Postglacial mass movements and their causes in fjords and lakes in western Norway

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Seismic profiles and sediment cores from sixteen fjords and five lakes in western Norway have been investigated in a search for Holocene mass-movement deposits. Tsunami deposits caused by the Storegga Slide (8200 cal. BP) are observed over most of the investigated area, both in fjords and in lakes. Five fjords provide evidence for a 2000-2200 cal. BP mass-movement event. Debris flow deposits and turbidites related to that event occur in Sunnmøre and Sunnfjord, suggesting triggering by one or more earthquakes close to the coast or on land. Similar mass-movement deposits occur in the same geographical area at 11 000-11 700 cal. BP. A period of debris flows, turbidity currents and snow avalanches, interpreted to be related to climatic irregularities, occurred around 2800-3200 cal. BP. Such events are recorded also from other periods, e.g. 1700-1800 cal. BP and 5300-5600 cal. BP, but they only occur in a few basins, and were thus probably related to local weather irregularities rather than regional climatic changes.

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Introduction

Sediment successions from Norwegian fjords record a wide variety of mass-movement processes (Terzagi 1957, Holtedahl 1965, Bjerrum 1971, Flaate & Janbu 1975, Karlsrud & By 1982, Syvitski et al. 1987, Aarseth et al. 1989, Emdal et al. 1996, Bøe et al. 2000, 2003). In many fjords gravitational mass movements are among the most pronounced sedimentary processes, and an understanding of these processes and triggering mechanisms are of vital importance when using fjord sediments to deduce past climatic changes and tectonic events.

The Norwegian coast was hit by a large tsunami caused by the Storegga Slide (Fig. 1) at 8200 cal. BP (Bondevik et al. 1997a, b, Bryn et al. 2002). The tsunami is recognized in the sedimentary record of coastal lakes as an erosional unconformity overlain by graded or massive sand with shell fragments, followed by redeposited organic detritus. These features can be seen along the coast, the highest levels being 10-11 m above the sea level of the time and in areas most proximal to the slide scar, in Sunnmøre.

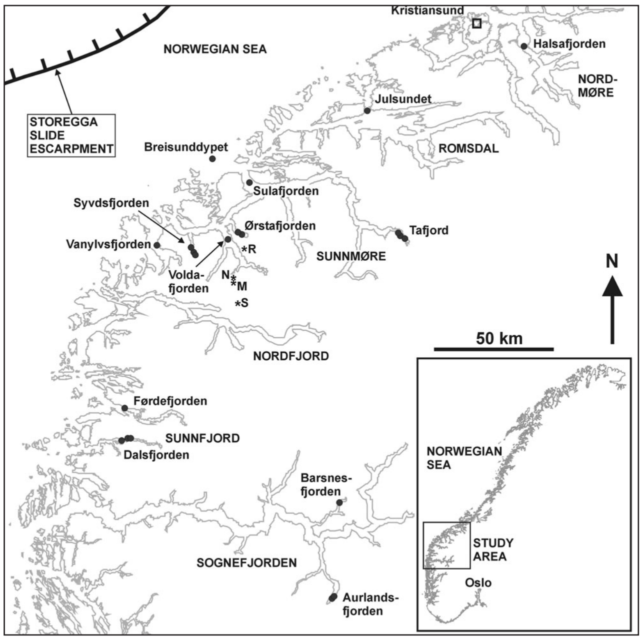

Fig. 1. Map of northwestern Norway showing the location of investigated fjords and lakes and position of fjord cores. M: Medvatnet; N: Nedstevatnet; R: Rotevatnet; S: Storsætervatnet.

Sejrup et al. (2001) investigated an 8.5 m long core from Voldafjorden in Sunnmøre (Fig. 1) and found turbidites at the ca. 2000, 8200 and 11 000 cal. BP levels. The 8200 cal. BP mass-movement event was correlated to the Storegga Slide tsunami (Bondevik et al. 1998; Grøsfjeld et al. 1999; Sejrup et al. 2001). Longva et al.

(2001) correlated the 2000 and 8200 cal. BP turbidites to seismic reflectors that occur at the level of major debris flow deposits along the submarine slopes of Voldafjorden. This suggested that both events could possibly be related to large tsunamis caused by offshore mega-slides (Longva et al. 2001). Similar debris-flow deposits were observed in seismic data from other fjords between Sognefjorden and Kristiansund (Fig. 1), and occasionally occur at the same stratigraphic level as in Voldafjorden.

A major task in the present study has been to map mass-movement deposits and to assess their triggering mechanisms. Possible links to climatic irregularities, tsunamis caused by offshore megaslides or earthquakes have been of particular interest, but other causes are also discussed.

Methods

Swath bathymetric data (EM 100, EM 1002 and EM 300) were acquired from fjords in Sogn og Fjordane and Møre og Romsdal during 1999-2001 by Statens Kartverk (Sjøkartverket), Fugro and GeoConsult under contract to the Geological Survey of Norway (NGU) and Norsk Hydro (NH). Shallow seismic data were acquired by NGU during 1997-2001 and by NH in 2001. Sleevegun, Geopulse, Topas, Pinger and Sparker were used alone or in combination on the various cruises. Penetration echosounder data from five lakes were obtained by GeoCore under contract to NGU in 2001.

Coring locations were chosen after interpretation of the seismic and acoustic data. The majority of the cores were aimed at penetrating mass-movement deposits. Cores were obtained from 41 fjord locations using HYBAV vibrocorer, gravity corer and Selcore, and from 26 locations in five lakes using piston corer (Fig. 1). All cores were investigated by means of X-ray inspection (XRI) and multi-sensor core logging (MSCL). Cores containing mass-movement deposits were sedimentologically described, and subsampled for grain-size analysis and ^{14}C-dating. In this paper we mainly treat sediment cores that have been dated; full datasets can be found in Bøe et al. (2002) and Lepland et al. (2002). AMS ^{14}C dating on foraminifers was performed to determine the age of mass movements in fjords, while the majority of the lake samples were dated by the conventional ^{14}C-method. Calibrated years before 1950 (cal. BP) are presented in the text; complete dating results with standard deviations are given in Tables 1 and 2.

Sediment cores from lakes at different elevations were studied because mass-movement deposits of the same age at both high and low elevations could indicate a local earthquake whereas tsunami deposits can only occur in lakes reached by the tsunami wave, at low elevations. Lakes close to Voldafjorden were chosen for detailed studies, as the stratigraphy and presence of mass-movement deposits in this fjord were well documented (Sejrup et al. 2001). Depositional ages of thin, mass-movement layers in lake gyttja were determined on samples containing equal amounts of material from above and below the layers. The Vedde Ash, deposited at ca. 12 000 cal. BP (Birks et al. 1996), is commonly recognized in the upper part of the glaciomarine/glaciolacustrine sediments, below the Holocene sequence.

Stratigraphy and mass-movement deposits in fjords and lakes

Sulafjorden – turbidites, tsunami deposits and debris-flow deposits

Swath bathymetry (Fig. 2) and seismic data (Fig. 3) show several debris-flow wedges along the margins of Sulafjorden. All the wedges appear to occur at the same stratigraphic level and extend up to ca. 1 km out from the fjord margins. A pronounced set of reflectors extends out from the wedges across the fjord basin.

Core NGU-2L/SC, from the central part of the fjord comprises, in its upper part (0-3.15 m) olive grey, homogeneous, strongly bioturbated clayey silt/silty clay with many shells and shell fragments (Fig. 4). The seismic data indicate homogeneous sediments over this interval (Fig. 3). Samples at 0.10 m, 1.84 m and 3.08 m depth gave ages of 614 cal. BP, 4851 cal. BP and 8111 cal. BP, respectively. No event younger than 8111 cal. BP is recorded in the core.

The lower part of NGU-2L/SC comprises a sequence fining up from fine sand to clay (Fig. 4). The sand in the lower part is planar and cross laminated. The age of 8111 cal. BP immediately above the upward fining unit suggests that it represents a turbidite deposited at the time of the Storegga Slide. Hagen (1981) described an interval of alternating coarse- and fine-grained layers at 1.87-3.45 m depth in a piston core from a nearby location (444 m water depth). His descriptions point to a tsunami deposit (see below) embedded in hemipelagic silty clays, probably also deposited at the time of the Storegga Slide. The base of the upward fining unit in NGU-2L/SC is not evident from the seismic data but the seismic and core data (Fig. 3) clearly show that the debris flow deposits along the margins of Sulafjorden are older than the Storegga Slide.

Storegga Slide (8200 BP) tsunami deposits have been studied by Bondevik et al. (1997b) in shallow marine basins and coastal lakes in western Norway. An erosio-

Table 1. ^{14}C dating results, fjord cores.

Fjord	Core ID	Depth (m)	Sample No.	Lab. No.	Species	Sample weight (mg)	Uncorrected ^{14}C age (BP)	^{13}C (‰) V-PDB	Reservoir corrected ^{14}C age (BP)	Calendar-year age (BP)
Barsnesfjorden	P0103008	0.18-0.23	2001-6	ETH-25050	*Globobulimina sp., Uvigerina mediterranea*	8,5	1215 ± 65	1.0 ± 1.2	815 ± 65	**736** (824-672)
Barsnesfjorden	P0103008	1.06-1.11	2001-7	ETH-25051	*Nonionellina labradorica*	5,2	2030 ± 60	1.6 ± 1.2	1630 ± 60	**1578** (1681-1514)
Dalsfjorden	P0103012	1.37-1.42	2001-10	ETH-25053	*Globobulimina sp., Cibicides sp.*	5,5	8905 ± 90	1.0 ± 1.2	8505 ± 90	**9458** (9765-9108)
Dalsfjorden	P0103013	0.92-1.02	2001-11	ETH-25492	*Mixed benthic foraminifera*	9.1	2600 ± 55	0.2 ± 1.2	2200 ± 55	**2297** (2331-2182)
Førdefjorden	P0103014	0.55-0.6	2001-13	ETH-25054	*Uvigerina mediterranea, Hyalinea balthica*	11,2	2640 ± 55	-0.7 ± 1.2	2240 ± 55	**2320** (2348-2285)
Vanylvsfjorden	P0103015	1.14-1.19	2001-14	ETH-24864	*Uvigerina mediterranea, Hyalinea balthica*	11	3190 ± 55	1.3 ± 1.2	2790 ± 55	**2962** (3064-2881)
Syvdsfjorden	P0103019	1.5-1.55	2001-15	ETH-24865	*Globobulimina sp.*	14	2665 ± 50	1.1 ± 1.2	2265 ± 50	**2333** (2359-2301)
Tafjorden	P0103026	0.28-0.33	2001-16	ETH-24866	*Globobulimina sp., Bulimina marginata, Uvigerina mediterranea*	8,6	1090 ± 55	2.7 ± 1.2	690 ± 55	**647** (679-616)
Tafjorden	P0103026	0.86-0.91	2001-18	ETH-25055	*Globobulimina sp., Uvigerina mediterranea, Hyalinea balthica*	9,4	3300 ± 70	1.0 ± 1.2	2900 ± 70	**3141** (3239-3021)
Aurlandsfjorden	P0103002	1.5-1.55	2001-21	ETH-25056	*Globobulimina sp., Uvigerina mediterranea*	7,5	3040 ± 70	2.0 ± 1.2	2640 ± 70	**2778** (2866-2736)
Breisunddjupet	HM129-03	1.58-1.63	2001-22	ETH-24867	*Uvigerina mediterranea, Hyalinea balthica*	9,5	3480 ± 60	0.8 ± 1.2	3080 ± 60	**3352** (3419-3297)
Breisunddjupet	HM129-03	1.41-1.46	2001-23	ETH-24868	*Uvigerina mediterranea, Hyalinea balthica*	11	7775 ± 65	-2.1 ± 1.2	7375 ± 65	**8204** (8321-8156)
Ørstafjorden	ØrstaGC1A	0.76-0.81	2001-24	ETH-24869	*Globobulimina sp.*	9,2	2760 ± 60	1.8 ± 1.2	2360 ± 60	**2454** (2605-2345)
Julsundet	NGU-6L/SC	0.71-0.75	2001-27	ETH-25317	*Hyalinea balthica*	18.1	3365 ± 55	0.2 ± 1.2	2965 ± 55	**3222** (3313-3148)
Julsundet	NGU-6L/SC	2.64-2.65	2001-28	ETH-25301	*Astarte sp. (Astarte sulcata)*	235.6	8885 ± 65	-0.2 ± 1.2	8485 ± 65	**9447** (9753-9106)

Table 1. Continued

Fjord	Core ID	Depth (m)	Sample No.	Lab. No.	Species	Sample weight (mg)	Uncorrected ^{14}C age (BP)	^{13}C (‰) V-PDB	Reservoir corrected ^{14}C age (BP)	Calendar-year age (BP)
Julsundet	NGU-6L/SC	5.07-5.11	2001-30	ETH-25318	*Melonis barleeanum*	33.6	10650 ± 75	1.9 ± 1.2	10250 ± 75	**11900, 11839,11723** (12269-11493)
Halsafjorden	NGU-4L/SC	0.06-0.07	-	KIA-18995	*Hyalinea balthica, Melonis barleeanum, Globobulimina sp.*	12.0	620 ± 25	-4.96 ± 0.1	220 ± 25	**272** (240-286)
Halsafjorden	NGU-4L/SC	1.51-1.55	2001-32	ETH-25319	*Hyalinea baltica*	24.9	3650 ± 50	2.2 ± 1.2	3250 ± 50	**3548** (3621-3464)
Halsafjorden	NGU-4L/SC	3.71-3.75	2001-33	ETH-25302	*Shell fragments*	15.9	7930 ± 75	0.3 ± 1.2	7530 ± 75	**8374** (8429-8322)
Halsafjorden	NGU-4L/SC	6.51-6.55	2001-36	ETH-25320	*Melonis barleeanum, Nonionellina labradorica*	20.4	12080 ± 80	3.6 ± 1.2	11680 ± 80	**13484** (13806-13413)
Sulafjorden	NGU-2L/SC	0.10.0.11	-	KIA-18996	*Hyalinea balthica*	16.7	1020 ± 30	-2.90 ± 0.17	620 ± 30	**614** (567-625)
Sulafjorden	NGU-2L/SC	3.04-3.08	2001-37	ETH-25321	*Uvigerina mediterranea*	46.6	7660 ± 65	1.3 ± 1.2	7260 ± 65	**8111** (8172-8012)
Sulafjorden	NGU-2L/SC	1.82-1.86	2001-38	ETH-25322	*Hyalinea balthica*	24.7	4665 ± 55	0.5 ± 1.2	4265 ± 55	**4851** (4949-4819)
Halsafjorden	NGU-4L/SC	4.98-5.02	2001-39	ETH-25493	*Melonis barleeanum, Noninonellina labradoricum, Globobulimina sp.*	31.2	10560 ± 75	-4.0 ± 1.2	10160 ± 75	**11657** (11913-11355)
Julsundet	NGU-6L/SC	0.45-0.50	2001-42	ETH-25667	*Mixed benthic foraminifera and gastropods*	9.1	3875 ± 60	2.2 ± 1.2	3475 ± 60	**3828** (3906-3725)
Ørstafjorden	ØrstaGC1A	0.49-0.52	2001-43	ETH-25669	*Globobulimina sp.*	35.7	2120 ± 50	0.1 ± 1.2	1720 ± 50	**1695** (1769-1615)
Breisunddjupet	HM129-04	0.25-0.30	2001-45	ETH-25670	*Uvigerina mediterranea*	35.0	4720 ± 55	0.8 ± 1.2	4320 ± 55	**4940** (5026-4847)
Breisunddjupet	HM129-04	2.29-2.34	2001-46	ETH-25668	*Shells (whole with periostracum)*	12.9	6530 ± 65	0.1 ± 1.2	6130 ± 65	**7011** (7147-6934)
Syvdsfjorden	P0103019	0.84-0.88	2001-47	ETH-25671	*Globobulimina sp.*	38.1	2185 ± 50	-2.6 ± 1.2	1785 ± 50	**1780** (1837-1701)

Table 2. ^{14}C dating results, lake cores.

Lake	Core ID	Depth (cm)	Sample ID	Lab. No.	Material	Sample weight (g)	Age ^{14}C (BP)	Calendar-year age (BP)	^{13}C (‰)	Remarks
Storsætervatnet	S1	72-77	S1-72	T-15551A	gyttja	5	4895±70	**5607** (5661-5590)	-29,2	Above and beneath 9 mm silt lamina
Storsætervatnet	S4	181-183	S4-181	T-15552A	gyttja	7,1	8195±135	**9181** (9416-9008)	-27,2	Above hiatus silt/gyttja
Storsætervatnet	S6	152-157	S6-154	T-15553A	gyttja	4,5	8055±150	**9006** (9243-8649)	-26,8	Above hiatus silt/gyttja
Storsætervatnet	S9	129-133	S9-133	T-15554A	gyttja	5,6	2585±80	**2744** (2765-2545)	-29	Above gravelly sand layer
Storsætervatnet	S9	144-147	S9-144	T-15555A	gyttja	5,2	7895±115	**8643** (8995-8544)	-29,8	Below gravelly sand layer
Storsætervatnet	S9	181-179	S9-180	T-15556A	gyttja	1,9	8285±145	**9366** (9473-9030)	-28,4	Above and beneath 1 cm sand layer
Storsætervatnet	S10	474	S10-474	TUa-3340A	gyttja	not determined	11345±75	**13254** (13448-13159)	-26,8	Organic laminae below Vedde Ash
Medvatnet	M2	60-64	M2-62	T-15513A	gyttja	2,3	3090±95	**3279** (3389-3167)	-29,9	Above and below 2 cm gravelly silt layer
Medvatnet	M2	160-164	M2-160	T-15557A	gyttja	3,4	4855±120	**5594** (5710-5472)	-29,3	Below pebbles and sand/silt clasts
Medvatnet	M4	90-93	M4-91	T-15514A	gyttja	3,3	3220±105	**3449** (3567-3355)	-28,6	Above and below 2 thin silt lamina
Medvatnet	M6	0-4	M6-02	T-15515A	gyttja	1,6	2505±80	**2619** (2745-2362)	-29,7	Above 9 cm thick sand layer
Nedstevatnet	N2	10-14	N2-12	T-15516A	gyttja	1,9	2880±105	**2979** (3207-2865)	-29,7	Above thick layer containing sand clasts
Nedstevatnet	N2	40-45	N2-42	T-15517A	gyttja	4,9	5780±80	**6600** (6718-6454)	-27,7	Below thick layer containing sand clasts
Nedstevatnet	N2	99-105	N2-103	T-15518A	gyttja	4,3	6430±65	**7367** (7425-7270)	-26,4	Above and below silt/sand lamina
Nedstevatnet	N3	42-45	N3-40	T-15558A	gyttja	3,5	5950±95	**6772** (6889-6667)	-27	Beneath 2 cm thick sand layer
Nedstevatnet	N3	300-306	N3-300	T-15520	shell	not determined	11030±70	**13009** (13146-12907)	-1 (assumed)	diamicton containing Astarte and M. truncata
Nedstevatnet	N3	270	N3-270	T-15519	shell	not determined	10225±120	**11793** (12325-11644)	-1 (assumed)	diamicton containing Mya truncata
Nedstevatnet	N5	14-18	N5-16	T-15521A	gyttja	2,8	2235±75	**2208** (2343-2132)	-29,1	Above tsunami layer
Nedstevatnet	N5	90-91	N5-90	TUa-3322a	gyttja	not determined	8805±80	**9845** (10147-9695)	-28	Above 2 thin sand lamina
Nedstevatnet	N5	96	N5-96	TUa-3341A	gyttja	not determined	9310±65	**10434** (10636-10405)	-26,8	2 mm thick gyttja lamina
Nedstevatnet	N5	105-113	N5-109	T-15522A	brown silt	0,8	9985±190	**11316** (11926-11198)	-24	Above and beneath 2 cm gravelly sand layer
Rotevatnet	R1	171-178	R1-175	T-15525A	gyttja	6,4	5880±130	**6700** (6854-6503)	-29,5	Above and beneath 3 mm silt lamina
Rotevatnet	R1	119-125	R1-121	T-15524A	gyttja	6,2	4605±115	**5314** (5469-5053)	-29,4	Above and beneath 2 mm distinct silt lamina
Rotevatnet	R1	21-28	R1-24	T-15523A	gyttja	5,9	1865±100	**1820** (1921-1633)	-29,5	Above and beneath silt lamina

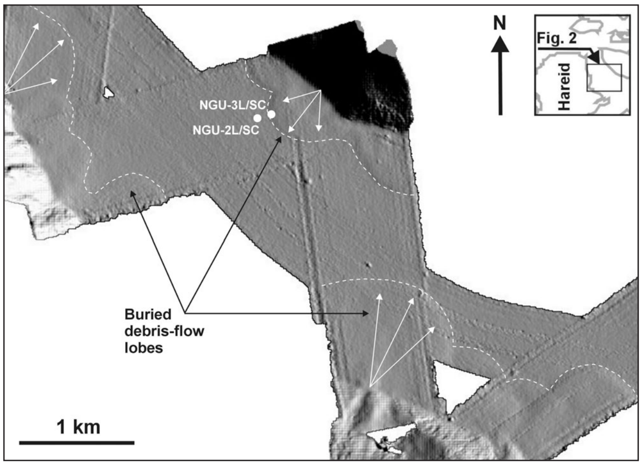

Fig. 2. Shaded relief image of multibeam bathymetric data and core locations, Sulafjorden. Illuminated from the northeast.White arrows indicate sediment transport direction of buried debris-flow lobes. See inset map and Fig. 1 for location.

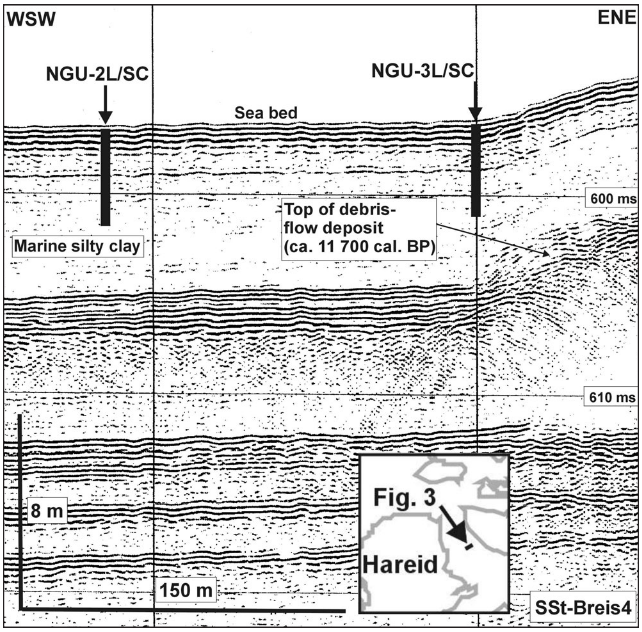

Fig. 3. Seismic profile (Sparker) with core locations, Sulafjorden. A sound velocity of 1600 m/s was used for conversion of milliseconds to meters. Vertical exaggeration ca. x 10. See inset map and Fig. 1 for location.

nal unconformity underlies the tsunami facies and is traced throughout the basins, with most erosion being found at the seaward portion of the lakes. The lowermost tsunami facies is a graded or massive sand that locally contains marine fossils. The sand bed thins and the grain size decreases in a landward direction. Above follows coarse organic detritus with rip up clasts (organic conglomerate) and finer organic detritus. The tsunami unit generally fines upwards. The higher basins generally show one sand bed, whereas basins closer to the sea level 8200 cal. years ago may show several sand beds separated by organic detritus. These alternations in the lower basins have been interpreted to reflect repeated waves of sea water entering the lakes. In basins that were some metres below sea level at 8200 cal. BP, the tsunami deposits are relatively minerogenic and commonly present as graded sand beds. In some of these basins organic-rich facies occur between the sand beds (Bondevik et al. 1997b).

Although the unit described by Hagen (1981) is probably a tsunami deposit, the typical shallow-water tsunami facies of Bondevik (1997b) has not been observed in cores from the deep fjords investigated in this project. What is commonly observed are turbidites and debris-flow deposits, and the interpretation of such deposits as related to the Storegga Slide tsunami relies on dating results. Gravity-flow deposits contemporary with the Storegga Slide tsunami are in many cases probably secondary features triggered by the tsunami wave passing along the fjord margin. The tsunami wave was not significantly influenced by the local topography, suggesting a very long wave length (Bondevik 1997a). If the Storegga Slide was triggered by an earthquake, this could also have triggered gravity flows along fjord margins.

Julsundet

Seismic data show that acoustically chaotic deposits occur at two stratigraphic levels in Julsundet (Fig. 5); core NGU-6LSC (Fig. 11) penetrates the uppermost one. The uppermost 0.1 m of the core comprises poorly sorted sand with many shells and shell fragments, underlain by olive grey, homogeneous (laminated in upper part), normally graded silty clay. Samples from the lowermost and middle parts of this bed gave ages of 3222 cal. BP and 3828 cal. BP, respectively. Fine sand with many sand-size shell fragments occurs at 0.77-0.88 m. This laminated/layered bed has a sharp, planar upper boundary and a sharp, undulating (load structures) lower boundary. We interpret a pronounced seismic reflector (Fig. 13) to indicate the presence of this bed, which, according to the dating results, has a (minimum) age of 3222 cal. BP.

An upward fining unit with an erosive lower boundary occurs at 0.88-2.67 m core depth (Fig. 4). The unit can be correlated with acoustically chaotic deposits, above a well-defined seismic reflector (Fig. 5). From base to top the unit comprises 1) 5 cm gravel with clasts up to 1 cm and clay clasts from the underlying unit up to 2 cm, 2) a well defined boundary towards planar laminated, upward fining, very coarse to fine sand, 3) cross-laminated and planar laminated, upward fining, fine to very fine sand, 4) planar laminated, upward fining, very fine sand to silt and 5) bioturbated, upward fining clayey silt to silty clay with large burrows in the uppermost part. A shell from the lowermost gravel bed gave an age of 9447 cal. BP. The shell may be reworked from an older

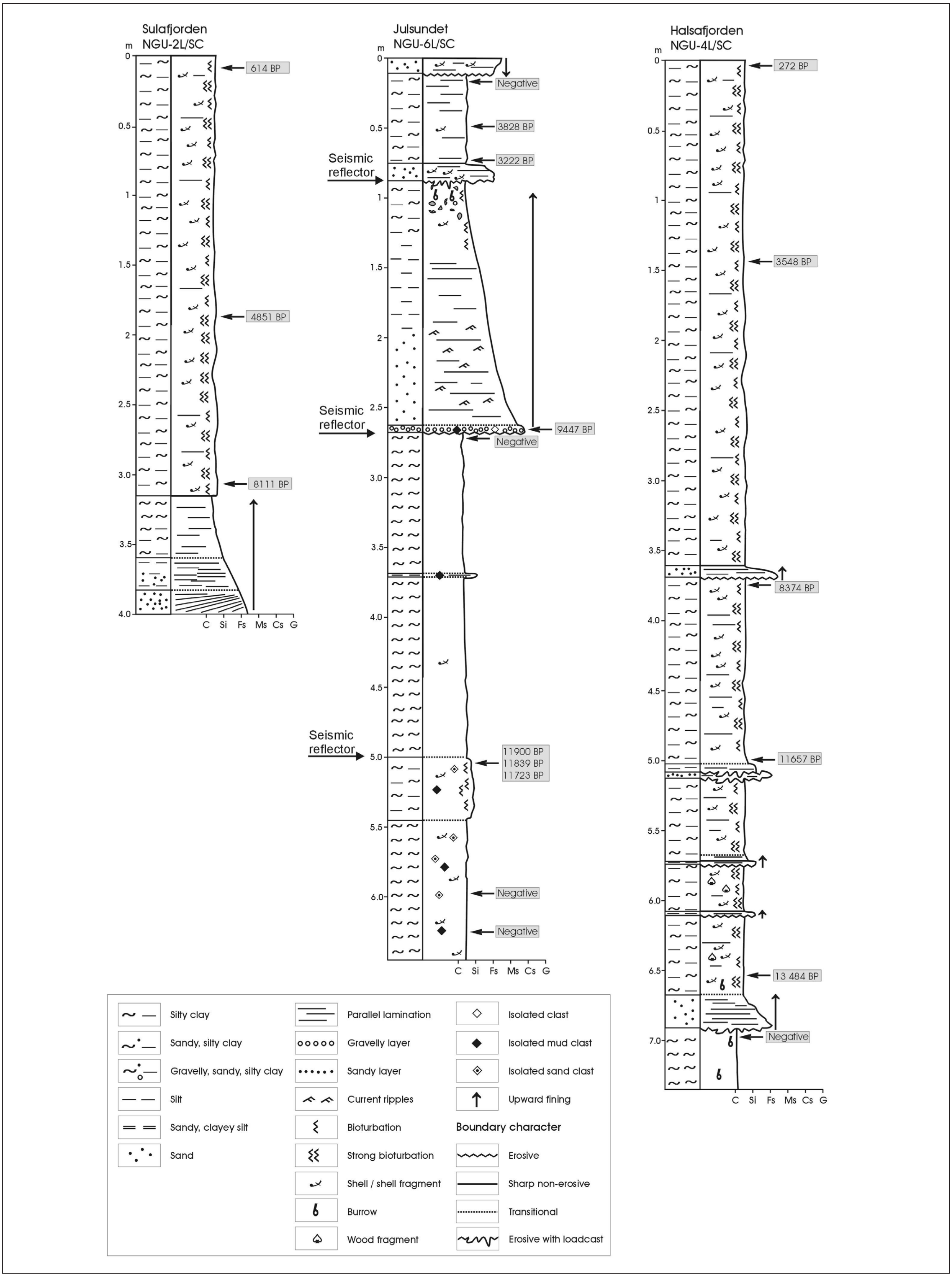

Fig. 4. Lithology of cores and dating results from Sulafjorden, Julsundet and Halsafjorden. 'Negative' indicates sediment samples with too low carbon contents for radiocarbon dating. See Fig. 1 for location of coring stations.

deposit, and the age of 9447 cal. BP thus probably represents a maximum age for the unit. We interpret the upward fining unit to be a turbidite related to the Storegga Slide tsunami.

Homogeneous grey clay occurs at 2.67-5.02 m (Fig. 4), while bioturbated, homogeneous, olive grey silty clay/clayey silt occurs at 5.09-5.47 m. Laminated and partly cemented silt bands are found at 3.70-3.72 m and 5.02-5.09 m. A sample from 5.11 m depth gave an age of ca. 11 800 cal. BP. Homogeneous, olive grey silty clay with many sand clasts up to 15 cm length occurs at 5.47-6.47 cm depth. The sand clasts are rich in shells and shell fragments, and are consolidated/partly cemented. The lowermost sediments are probably glaciomarine in origin, with sand clasts dropped from floating ice.

Halsafjorden

Acoustically chaotic debris-flow deposits occur at three stratigraphic levels along the margins of Halsafjorden. A seismic reflector at the level of the uppermost debris-flow deposit can be traced towards the site of core NGU-4L/SC, where it occurs at 5-6 m depth (Fig. 6). The uppermost 6.91 m of this core (Fig. 4) comprise strongly bioturbated, olive grey, homogeneous silty clay/clayey silt with many shells and shell fragments less than 1 mm in diameter and five normally graded sand and silt turbidites (Fig. 11). Millimeter-scale concretions and rods of authigenic pyrite occur abundantly in the interval 6.11-6.36 m. Homogeneous, light grey clay occurs in the lowermost part of the core.

Samples at 0.06 m and 1.53 m depth gave ages of 272 cal. BP and 3548 cal. BP, respectively. Dates below the uppermost mass-movement deposit and above the second from the top gave ages of 8374 cal. BP and 11 657 cal. BP, which represent maximum and minimum ages for these deposits, respectively. A sample above the lowermost mass-movement deposit gave an age of 13 484 cal. BP, which is its minimum age.

The age of 8374 cal. BP suggests that the graded bed at 3.61-3.70 m can be related to the Storegga Slide tsunami. The uppermost fjord margin debris-flow deposit/seismic reflector at 5-6 m depth can most probably be correlated with the turbidite at 5.02-5.13 m depth in the core, which implies that it is ca. 11 700 cal. years old (older than 11 657 cal. BP).

Aurlandsfjorden

Seismic data show that a large part of the inner fjord basin in Aurlandsfjorden (inner part of Sognefjorden, Fig. 1) is filled by acoustically chaotic slide, debris-flow and rock avalanche deposits, covered by stratified sediments. The 1.64 m long core P0103002 from the inner Aurlandsfjorden consists of homogeneous, bioturbated, dark grey silty clay with some isolated clasts (Fig.

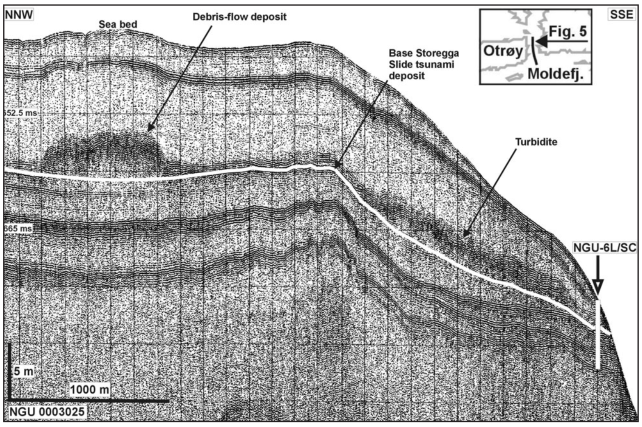

Fig. 5. Seismic profile (Topas) and core location in Julsundet. A sound velocity of 1600 m/s was used for conversion of milliseconds to meters. Vertical exaggeration ca. x 70. See inset map and Fig. 1 for location.

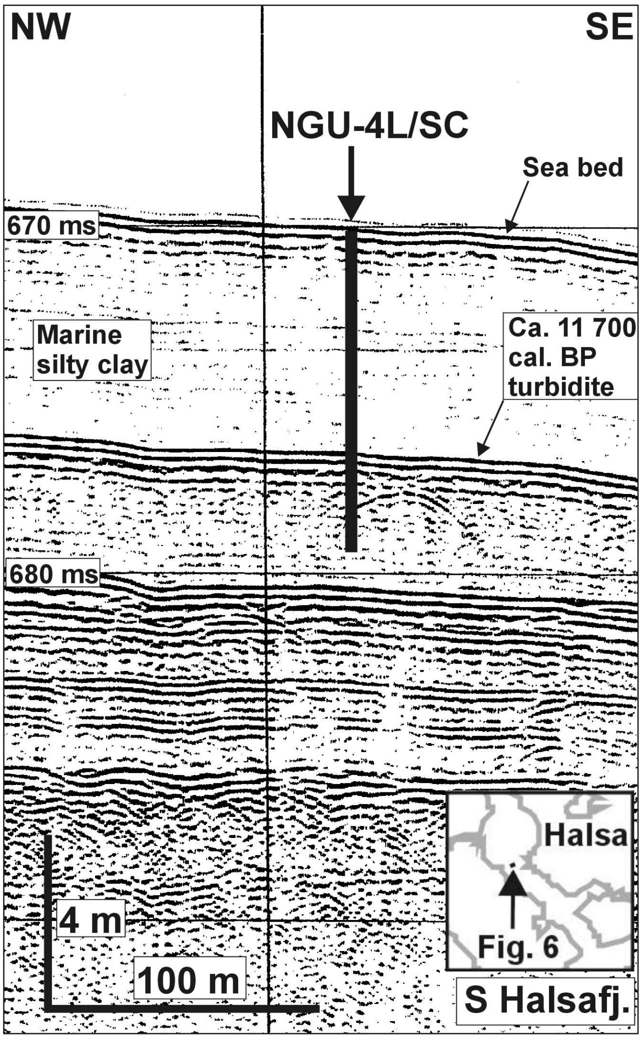

Fig. 6. Seismic profile (Sparker) and core location, Halsafjorden. A sound velocity of 1600 m/s was used for conversion of milliseconds to meters. Vertical exaggeration ca. x 17. See inset map and Fig. 1 for location.

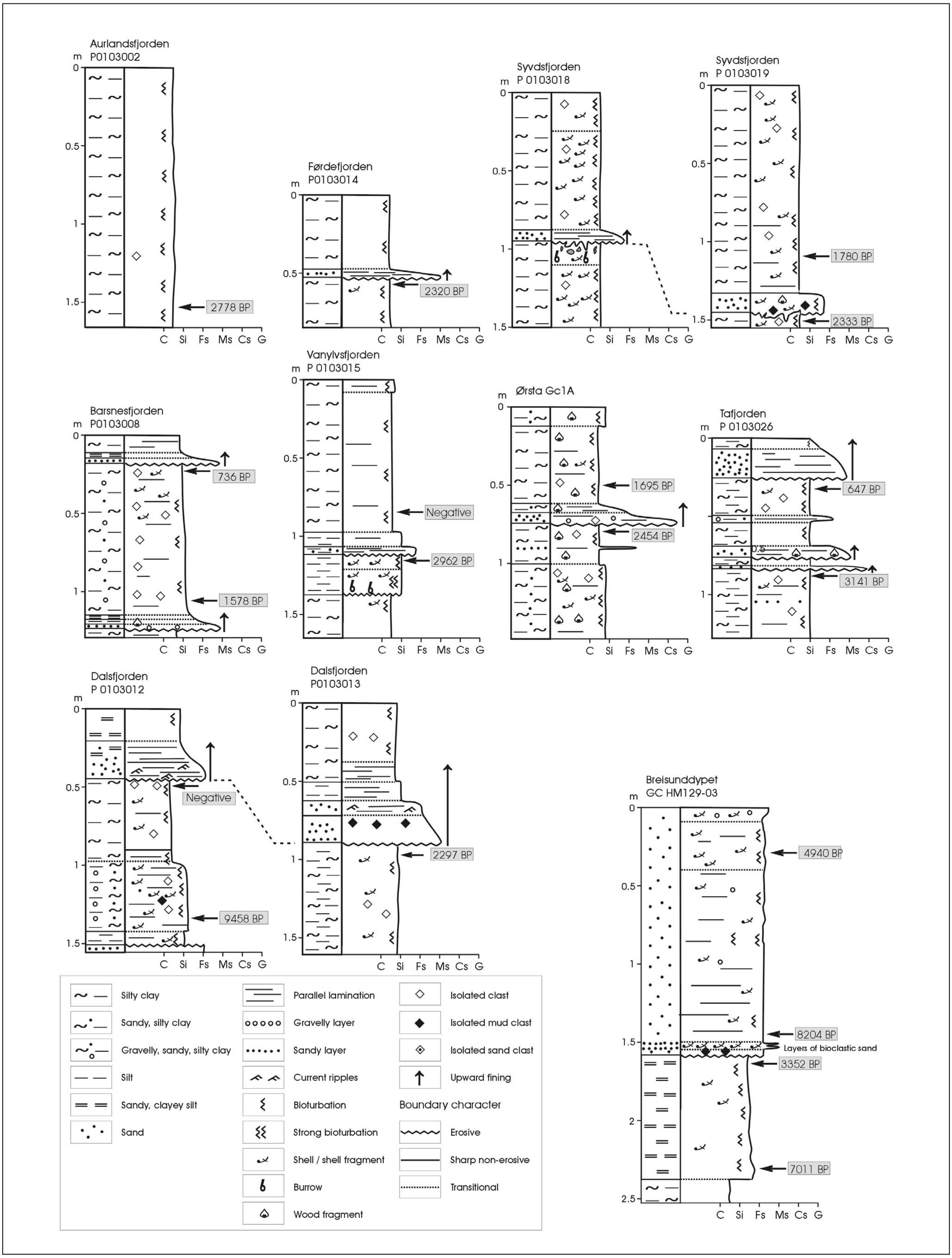

Fig. 7. Lithology and dating results on short gravity cores from Sogn, Sunnfjord and Sunnmøre. 'Negative' indicates sediment samples with too low a carbon content for radiocarbon dating. See Fig. 1 for location of coring sites. The location of cores is also shown in Fig. 9 (Syvdsfjorden), Fig. 13 (Tafjorden) and Fig. 15 (Breisunddypet).

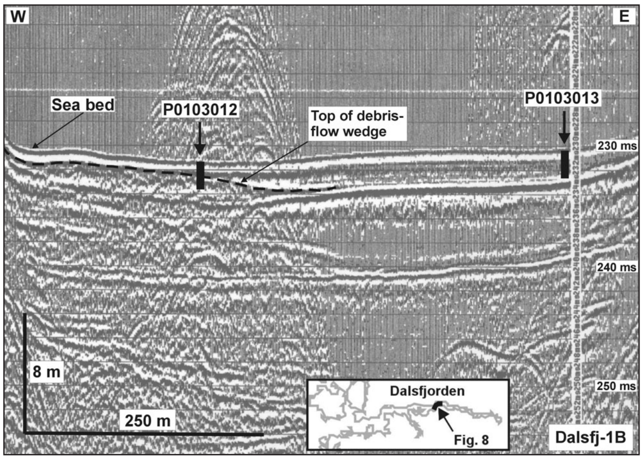

Fig. 8. Seismic profile (Sparker) with core locations, Dalsfjorden. Note that core P0103012 penetrates acoustically chaotic debris flow deposits, in its lowermost part. Vertical exaggeration ca. x 15. See inset map and Fig. 1 for location.

7). Seismic data suggest that debris-flow deposits occur immediately below the base of the core. A sample from the lowermost part of the core gave an age of 2778 cal. BP, showing that in this part of Aurlandsfjorden, there are no traces of any younger mass-movement deposits. The age indicates that the underlying debris-flow deposit is approximately 3000 cal. years old.

Barsnesfjorden

Seismic data show acoustically chaotic deposits along the northwestern margin of the fjord. Core P0103008 comprises silty and sandy laminated clay with shells (Fig. 7). The core contains two normally graded medium sand turbidites. The lowermost one has a silt/sand layer rich in plant fragments. A sample just below the uppermost turbidite gave an age of 736 cal. BP, representing a maximum age for that turbidite. A sample just above the lowermost turbidite gave an age of 1578 cal. BP, which represents a minimum age for the lowermost turbidite.

Dalsfjorden

Seismic data show acoustically chaotic mass-movement wedges at three stratigraphic levels along the fjord margins. Core P0103012 (Fig. 7) penetrates the uppermost of these wedges (Fig. 8), and the sediments below 0.95 m depth are probably from the acoustically chaotic wedge. The core contains a turbidite at 0.20-0.43 m, and a bioturbated, diffusely banded, dark grey, gravelly sandy silt with shells and brown clasts of clayey silt at 0.95-1.43 m. A sample from the lowermost part of the poorly sorted silt bed gave an age of 9458 cal. BP. Grey silt and massive, fine sand occur in the lower part of the core. Core P0103013 (Fig. 7) contains a classical Bouma-type turbidite at 0.38-0.91 m depth. A sample below the erosional boundary gave an age of 2297 cal. BP, representing a maximum age for the turbidite.

Seismic data suggest that the turbidite in the upper part of core P0103012 can be correlated with the turbidite in core P0103013, which is 2000-2200 cal. years old, accounting for some erosion at its base. The uppermost wedge of chaotic debris-flow deposits seen in the seismic data (Fig. 8) and the lower part of P0103012 (Fig. 7) has thus to be older than this. The age of 9458 cal. BP probably reflects old sediments redeposited by a younger event, but its age remains unknown.

Førdefjorden

Seismic data show extensive, acoustically chaotic debris-flow deposits in Førdefjorden. Core P0103014 (Fig. 7), from the outer, central part of the fjord but not located on a seismic line, contains a turbidite at 0.47-0.54 m depth. A sample from immediately below the turbidite gave an age of 2320 cal. BP, representing a maximum age for the turbidite.

Vanylvsfjorden

In Vanylvsfjorden, seismic data show a pronounced reflector at ca. 2 m depth. Core P0103015 contains a turbidite at 0.96-1.13 m depth (Fig. 7), while a strongly bioturbated silt bed with an erosive lower surface occurs at 1.13-1.37 m. A sample from the top of this silt bed gave an age of 2962 cal. BP, which represents a maximum age for the turbidite. If the dated silt bed is a mass-movement deposit with redeposited sediments, the age of the overlying turbidite may be younger than suggested by the dating.

Syvdsfjorden

In Syvdsfjorden, swath bathymetry (Fig. 9) and seismic data (Fig. 10) show slide scars, debris-flow deposits and associated reflectors at several stratigraphic levels. Debris lobes, frequently stacked, occur along the northeastern and southwestern fjord margins as well as axially along the fjord. One turbidite occurs in core P0103018, while a debris-flow deposit with shells, wood fragments and mud clasts occurs in P0103019 (Fig. 7). Samples from below and above the debris-flow deposit in P0103019 gave ages of 2333 cal. BP and 1780 cal. BP, respectively. The short distance between the two cores suggests that the turbidite in P0103018 and the debris-flow deposit in P0103019 can be correlated. The difference in depth, thickness and lithology is probably due to sedimentological variations along the outer margin of a debris-flow lobe (Figs. 9 and 10). Seismic correlation between cores P0103017 and P0103019 suggests that two thin turbidites in P0103017 (Fig. 9) are around 1000 years old.

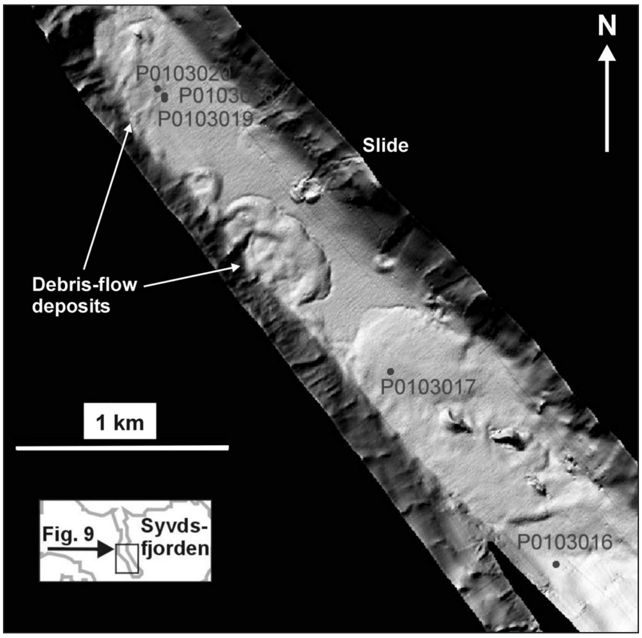

Fig. 9. Shaded relief image of multibeam bathymetric data and core locations, Syvdsfjorden. Note several debris flow lobes and slide scars/slide deposits on the seabed. See inset map and Fig. 1 for location.

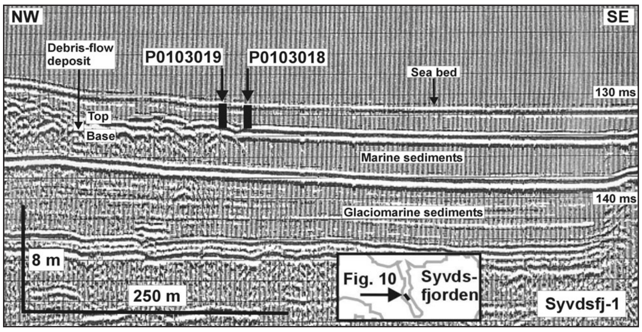

Fig. 10. Seismic profile (Sparker) with core locations, Syvdsfjorden. Note that P0103019 penetrates debris flow deposits. Vertical exaggeration ca. x 12. See inset map and Fig. 1 for location.

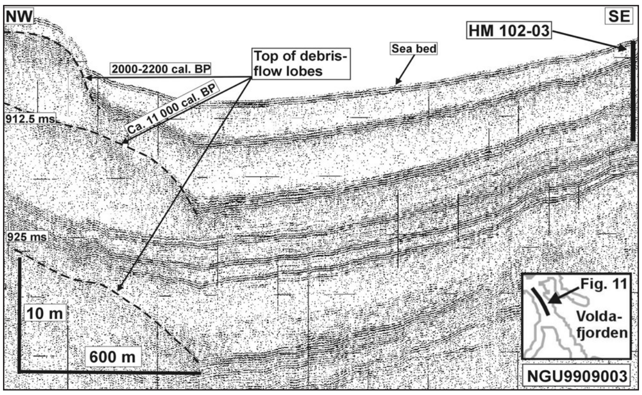

Fig. 11. Seismic profile (Topas) from Voldafjorden. Note major debris flow deposits in the southeast and associated seismic reflectors at three stratigraphic levels. The location of core HM102-03SC (Sejrup et al. 2001) is indicated. Vertical exaggeration ca. x 40. See inset map and Fig. 1 for location.

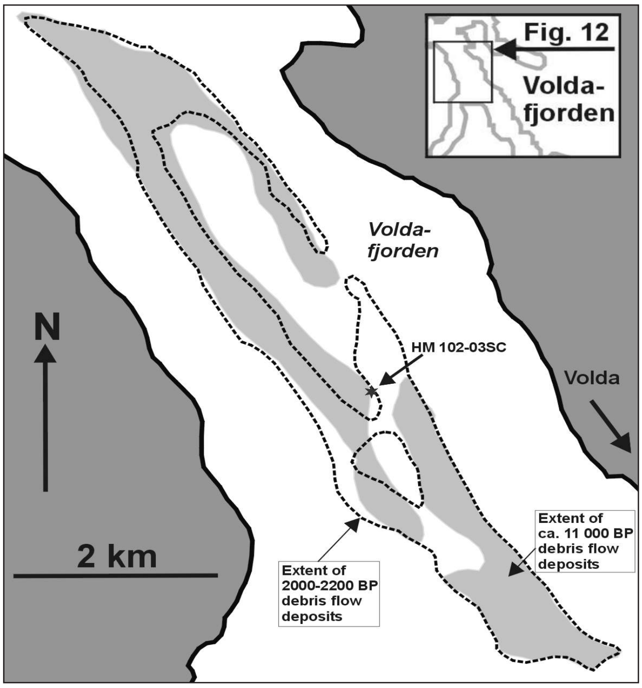

Fig. 12. Areal distribution of debris flow deposits at the 2000-2200 cal. BP and ca. 11 000 cal. BP levels in Voldafjorden. The location of core HM102-03SC (Sejrup et al. 2001) is indicated. See inset map and Fig. 1 for location.

Voldafjorden

Seismic data (Fig. 11) show that major debris-flow wedges occur at three stratigraphic levels along the margins of Voldafjorden. In addition, the swath bathymetry exhibits two small, relatively young slide scars. The volumes of the wedges appear to decrease with age but prominent reflectors extending from them can be traced across the fjord basin (Fig. 11). A core penetrating reflectors associated with the two uppermost wedges, which have quite similar distributions (Fig. 12), was investigated by Sejrup et al. (2001) (see introduction).

Ørstafjorden

Seismic data and swath bathymetry show the presence of acoustically chaotic deposits in Ørstafjorden, and small debris lobes along its margins. In the outer part of the fjord, acoustically chaotic deposits occur at the level of a pronounced reflector, at ca. 2.4 m depth. In the innermost part of Ørstafjorden, a northwestward thinning sediment wedge occurs directly above a similar reflector. The cored succession comprises up to 1.92 m of very dark grey silty and sandy clay rich in organic matter/fragments, but none of the cores reach the pronounced reflector. Dating below and above a turbidite in Ørsta-GC1A (Fig. 7) gave ages of 2454 cal. BP and 1695 BP, respectively. The turbidite is recognized as a very weak reflector in the middle of the uppermost, semitransparent unit, and can probably be correlated with turbidites in the other cores from Ørstafjorden.

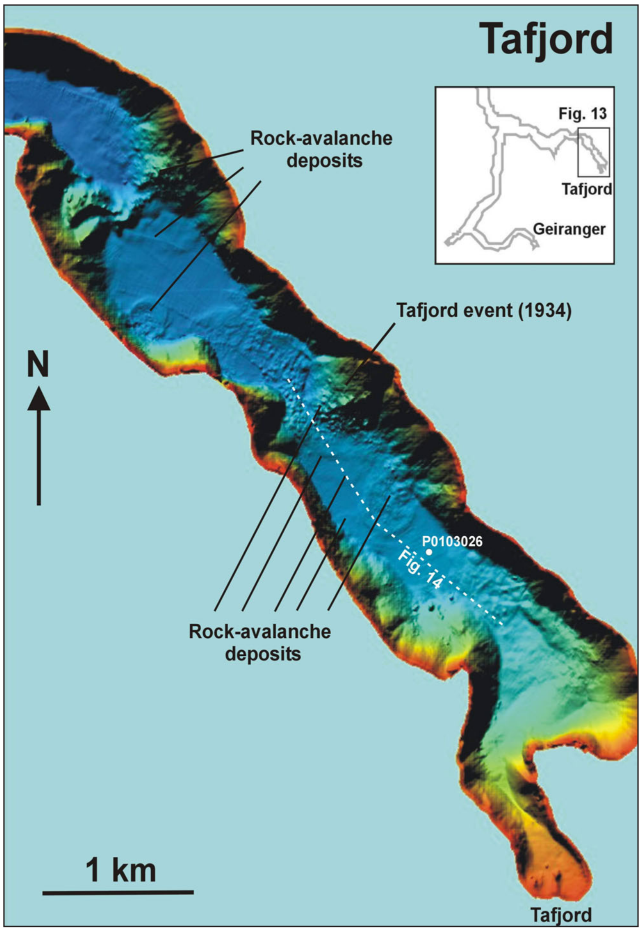

Fig. 13. Shaded relief image of multibeam bathymetric data, Tafjorden. Note numerous rock-avalanche cones and debris flow lobes along the fjord margins. The locations of a seismic profile (Fig. 14) and a core (Fig. 7) are shown. See inset map and Fig. 1 for location.

The turbidite is thickest and coarsest in the inner, southeastern part of Ørstafjorden, suggesting that it has originated from that area.

Tafjorden

Numerous slide scars occur along the subaerial slopes of Tafjorden. Swath bathymetry (Fig. 13) and seismic data (Fig. 14) show many large cones of rock-avalanche debris accumulated throughout the Holocene, and particularly during the second half of this period. About 3 million m^3 (Blikra et al. 2002) of rock and talus avalanched into Tafjorden in 1934 (Figs. 13 and 14), and the tsunami generated by the slide reached a maximum height of 62 m above sea level, killing 40 people. Even larger rock avalanches are identified below the 1934 slide deposits. A rock avalanche estimated to comprise more than 100 million m^3 occurs on land (Blikra et al. 2002). The avalanche debris can be traced into the fjord, with a runout distance of more than 2 km along the fjord bottom.

Core P0103026, from the inner part of Tafjorden, contains 4 mass-movement deposits (Fig. 7). Samples below the uppermost and lowermost of these gave ages of 647 cal. BP and 3141 cal. BP, respectively, representing maximum ages for the depositional events. The thin hemipelagic deposit on top of the uppermost coarse grained bed points to a very young age, possibly the 1934 event, in which case the uppermost bed may be a tsunami deposit. From sedimentation rates, it can be estimated that the two other turbidites/tsunami deposits in P0103026 occurred around 1700 cal. BP and 2500 cal. BP, but these ages are very approximate.

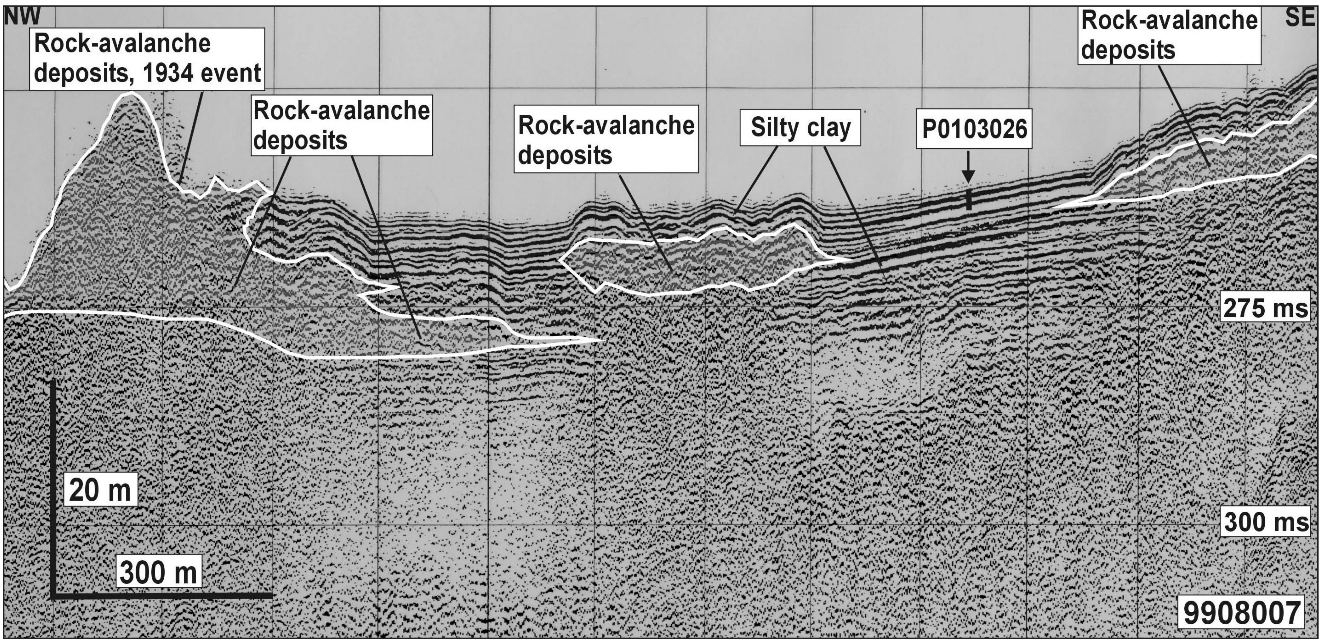

Fig. 14. Seismic profile from Tafjorden showing the interlayered relationship between rock avalanche deposits and hemipelagic, silty clay. Vertical exaggeration ca. x 14. See Fig. 13 for location of the seismic profile.

Breisunddypet

Breisunddypet is the offshore extension of Sulafjorden. The trough cuts approximately 100 m into the shelf and ends abruptly a few kilometres before it reaches the shelf edge/Storegga Slide escarpment. The swath bathymetry (Fig. 15) shows several debris flow lobes along the margins of the trough. Gravity core HM129-03 is located close to the southeastern margin of a debris flow deposit with a rugged surface morphology (Fig. 15). A sharp and undulating, erosive boundary, evident as a reflector in the seismic data, occurs at 1.6 m core depth (Fig. 7). Below the boundary, bioturbated, sandy silt with numerous shells and shell fragments occurs. Samples from the uppermost and lowermost parts of this gave ages of 3352 cal. BP and 7011 cal. BP, respectively. The age of 3352 cal. BP represents a maximum age of the boundary at 1.6 m depth. Above the boundary, the sediment comprises bioturbated and laminated silty and clayey sand. Immediately above the boundary there are clasts of very dark grey silty clay similar to the sediment below 2.37 m, and two layers of light grey bioclastic sand with clasts of sandy silt similar to the sediment below the boundary (Fig. 7). Samples above the bioclastic sand layers and in the upper part of the core gave ages of 8204 cal. BP and 4940 cal. BP, respectively.

Core 129-04 was obtained 300 m southeast of HM129-03. The swath bathymetry shows an even sea bed here, but the eastern boundary of an old debris flow deposit, with an upper boundary at ca. 2.4 m depth (estimated from seismic data), is well defined east of the coring location (Fig. 15). We interpret a transitional boundary at 1.15 m depth in this core to correlate with the boundary at 2.37 m depth in HM129-03, and the old debris flow deposit is thus older than 7011 cal. BP. If the correlation is correct, the bed of sandy silt below the boundary at 1.6 m depth thins towards the west, possibly as a result of erosion. Erosion may have occurred because of strong ocean currents, but a debris flow or a slide may also have eroded the sea bed. Above the level of rip-up clast and well-sorted carbonate sand layers, lamination and bioturbation suggest normal marine sedimentation although the dating results indicate that the sediments represent redeposited mass-movement deposits or possibly a slide block.

Storsætervatnet (277 m a.s.l.) and Rotevatnet (47 m a.s.l.)

All the investigated lake successions comprise Holocene gyttja on top of glaciolacustrine/glaciomarine sediments. The gyttja frequently contains laminae and layers of silt, sand and gravel. In Storsætervatnet (Fig. 1), dating of a layer rich in organic material in the lower part of core S10 gave an age of 13 254 cal. BP (Fig. 16), which is interpreted to represent a minimum age for the deglaciation of the lake. Gyttja above an erosional boundary in cores S4 and S6 gave ages of 9181 cal. BP and 9006 cal. BP, indicating erosion (slumping) and removal of the uppermost glaciolacustrine sediments (including Vedde Ash) and the earliest Holocene gyttja, around 9200 cal. BP. A 9366 cal. BP silt layer in S9 is probably related to the slumping. Dating below and above two graded sand/silt layers in S9 gave ages of 8643 cal. BP and 2744 cal. BP, respectively. The layers were probably deposited by debris flows some time after 8643 cal. BP, but before 2744 cal. BP. The apparent long hiatus may be explained as due to a considerable erosion at the base of the layers. The age of the uppermost debris flow may be close to 2800 cal. BP, while the lowermost debris-flow deposit can probably be correlated with a layer that is 5607 cal. years old in core S1.

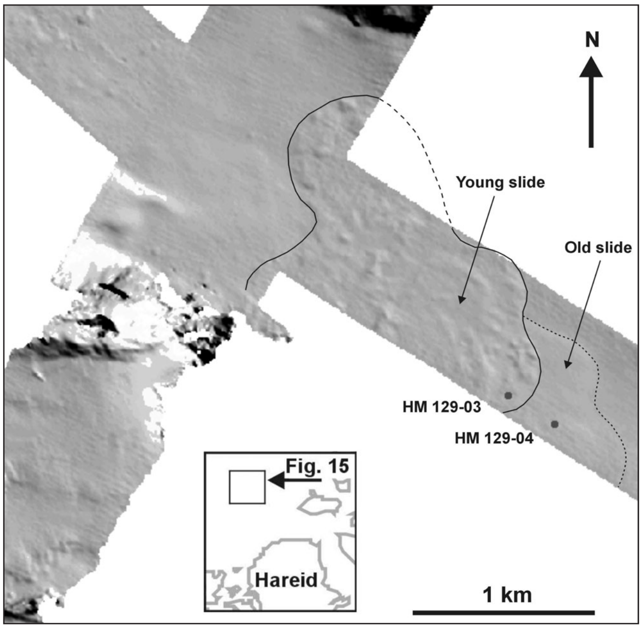

Fig. 15. Shaded relief image of multibeam bathymetric data and core locations, Breisunddypet. Note relatively young, hummocky debris flow deposits on the seabed northwest of core HM 129-03 and older, more diffuse debris flow lobes beneath core HM 129-04. See inset map and Fig. 1 for location.

In Rotevatnet (Fig. 1), three silt laminae in gyttja yielded ages of 1820 cal. BP, 5314 cal. BP and 6700 cal. BP (Fig. 16). A silt lamina between the two oldest ones was not dated, but if we assume a constant sedimentation rate of the gyttja between the dated laminae, it is ca. 6200 cal. years old. Three silt laminae in the lower part of the gyttja are interpreted to have been deposited in the earliest Holocene ca. 10-11 500 cal. BP.

Medvatnet (12.5 m a.s.l.) and Nedstevatnet (9 m a.s.l.)

Sand and silt laminae/layers in gyttja were dated in several cores from Medvatnet and Nedstevatnet (Figs. 1 and 16). These deposits are typically poorly sorted, and frequently contain pebbles and plant fragments. We

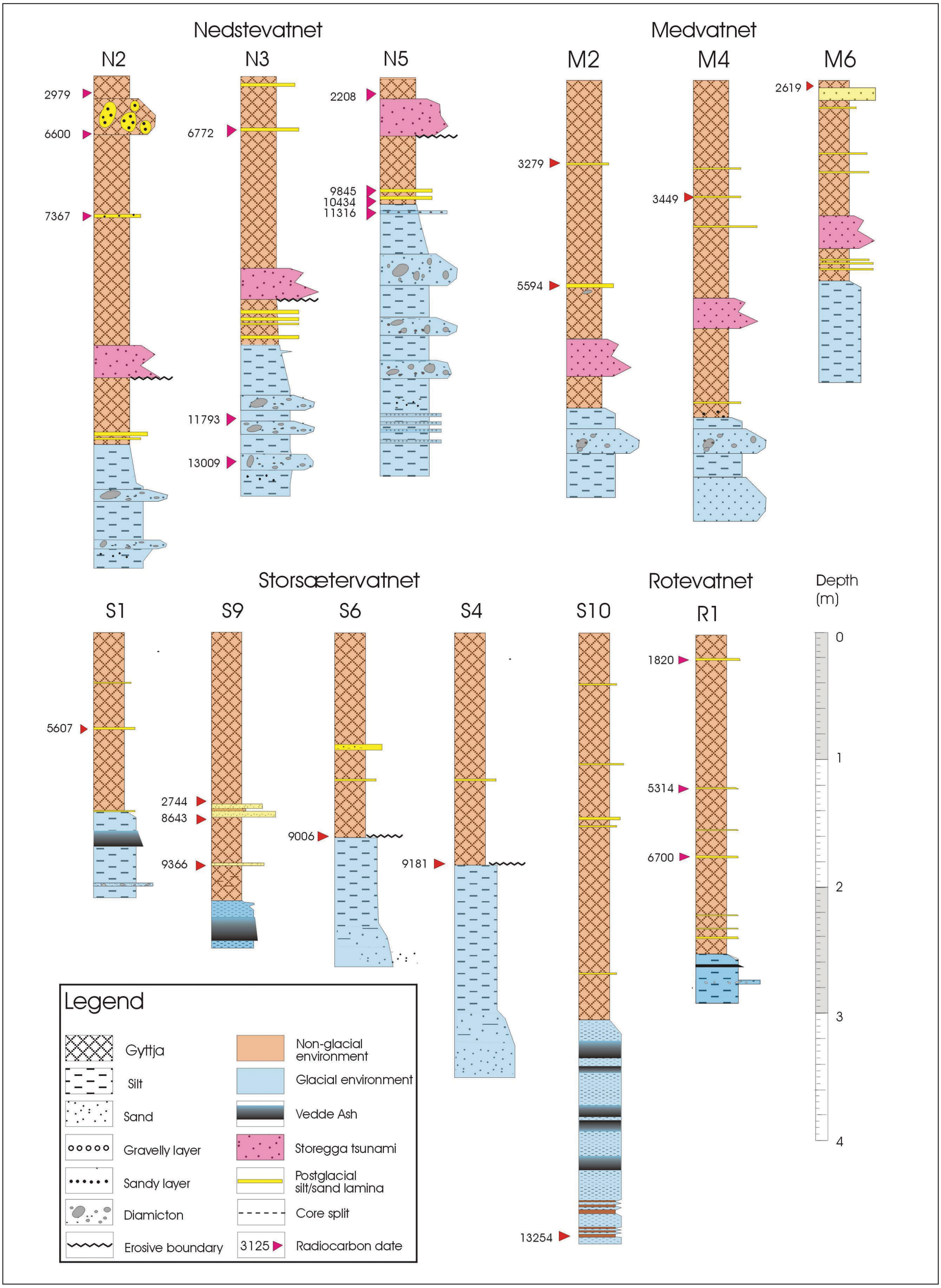

Fig. 16. Lithology of dated cores from Storsætervatnet, Medvatnet, Nedstevatnet and Rotevatnet. See Fig. 1 for location of the lakes.

interpret this to be due to small turbidity currents, snow avalanches from the surrounding high mountains or flood events. The following dating results were obtained: 2619 cal. BP (M6, minimum age), 3449 cal. BP (M4), 3279 cal. BP (M2), 5594 cal. BP (M2, maximum age), 7367 cal. BP (N2), 6772 cal. BP (N3, maximum age). Age determinations below and above a sand bed in the upper part of N2 gave ages of 6600 cal. BP and 2979 cal. BP, suggesting that the deposit is around 3200 cal. years old. From sedimentation rates, we assume the age of a silt lamina in the upper part of N3 to be ca. 6400 cal. years old. Correlation of core data with penetration echosounder data suggests that the uppermost soft gyttja may have been lost in the coring process both in Medvatnet and Nedstevatnet. Thus, coarse-grained layers in the uppermost gyttja, if ever present, may also have been lost.

A gravelly sand unit, up to 35 cm thick, occurs in the lower part of the gyttja in all the cores from Medvatnet and Nedstevatnet (Fig. 16). It comprises two to four gravelly sand layers separated by thin, organic-rich horizons. The sand layers are massive, fining upwards or coarsening upwards. Wood fragments and crushed shells of bivalves and snails are common. The lower boundary, and often also the upper boundary of the unit, are sharp. The lithology and dating results (e.g. 7367 cal. BP above the unit in core N2 and 9845 below it in core N5) suggest that this unit is a Storegga Slide tsunami deposit (see above). At the time of the Storegga Slide, Nedstevatnet was beneath the sea level at the time, and Medvatnet was very close to it (see below).

Silt and sand laminae at the boundary between glaciomarine sediments and gyttja in N5 gave ages of 9845 cal. BP, 10 434 cal. BP and 11 316 cal. BP. Ages of 11 793 cal. BP and 13 009 cal. BP were obtained on diamictic layers in glaciomarine sediments in N3, showing that these were deposited during the Younger Dryas.

Temporal and spatial distribution of events and their causes

Mass movements in western Norway have occurred at various times over the past 12 000 cal. years, but they were especially numerous at 2000-2200, 2800-3200, 8200 and before 10 000 cal. BP (Fig. 17, Table 3). Several thin silt and sand layers occur in the lowermost part of the Holocene gyttja and in the uppermost part of the glaciomarine succession, in several of the lake cores. Also the data from Voldafjorden and Halsafjorden show that the earliest Holocene was a time of frequent mass movements. We ascribe this mainly to high sedimentation rates, partly caused by rapid land uplift (with or without associated earthquakes) and highly erodable river banks due to lack of a stabilising vegetation. Major slide and debris-flow deposits occur at the 11 000-11 700 cal. BP stratigraphic level in some fjords in Sunnfjord, Sunnmøre and Nordmøre. We interpret this to be related to one or several earthquakes in the Sunnfjord-Sunnmøre region (see interpretation below). A large rock-slope failure in Ørstafjorden at ca. 11 000-11 700 cal. BP (Blikra 1994) supports an earthquake triggering mechanism.

Radiocarbon dating and sedimentological interpretations of cores have shown that mass-movement deposits related to the Storegga Slide tsunami occur in Sognesjøen (Haflidason 2002), Voldafjorden (Sejrup et al. 2001), Sulafjorden, Julsundet and Halsafjorden (Table 3, Fig. 17). Also Medvatnet and Nedstevatnet exhibit a deposit that we ascribe to the Storegga Slide tsunami. Nedstevatnet was located a few metres below sea level at 8200 cal. BP, while Medvatnet was slightly above or close to it. The other investigated lakes were at too high an elevation to be reached by the tsunami wave and they show no trace of it. Medvatnet and Nedstevatnet lie well beneath the Younger Dryas sea level which, according to Fareth (1987), was 44 m a.s.l. Using late- and postglacial shoreline displacement curves from Sunnmøre (Svendsen & Mangerud 1987, 1990) it is reasonable to assume that Medvatnet was isolated from the sea at ca. 10 200 cal. BP and was probably re-connected during the marine Tapes transgression maximum. The final isolation might have occurred shortly before the tsunami event. For Nedstevatnet, the last isolation was around 5000 cal. BP. The typical mass-movement deposits in Medvatnet and Nedstevatnet are up to 2 cm thick silt and sand lamina and layers, which we interpret as small/distal turbidites. There are a few thicker layers, but these are local and cannot be traced from core to core. Thicker sand beds in two cores from Nedstevatnet and Medvatnet only occur in the southernmost parts of the lakes, and are interpreted to represent debris-flow deposits/turbidites. If sand beds were tsunami deposits, they should be thicker and more pronounced in the parts of the lakes closest to where the tsunami wave would enter the basin, i.e. the north (see above). Since this is not observed in Nedstevatnet and Medvatnet, the tsunami connection can be excluded.

The new core data and dating results indicate that the thick and regionally extensive slide and debris-flow deposits in Halsafjorden and Sulafjorden are older than the Storegga Slide. In Voldafjorden, the reflector associated with the middle fjord margin debris-flow deposits appears to occur at the level of the ca. 11 000 cal. BP turbidite in the core described by Sejrup et al. (2001). Only in Julsundet is a debris-flow deposit interpreted to occur at the stratigraphic level of the Storegga Slide tsunami. What triggered the Storegga Slide is still an open question, but our data do not provide evidence that it was due to a major earthquake with an epicenter on

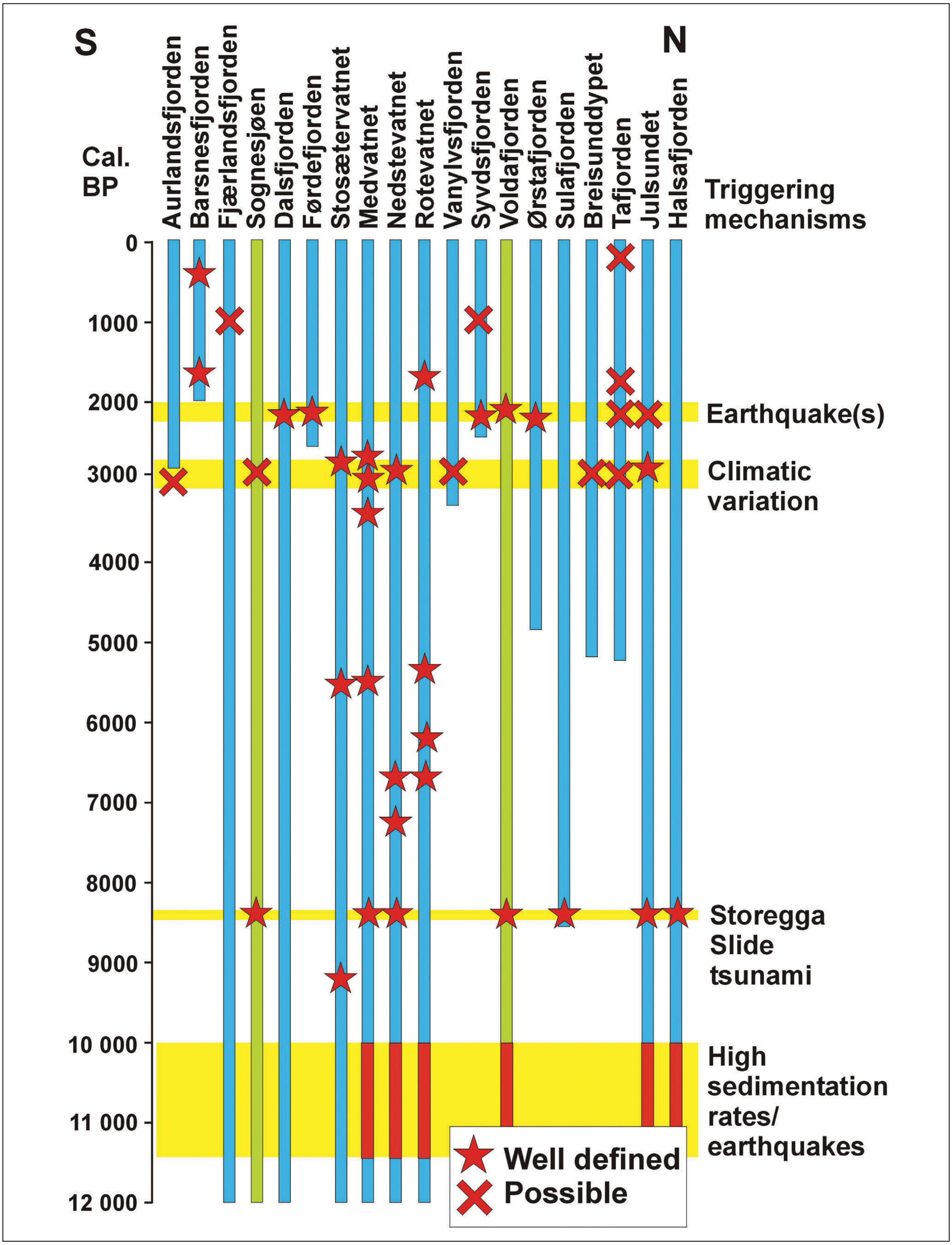

Fig. 17. Temporal and spatial distribution of pre-historic mass-movement events and their interpreted causes. Note that the ages of events involve interpretation of dating results, lithostratigraphy, swath bathymetry and seismic data. Blue colour indicates recovery of new cores; green colour indicates cores from Voldafjorden (Sejrup et al. 2001) and Sognesjøen (Haflidason 2002); yellow indicates time intervals of relatively high mass-movement activity. Red bars indicate numerous mass-movement episodes in the time interval 10 000-11 500 cal. BP.

Table 3. Temporal and spatial distribution of Holocene, pre-historic events in the investigated fjord and lake cores. Ages of events are interpreted from radiocarbon dating results, sediment stratigraphy, swath bathymetry and seismic data. Asterix indicates that an event with certainty has not been recorded in the investigated core (negative evidence).

Area	Interpreted age (cal. years BP) of events observed in cores										
	<500	<1500	1700-1800	2000-2200	2800-3200	5300-5600	6000-6200	6700	7300	8200	9300	10-13000
Aurlandsfjorden	*	*	*	*	ca. 3000							10-11 500
Barsnesfjorden	500	*	1700									
Sognesjøen	*	*	*	*	3000					8200		11-12 000
Dalsfjorden	*	*	*	2100								
Førdefjorden	*	*	*	2100								
Storsætervatnet					2800	5600	*	*	*	*	9300	
Medvatnet					2800, 3200	5500	*	*	*	8200		10-13 000
Nedstevatnet					3000	*	6400	6700	7300	8200		10-13 000
Rotevatnet			1800	*	*	5300	6200	6700	*	*		10-13 000
Vanylvsfjorden	*	*	*	*	2800							
Syvdsfjorden	*	ca. 1000	*	2100								
Voldafjorden	*	*	*	2100	*	*	*	*	*	8200	*	11-13 000
Ørstafjorden	*	*	*	2100								
Sulafjorden		*	*	*	*	*	*	*	*	8200		
Breisunddypet				?	?							
Tafjorden	<400		?	?	?							
Midfjorden												
Julsundet				?	?					8200		
Tingvollfjorden												
Halsafjorden	*	*	*	*	*	*	*	*	*	8200		11 700-13 000

land or close to the coast. If this was the cause, simultaneous, major debris-flow deposits should be present in the fjords, but this is not the case.

Mass-movement deposits in Aurlandsfjorden, Vanylvsfjorden, Tafjorden, Julsundet, Storsætervatnet and Nedstevatnet cluster around 2800-3200 cal. BP (Table 3, Fig. 17). The age of 3329 cal. BP for a deposit beneath an erosion surface in a core from Beisunddypet suggests that this may possibly be ca. 3000 cal. years old also. In Medvatnet, a snow avalanche deposit has an age of 3279 cal. BP, while a debris flow occurred some time during 2600-3000 cal. BP. Dating below a turbidite in a core from Sognesjøen has given ages of 2900-3200 cal. BP (Haflidason 2002). An increase in debris flow frequency in western Norway after ca. 3200 cal. BP has been recorded by Blikra & Nemec (1998), who interpreted this to be climatically controlled. This accords with an increase in water-flow processes in some colluvial systems (Blikra & Nemec 1993a, b). Nesje et al. (1995) recognized a period of increased erosion and mass-flow activity in the Ålfotbreen area in western Norway in the period 3100-2700 cal. BP. In addition, many floods have occurred over the past 3000 cal. years in Atnsjøen in south central Norway (Nesje et al. 2001), and there was an increase in slopewash processes in Leirdalen in western Norway some time after 3200 cal. BP (Matthews et al. 1986, 1997). The spread of ages within the 2800-3200 cal. BP interval is probably too large for these to be simultaneous events hence supporting the view that they were due to local climatic irregularities.

In Voldafjorden (Sejrup et al. 2001), Syvdsfjorden, Ørstafjorden, Førdefjorden and Dalsfjorden turbidites occur at 2000-2200 cal. BP (Table 3, Fig. 17). The turbidites in Syvdsfjorden and Voldafjorden are related to extensive debris-flow deposits along the fjord margins. It is possible that mass-movement deposits occur at the 2000-2200 cal. BP level also in Tafjorden, Breisunddypet, and Julsundet, but the dating results are not conclusive. Although we suggest that the the mass movements at 2000-2200 cal. BP are related to one or several earthquakes (see below), a climatic control during this time period cannot be excluded. Nesje et al. (1991) and Sletten et al. (2003) have identified an increase in the number of turbidity currents and debris flows around 2000 cal. BP, and ascribed this to a short lived climatic event. Also Karlén & Matthews (1992) and Matthews & Karlén (1992) indicated a climatic deterioration around 2200-2100 cal. BP.

As 2000-2200 cal. BP mass-movement deposits are observed with certainty in only a restricted area of Sunnfjord and Sunnmøre, it is not likely that a major tsunami occurred in the offshore area, at that time. Earlier investigations have shown no indication of a 2000-2200 BP large slide that may have created a tsunami in the Storegga area, nor are any mass-movement deposits from that time found on land or in the investigated lakes. This suggests that the mass movements were most likely related to one or more earthquakes in the coastal area. Failure of locally unstable sedimentary successions may have caused local tsunamis. Although climatic irregularities have been deduced for this time, the simultaneous occurrence of large events in five fjords supports an earthquake triggering model.

Seismic data show that there is a striking similarity in areal distribution of major mass-movement deposits at the 2000-2200 cal. BP and 11 000-11 700 cal. BP stratigraphic levels in some fjords in Sunnmøre, e.g. in Voldafjorden (Fig. 12) and Syvdsfjorden. This may suggest a common triggering mechanism. If our interpretation of the 2000-2200 cal. BP event above is correct, i.e. that debris flows and turbidites were caused by an earthquake on land or close to the coast, then the older regional event may have been triggered in the same way.

The major slide and debris-flow deposits at the 2000-2200 cal. BP and 11 000-11 700 cal. BP stratigraphic levels are thick and very extensive along fjord margins in Sunnfjord and Sunnmøre. In Nordmøre, slide and debris-flow deposits are absent at the 2000-2200 cal. BP level, while they are rare and not very extensive at the 11 000-11 700 cal. BP level. This suggests that the epicenters of the triggering earthquakes were located in the Sunnfjord-Sunnmøre region. The area off Sunnmøre and especially Sogn og Fjordane is neotectonically active (Byrkjeland et al. 2000, Dehls et al. 2000), and earthquakes up to magnitude 5 (Richter scale) occur regularly today. The present models for the decrease in seismic activity between the great burst of seismicity about 8000 years ago and the present level include a reasonable likelihood for magnitudes up to 7 as late as 2000 cal. years ago (NORSAR 2001). For stable regions like the Norwegian margin one can also, at times, expect several relatively strong earthquakes over a short period of time, e.g. 200-400 years, within a geographically restricted area (NORSAR 2001). The neotectonically active Berill Fault (Anda et al. 2002) may have caused rock avalanches in the inner fjord area of Møre og Romsdal (Innfjorden and Tafjorden) 3000 cal. years ago and possibly later. Several mass-movement deposits in Tafjorden, also the ones in core P0103026 (Fig. 7), are probably tsunami deposits related to large rock avalanches.

The apparent absence of 2000-2200 cal. years old mass-movement deposits in the investigated lakes can possibly be ascribed to overpenetration by the piston corer, in some of them. However, it has been shown from other areas that relatively small earthquakes may cause sliding of soft sediments in narrow and deep fjords. The acoustic impedance at the overburden/bedrock discontinuity leads to a high value for the resonance amplification effect (Benjuemea et al. 2002). Substantial variations in amplification effects occur due to large variations in stratigraphy and bedrock topography. This may explain why earthquakes have caused sliding of unstable sediments in many of the fjords, but not in the lakes.

The temporal and spatial distribution of many small mass-movement events in the cores suggest that most of them are caused by episodic disturbances under weather conditions, which may be unrelated to regional climatic changes. However, there are a few possible exceptions. Mass-movement deposits from 1700-1800 cal. BP in Barsnesfjorden, Tafjorden and Rotevatnet are coincident with other events at that time, described by Blikra & Nemec (1993a), Blikra & Nesje (1994), Blikra (1994) and Bøe et al. (2003). The events at 5300-5600 cal. BP in Medvatnet, Storsætervatnet and Rotevatnet correlate with events in Western Norway, where previous studies have shown a general climatic deterioration since ca. 6000 cal. BP (Dahl & Nesje 1996; Gunnarsdóttir 1996; Nesje et al. 2000; Barnett et al. 2001), lowering of tree limits at ca. 5800 cal. BP (Selsing & Wishman 1984; Kullman 1988; Gunnarsdóttir 1996), a higher frequency of large spring floods and debris flow after 5800 cal. BP (Blikra & Nemec 1998), and increasing snow-avalanche activity after 5400 cal. BP (Blikra & Selvik 1998). Mass-movement events in Rotevatnet and Nedstevatnet around 6700-6800 cal. BP (Table 3, Fig. 17) correlate with neoglacial stages in western Norway at that time (Blikra & Nemec 1998).

Conclusions

Sixteen fjords and five lakes in western Norway have been investigated in a search for mass-movement deposits.

1) Deposits related to the Storegga Slide (8200 cal. BP) tsunami are observed over most of the investigated area. These are found in lakes that were close to or below sea level at the time of the Storegga Slide. Turbidites and debris-flow deposits that were possibly triggered by the tsunami wave passing along the fjord margins occur in the deep fjords.

2) Five of the investigated fjords (Dalsfjorden, Førdefjorden, Syvdsfjorden, Voldafjorden, Ørstafjorden) provide evidence for a semi-regional 2000-2200 cal. BP event. The geographic restriction of the 2000-2200 cal. BP debris-flow deposits and turbidites in the fjords suggests that one or more earthquakes on land or close to the coast, and not a tsunami generated by an offshore megaslide, triggered this event.

3) There is a striking similarity in geographic distribution of major mass-movement deposits at the 2000-2200 cal. BP and 11 000-11 700 cal. BP stratigraphic levels in some fjords in Sunnmøre. This suggests a common triggering mechanism, i.e. one or several earthquakes. The slide and debris-flow deposits at the two levels are thick and very extensive along fjord margins in Sunnfjord and Sunnmøre. In Nordmøre, similar deposits occur at the 11 000-11 700 cal. BP level, but are fewer and smaller. This suggests that the epicenters of the triggering earthquakes were located in the Sunnfjord-Sunnmøre region, which is a neotectonically active region where earthquakes up to magnitude 5 occur regularly today.

4) Mass-movement deposits from the time interval 2800-3200 cal. BP were found in several fjords and lakes. The spread of ages within this interval is probably too great for all the events to have taken place simultaneously, and climatic causes are suggested.

5) The studied fjord successions indicate that no tsunamis caused by megaslides in the Storegga area have hit the coast of Western Norway during the last 8000 cal. years.

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References

Aarseth, I., Lønne, Ø. & Giskeødegaard, O. 1989: Submarine slides in glaciomarine sediments in some western Norwegian fjords. *Marine Geology 88,* 1-21.

Anda, E., Blikra, L.H. & Braathen, A. 2002: The Berill fault - first evidence of neotectonic faulting in southern Norway. *Norwegian Journal of Geology 82,* 175-182.

Barnett, C., Dumayne-Peaty, L. & Matthews, J. A. 2001: Holocene climatic change and tree-line response in Leirdalen, central Jotunheimen, south central Norway. *Review of Palaeobotany and Palynology 117,* 119-137.

Benjuema, B., Hunter, J.A., Pulland, S.E., Burns, R.A. & Good, R.L. 2002: Near-surface seismic studies to estimate potential earthquake ground motion amplification at a thick soil site in the Ottawa river valley, Canada (unpublished manuscript).

Birks, H.H., Gulliksen, S., Haflidason, H., Mangerud, J. & Possnert, G. 1996: New radiocarbon dates for the Vedde Ash and Saksunarvatn Ash from Western Norway. *Quaternary Reserach 45,* 119-127.

Bjerrum, L. 1971: Subaqueous slope failures in Norwegian fjords. *Norwegian Geotechnical Institute Publication 88,* 1-8.

Blikra, L.H. 1994: Postglacial colluvium in western Norway: Sedimentology, geomorphology and palaeoclimatic record. Unpubl. dr. scient. thesis, University of Bergen, 250 pp.

Blikra, L. H. & Nemec, W. 1993a: Postglacial avalanche activity in western Norway: depositional facies sequences, chronostratigraphy and palaeoclimatic implications. *Paläoklimaforschung 11,* 143-162.

Blikra, L. H. & Nemec, W. 1993b: Postglacial fan deltas in western Norway: a case study of snow avalanche-dominated, colluvial fans prograding into deep fjords. *In Abstracts 3rd International workshop on fan deltas.* University of Seoul, 1-4.

Blikra, L.H. & Nesje, A. 1994: Holocene avalanche activity in western Norway: chronostratigraphy and palaeoclimatic implications. *Paläoklimaforschung 19,* 299-312.

Blikra, L.H. & Nemec, W. 1998: Postglacial colluvium in western Norway: depositional processes, facies and palaeoclimatic record. *Sedimentology 45,* 909-959.

Blikra, L.H. & Selvik, S.F. 1998: Climatic signals recorded in snow avalanche-dominated colluvium in western Norway: depositional facies successions and pollen records. *The Holocene 8,* 631-658.

Blikra, L.H., Braathen, A., Anda, E., Stalsberg, K. & Longva, O. 2002: Rock avalanches, gravitational bedrock fractures and neotectonic faults onshore northern West Norway: Examples, regional distribution and triggering mechanisms. *NGU Report 2002.016,* 48 pp.

Bondevik, S., Svendsen, J.I., Johnsen, G., Mangerud, J. & Kaland, P.E. 1997a: The Storegga tsunami along the Norwegian coast, its age and runup. *Boreas 26,* 29-53.

Bondevik, S., Svendsen, J.I. & Mangerud, J. 1997b: Tsunami sedimentary facies deposited by the Storegga tsunami in shallow marine basins and coastal lakes, western Norway. *Sedimentology 44,* 1115-1131.

Bondevik, S., Svendsen, J. I. & Mangerud, J. 1998: Distinction between the Storegga Tsunami and the Holocene marine transgression in coastal basin deposits of western Norway. *Journal of Quaternary Science 13,* 529-537.

Byrkjeland, U., Bungum, H. & Eldholm, O. 2000: Seismotectonics of the Norwegian continental margin. *Journal of Geophysical Research 105,* 6221-6236.

Bøe, R., Hovland, M., Instanes, A., Rise, L. & Vasshus, S. 2000: Submarine slide scars and mass movements in Karmsundet and Skudenesfjorden, southwestern Norway: morphology and evolution. *Marine Geology 167,* 147-165.

Bøe, R., Lepland, A., Blikra, L.H., Longva, O. & Sønstegaard, E. 2002: Postglacial mass movements in western Norway with special emphasis on the 2000-2200 BP and 2800-3200 BP periods - final report. *NGU Report 2002.020,* 115 pp.

Bøe, R., Rise, L, Blikra, L.H., Longva, O. & Eide, A. 2003: Holocene mass-movement processes in Trondheimsfjorden, Central Norway. *Norwegian Journal of Geology 83,* 3-22.

Dahl, S. O. & Nesje, A. 1996: A new approach to calculating Holocene winter precipitation by combining glacier equilibrium-line altitude and pine-tree limits: a case study from Hardangerjøkulen, central southern Norway. *The Holocene 6,* 381-398.

Dehls, J., Olesen, O., Bungum, H., Hicks, E.C., Lindholm, C.D. & Riis, F. 2000: Neotectonic map: Norway and adjacent areas. Geological Survey of Norway, Trondheim.

Emdal, A., Janbu, N. & Sand, K. 1996: The shoreline slide at Lade. Landslides. *Proceedings of the seventh international symposium on landslides.* Trondheim 17 –21 June 1996. A. A. Balkema, Rotterdam.

Fareth, O.W. 1987: Glacial geology of Middle and Inner Nordfjord, western Norway. *Norges geologiske undersøkelse 408,* 1-55.

Flaate, K. & Janbu, N. 1975: Soil exploration in a 500 m deep fjord, western Norway. *Marine Geotechnology 1,* 117-139.

Gunnarsdóttir, H. 1996: Holocene vegetation history in the northern parts of the Gudbrandsdalen valley, south central Norway. Unpubl. Dr. Scient. Thesis No. 8, University of Oslo, Oslo.

Grøsfjeld, K., Larsen, E., Sejrup, H. P., de-Vernal, A., Flatebø, T., Vestbø, M., Haflidason, H. & Aarseth, I. 1999: Dinoflagellate cysts reflecting surface-water conditions in Voldafjorden, western Norway during the last 11 300 years. *Boreas 28,* 403-415.

Haflidasson, H. 2002: Chronological investigation of the Storegga Slide Events: Summary Report to Norsk Hydro. *University of Bergen, Department of Geology, Report No. 100-01/02,* 42 pp.

Hagen, J. 1981: Maringeologiske undersøkelser i Sulafjorden, Breisunddjupet og tilgrensende områder av kontinentalhylla utenfor Møre. Unpubl. cand. scient thesis, University of Bergen, 373 pp.

Holtedahl, H. 1965: Recent turbidites in the Hardangerfjord, Norway. *Colston Res. Soc. Proc. 17,* 10-141.

Karlén, W. & Matthews, J. A. 1992: Reconstructing Holocene glacier variations from glacial lake sediments: studies from Nordvestlandet and Jostedalsbreen-Jotunheimen, southern Norway. *Geografiska Annaler 74A,* 327-348.

Karlsrud, K. & By, T. 1982: Stability evaluation for submarine slopes - results of new investigations of the Orkdalsfjorden slide. *Norwegian Geotechnical Institute Report 52207-9,* 15 pp.

Kullman, L. 1988: Holocene history of the forest-alpine tundra ecotone in the Scandes Mountains (central Sweden). *New Phytologist 108,* 101-110.

Lepland, A., Bøe, R., Sønstegaard, E. Haflidason, H., Hovland, C., Olsen, H. & Sandnes, R. 2002: Sedimentological descriptions and results of analytical tests of sediment cores from fjords and lakes in northwest Western Norway - final report. *NGU Report 2002.14,* 198 pp.

Longva, O., Blikra, L.H., Olsen, H.A. & Stalsberg, K. 2001: Regional landslide occurrences and possible post-glacial earthquake activity in northwest Western Norway: Phase A1: interpretation of seismic data and proposal of core-locations in fjords and along the coast. *NGU Report 2001.048,* 46 pp.

Matthews, J.A. & Karlén, W. 1992: Asynchronous neoglaciation and Holocene climatic change reconstructed from Norwegian glaciolacustrine sedimentary sequences. *Geology 20,* 991-994.

Matthews, J. A., Harris, C. & Ballantyne, C. K. 1986: Studies on a gelifluction lobe, Jotunheimen, Norway: ^{14}C chronology, stratigraphy, sedimentology and palaeoenvironment. *Geografiska Annaler 68A,* 345-360.

Matthews, J. A., Dahl, S. O., Berrisford, M. S., Nesje, A., Dresser, P. Q. & Dumayne -Peaty, L. 1997: A preliminary history of Holocene colluvial (debris-flow) activity, Leirdalen, Jotunheimen, Norway. *Journal of Quaternary Science 12,* 117-129.

Nesje, A., Kvamme, M., Rye, N. & Løvlie, R. 1991: Holocene glacial and climatic history of the Jostedalsbreen region, western Norway; evidence from lake sediments and terrestrial deposits. *Quaternary Science Reviews 10,* 87-114.

Nesje, A., Dahl, S. O. & Løvlie, R. 1995: Late Holocene glaciers and avalanche activity in the Ålfotbreen area, western Norway: evidence from a lacustrine sedimentary record. *Norsk Geologisk Tidsskrift 75,* 120-126.

Nesje, A., Dahl, S. O., Andersson, C. & Matthews, J. A. 2000: The lacustrine sedimentary sequence in Sygneskardvatnet, western Norway: a continuous, high-resolution record of the Jostedalsbreen ice cap during the Holocene. *Quaternary Science Reviews 19,* 1047-1065.

Nesje, A., Dahl, S.O., Matthews, J.A. & Berrisford, M.S. 2001: A ~4500-year record of river floods obtained from a sediment core in lake Atnsjøen, eastern Norway. *Journal of Paleolimnology 25,* 329-342.

NORSAR 2001: Ormen Lange Geohazards Study, Task 9; Earthquake Hazard Considerations. *Report for Norwegian Geotechnical Institute (NGI) and Norsk Hydro a.s., September 2001,* 95 pp.

Sejrup, H.P., Haflidason, H., Flatebø, T., Klitgaards Kristensen, D., Grøsfjeld, K. & Larsen, E. 2001: Late-glacial to Holocene environmental changes and climate variability: evidence from Voldafjorden, western Norway. *Journal of Quaternary Science 16,* 181-198.

Selsing, L. & Wishman, F. 1984: Mean summer temperatures and circulation in a Southwest Norwegian mountain area during the Atlantic period, based upon changes of the alpine pine-forest limit. *Annual Glaciology 5,* 127-132.

Sletten, K, Blikra, L.H., Ballantyne, C.K., Nesje, A & Dahl, S.O. 2003: Holocene debris flows recognized in a lacustrine sedimentary succession; sediment characteristics, chronostratigraphy and cause of triggering. *The Holocene 13* (in press).

Svendsen, J.I. & Mangerud, J. 1987: Late Weichselian and Holocene sea-level history for a cross-section of western Norway. *Journal of Quaternary Science 2,* 113-132.

Svendsen, J.I. & Mangerud, J. 1990: Sea-level changes and pollen stratigraphy on the outer coast of Sunnmøre, western Norway. *Norsk Geologisk Tidsskrift 70,* 111-134.

Syvitski, J.P.M., Burrell, D.C. & Skei, J.M. 1987: Fjords: *Processes and Products.* Springer-Verlag, New York, 379 pp.

Terzaghi, K. 1957: Varieties of Submarine Slope Failures. *Norges Geotekniske Institutt Publikasjon 25,* 1-17.