Frequency and triggering mechanisms of submarine landslides of the North Norwegian continental margin

Jan Sverre Laberg, Tore O. Vorren, Neil H. Kenyon & Michael Ivanov

Laberg, J.S., Vorren, T.O., Kenyon, N.H. & Ivanov, M.: Frequency and triggering mechanisms of submarine landslides of the North Norwegian continental margin. *Norwegian Journal of Geology*, Vol. 86, pp. 155-161. Trondheim 2006. ISSN 029-196X.

The frequency of submarine landslides was investigated through the occurrence of sandy turbidites in a 16 m long piston core and a shorter gravity core from the abyssal plain of the Lofoten Basin, Norwegian Sea, and with correlation to high-resolution deep-towed side-scan sonar (30 kHz) and seismic reflection data (5.5 kHz). The turbidites occur in five intervals separated by periods of hemipelagic mud deposition. The youngest turbidite (interval 1) is correlated with the Trænadjupet Slide (c. 4 ^{14}C ka BP). Three older turbidites (interval 2), one of which correlates to the Nyk Slide (c. 16 ^{14}C ka BP), were probably released during the late Weichselian, preceded by a long period (the middle and early (?) Weichselian) of hemipelagic sedimentation. The interval 1 and 2 slides occurred during or after the presence of the Fennoscandian Ice Sheet at the shelf break, indicating that their release was related to the presence of grounded ice at the shelf break. We suggest that submarine landslides were favoured by sediment and ice sheet loading during the glacial maxima (Late Weichselian), and by earthquakes induced by the isostatic rebound following ice sheet melting (Holocene). For the pre-middle Weichselian intervals 3, 4 and 5, neither the age of the slides nor the glacial history are known in detail. Also in this period the turbidites occur only in certain time periods, and are separated by longer intervals of hemipelagic sedimentation. We speculate that the pre-middle Weichselian turbidites were deposited as a consequence of slides occurring during or immediately after Marine Isotope Stages 6, 10 and 12 glaciations, i.e. inferred periods of ice advance to the shelf break.

Jan Sverre Laberg, Department of Geology, University of Tromsø, NO-9037 Tromsø, Norway, E-mail: jan.laberg@ig.uit.no; Tore O. Vorren, Department of Geology, University of Tromsø, NO-9037 Tromsø, Norway; Neil H. Kenyon, (2) National Oceanography Centre, Empress Dock, Southampton SO14 3ZH, UK; Michael Ivanov,UNESCO Centre for Marine Geology and Geophysics, Lomonosov Moscow State University, Moscow 119899, Russia.

Introduction

The combination of factors determining the triggering of large submarine landslides is often enigmatic and several hypotheses, including gas hydrate dissociation and plate tectonic seismicity, have been suggested (e.g. O´Leary 1991; Hampton et al. 1996; Locat & Lee 2002). A prerequisite for an improved evaluation of the triggering mechanisms is information on *when* these events occurred. In this paper the problem is approached by studying the most distal part of the reworked sediments from nearby slope failures, as previously done by Weaver & Kuijpers (1983), Goldfinger et al. (2003) and Huh et al. (2004). Based on new high-resolution seismic, side-scan and core data from the Lofoten Basin, Norwegian Sea (Fig. 1), our aim is to discuss the frequency and triggering of Middle-Upper Pleistocene and Holocene submarine landslides offshore northern Norway.

Data

A ~16 m long giant piston core (Calypso core MD99-2293) was raised from about 3060 m water depth on the abyssal plain of the Lofoten Basin as part of the IMAGES V cruise by RV *Marion Dufresne* in 1999 (Figs. 1 & 2). The core was logged on board by a *Geotek* Multisensor core logger, opened, photographed and visually described. A Munsell soil colour chart was used for sediment colour description. Gravity core JM95-5/1, raised from one of the distal debris flow deposits (Fig. 1), was sampled by the University of Tromsø research vessel *Jan Mayen* in 1995 using a 6 m long steel pipe and inner PVC liners of 110 mm diameter. Post-cruise studies of both cores at the University of Tromsø included improved core description based on visual inspection and X-radiographs (of split cores), and sub-sampling for grain-size analyses performed by wet sieving of the > 0.063 mm fractions and by a Micromeritics SediGraph 5100 of the < 0.063 mm fractions. ^{14}C AMS dating was carried out on hand-picked foraminifera of the species *N. pachyderma.* The laboratory in Trondheim prepared the sample, and the AMS measurements were preformed in Uppsala. All dates are reported in ^{14}C years BP and corrected for a reservoir effect of 440 years (Mangerud & Gulliksen, 1975). The Lofoten Basin was visited again as part of the Training Trough Research cruise 13 in 2003 using RV *Professor Logachev*. This time deep-towed high-resolution side-scan (30 kHz) data were acquired simultaneously with deep-towed sub-bottom profiles (5.5 kHz) in the southern part of the basin including the site of core MD99-2293 using the MAK IM system.

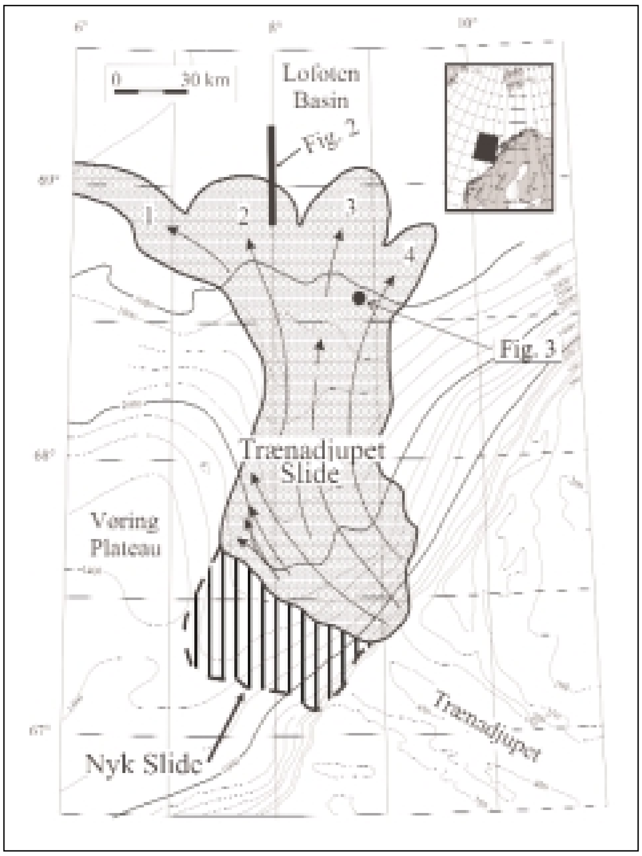


Fig. 1: Bathymetric map showing the location of the Trænadjupet Slide including the four distal depositional lobes (1 – 4) and the Nyk Slide. The location of figures 2 and 3 is also indicated.

The continental slope record

The upper slope record

Two submarine landslides are known to have occurred on the upper continental slope at the mouth of the Trænadjupet shelf trough. The Nyk Slide (Fig. 1) has a ^{14}C age of about 16 ka BP (Lindberg et al. 2004). Part of the same area was affected again by the Trænadjupet Slide (Fig. 1), which has a ^{14}C age of about 4 ka BP (Laberg & Vorren, 2000; Laberg et al. 2002a). Other slope escarpments northeast of the Trænadjupet Slide (Laberg et al., 2002b) indicate a long record of slope failures on this continental margin.

The lower slope record

On the lower continental slope, four depositional lobes (Fig. 1) comprise sediments released by submarine landslides on the upper slope (Dowdeswell et al. 1996, 2002; Laberg et al. 2002b). Gravity core JM95-5/1 was acquired from the easternmost of these lobes, lobe 4 (Fig. 1). The core is dominated by a matrix-supported grayish-grayish brown diamicton (Fig. 3), inferred to represent a debris flow deposit generated by one of the slides of the upper slope. This diamicton is capped by 26 cm of yellow brown hemipelagic mud. Two levels were dated from the debris flow matrix; a ^{14}C age of 19,325 +/-120 years BP was obtained at 202-204 cm depth and 21,180 +/-145 years BP at 61-63 cm depth (Fig. 3 and Tab. 1). Thus the debris flow sediments must be younger than 19,325 ^{14}C years BP. However, a sample from the base of the muds at 22-24 cm core depth provides an age of 18,735 +/-165 years BP. Due to the lack of Ice-Rafted debris (IRD), the hemipelagic cap is considered to be of Holocene age. Because there is no sedimentological evidence of a hiatus between the dated sediments and the Holocene sediments we consider the age of the base of the hemipelagic mud to be erroneous, and it is therefore not included in the discussion below.

The Lofoten Basin record

Seismic stratigraphy and sea-floor morphology

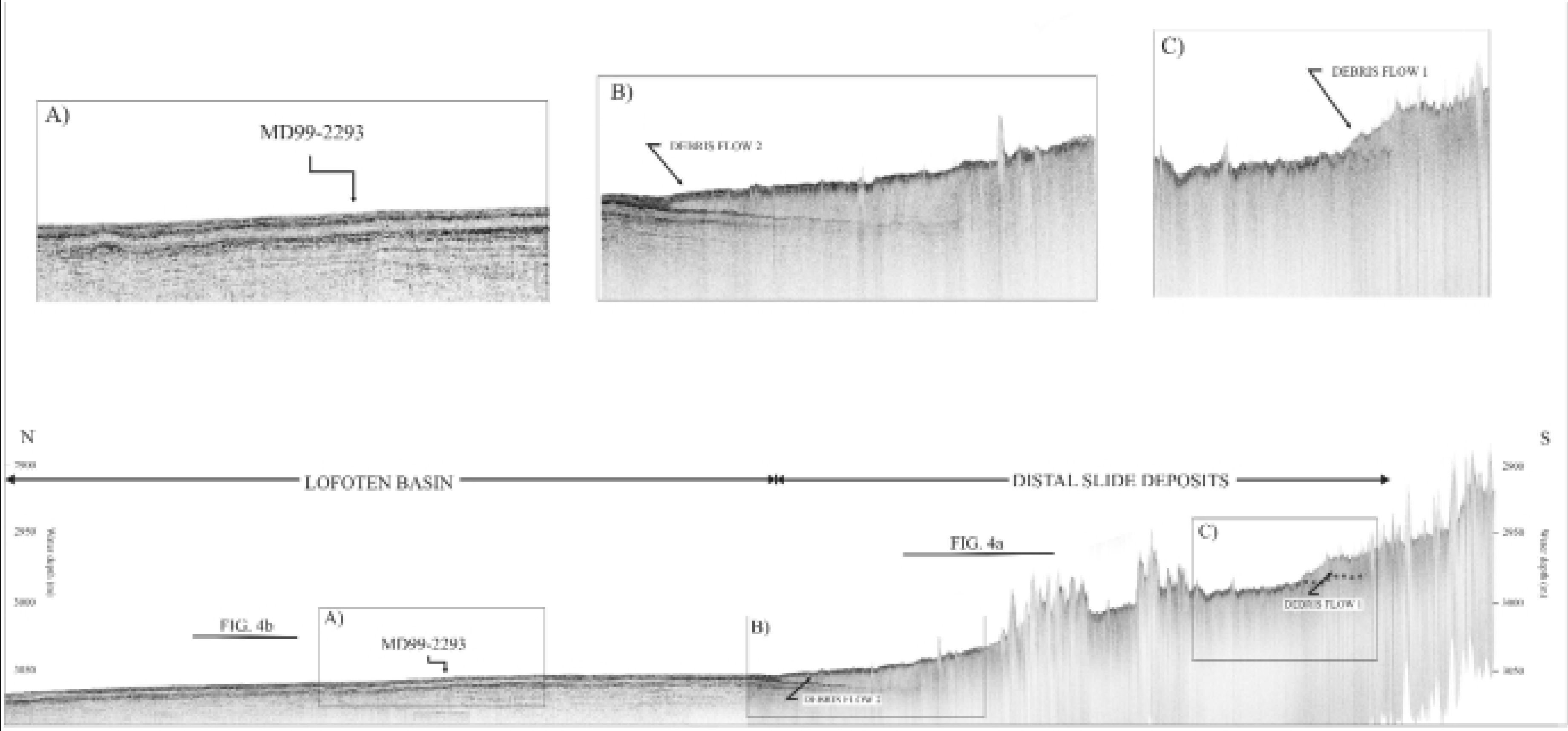
In the subbottom profile across the lobe 2 deposits (Fig. 2) two stacked debris flows terminate. Both debris flows have a transparent internal seismic signature and are at least several tens of meters thick. Their maximum thickness could not be mapped more precisely due to limited penetration (Fig. 2). The debris flow deposits determine an irregular surface morphology with local relief up to 50 m (Fig. 2). The side-scan sonar data show that the irregular morphology is due to the presence of large blocks, the largest more than 100 m across (Fig. 4a). Slide deposits of comparable scale have been described from similar settings (e.g. Canals et al. 2004; see also Ó Cofaigh et al. 2006).

Further into the Lofoten Basin the seismic signature is characterised by acoustic lamination, part of which can also be followed below the two debris flow deposits (Fig. 2). In this area the side scan data display parallel to subparallel lineations on the sea-floor that are inferred to be linear depressions and ridges that can be followed for several kilometres (Fig. 4b). From the orientation of these lineations, parallel with the flow direction of the Trænadjupet Slide, we suggest that they are erosional furrows formed by turbidity currents flowing into the basin.

Lithostratigraphy of core MD99-2293

Core MD99-2293 (Fig. 5) was raised from the area of lineations distal to the slide deposits (Figs. 2 and 4b). The core is dominated by various clay-rich sediments that represent hemipelagic and/or pelagic input to the basin. Scattered lithified and mud clasts are inferred to represent ice-rafted material. Colour mottling indicates bioturbation within some intervals. Interbedded are layers of massive, normal graded fine or medium sand, some grading upwards into laminated or homogeneous mud.

Fig. 2: *High-resolution (5.5 kHz) deep-towed sub-bottom profile across depositional lobe 2 which includes two debris flow deposits (1 and 2). The location of core MD99-2293 (see Fig. 5) and Figures 4a and b is shown. See Fig. 1 for location.*



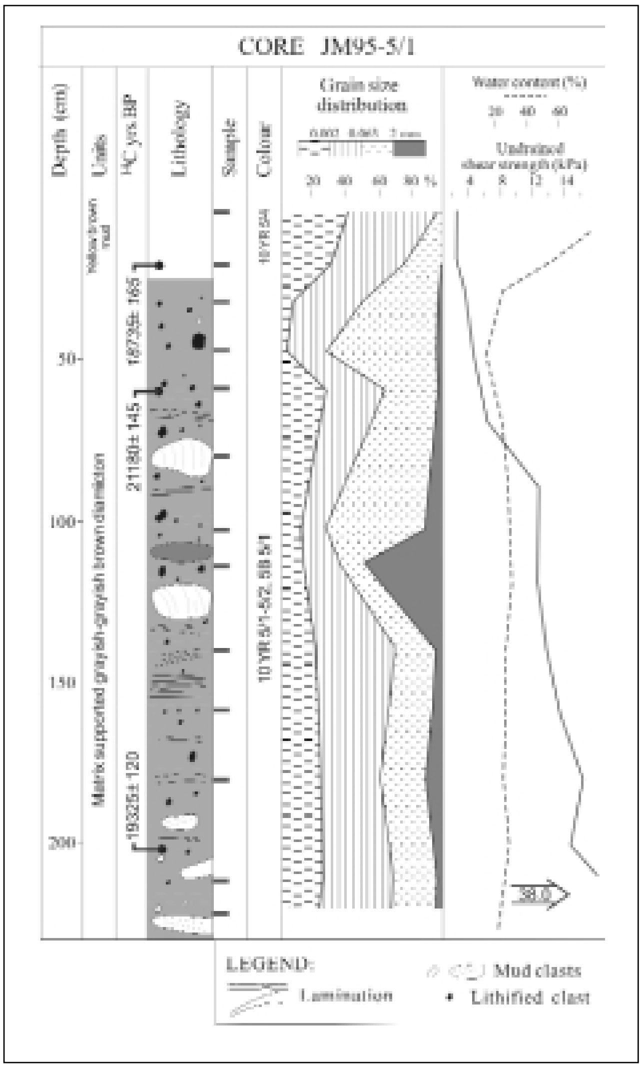


Fig. 3: Lithology, physical properties and ^{14}C AMS dating of gravity core JM95-5/1. See Figure 1 for location.

These layers have well-defined lower boundaries and are interpreted to be turbidites. Five turbidite intervals have been identified. In the upper 5 meters of the core, the interval 1 turbidite is at 55 – 90 cm depth; interval 2, comprising three turbidites, occurs from 350 to 490 cm. Down to a depth of about 930 cm there is a sequence comprising hemipelagic/pelagic sediments only. Below this, three turbidites are found in interval 3 (930 – 940, 1060 – 1090, and 1150 – 1160 cm); four in interval 4 between 1305 and 1345 cm, and three in interval 5 (1530 - 1610 cm).

^{14}C - dates

Eight ^{14}C accelerator mass spectrometry (AMS) dates have been obtained in core MD99-2293 (Fig. 5 and Table 1). The age reversals at the core top are inferred to be due to contamination by the inflow of younger sediments (at 310-312 cm) or the sampling of distal, muddy turbidites comprising older, reworked sediments (at 100-102 cm) (Fig. 5). Thus the dates of 5450 ± 70 ^{14}C years BP and 14,965 ± 120 ^{14}C years BP are considered to be incorrect and are not included in the discussion below.

Discussion

The turbidites of core MD99-2293 most likely originated from submarine landslides on the continental slope to the south.

When did these slides occur?

The dates show that the three turbidites of interval 2 (Fig. 5) were deposited in the period between 19,165 and 12,510 ^{14}C years BP. The interval 1 turbidite is younger than 8,860 ^{14}C years BP. This indicates that three interval 2 slides were released during the late Weichselian and that the interval 1 turbidite is of Holocene age. The Nyk Slide at about 16 ^{14}C ka probably caused the deposition of the middle or youngest turbidite within interval 2. The youngest turbidite (interval 1) coincides with the Holocene Trænadjupet Slide. From these results we suggest that the four depositional lobes in the Lofoten Basin (lobe 1-4, Fig. 1) were deposited during the three late Weichselian and the Holocene events, respectively. Although the precise age of each lobe is not known, this interpretation implies that the areal extent of the Holocene Trænadjupet Slide may be smaller than previously estimated (see Laberg et al. 2002b).

Core MD99-2293 shows that prior to the late Weichselian there was a long period (between turbidite intervals 2 and 3) including the middle (and early?) Weichselian when no turbidites reached this part of the basin, indicating that no major slides occurred on the nearby slope. Below this the turbidites occur in three of the intervals (intervals 3, 4 and 5) separated by periods of hemipelagic/pelagic sedimentation.

Why did these slides occur?

The slope instability and triggering of the slides could be related to: 1) glacio-eustatic sea-level fluctuations, 2) gas hydrate dissociation or 3) the presence of grounded ice at the shelf break and earthquakes during the following period of isostatic rebound. *1)* We find glacio-eustatic sea-level fluctuations less likely than the other factors because slides have been triggered during highstand as well as lowstand periods. During lowstands, shelf exposure and sediment instability due to fluvial sediment input to the continental slope as discussed by Maslin et al. (2004) would not take place because the shelf break is

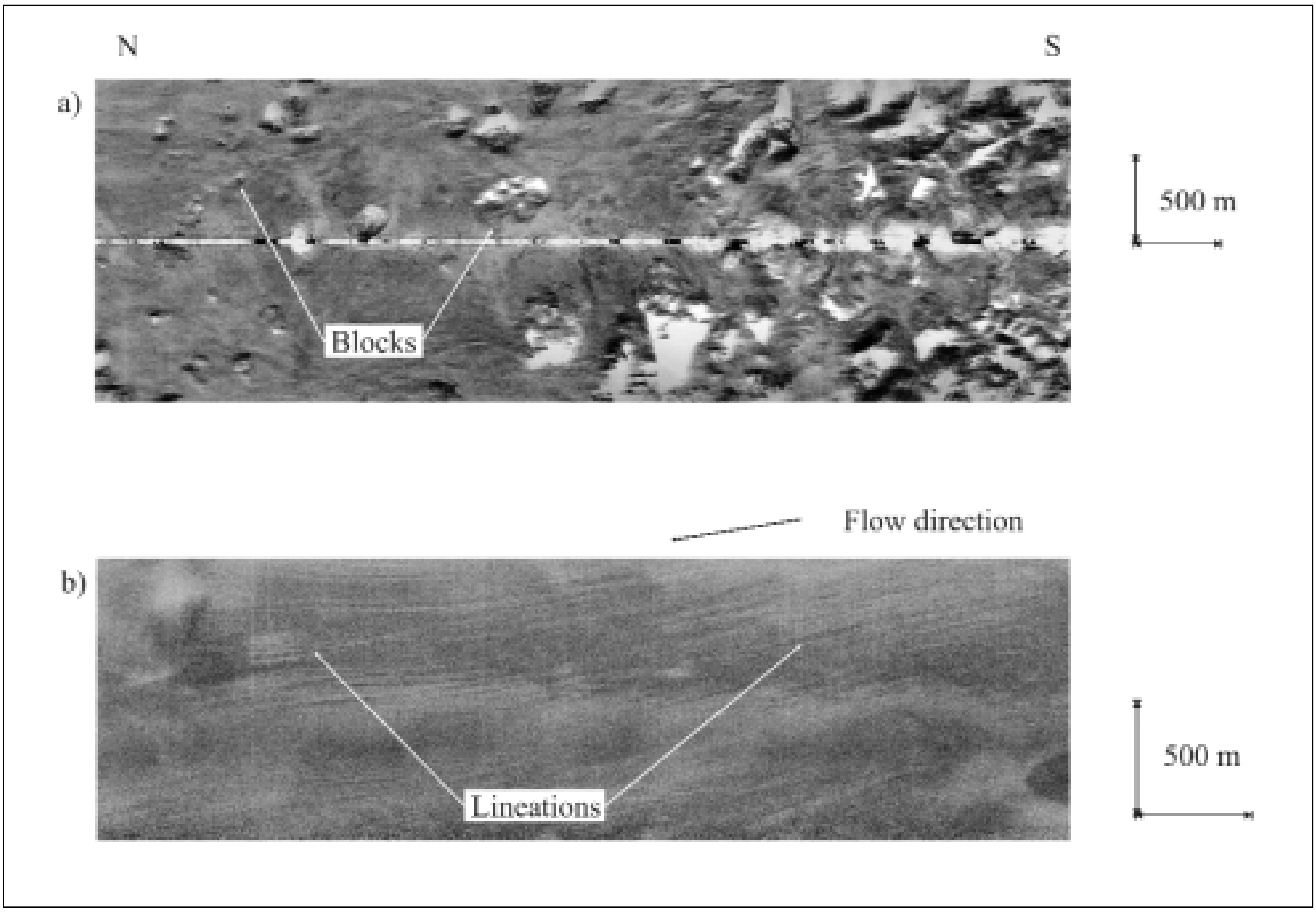


Fig. 4: Deep-towed side-scan sonar record (30 kHz) from (a) an area of irregular relief of the distal slide deposits corresponding to blocks of consolidated sediments within an unconsolidated matrix, (b) the sea-floor immediately outside the distal debris flow deposits showing lineations inferred to be formed by turbidity current erosion. See Figure 2 for location.

located too deep, from 300 to 500 m water depth. *2)* So far no indication of gas hydrates has been found on this part of the Norwegian margin. If gas hydrates were present, then dissociation would occur during interglacials because the temperature increase due to inflow of warm Atlantic water, rather than the pressure drop due to sea-level fall, controls the gas hydrate melting (e.g. Mienert et al. 2000; Vogt & Jung 2002) and thus does not explain the triggering of the Late Weichselian events.

3) Dahlgren & Vorren (2003) indicated that during the late Weichselian the Fennoscandian ice sheet first reached the shelf break offshore mid-Norway at c. 22,000 ^{14}C years BP. Subsequently, several oscillations of the ice front occurred between 21,000 and 15,500 ^{14}C years BP. During this period the three slides that have generated the turbidites of interval 2 may have been triggered by the rapid loading of the sediments deposited on the continental slope in front of the ice sheet where an average sedimentation rate of 65 m/ka has been estimated (Laberg et al. 2003). The direct effect of ice loading on slope instability has been demonstrated for the Canadian Atlantic margin (Mulder & Moran 1995). During the Holocene the area of study was, and still is, under isostatic re-adjustment due to the ice melting. Earthquake activity is one consequence of this rebound (e.g. Gudmundsson 1999) and has been considered the most likely triggering mechanism of the mid Holocene Trænadjupet Slide (Laberg & Vorren 2000; Leynaud & Mienert 2003).

For the pre late-Weichselian interval, neither the age of the slides nor the glacial history are known in detail. However, also in this period the slides occurred during relatively short episodes separated by longer intervals without large-scale sliding activity, though the latter may include hiatuses due to turbidity current erosion. Prior to the late Weichselian glacial maximum the ice sheet was present at the shelf break during Marine Isotope Stage (MIS) 6 (128-186 ka BP), 10 (339-362 ka BP), 12 (423-478 ka BP) as well as earlier glacials (Dahlgren et al., 2002). We speculate that the turbidites of intervals 3, 4 and 5 were deposited during or immediately after MIS 6, 10 and 12 glaciations, respectively.

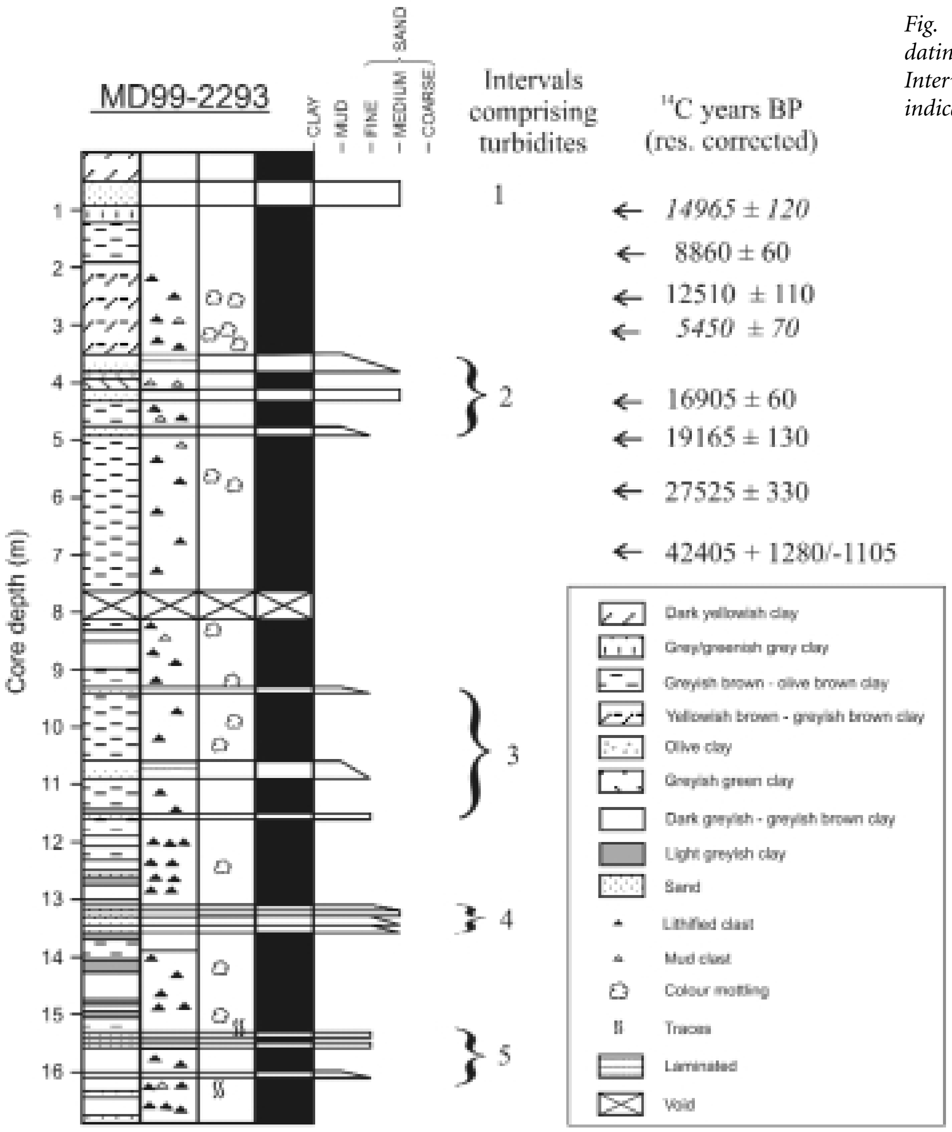


Fig. 5: Lithology and 14C AMS dating of calypso core MD99-2293. Intervals comprising turbidites are indicated. See Figure 2 for location.

Table 1. AMS-radiocarbon dates obtained from the cores. The dating results have been corrected for a reservoir effect of 440 years following Mangerud and Gulliksen (1975).

Gravity core	Core depth (cm)	Lab. ref. nr.	Dated material	Weight of dated material	14C years BP (reservoir corrected)
MD99-2293	100-102	TUa-3616	N. pachyderma	8,0 mg	14965 +/- 120
MD99-2293	180-184	TUa-4963	N. pachyderma	9,2 mg	8860 +/- 60
MD99-2293	253-256	TUa-3916II	N. pachyderma	9,7 mg	12510 +/- 110
MD99-2293	310-312	TUa-3916I	N. pachyderma	8,1 mg	5450 +/- 70
MD99-2293	435-437	TUa-3917	N. pachyderma	8,1 mg	16905 +/- 160
MD99-2293	490-492	TUa-3617	N. pachyderma	12,2 mg	19165 +/- 130
MD99-2293	585-587	TUa-4237	N. pachyderma	18,5 mg	27525 +/- 330
MD99-2293	690-692	TUa-4238	N. pachyderma	10,5 mg	42405 +1280/-1105
JM95-5/1	22-24	TUa-2936	N. pachyderma	12,5 mg	18735 +/- 165
JM95-5/1	61-63	TUa-1368	N. pachyderma	20,8 mg	21180 +/- 145
JM95-5/1	202-204	TUa-1369	N. pachyderma	24,0 mg	19325 +/- 120

Acknowledgement: This work is a contribution to the EUROSTRATAFORM program. Financial support from EC 5th Framework project number EVK3-CT-2002-00079 to the University of Tromsø is gratefully acknowledged. The IMAGES core was sampled from the French Research vessel *Marion Dufresne* as part of the international IMAGES-1999 cruise and we offer our sincere thanks to the master, crew and chief scientists, L. Labeyrie and E. Jansen. The side-scan sonar and seismic data were acquired during Leg 1 of Training Trough Research Cruise (TTR) 13 in 2003 using RV *Professor Logachev* and we offer our sincere thanks to the master, crew and chief scientists M. Ivanov and N. H. Kenyon. The TTR 13 participation by the University of Tromsø was generously funded by the SEABED project (contract no. NHT-B44-VK09546-00). We would also like to thank the master and crew of RV *Jan Mayen* for data collection assistance, E. Ellingsen and T. Dahl for laboratory assistance, and T. Midtun who produced the figures. L. Wilson corrected the English language and the manuscript benefited from constructive reviews by A. Camerlenghi and an anonymous referee.

References

Canals, M., Lastras, G., Urgeles, R., Casamor, J.L., Mienert, J., Cattaneo, A., De Batist, M., Haflidason, H., Imbo, Y., Laberg, J.S., Locat, J., Long, D., Longva, O., Masson, D.G., Sultan, N., Trincardi, F. & Bryn, P. 2004: Slope failure dynamics and impacts from seafloor and shallow sub-seafloor geophysical data: an overview. *Marine Geology* 213, 9-72.

Dahlgren, K.I.T. & Vorren, T.O. 2003: Sedimentary environment and glacial history during the last 40 ka of the Vøring continental margin, mid-Norway. *Marine Geology* 193, 93-127.

Dahlgren, K.I.T., Vorren T.O. & Laberg, J.S. 2002: Late Quaternary glacial development of the mid-Norwegian margin – 65 to 68° N. *Marine and Petroleum Geology* 19, 1089-1113.

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. *Geophysical Research Letters* 23, 3535-3538.

Dowdeswell, J.A., Ó Cofaigh, C., Taylor, J., Kenyon, N.H., Mienert, J. & Wilken, M. 2002: On the architecture of high-latitude continental margins: the influence of ice-sheet and sea-ice processes in the Polar North Atlantic. *In* Dowdeswell, J.A. & Ó Cofaigh, C. (eds.); *Glacier-influenced sedimentation on high-latitude continental margins.* Geological Society, London, Special Publications 203, 33-54.

Goldfinger, C., Nelson, C.H., Johnson, J.E. & The Shipboard Scientific Party 2003: Holocene earthquake records from the Cascadia Subduction Zone and Northern San Andreas Fault based on precise dating of offshore turbidites. *Annual Review Earth Planetary Science* 31, 555-577.

Gudmundsson, A. 1999: Postglacial crustal doming, stresses and fracture formation with application to Norway. *Tectonophysics* 307, 407-419.

Hampton, M.A., Lee, H.J. & Locat, J. 1996: Submarine landslides. *Reviews of Geophysics* 34, 33-59.

Huh, C.-A., Su, C.-C., Liang, W.-T. & Ling, C.-Y. 2004: Linkages between turbidites in the southern Okinawa Trough and submarine earthquakes. *Geophysical Research Letters* 31, L12304, doi: 10.1029/2004GL019731.

Laberg, J.S. & Vorren, T.O. 2000: The Trænadjupet Slide, offshore Norway - morphology, evacuation and triggering mechanisms. *Marine Geology* 171, 95-114.

Laberg, J.S., Vorren, T.O., Mienert, J., Bryn, P. & Lien, R. 2002a: The Trænadjupet Slide: a large slope failure affecting the continental margin of Norway 4000 years ago. *Geo-Marine Letters* 22, 19-24.

Laberg, J.S, Vorren, T.O., Mienert, J., Evans, D., Lindberg, B., Ottesen, D., Kenyon, N.H. & Henriksen, S. 2002b: Late Quaternary paleoenvironment and chronology in the Trænadjupet Slide area offshore Norway. *Marine Geology* 188, 35-60.

Laberg, J.S., Vorren, T.O., Mienert, J., Haflidason, H., Bryn, P. & Lien, R. 2003: Preconditions leading to the Holocene Trænadjupet Slide offshore Norway. *In* Locat, J. and Mienert, J. (Eds.); *Submarine mass movements and their consequences*, 247-254. Kluwer Academic Publishers, Netherlands.

Leynaud, D. & Mienert, J. 2003: Slope stability assessment of the Trænadjupet Slide area offshore the Mid-Norwegian margin. *In* Locat, J. and Mienert, J. (Eds.), *Submarine mass movements and their consequences*, 255-265. Kluwer Academic Publishers, Netherlands.

Lindberg, B., Laberg, J.S. & Vorren, T.O. 2004: The Nyk Slide – morphology, progression, and age of a partly buried submarine slide offshore northern Norway. *Marine Geology* 213, 277-289.

Locat, J. & Lee, H.J. 2002: Submarine landslides: advances and challenges. *Canadian Geotechnical Journal* 39, 193-212.

Mangerud, J. & Gulliksen, S. 1975: Apparent radiocarbon ages of Recent marine shell from Norway, Spitsbergen and Arctic Canada. *Quaternary Research* 5, 263-273.

Maslin, M., Owen, M., Day, S. & Long, D. 2004: Linking continental-slope failures and climate change: testing the clathrate gun hypothesis. *Geology* 32, 53-56.

Mienert, J., Andreassen, K., Posewang, J. & Lukas, D. 2000: Changes of the hydrate stability zone of the Norwegian margin from glacial to interglacial times. *Annals of the New York Academy of Sciences* 912, 200-210.

Mulder, T. & Moran, K. 1995: Relationship among submarine instabilities, sea level variations, and the presence of an ice sheet on the continental shelf: An example from the Verrill Canyon Area, Scotian Shelf. *Paleoceanography* 10, 137-154.

Ó Cofaigh, C., Dowdeswell, J.A. & Kenyon, N.H. 2006: Geophysical investigations of a high-latitude submarine channel system and associated channel-mouth lobe in the Lofoten Basin, Polar North Atlantic. *Marine Geology* 226, 41-50.

O´Leary, D.W. 1991: Structure and morphology of submarine slab slides: clues to origin and behaviour. *Marine Geotechnology* 10, 53-69.

Vogt, P.R. & Jung, W.-Y. 2002: Holocene mass wasting on upper non-Polar continental slopes-due to post-Glacial ocean warming and hydrate dissociation? *Geophysical Research Letters* 29, 9, 10.1029/2001GL013488.

Weaver, P.P.E. & Kuijpers, A. 1983: Climatic control of turbidite deposition on the Madeira Abyssal Plain. *Nature* 306, 360-363.