.g. McCabe and Clark, 1998).

Heinrich events (HE) were abrupt episodes of massive IRD events in the North Atlantic (Heinrich, 1988; Andrews and Tedesco, 1992; Bond et al., 1992; Broecker et al., 1992; Broecker, 1994), but other indications are seen globally during the last glacial cycle (e.g. Schulz et al., 1998; Cacho et al., 1999; Wang et al., 2001). Six such events, labeled H1–H6, have been identified. Based on the high detrital carbonate concentration and other provenance proxies HE appear to have been derived from the Hudson Strait region (Andrews, 1998; Hemming, 2004, for reviews), however, with contrasting differences during HE 3 and HE 6 (e.g. Grousset et al., 1993; Gwiazda et al., 1996). While the mechanisms for the origin still are under debate (see Hemming, 2004, for review), the release of large amounts of freshwater associated with each HE is thought to lead to disruptions in the thermohaline circulation in the North Atlantic (Broecker et al., 1992; Ganopolski and Rahmstorf, 2001). HE 1 represents a short perturbation of the warming trend during the last deglaciation and was most likely triggered by internal instability of the Laurentide Ice Sheet (McCabe and Clark, 1998). The release of icebergs and freshwater, however, not only from the Laurentide and Greenland ice margins but also during ice retreats of the Fennoscandian and the Svalbard–Barents Sea ice sheets (e.g. Sejrup et al., 1994; Sarnthein et al., 1995; Elverhøi et al., 1995; Knies et al., 1999; Lekens et al., 2005,) disrupted the thermohaline circulation and reduced the meridional heat transport in the Nordic Seas (e.g. Sarnthein et al., 1995, 2001). According to McCabe and Clark (1998), the accompanied cooling due to freshwater forcing triggered the re-advance of the British ice sheet at ~ 14 ^{14}C ka B.P. However, the findings from this study and published results from the Mid-Norwegian (Nygård et al., 2004)

and Barents Sea margin (Polyak et al., 1997; Kleiber et al., 2000; Knies et al., 2001) suggest a synchronous re-advance of all major circum-North Atlantic/Nordic seas ice sheets in response to freshwater perturbations and short-term cooling associated with HE 1. The difference in timing (± 0.3 ka) is within the constraints of the radiocarbon dating chronology for marine and terrestrial data during the last deglaciation (e.g. Björck et al., 2003; Bondevik et al., 2006.). Interestingly, a short-term re-advance of the Barents–Kara Sea ice sheets was recently postulated at ~ 55 ka (Larsen et al., 2006) shortly after the release of freshwater to the North Atlantic and Nordic Sea region associated with HE 6. It may provide – apart from the last deglaciation – another intriguing example for the delay of Northern Hemisphere deglaciation during the last glacial cycle due to freshwater forcing.

The retreat of the ice sheet in Vestfjorden inferred from non-bioturbated, laminated sediments at ~ 13.0 ^{14}C ka B.P. corresponds to a rapid warming documented in onshore and offshore records adjacent to the study area (Vorren et al., 1988; Hald et al., 1996; Hald and Aspeli, 1997; Vorren and Alm, 1999; Vorren and Plassen, 2002). With the transgressive warming by Atlantic water inflow and rapidly rising insolation, the ice in Vestfjorden receded towards the inner coastline and did not reach the core locations afterwards. These ice-distal conditions at approximately 12.8 ^{14}C ka B.P. are inferred from a marked environmental shift from laminated sediments of Unit 2 to the deposition of calcite-rich, bioturbated mud with some intercalated IRD in Unit 3 (Fig. 6), which corresponds to the onset of the Bølling climatic amelioration.

After the amelioration, distinct maxima in the coarse fraction and increased dolomite contents (up to 5.8%) in PS62/289 (proximal) and (up to 2.0%) in PS62/288 (distal) at the base of Unit 3 (Fig. 6) resemble the patterns of Unit 1. This may indicate another pulse of deposition of glacially eroded calcite and dolomite marbles from Ofotfjorden region to Vestfjorden. The timing of the older event is constrained by two AMS ^{14}C dates in PS62/288 and lies between 12.8 and 11.9 ^{14}C ka B.P. This event may be contemporaneous with the Skarpnes Event, an ice sheet re-advance on the adjacent Norwegian mainland during the Older Dryas at ~ 12.2 ^{14}C ka B.P. (Vorren and Elvsborg, 1979) (Fig. 7). Skarpnes moraines are mapped and dated in tributary fjords to Andfjorden (Andersen, 1968; Vorren and Elvsborg, 1979), while their distribution in Vestfjorden is more uncertain (Bergstrøm et al., 2005). Bergstrøm et al. (2005) suggested that the Skarpnes moraines were possibly overridden by subsequent FIS re-advance during the Younger Dryas (Tromsø–Lyngen Event). However,

along the southern side of Vestfjorden (between Ofotfjorden and Bodø), there are indications of re-advances during the Skarpnes Event where the ice margin supposedly crossed the coastline and invaded parts of Vestfjorden basin (Olsen, 2002; Olsen et al., 2002). Icebergs released from the protruding ice sheets may have reached the core positions in the outer part of Vestfjorden during this period, where IRD, enriched in detrital dolomite, was released. It is currently speculative as to whether a third prominent spike in detrital dolomite (up to 2.0%) and a coarse fraction in cores PS62/288 and PS62/289 (Fig. 6), after the postulated Skarpnes Event, is concurrent with the Tromsø Lyngen Event (Younger Dryas). Although the available AMS ^{14}C date of 11.9 ka B.P. for the base of this maximum is a strong argument, further studies are required on the other cores. However, taking into account the good correspondence between regional glacial fluctuations prior to 13.1 and ~ 12.2 ^{14}C ka B.P. (Fig. 7), and prominent spikes in the coarse fraction and detrital dolomite, we hypothesize that the Younger Dryas glacial event is similarly expressed by our mineralogical and sedimentological fingerprints. Together, we postulate that glacial fluctuations in the Trænadjupet–Vestfjorden–Ofotfjorden ice drainage system occurred during the last deglaciation and may be best reconstructed by using high-resolution, well-dated records of mineralogical fingerprints that trace glacially eroded input of Neoproterozoic–Early Silurian calcite and dolomite marbles to marble outcrops on the Norwegian mainland in Vestfjorden. Multiple advances of the Fennoscandian Ice Sheet in response to meltwater injections during the last deglaciation provide additional evidence for climate response to freshwater forcing on millennial time-scales.

6. Conclusions

A sequence of events concerning the Vestfjorden palaeo-ice stream was studied during the last deglaciation. After the initial break-up of the Fennoscandian Ice Sheet and retreat from the shelf edge into the inner part of Vestfjorden at about 15–14 ^{14}C ka B.P., the ice re-advanced towards the outer part of Vestfjorden prior to 13.1 ^{14}C ka B.P. This is inferred from diamictos interpreted as basal tills and associated contemporaneous build-up of grounding zone wedges in the central Vestfjorden. The event coincides with observations of ice sheet advance in adjacent fjord systems, the Mid-Norwegian continental shelf and the Barents Sea, suggesting a common response of the Fennoscandian and Svalbard–Barents Sea ice sheets during the last deglaciation.

The common trigger for this regional event might have been disruption of the thermohaline circulation and short-term cooling associated with iceberg release and meltwater injection during Heinrich Event 1. Subsequent to a recession during climate amelioration in the Bølling interstadial, the ice sheet re-advanced again at least towards the inner part of Vestfjorden during the Skarpnes Event (~ 12.2 ^{14}C ka B.P., Older Dryas). This is inferred both from onshore observations and prominent IRD spikes enriched in detrital dolomite and calcite indicative of glacial erosion of calcitic and dolomitic marble outcrops in Ofotfjorden. A similar sequence of events, although with a less well-constrained timing, is also postulated for the Tromsø–Lyngen Event (Younger Dryas).

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References

- Alm, T., 1993. Øvre-Ærsvatn-palynostratigraphy of a 22,000 to 10,000 B.P. lacustrine record on Andøya, northern Norway. *Boreas* 22, 171–188.
- Andersen, B.G., 1968. Glacial geology of western Troms, north Norway. *Nor. Geol. Unders.* 256, 1–160.
- Andersen, B.G., Mangerud, J., Sørensen, R., Reite, A., Sveian, H., Thoresen, M., Bergström, B., 1995. Younger Dryas ice marginal deposits in Norway. *Quat. Int.* 28, 147–169.
- Andersen, E.S., Dokken, T.M., Elverhøi, A., Solheim, A., Fossen, I., 1996. Late Quaternary sedimentation and glacial history of the western Svalbard margin. *Mar. Geol.* 133, 123–156.
- Andrews, J.T., 1998. Abrupt changes (Heinrich events) in late Quaternary North Atlantic marine environments: a history and review of data and concepts. *J. Quat. Sci.* 13, 3–16.
- Andrews, J.T., Tedesco, K., 1992. Detrital carbonate-rich sediments, northwestern Labrador Sea: implications for ice-sheet dynamics and iceberg rafting (Heinrich) events in the North Atlantic. *Geology* 20, 1087–1090.

- Bargel, T.H., 2003. Quaternary geological mapping of Central Fennoscandia and Nordland: deglaciation, deposition, stratigraphy and applications. Doktor Ingeniør Thesis. Department of Geology and Mineral Resources Engineering, NTNU, 324 pp.
- Bauch, H.A., Erlenkeuser, H., Spielhagen, R.F., Matthiessen, J., Thiede, J., Heinemeier, J., 2001. A multiproxy reconstruction of the evolution of deep and surface waters in the sub arctic Nordic seas over the last 30,000 yr. *Quat. Sci. Rev.* 20, 659–678.
- Bergström, B., Olsen, L., Sveian, H., 2005. The Tromsø–Lyngen glacial readvance (early Younger Dryas) at Hinnøya–Ofotfjorden, northern Norway. *Nor. Geol. Unders. Bull.* 445, 73–88.
- Björck, S., Koç, N., Skog, G., 2003. Consistently large marine reservoir ages in the Norwegian Sea during the Last Deglaciation. *Quat. Sci. Rev.* 22, 429–435.
- Bond, G., et al., 1992. Evidence for massive discharges of icebergs into the North Atlantic Ocean during the last glacial period. *Nature* 360, 245–249.
- Bondevik, S., Mangerud, J., Birks, H.H., Gulliksen, S., Reimer, P., 2006. Changes in North Atlantic radiocarbon reservoir ages during the Allerød and Younger Dryas. *Science* 312, 1514–1517.
- Broecker, W.S., Bond, G.C., Klas, M., Clark, E., McManus, J.F., 1992. Origin of the northern Atlantic's Heinrich events. *Clim. Dyn.* 6, 265–273.
- Broecker, W.S., 1994. Massive iceberg discharges as triggers for global climate change. *Nature* 372, 421–424.
- Boulton, G.S., 1990. Sedimentary and sea level changes during glacial cycles and their control on glaciomarine facies architecture. In: Dowdeswell, J.A., Scourse, J.D. (Eds.), *Glaciomarine Environments: Processes and Sediments*. Geological Society Special Publication, vol. 53, pp. 15–52.
- Cacho, I., Grimalt, J.O., Pelejero, C., Canals, M., Sierro, F.J., Flores, J.A., Shackleton, N., 1999. Dansgaard–Oeschger and Heinrich event imprints in Alboran Sea paleotemperatures. *Paleoceanography* 14, 698–705.
- Clark, C.D., 1994. Large-scale ice-moulding: a discussion of genesis and glaciological significance. *Sediment. Geol.* 91, 253–268.
- Dahlgren, K.I.T., Vorren, T., 2003. Sedimentary environment and glacial history during the last 40 ka of the Vøring continental margin, mid-Norway. *Mar. Geol.* 193, 93–127.
- Dokken, T.M., Jansen, E., 1999. Rapid changes in the mechanism of ocean convection during the last glacial period. *Nature* 401, 458–461.
- Dowdeswell, J.A., Siegert, M.J., 1999. Ice-sheet numerical modeling and marine geophysical measurements of glacier-derived sedimentation on the Eurasian Arctic continental margins. *Geol. Soc. Amer. Bull.* 111, 1080–1097.
- Dowdeswell, J.A., Kenyon, N.H., Elverhøi, A., Laberg, J.S., Hollender, F.-J., Mienert, J., Siegert, M.J., 1996. Large-scale sedimentation on the glacier-influenced Polar North Atlantic margins: long-range side-scan sonar evidence. *Geophys. Res. Lett.* 23, 3535–3538.
- Eide, L.I., 1979. Evidence of a topographically trapped vortex on the Norwegian continental shelf. *Deep Sea Res.* 26, 601–621.
- Elverhøi, A., Solheim, A., 1983. The Barents Sea ice-sheet: a sedimentological discussion. *Polar Res.* 1, 23–32.
- Elverhøi, A., Fjeldskaar, W., Solheim, A., Nyland-Berg, M., Russwurm, L., 1993. The Barents Sea ice sheet — a model of its growth and decay during the last ice maximum. *Quat. Sci. Rev.* 12, 863–873.
- Elverhøi, A., Andersen, E.S., Dokken, T.M., Hebbeln, D., Spielhagen, R.F., Svendsen, J.I., Sørflaten, M., Rørnes, A., Hald, M., Forsberg, C.F., 1995. The growth and decay of the Late Weichselian Ice Sheet in western Svalbard and adjacent areas based on provenance studies of marine sediments. *Quat. Res.* 44, 303–316.
- Evans, D., Harrison, Z., Shannon, P.M., Laberg, J.S., Nielsen, T., Ayers, S., Holmes, R., Hout, R.J., Lindberg, B., Haflidason, H., Long, D., Kuijpers, A., Andersen, E.S., Bryn, P., 2005. Palaeoslides and other mass failures of Pliocene to Pleistocene age along the Atlantic continental margin of NW Europe. *Mar. Petrol. Geol.* 22, 1131–1148.
- Ganopolski, A., Rahmstorf, S., 2001. Rapid changes of glacial climate simulated in a coupled climate model. *Nature* 409, 153–158.
- Geddes, N.R., Scott, J.C., 1994. ROCKY WATER 93/6 Detailed ocean structure for the Vestfjord and adjacent regions. Defence Research Agency Report DRA/US/USSF/TM94021/1.0. 169 pp.
- Görlich, K., Weslawski, J.M., Zajaczkowski, M., 1987. Suspension settling effect on macrobenthos biomass distribution in the Hornsund fjord, Spitsbergen. *Polar Res.* 5, 175–192.
- Grobe, H., 1987. A simple method for determination of ice rafted debris in sediment cores. *Polarforschung* 57, 123–126.
- Grousset, F.E., Labeyrie, L., Sinko, J.A., Cremer, M., Bond, G., Duprat, J., Cortijo, E., Huon, S., 1993. Patterns of ice rafted detritus in the glacial North Atlantic (40–55°N). *Paleoceanography* 8, 175–192.
- Gwiazda, R.H., Hemming, S.R., Broecker, W.S., 1996. Provenance of icebergs during Heinrich event 3 and the contrast to their sources during other Heinrich episodes. *Paleoceanography* 11, 371–378.
- Haflidason, H., Lien, R., Sejrup, H.P., Forsberg, C.F., Bryn, P., 2005. The dating and morphometry of the Storegga Slide. *Mar. Petrol. Geol.* 22, 123–136.
- Hald, M., Dokken, T.M., Hagen, S., 1996. Palaeoceanography on the European arctic margin during the last deglaciation, in Late Quaternary Palaeoceanography of the North Atlantic Margin. In: Andrews, J.T., Austin, W.E.N., Bergsten, H., Jennings, A. (Eds.), *Geological Society Special Publication*, London, pp. 275–287.
- Hald, M., Aspel, R., 1997. Rapid climatic shifts of the northern Norwegian Sea during the last deglaciation and the Holocene. *Boreas* 26, 15–28.
- Hebbeln, D., Dokken, T.M., Andersen, E.S., Hald, M., Elverhøi, A., 1994. Moisture supply for northern ice-sheet growth during the Last Glacial Maximum. *Nature* 370, 357–359.
- Heinrich, H., 1988. Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 years. *Quat. Res.* 29, 142–152.
- Hemming, S.R., 2004. Heinrich Events: massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint. *Rev. Geophys.* 42, RG1005. doi:10.1029/2003RG000128.
- Hjelstuen, B.O., Sejrup, H.P., Haflidason, H., Nygård, A., Ceramicola, S., Bryn, P., 2005. Late Cenozoic glacial history and evolution of the Storegga slide area and adjacent slide flank regions, Norwegian continental margin. *Mar. Petrol. Geol.* 22, 57–69.
- Jokat, W., 2003. The Expedition ARKTIS XVIII/2 of RV “Polarstern” in 2002 contributions of the participants. *Rep. Polar Res.*, vol. 449. 146 pp.
- Jones, G.A., Keigwin, L.D., 1988. Evidence from Fram Strait (78° N) for early deglaciation. *Nature* 336, 56–59.
- Kleiber, H.P., Knies, J., Niessen, F., 2000. The Late Weichselian glaciation of the Franz Victoria Trough, northern Barents Sea: ice sheet extent and timing. *Mar. Geol.* 168, 25–44.
- Knies, J., Vogt, C., Stein, R., 1999. Late Quaternary growth and decay patterns of the Svalbard–Barents Sea ice sheet and paleoceanographic evolution in the adjacent Arctic Ocean. *Geo Mar. Lett.* 18, 195–202.
- Knies, J., Kleiber, H.-P., Matthiessen, J., Müller, C., Nowaczyk, N., 2001. Marine ice-rafted debris records constrain maximum extent

- of Saalian and Weichselian ice-sheets along the northern Eurasian margin. *Glob. Planet. Change* 31, 45–64.
- Knies, J., Hald, M., Ebbesen, H., Mann, U., Vogt, C., 2003. A deglacial–middle Holocene record of biogenic sedimentation and paleoproductivity changes from the northern Norwegian continental shelf. *Paleoceanography* 18, 1096. doi:10.1029/2002PA000872.
- Koç, N., Jansen, E., 1994. Response of the high latitude Northern Hemisphere to orbital climate forcing: evidence from the Nordic Seas. *Geology* 22, 523–526.
- Laberg, J.S., Vorren, T.O., 1996. The middle and Late Pleistocene evolution of the Bear Island Trough Mouth Fan. *Glob. Planet. Change* 12, 309–330.
- Laberg, J.S., Vorren, T.O., Mienert, J., Evans, D., Lindberg, B., Ottesen, D., Kenyon, N.H., Henriksen, S., 2002. Late Quaternary palaeoenvironment and chronology in the Trænadjupet Slide area offshore Norway. *Mar. Geol.* 188, 35–60.
- Laberg, J.S., Eilertsen, R.S., Salomonsen, G.R., Vorren, T.O., in press. Submarine push moraine formation during the early Fennoscandian Ice Sheet deglaciation. *Quat. Res.*
- Larsen, E., Kjær, K., Demidov, I.N., Funder, S., Grøsfjeld, K., Hnoumark-Nielsen, M., Jensen, M., Linge, H., Lyså, A., 2006. Late Pleistocene glacial and lake history of northwestern Russia. *Boreas* 35, 394–424.
- Lehman, S.J., Jones, G.A., Keigwin, L.D., Andersen, E.S., Butenko, G., Østmo, S.R., 1991. Initiation of Fennoscandian ice-sheet retreat during the last deglaciation. *Nature* 349, 513–516.
- Lekens, W., Sejrup, H.P., Hafliðason, H., Petersen, G.Ø., Hjelstuen, B.O., Knorr, G., 2005. Laminated sediments preceding Heinrich Event 1 in the Northern North Sea and Southern Norwegian Sea; origin, processes and regional linkage. *Mar. Geol.* 216, 27–50.
- Longva, O., Thorsnes, T., 1997. Skagerrak in the past and at the present — an integrated study of geology, geochemistry, hydrography and microfossil ecology. *Norges Geologiske Undersøkelse Special Publication*, vol. 8. 100 pp.
- Løseth, H., Tveten, E., 1996. Post-Caledonian structural evolution of the Lofoten and Vesterålen offshore and onshore areas. *Nor. Geol. Tidsskr.* 76, 215–230.
- Lubinski, D.J., Korsun, S., Polyak, L., Forman, S.L., Lehman, S.J., Herlihy, F.A., 1996. The last deglaciation of the Franz Victoria Trough, northern Barents Sea. *Boreas* 25, 89–100.
- Mangerud, J., Andersen, S.V., Berglund, B.E., Donner, J.J., 1974. Quaternary stratigraphy of Norden, a proposal for terminology and classification. *Boreas* 3, 109–128.
- McCabe, A.M., Clark, P.U., 1998. Ice-sheet variability around the North Atlantic Ocean during the last deglaciation. *Nature* 392, 373–377.
- McMullen, K., Domack, E., Leventer, A., Olson, C., Dunbar, R., Brachfeld, S., 2006. Glacial morphology and sediment formation in the Mertz Trough, East Antarctica. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 231, 169–180.
- Melezhik, V.A., Robert, D., Gorokhov, I.M., Fallick, A.E., Zwaan, K.B., Kuznetsov, A.B., Pokrovsky, B.G., 2002. Isotopic evidence for a complex Neoproterozoic to Silurian rock assemblage in the North-Central Norwegian Caledonides. *Precambrian Res.* 114, 55–86.
- Melezhik, V.A., Zwaan, K.B., Motuza, G., Robert, D., Solli, A., Fallick, A.E., Gorokhov, I.M., Kuznetsov, A.B., 2003. New insights into the geology of high-grade Caledonian marbles based on isotope chemostratigraphy. *Nor. J. Geol.* 83, 209–242.
- Mitchelson-Jacob, G., Sundby, S., 2001. Eddies of Vestfjorden, Norway. *Cont. Shelf Res.* 21, 1901–1918.
- Norges Byggstandardiseringsråd, 1988. Geoteknisk prøving. Laboratoriemetoder. Bestemmelse av udrenert skjærstyrke ved konusprøving. Norsk Standard, vol. 8015. 11 pp.
- Nørgaard-Pedersen, N., Spielhagen, R.F., Thiede, J., Kassens, H., 1998. Central Arctic surface environment during the past 80,000 years. *Paleoceanography* 13, 193–204.
- Nygård, A., Sejrup, H.P., Hafliðason, H., Cecci, M., Ottesen, D., 2004. The deglaciation history of the southwestern Fennoscandian Ice Sheet between 15 and 13 ¹⁴C ka. *Boreas* 33, 1–17.
- Nygård, A., Sejrup, H.P., Hafliðason, H., Bryn, P., 2005. The glacial North Sea Fan, southern Norwegian Margin: architecture and evolution from the upper continental slope to the deep-sea basin. *Mar. Petrol. Geol.* 22, 71–84.
- Ó Cofaigh, C., Dowdeswell, J.A., 2001. Laminated sediments in glaciomarine environments: diagnostic criteria for their interpretation. *Quat. Sci. Rev.* 20, 1411–1436.
- Ó Cofaigh, C., Taylor, J., Dowdeswell, J.A., Pudsey, C.J., 2003. Palaeo-ice streams, trough mouth fans and high latitude continental slope sedimentation. *Boreas* 32, 37–55.
- Olsen, L., 2002. Mid and Late Weichselian ice-sheet fluctuations northwest of the Svartisen glacier, Nordland, northern Norway. *Geol. Surv. Nor. Bull.* 440, 39–52.
- Olsen, L., Sveian, H., van der Borg, K., Bergström, B., Broekmans, M., 2002. Rapid and rhythmic ice sheet fluctuations in western Scandinavia 15–40 kyr — a review. *Polar Res.* 21, 235–242.
- Ottesen, D., Rise, L., Rokoengen, K., Sættem, J., 2001. Glacial processes and large-scale morphology on the mid-Norwegian continental shelf. In: Martinsen, O.J., Dreyer, T. (Eds.), *Sedimentary Environments Offshore Norway — Palaeozoic to Recent*. NPF Spec. Publ. vol. 10. Elsevier, Amsterdam, pp. 439–447.
- Ottesen, D., Dowdeswell, J.A., Rise, L., 2005a. Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: the 2,500 km-long Norwegian–Svalbard margin (57°N to 80°N). *Geol. Soc. Amer. Bull.* 117, 1033–1050.
- Ottesen, D., Rise, L., Knies, J., Olsen, L., Henriksen, S., 2005b. The Vestfjorden–Trænadjupet paleo-ice stream drainage system, mid-Norwegian continental shelf. *Mar. Geol.* 218, 175–189.
- Petschick, R., Kuhn, G., Ginge, F.X., 1996. Clay mineral distribution in surface sediments of the South Atlantic: sources, transport, and relation to oceanography. *Mar. Geol.* 130, 203–229.
- Polyak, L., Forman, S.L., Herlihy, F.A., Ivanov, G., Krinitsky, P., 1997. Late Weichselian deglacial history of the Svyataya (Saint) Anna Trough, northern Kara Sea, Arctic Russia. *Mar. Geol.* 143, 169–188.
- Polyak, L., Solheim, A., 1994. Late- and postglacial environments in the northern Barents Sea west of Franz Josef Land. *Polar Res.* 13, 197–207.
- Reite, A., 1994. Weichselian and Holocene geology of Sør-Trøndelag and adjacent parts of Nord-Trøndelag country, Central Norway. *Geol. Surv. Nor. Bull.* 426, 1–30.
- Rise, L., Ottesen, D., Berg, K., Lundin, E., 2005. Large-scale development of the mid-Norwegian shelf and margin during the last 3 million years. *Mar. Petrol. Geol.* 22, 33–44.
- Rise, L., Bøe, R., Lyså, A., Olsen, H.A., Sveian, H., in press. Quaternary stratigraphy and deglaciation history of Trondheimsfjorden, central Norway. *Norwegian Journal of Geology*.
- Roberts, D., Gee, D., 1985. An introduction to the structure of the Scandinavian Caledonides. In: Gee, D.G., Sturt, B.A. (Eds.), *The Caledonide Orogen — Scandinavia and Related Areas*. Part 1. Wiley, Chichester, pp. 55–68.
- Rokoengen, K., Sættem, J., 1983. Shallow bedrock geology and Quaternary thickness off northern Helgeland, Vestfjorden and Lofoten. Continental Shelf Institute (IKU) Project report P-155/2/83.

- Rokoengen, K., Frengstad, B., 1999. Radiocarbon and seismic evidence of ice-sheet extent and the last deglaciation on the mid-Norwegian continental shelf. *Nor. Geol. Tidsskr.* 79, 129–132.
- Samthein, M., Jansen, E., Weinelt, M., Amhold, M., Duplessy, J.C., Erlenkeuser, H., Flatøy, A., Johannessen, G., Jung, S., Koç, N., Labeyrie, L., Maslin, M., Pflaumann, U., Schulz, H., 1995. Variations in Atlantic surface ocean paleoceanography, 50–80°N: a time-slice record of the last 30,000 years. *Paleoceanography* 10, 1063–1094.
- Samthein, M., Stattegger, K., Dreger, D., Erlenkeuser, H., Grootes, P., Haupt, B.J., Jung, S., Kiefer, T., Kuhnt, W., Pflaumann, U., Schäfer-Neth, C., Schulz, H., Schulz, M., Seidov, D., Simstich, J., van Kreveld, S., Vogelsang, E., Völker, A., Weinelt, M., 2001. Fundamental modes and abrupt changes in North Atlantic circulation and climate over the last 60 ky — concepts, reconstruction and numerical modeling, in the northern North Atlantic: a changing environment. In: Schäfer, P., Ritzrau, W., Schlüter, M., Thiede, J. (Eds.), Springer Verlag, Berlin, pp. 365–410.
- Schulz, H., von Rad, U., Erlenkeuser, H., 1998. Correlation between Arabian Sea and Greenland climate oscillations of the past 110,000 years. *Nature* 393, 54–57.
- Sejrup, H.P., Hafliðason, H., Aarseth, I., Forsberg, C.F., King, E., Long, D., Rokoengen, K., 1994. Late Weichselian glaciation history of the northern North Sea. *Boreas* 23, 1–13.
- Sejrup, H.P., Larsen, E., Landvik, J., King, E.L., Hafliðason, H., Nesje, A., 2000. Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the northern North Sea region. *Quat. Sci. Rev.* 19, 667–685.
- Sejrup, H.P., Larsen, E., Hafliðason, H., Berstad, I.M., Hjelstuen, B.O., Jonsdottir, H., King, E.L., Landvik, J., Longva, O., Nygård, A., Ottesen, D., Raunholm, S., Rise, L., Stalsberg, K., 2003. Configuration, history and impact of the Norwegian Channel Ice Stream. *Boreas* 32, 18–36.
- Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Hafliðason, H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M.S., Vorren, T.O., 2005. Pleistocene glacial history of the NW European continental margin. *Mar. Petrol. Geol.* 22, 1111–1129.
- Stuiver, M., Pearson, G.W., Braziunas, T.F., 1986. Radiocarbon age calibration of marine samples back to 9000 cal. yr BP. *Radiocarbon* 28, 980–1021.
- Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J., Spurk, M., 1998. INTCAL98 radiocarbon age calibration, 24000–0 cal BP. *Radiocarbon* 40, 1041–1083.
- Svendsen, J.I., Mangerud, J., 1987. Late Weichselian and Holocene sea-level history for a cross-section of western Norway. *J. Quat. Sci.* 2, 113–132.
- Svendsen, J.I., Mangerud, J., 1990. Sea-level changes and pollen stratigraphy on the outer coast of Sunnmøre, western Norway. *Nor. Geol. Tidsskr.* 70, 111–134.
- Svendsen, J.I., Elverhøi, A., Mangerud, J., 1996. The retreat of the Barents Sea ice sheet on the western Svalbard margin. *Boreas* 25, 244–256.
- Tull, J.F., Bartley, J.M., Hodges, K.V., Andresen, A., Steltenpohl, M.G., White, J.M., 1985. The Caledonides in the Ofoten region (68–69° N), north Norway: key aspects of tectonic evolution. In: Gee, D.G., Sturt, B.A. (Eds.), *The Caledonide Orogen — Scandinavia and Related Areas*. Part 1. Wiley, Chichester, pp. 553–568.
- Vogt, C., 1997. Regional and temporal variations of mineral assemblages in Arctic Ocean sediments as climatic indicator during glacial/interglacial changes. *Rep. Polar Res.*, vol. 251. 309 pp.
- Vogt, C., Knies, J., Spielhagen, R.F., Stein, R., 2001. Detailed mineralogical evidence for two nearly identical glacial/deglacial cycles and Atlantic water advection to the Arctic Ocean during the last 90,000 years. *Glob. Planet. Change* 31, 23–44.
- Vorren, K.D., Alm, T., 1999. Late Weichselian and Holocene environments of lake Endletvatn, Andøya, northern Norway: as evidenced primarily by chemostratigraphical data. *Boreas* 28, 505–520.
- Vorren, T.O., Elvsborg, A., 1979. Late Weichselian deglaciation and paleoenvironment of the shelf and coastal areas of Troms, north Norway — a review. *Boreas* 8, 247–253.
- Vorren, T., Plassen, L., 2002. Deglaciation and palaeoclimate of the Andfjord–Vågsfjord area, North Norway. *Boreas* 31, 97–125.
- Vorren, T.O., Edvardsen, M., Hald, M., Thomsen, E., 1983. Deglaciation of the continental shelf off southern Troms, North Norway. *Nor. Geol. Unders. Bull.* 380, 173–187.
- Vorren, T.O., Hald, M., Lebesbye, E., 1988. Late Cenozoic environment in the Barents Sea. *Paleoceanography* 3, 601–612.
- Wang, Y.J., Cheng, H., Edwards, R.L., An, Z.S., Wu, J.Y., Shen, C.-C., Dorale, J.A., 2001. A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China. *Science* 294, 2345–2348.