A modern canyon-fed sandy turbidite system of the Norwegian Continental Margin

Jan Sverre Laberg, Tore O. Vorren, Neil H. Kenyon, Mikhail Ivanov & Espen S. Andersen

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The sedimentary processes and evolution of a presumably old but still relatively recent active canyon-fed sandy turbidite system on the Norwegian continental margin, the Andøya Canyon - Lofoten Basin Channel system, were studied using high-resolution seismic, deep-towed side-scan sonar records and cores (gravity and vibro cores). The canyon has a length of about 40 km and represents a continental slope incision of up to 1100 m. From the canyon mouth, a deep-sea channel up to 30 m deep and 3 km wide continues for approximately 200 km into the deepest part of the Lofoten Basin. The most recent activity of this system was deposition of coarse-grained sediments from turbidity currents as indicated by sediment waves on the canyon floor, thin sand layers within the levees and a sandy lobe at the channel mouth. From this modern system we suggest that there are a number of features that could be of relevance for hydrocarbon exploration of deep-water turbidite systems: a) this canyon-fed system probably received sand from piracy of shelf sediments and/or canyon wall erosion, b) the sandy deposits are located in the deepest part of the basin, about 200 km outside the canyon mouth, c) the sandy lobe is connected to the source area by a straight channel with poorly developed mud-rich levees, d) the sandy deposits have a sheet-like or tabular geometry, e) post-depositional deformation of the sand could be widespread suggesting rapid sand deposition. Thus, modern, canyon-fed sandy turbidite systems provide additional data relevant for future hydrocarbon prospecting in deep-water areas.

Jan S. Laberg, Tore O. Vorren, Department of Geology, University of Tromsø, NO-9037 Tromsø, Norway (E-mail: jan.laberg@ig.uit.no); Neil H. Kenyon, National Oceanography Centre, Empress Dock, Southampton SO14 3ZH, UK; M. Ivanov, UNESCO Centre for Marine Geology and Geophysics, Moscow State University, Moscow 119899, Russia; Espen S. Andersen; Norsk Hydro ASA, N-0246 Oslo, Norway

Introduction

On the continental margin offshore Norway Lower Tertiary sandy turbidites form oil and gas reservoirs in both the North Sea (Enjolras et al. 1986; Dreyer et al. 2004) and the Norwegian Sea (Gjelberg et al. 2001; Smith & Möller 2003; Möller et al. 2004). Sandy turbidites have also been drilling targets in the Barents Sea (Knutsen & Larsen 1996; Ryseth et al. 2003). Experience from these and other studies have, however, shown that the existence of stratigraphic traps, as exemplified by sandy turbidites, may be difficult to predict. This is probably partly because the natural variability in continental margin turbidite systems is greater than can be encompassed in a few simple model types based on facies schemes or tectonic setting (e.g. Piper & Normark 2001; Kenyon et al. 2002).

In order to address this problem additional information on sandy turbidite systems can be obtained from the study of modern analogues. Here we present high-resolution seismic, side-scan and core data from a modern turbidite system in the Lofoten Basin, Norwegian Sea; the Andøya Canyon - Lofoten Basin Channel (Fig. 1). The aim is to elucidate the morphology, architecture and sedimentary processes of this system.

Physiography

The Lofoten Basin is situated in the north-eastern Norwegian Sea (Fig. 1). The basin is bounded by the western Barents Sea continental slope, the north Norwegian continental slope, the Northern Vøring Plateau slope, the Jan Mayen Fracture Zone, and part of the mid-oceanic spreading ridge (the Mohns Ridge). The deepest part of the basin is located to the south and southwest where water depth exceeds more than 3000 m. The basin asymmetry is due to the thick wedge of prograding Late Cenozoic sediments off the western Barents Sea (Vorren et al. 1991; Faleide et al. 1996; Dahlgren et al. 2005).

The adjacent continental margin has a narrow shelf, a relatively steep slope and a thin succession of Cenozoic sediments; thus it is sediment starved in marked contrast to the margin further south (Dahlgren et al. 2002) and north (Vorren et al. 1991). For instance, sediment drifts inferred to consist of deep-water facies equivalent to the Miocene – Early Pliocene Kai and Late Pliocene – Pleistocene Naust formations offshore mid-Norway (Laberg et al. 2005) occur as isolated patches on the slope (Laberg et al. 2001). Also, only a very limited amount of glacigenic sediments (the Naust

Formation) have been deposited in this area due to the barrier (and consequently damming effect) of the Lofoten islands mountain chain. Ice draining from the east was routed southwest through Vestfjorden, continuing west through Trænadjupet where the ice front reached the shelf break and large amounts of sediments were released on to the slope (Laberg et al. 2002).

Database

High-resolution, single channel seismic data (Fig. 2) were acquired by RV *Jan Mayen* of the University of Tromsø in 2002 using an airgun array of two 0,6 litre sleeve guns. The filter setting of the Geopulse Receiver was 100-700 Hz. The seismic records revealed a penetration of up to 2 sec two-way travel time (TWT) and a vertical resolution of up to 1-2 m. High resolution, deep-towed side-scan sonar data (using the Russian MAK system at 30 and 100 kHz) co-registered with sub bottom profiles (5kHz) and the cores (gravity and vibro cores) were acquired during Leg 1 of Training Through Research (TTR) 13 in 2003 using the Russian research vessel *Professor Logachev.*

The Andøya Canyon

Morphology and evolution

The Andøya Canyon is an approximately 40 km long (lower termination at 15° E), straight, downslope-oriented canyon located where the average continental slope gradient is more than 4° (Fig. 2). On the upper slope, the canyon is characterised by a V-shaped cross-section, steep walls, and the width between canyon shoulders is about 8 km (Fig. 3a). The sidewall morphology is relatively smooth (Fig. 3a) but irregular areas occur (see Laberg et al. 2000). The canyon is up to 1100 m deep and has an outer shelf incision of about 6 km. Such a morphology was considered by Shepard & Dill (1966) to be typical of submarine canyons. Further downslope the canyon has a U-shaped cross-section, and is up to 25 km wide. The canyon floor is located about 900 m below the shoulders (Fig. 3b). In this area the canyon walls and floor are dominated by an irregular relief.

From the above observations and results from modern analogues (e.g. Shepard 1981) we suggest a combination of processes responsible for canyon formation. The incision in the upper V-shaped, part of the canyon was probably caused by a combination of processes including downslope flowing turbidity currents generated from mass wasting in the headwall and sidewall areas, piracy of winnowed shelf sediments, bottom currents and/or upwelling within the canyon. The latter process has recently been shown to occur in this area (Skardhamar & Svendsen 2004) but its effect on the seabed sediments is not known.

In the lower part of the canyon, retrogressive sidewall collapse due to sliding/slumping seems to have been active as indicated by the wider, U-shaped cross-section and irregular relief. Thus the Andøya Canyon may exemplify canyon formation both by downslope erosion from fluid flow processes and sidewall and headwall retrogressive sliding and slumping, as previously have been shown for low-latitude canyons (Shepard 1981; Pratson et al. 1994; Pratson & Coakley 1996). A more detailed presentation of the canyon morphology is given by Laberg et al. (submitted).

Deposits from turbidity currents are found as a thick levee on the northern flank of the canyon mouth (Fig. 3c) and flanking the Lofoten Basin Channel, although their development is much less pronounced for the latter area. The levee is particularly well developed on the right side (looking downslope) of the canyon mouth due to 1) the marked reduction in slope gradient, and 2) the channel turns almost 90° west. Both of these factors probably led to a decrease in flow velocity and sediment overspill, deflected to the right by the Coriolis force.

The fact that a channel continues from the mouth of the canyon into the deepest part of the basin indicates that the current velocity was still high enough for at least some of the currents to be erosional after passing the base of the slope. This hypothesis is also supported by the fact that the Lofoten Basin Channel is a straight channel which is also a characteristic of erosional flows (Kneller 2003). No meandering has been seen (e.g. Dowdeswell et al. 1996).

Weichselian and Holocene processes

Side-scan sonar and cores reveal details about the most recent evolution of the canyon. Side-scan sonar data crossing the canyon mouth at the base of the slope display a more than 1 km wide sediment wave field, covering about half the canyon floor (Fig. 4). The waves are oriented transverse to flow direction, and have a wavelength of some tens of meters. However, this may vary both along and across the floor, as in the case with other similar canyons, such as the Eastern Valley sediment wave field of the Laurentian Fan (Hughes Clarke et al. 1990). The sediment wave field is draped by some tens of centimetres of mud.

Coring of the sediment waves was not successful. However, information gained from comparable settings, such as the Eastern Valley of the Laurentian Fan (Hughes Clarke et al. 1990) as well as in canyons offshore Corsica and Sardinia (Kenyon et al. 2002),

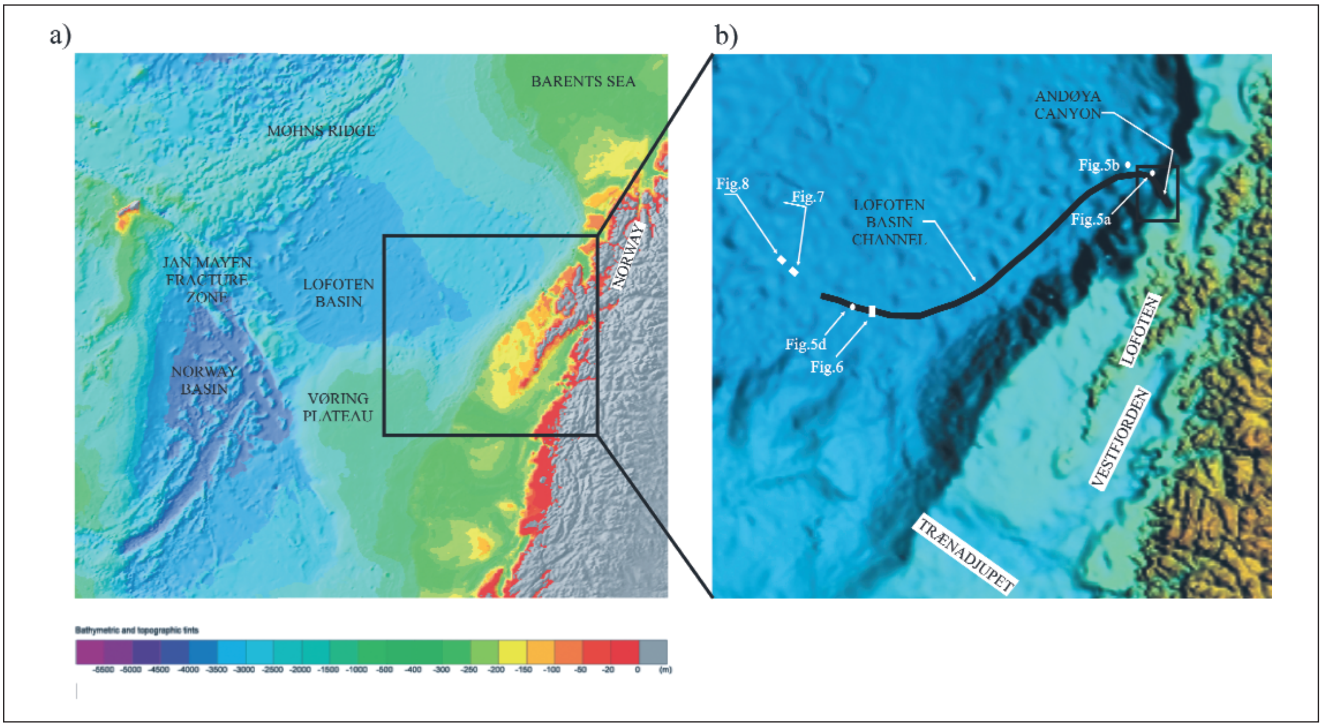

Fig. 1: (a) Bathymetric map showing the location of the study area (from The International Bathymetric Chart of the Arctic Ocean (Jakobsson et al., 2000)), and (b) the location of the Andøya Canyon - Lofoten Basin Channel system and sandy lobe at the channel mouth. Location of Figures 2 (box) 5a, 5b, 5d, 6-8 is indicated.

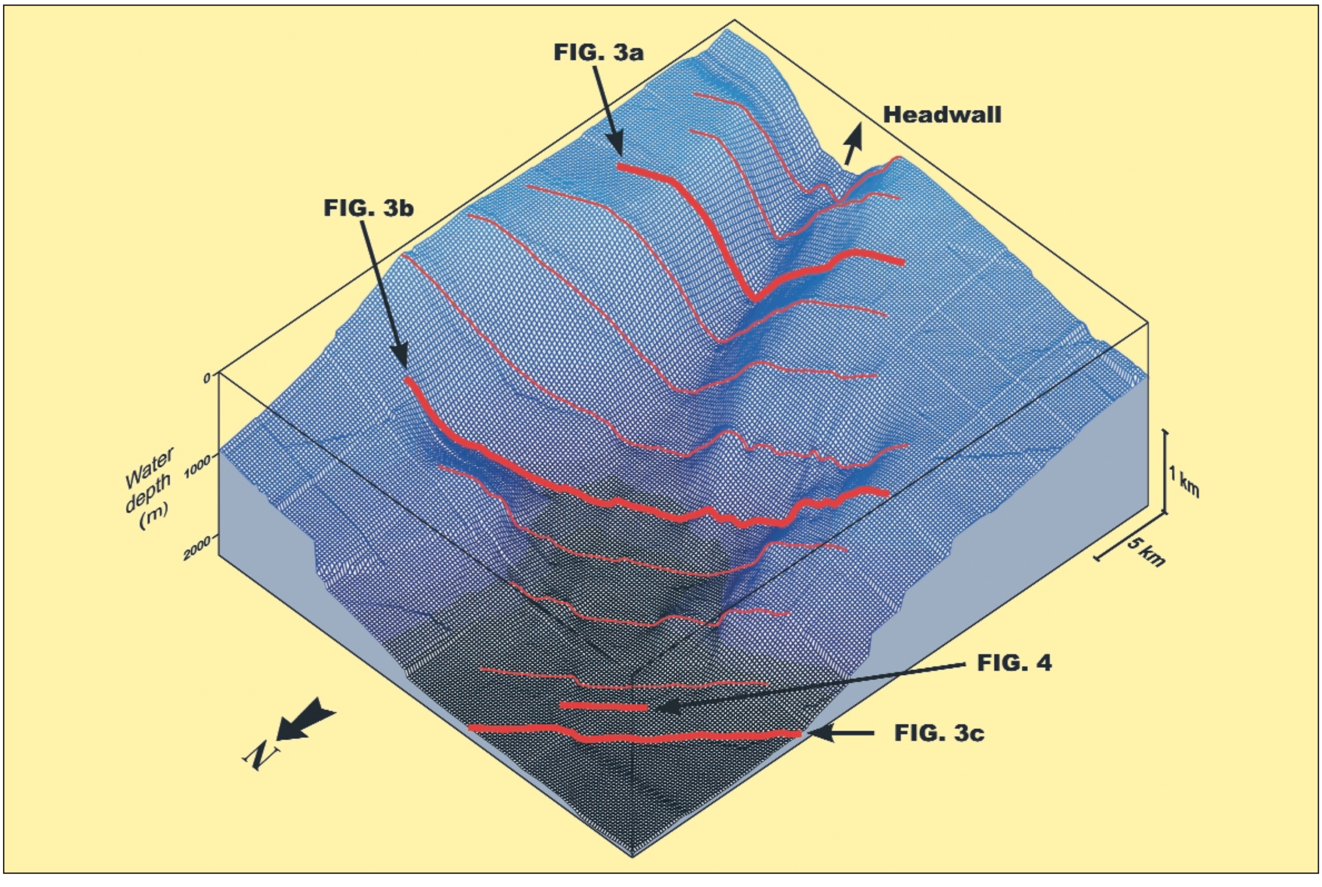

Fig. 2: 3D model of the morphology of the studied part of the Andøya Canyon as seen from NNE based on the single channel seismic data. Location of the single channel seismic lines is indicated by the red lines. The location of Figs. 3a-c and 4 is shown. See Fig. 1b for location of the figure.

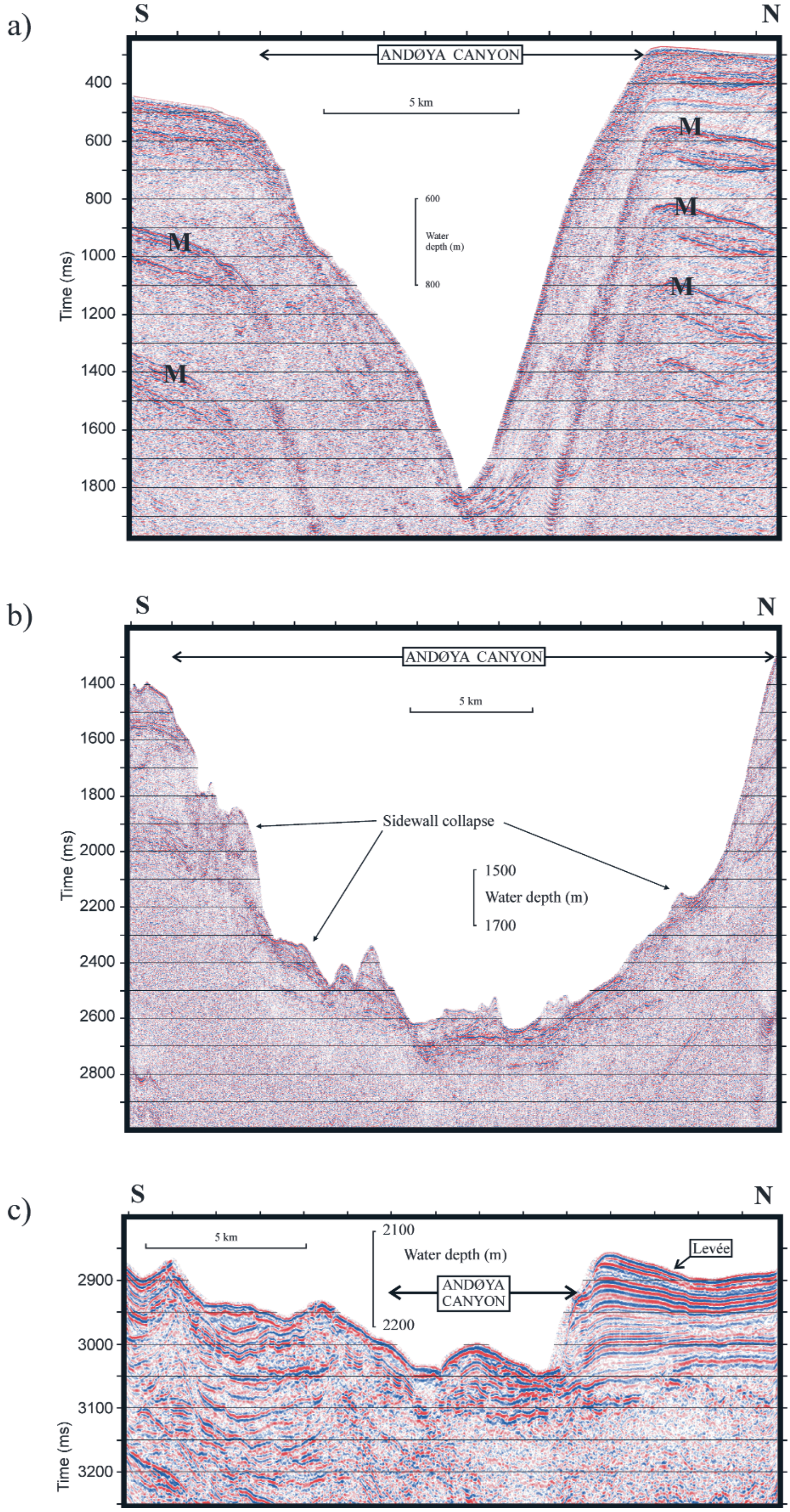

Fig. 3: High-resolution seismic profiles crossing the upper (a), middle (b) and lowermost part of the canyon (c). M = multiple. For location, see Fig. 2.

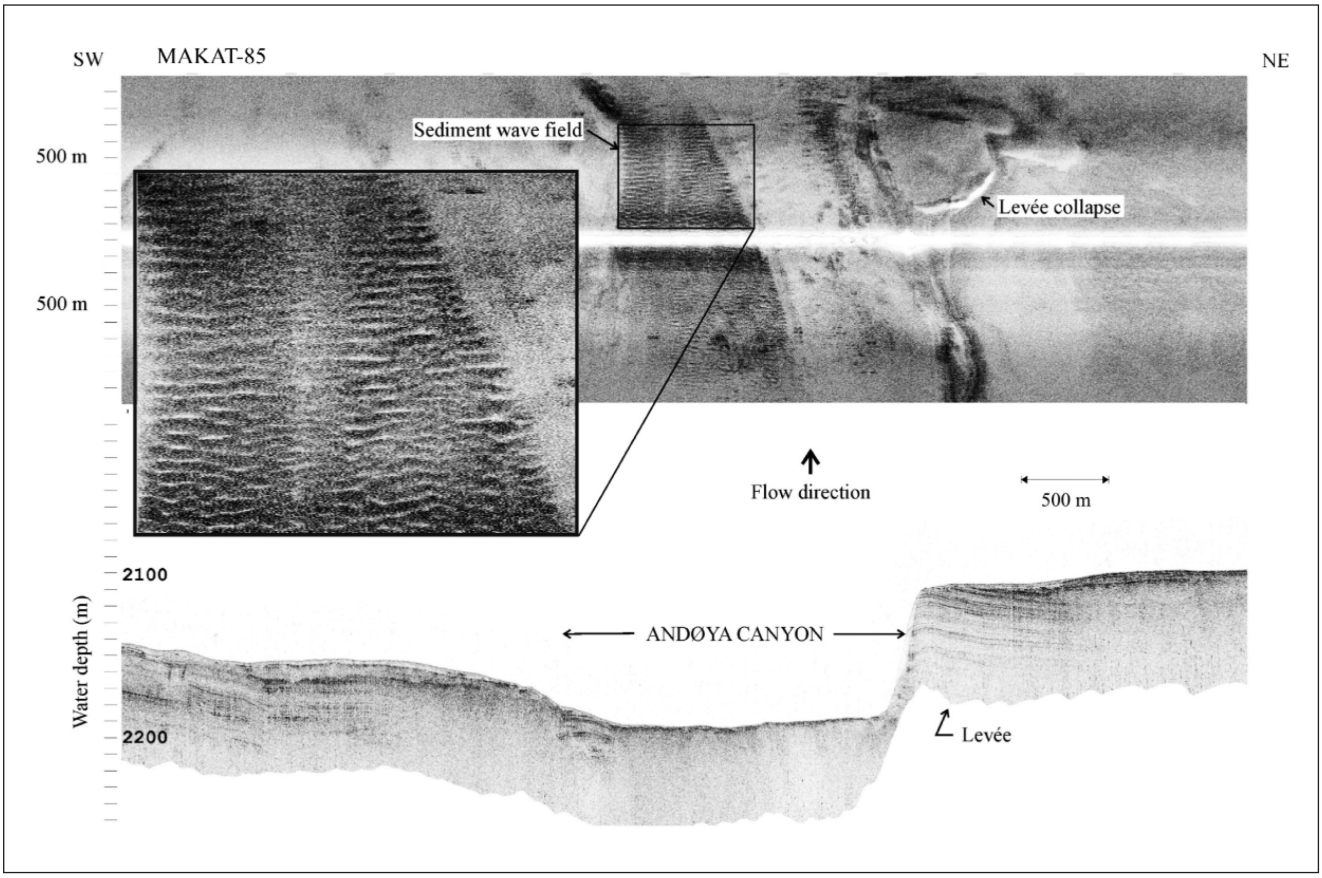

Fig. 4: Part of side-scan profile MAKAT-85 (30 kHz) across the lowermost part of the Andøya Canyon (and corresponding sub-bottom profile) showing the sediment wave field occupying about 50 % of the canyon floor in this area. A collapsed part of the levee is also seen. See Fig. 3 for location.

suggests that sand, gravel and possibly pebbles are likely to comprise the sediment waves (see also Wynn et al. 2002 for a further discussion). This leads us to propose that the sediment waves in the canyon mouth area are composed of coarse-grained sediments deposited by turbidity currents.

Support for this interpretation is the fact that cores recovered from levee deposits consist of sand layers interbedded with hemipelagic and/or turbiditic mud (Figs. 5a and b). The sand layers, inferred to be turbidites, show that at least some of the turbidity currents transported sand in suspension, implying that coarser sediments were transported in the lower part of the current (as bedload). If deposited from turbidity current overspill, some of the coarse-grained turbidity currents had a thickness of more than 100 m. This is probably not extreme, as modern in situ measurements of canyon-confined turbidity currents have shown sediment plumes reaching 170 m above the canyon floor (Xu et al. 2004).

In conclusion, the Andøya Canyon is probably an old feature formed by a combination of processes. More recent activity seems to have been by coarse-grained turbidity currents. Present day activity in this system is not known.

The distal channel

Turbidity currents initiated in the Andøya Canyon moved up to 200 km through the Lofoten Basin Channel to end up in the deepest part of the Lofoten Basin (Fig. 1). The distal part of the channel is about 3 km wide and some tens of meters deep (Fig. 6). The channel morphology, showing different levels of erosion, suggests that some of the currents filled the whole channel while others were restricted to the central, deepest part. Transverse bedforms, inferred to be sediment waves with a wavelength < 100 m, also imply sediment deposition from and modification by turbidity currents.

Levees are not well developed in this area. A short gravity core sample from the northern channel flank was composed of two massive, fine-grained sand layers interbedded with bioturbated mud (Fig. 5c). This indicates the sandy nature of the most recent currents, which we interpret to have been at least 25 m thick in order to spill over the channel. The mud could be the Bouma division E and/or the background hemipelagic sediments. Separating the two is difficult from the present database.

Slightly further into the basin a core sample from the

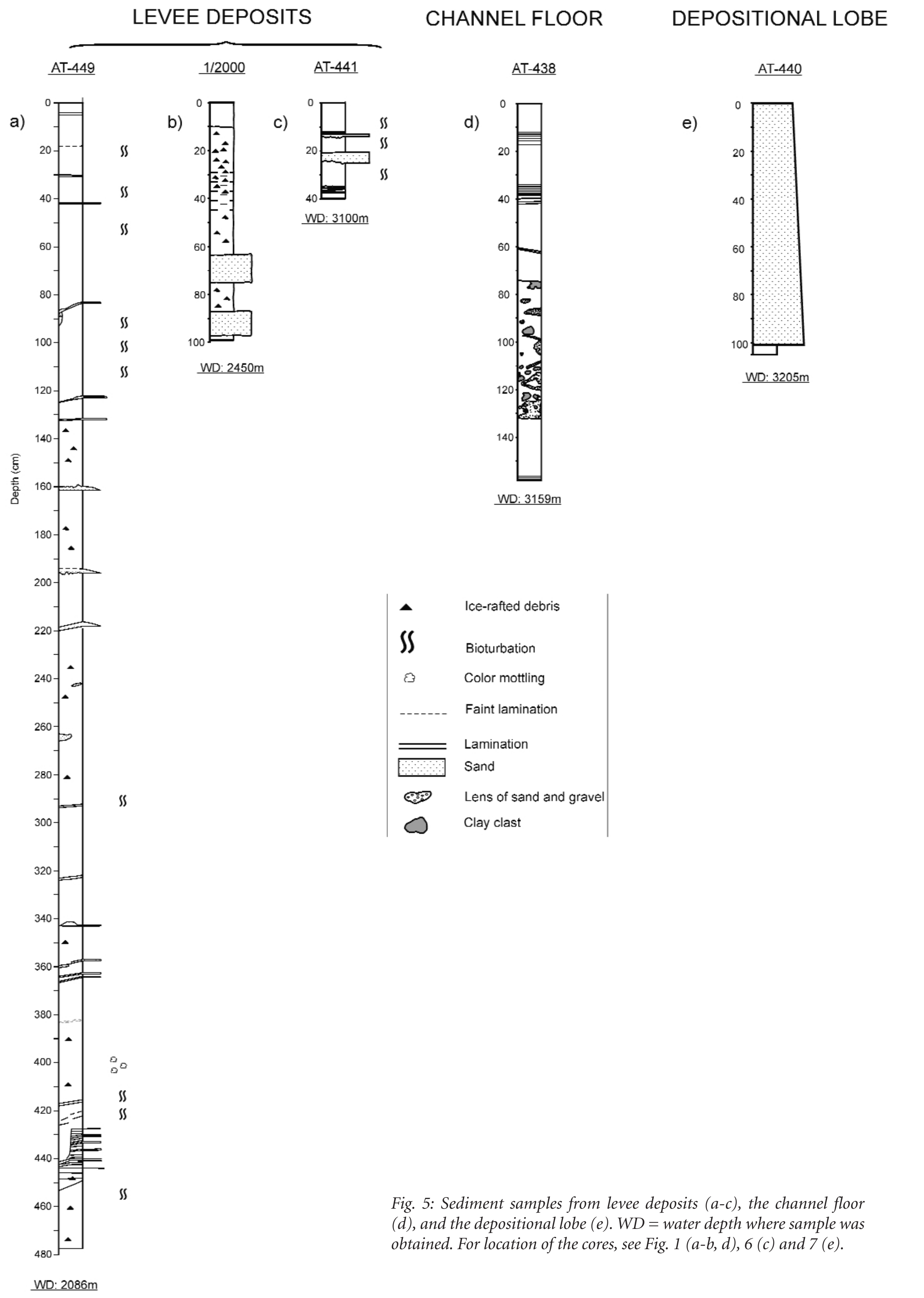

Fig. 5: Sediment samples from levee deposits (a-c), the channel floor (d), and the depositional lobe (e). WD = water depth where sample was obtained. For location of the cores, see Fig. 1 (a-b, d), 6 (c) and 7 (e).

channel floor displays about 75 cm of mud overlying a 57 cm thick interval of sand and gravel lenses and some clay clasts in a muddy matrix. Below is about 20 cm of mud (Fig. 5d). The mud-sand-gravel facies association may represent channel floor sediments deposited from and modified by turbidity currents. Alternatively, they may represent debris flow deposits. The overlying laminated intervals probably correspond to the Bouma D division while the massive mud could be the Bouma E division or hemipelagic sediments.

The sediments deposited at the channel mouth

At the mouth of the Lofoten Basin Channel, Dowdeswell et al. (1996) suggested the presence of a sandy lobe on the basis of the backscatter signature of GLORIA long-range side-scan sonar data. Our data confirm this interpretation. High-resolution sub-bottom profiler records show units of 2 to 5 m thickness that can be followed for several tens of kilometres (Fig. 7). They are separated by continuous to slightly discontinuous medium to high amplitude reflections, indicating a high acoustic contrast. Sediment waves are present at some levels (Fig. 7).

An approximately 1 m long vibro core sample from this area comprised an upper unit of normal graded medium to fine sand overlying a thin clay layer (Fig. 5e). The sand is inferred to have been deposited from a waning turbidity current (Bouma (1962) division A), common where periodic surge-type currents flow onto large abyssal plains (e.g. Kneller 1995). The basal mud could be the Bouma division E and/or the background hemipelagic sediments. From the data at hand it is not possible to discriminate between the two alternatives. The sediment waves are most likely formed by turbidity currents but from the present data base it is not known whether they formed as giant antidunes as favoured by Howe (1996) and Wynn et al. (2000) for deep-sea sediment wave fields in the North East Atlantic, or by other processes (e.g. the lee-wave model of Flood 1988).

The core data indicate that the uppermost seismic unit consists of sand, and that the strong acoustic contrast is due to thin layers of hemipelagic and/or Bouma E clay (less than 1m thick) separating the sand layers. The repetition in seismic facies that we observe on the profile data (Fig. 7) further suggests that the uppermost part of the sandy lobe is composed of a series of stacked sandy units separated by thin intervals of hemipelagic and/or turbiditic mud.

Sediment accumulation rates could not be estimated because only short sediment samples comprising one event were recovered from the depositional area. Thus,

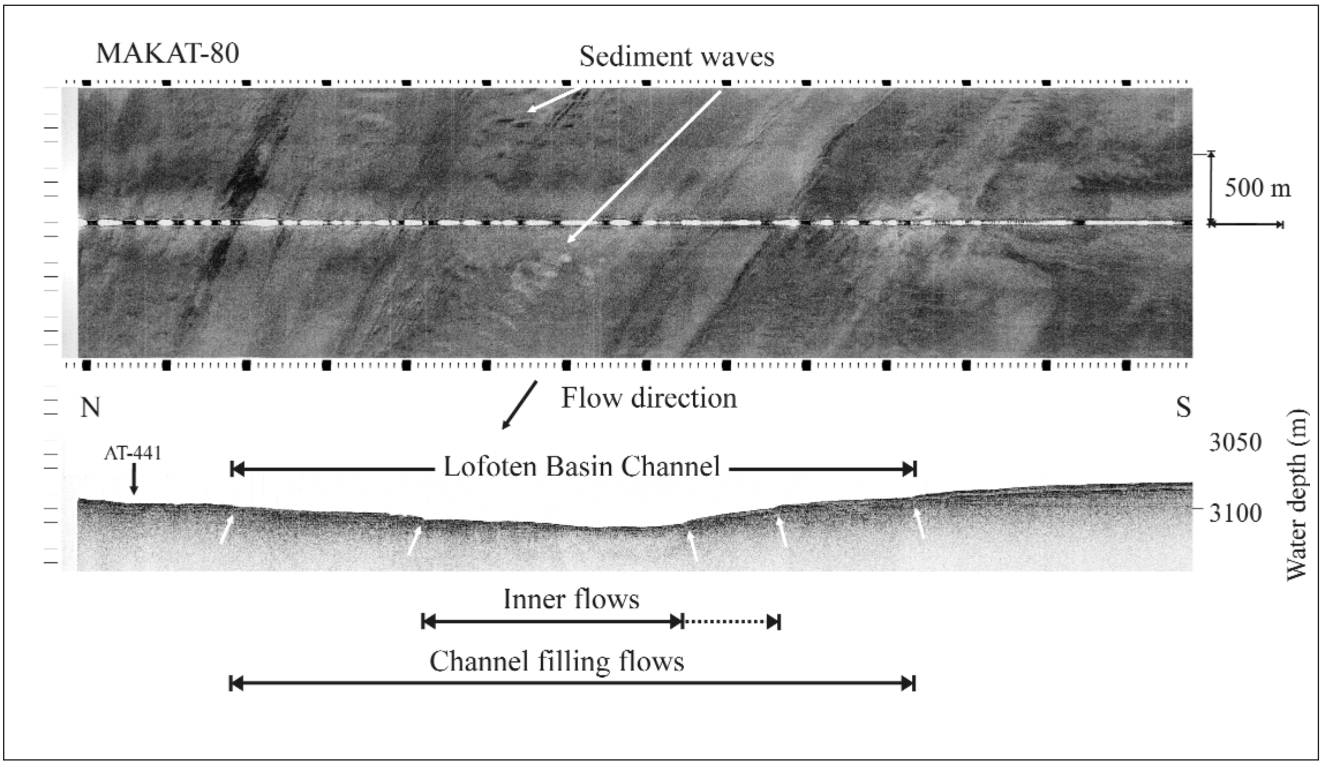

Fig. 6: Part of side-scan profile MAKAT-80 (30 kHz) and corresponding sub-bottom profile across the distal part of the Lofoten Basin Channel. White arrows indicate outer termination of different intensity of erosion inferred to be related to the size of the turbidity current. Sediment waves are also seen in this part of the channel. The location of core AT-441 (Fig. 5c) is shown. For location of the profile, see Fig. 1.

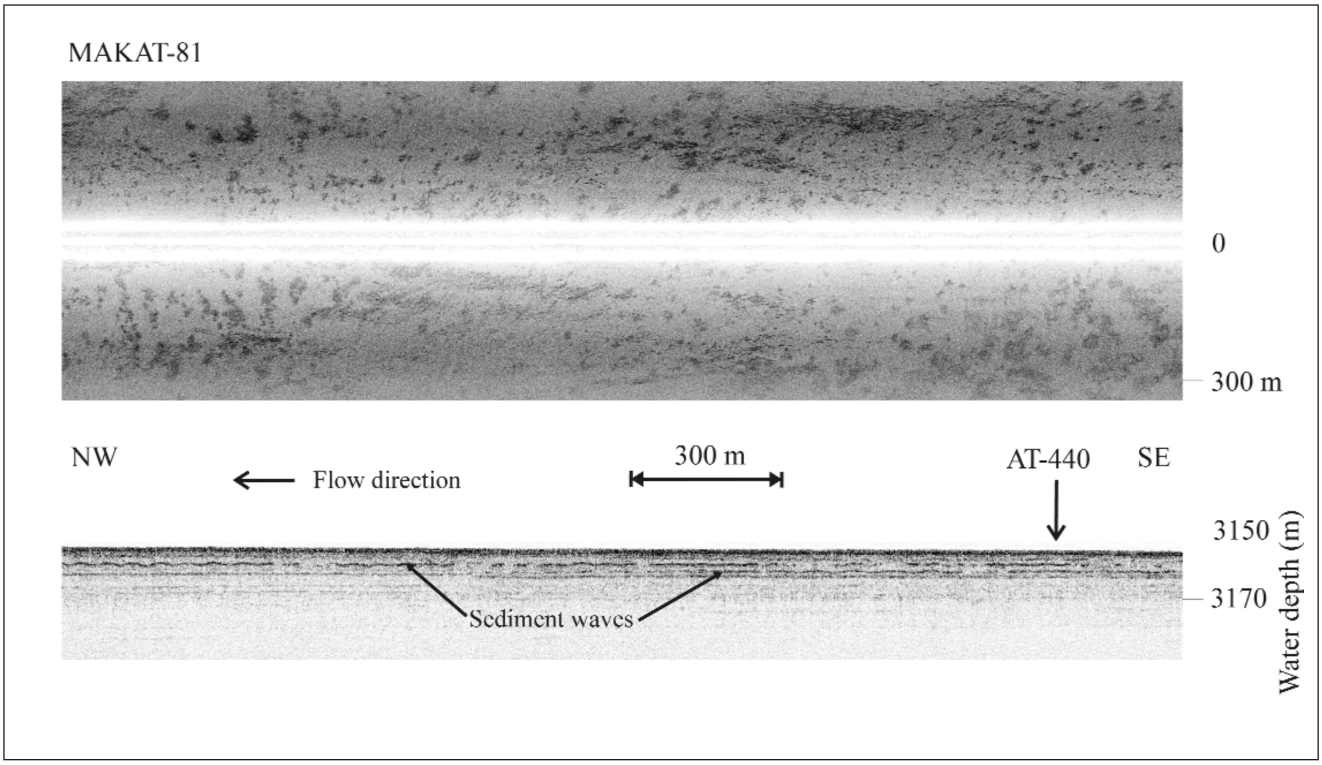

Fig. 7: Part of side-scan profile MAKAT-81 (100 kHz) and corresponding sub-bottom profile across the proximal part of the sandy lobe (located in Fig. 1). Individual seismic units reach a thickness of 2 - 5 m. The side-scan data reveal a patchy signature; high backscatter patches within a low backscatter matrix. The location of core AT-440 (Fig. 5e) is indicated.

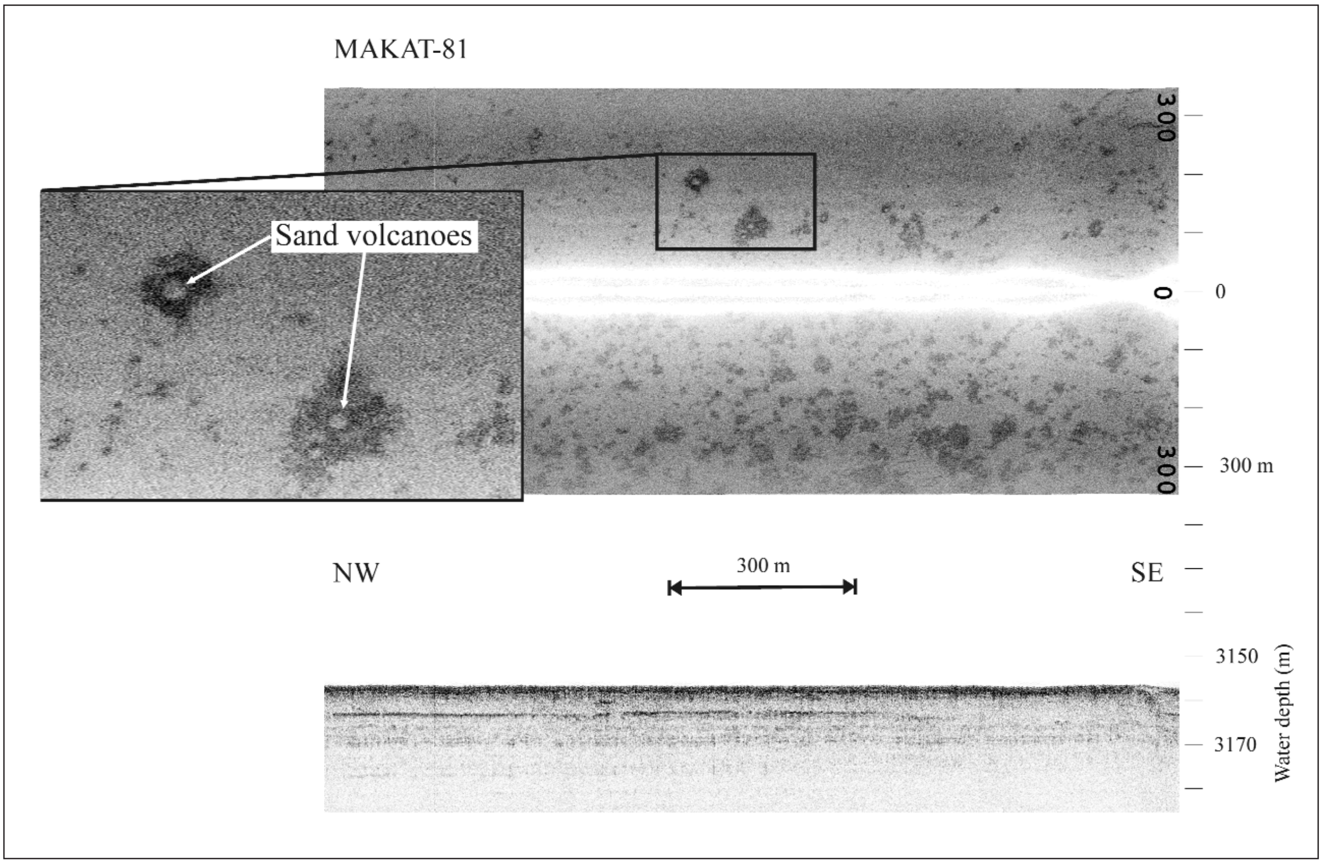

Fig. 8: Part of side-scan profile MAKAT-81 (100 kHz) showing details of the high backscatter patches where enclosing circular low backscatter features are inferred to be sand volcanoes. For location, see Fig. 1.

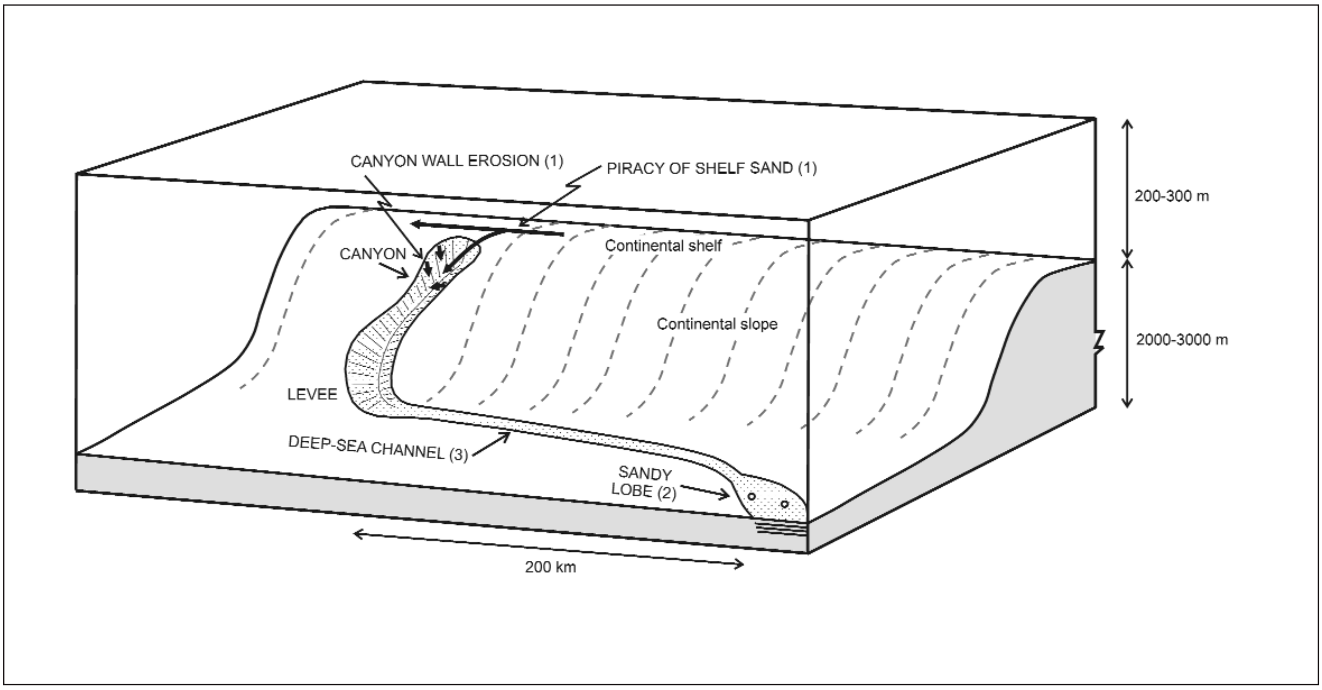

Fig. 9: Schematic sketch of a modern slope canyon – basin channel and attached sandy lobe depositional system, Norwegian Sea. See text for further discussion.

it is presently not known whether the Andøya Canyon - Lofoten Basin Channel system represents a sediment-starved system as has been suggested for the Ormen Lange turbidite system offshore SW Norway (Smith & Möller 2003).

100 kHz side-scan sonar records from the depositional area show high backscatter patches within a low backscatter matrix. Some of the patches are high backscatter zones enclosing low backscatter circles up to 10-15 m in diameter (Figs. 7 and 8). The origin of these circular features is enigmatic. Our hypothesis is that they represent sand volcanoes related to dewatering following rapid deposition of the Bouma A division sands, and collapse due to unstable grain packing. Further studies are needed in order to verify the origin of these features.

Relevance for hydrocarbon exploration of turbidite systems

Although there is a large variability in continental margin turbidite systems the large mud-rich submarine fans have so far received most attention (e.g. Kenyon et al. 2002). From the modern canyon-channel system presented here we suggest that there are a number of features that could be of relevance for hydrocarbon exploration of deep-water turbidite systems. In particular:

1. *Sediment source.* This study documents the presence of canyon-fed turbidite systems on the Norwegian continental margin. As there is no identifiable fluvial contribution, the sediments probably originated from reworking of Cenozoic and possibly also Mesozoic sand comprising the modern shelf succession (Sigmond 1992) outcropping in the canyon (Fig. 9). In addition, sand may have originated from piracy of shelf sediments presently transported along the shelf and upper slope by the Norwegian current (Holtedahl & Bjerkli 1975; Kenyon 1986) (Fig. 9). This canyon-fed turbidite system differs from the fluvial input model (delta front turbidites) as favoured by Gjelberg et al. (2001) for the Ormen Lange reservoir sand. This suggests that a range of feeder systems and associated turbidite systems may have existed in the Cenozoic offshore Norway.

2. *Location of sand deposits.* In contrast to other previously described canyon systems in a passive margin setting (e.g. Kenyon et al. 2002) the sandy lobe in the Lofoten Basin is not located at the canyon mouth at the base of the slope but c. 200 km to the southwest in the deepest part of the basin (Fig. 9). Thus sand may not always be located at the canyon mouth, but may be routed further into the basin. What factors control the location of the sandy lobe is not known in detail, but turbidity current velocity is probably one important factor.

3. *Connection to the source area.* The sandy lobe is connected to the source area by a straight channel with poorly developed mud-rich levees except at the canyon

mouth where the channel makes a sharp 90° turn (see above) (Fig. 9). Detection of this kind of low relief channel may be difficult on conventional multichannel seismic profiles. Thus the lack of detectable channels in ancient systems may not preclude the presence of sandy turbidites in the deepest part of the paleo-basin.

4. *Depositional architecture.* High-resolution seismic lines running from the channel mouth into the basin display several laterally continuous 2 - 5 m thick units thinning (1 - 3 m) into the basin suggesting a sheet-like or tabular geometry of the sand (Fig. 9).

5. *Post-depositional sand deformation.* As indicated by the possible sand volcanoes (Fig. 9) post-depositional deformation of the sand could be widespread suggesting rapid sand deposition. Water escape structures have also been reported from cores penetrating the Ormen Lange reservoir sand (Smith & Möller 2003).

Conclusions

1) A canyon-fed sandy turbidite system, the Andøya Canyon - Lofoten Basin Channel and attached sandy lobe has been identified on the Norwegian continental margin.

2) This presumably old system has been active relatively recently as indicated by sediment waves on the canyon floor, thin sand layers within the levees and a sandy lobe composed of thin, stacked sheet sands at the channel mouth.

3) This system offers additional evidence that a range of processes control sand deposition in turbidite systems. The Andøya Canyon systems main characteristics are: 1) the shelf/upper slope source area, 2) the distal basin location of sandy deposits, 3) their connection to the source area through a long straight channel, 4) the lobate/sheet geometry of the sandy deposits, and 5) post-depositional deformation of the sand.

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References

Bouma, A.H. 1962: *Sedimentology of some flysch deposits: a graphic approach to facies interpretation.* Elsevier, Amsterdam, 168 pp.

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.

Dahlgren, K.I.T., Vorren, T.O., Stoker, M.S., Nielsen, T., Nygård, A. & Sejrup, H.P. 2005. Late Cenozoic prograding wedges on the NW European margin: their formation and relationship to tectonics and climate. *Marine and Petroleum Geology 22*, 1089-1110.

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.

Dreyer, T., Bujak, J., Brunstad, H., Ramberg, J. & Søyseth, L. 2004: Mixed deep- and shallow-water depositional model for the Forties Sandstone Member in the south Central Graben, North Sea. *Norwegian Journal of Geology 84,* 191-233.

Enjolras, J.M., Gouadain, J., Mutti, E. & Pizon, J. 1986: New turbiditic model for the Lower Tertiary sands in the south Viking Graben. *In*: Spencer, A.M. et al. (eds.): *Habitat of hydrocarbons on the Norwegian continental shelf.* Graham & Trotman, London, 171-178.

Faleide, J.I., Solheim, A., Fiedler, A., Hjelstuen, B.O., Andersen, E.S. & Vanneste, K. 1996: Late Cenozoic evolution of the western Barents Sea – Svalbard continental margin. *Global and Planetary Change 12,* 53-74.

Flood, R.D. 1988: A lee wave model for deep-sea mudwave activity. *Deep-Sea Research 35,* 973-983.

Gjelberg, J.G., Enoksen, T., Kjærnes, P., Mangerud, G., Martinsen, O.J., Roe, E. & Vågnes, E. 2001: The Maastrichtian and Danian depositional setting along the eastern margin of the Møre Basin (mid-Norwegian Shelf): implications for reservoir development of the Ormen Lange Field. *In*: O.J. Martinsen and T. Dreyer (eds.): *Sedimentary environments offshore Norway – Palaeozoic to Recent.* NPF Special Publication 10, 421-440, Elsevier Science B.V., Amsterdam.

Holtedahl, H., & Bjerkli, K. 1975: Pleistocene and recent sediments of the Norwegian continental shelf (62°-71° N), and the Norwegian Channel area. *Norges Geologiske Undersøkelser, 316,* 241-252.

Howe, J.A. 1996: Turbidite and contourite sediment waves in the northern Rockall Trough, North Atlantic Ocean. *Sedimentology 43*, 219-234.

Hughes Clarke, J.E., Shor, A.N., Piper, D.J.W. & Mayer, L.A. 1990: Large-scale current-induced erosion and deposition in the path of the 1929 Grand Banks turbidity current. *Sedimentology 37,* 613-629.

Jakobsson, M., Cherkis, N.Z., Woodward, J., Macnab, R. & Coakley, B. 2000: A new grid of Arctic bathymetry aids scientists and mapmakers; Eos, Transactions, American Geophysical Union 81, p. 89, 93, 96.

Kenyon, N.H. 1986: Evidence from bedforms for a strong poleward current along the upper continental slope of Northwest Europe. *Marine Geology 72,* 187-198.

Kenyon, N.H., Klaucke, I., Millington, J. & Ivanov, M.K. 2002: Sandy submarine canyon-mouth lobes on the western margin of Corsica and Sardinia, Mediterranean Sea. *Marine Geology 184,* 69-84.

Kneller, B. 1995: Beyond the turbidite paradigm: physical models for deposition of turbidites and their implications for reservoir prediction. *In*: Hartley, A.J., Prosser, D.J. (eds.): *Characterization of deep marine clastic systems.* Geological Society of London, Special Publication 94, 31-49.

Kneller, B. 2003: The influence of flow parameters on turbidite slope channel architecture. *Marine and Petroleum Geology 20,* 901-910.

Knutsen, S.-M. & Larsen, K.-B. 1996: Late Pliocene sand ridges at the western margin of the Barents Sea – do they monitor Late Pliocene glaciations? *Global and Planetary Change 12,* 159-169.

Laberg, J.S., Dahlgren, K.I.T., Vorren, T.O., Haflidason, H. & Bryn, P. 2001: Seismic analyses of Cenozoic contourite drift development in the Northern Norwegian Sea. *In*: Rebesco, M. and Stow, D.A.V. (Eds.): *Seismic expression of contourites and related deposits.* Marine Geophysical Researches 22, 401-416.

Laberg, J.S., Guidard, S., Mienert, J., Vorren, T.O., Haflidason, H. & Nygård, A. Submitted: Morphology and morphogenesis of a high-latitude canyon; the Andøya Canyon, Norwegian Sea. *Marine Geology.*

Laberg, J.S., Stoker, M.S., Dahlgren, K.I.T., de Haas, H., Haflidason, H., Hjelstuen, B.O., Nielsen, T., Shannon, P.M., Vorren, T.O., van Weering, T.C.E., Ceramicola, S. 2005. Cenozoic alongslope processes and sedimentation on the NW European Atlantic margin. *Marine and Petroleum Geology 22,* 1069-1088..

Laberg, J.S., Vorren, T.O. and Knutsen, S.-M. 2002: The Lofoten Drift, Norwegian Sea. *In*: Stow, D.A.W., Pudsey, C.J., Howe, J.A., Faugeres, J.-C. and Viana, A. (Eds.): *Deep-water contourite systems: modern drifts and ancient series, seismic and sedimentary characteristics.* Geological Society, London, Memoirs 22, 57-64.

Laberg, J,S., Vorren, T.O., Dowdeswell, J.A., Kenyon, N.H. & Taylor, J. 2000: The Andøya Slide and the Andøya Canyon, north-eastern Norwegian-Greenland Sea. *Marine Geology 162*, 259-275.

Möller, N.K., Gjelberg, J.G., Martinsen, O., Charnock, M.A., Færseth, R.B., Sperrevik, S., Cartwright, J.A. 2004: A geological model for the Ormen Lange hydrocarbon reservoir. *Norwegian Journal of Geology 84,* 169-190.

Piper, D.J.W. & Normark, W.R. 2001: Sandy fans – from Amazon to Hueneme and beyond. *American Association of Petroleum Geologists Bulletin 85,* 1407-1438.

Pratson, L.F. & Coakley, B.J. 1996: A model for the headward erosion of submarine canyons induced by downslope-eroding sediment flows. *Geological Society of America Bulletin 108,* 225-234.

Pratson, L.F., Ryan, W.B.F., Mountain, G.S. & Twichell, D.C. 1994: Submarine canyon initiation by downslope-eroding sediment flows: evidence in late Cenozoic strata on the New Jersey continental slope. *Geological Society of America Bulletin 106,* 395-412.

Ryseth, A., Augustson, J.H., Charnock, M., Haugerud, O., Knutsen, S.-M., Midbøe, P.S., Opsal, J.G. & Sundsbø, G: 2003. Cenozoic stratigraphy and evolution of the Sørvestnaget Basin, southwestern Barents Sea. *Norwegian Journal of Geology 83,* 107-130.

Shepard, F.P. 1981: Submarine canyons: multiple causes and long-term persistence. *American Association of Petroleum Geologists Bulletin 65,* 1062-1077.

Shepard, F.P. & Dill, R.F. 1966: *Submarine canyons and other sea valleys.* Rand McNalley & Co, Chicago, 381 pp.

Sigmond, E.M.D. 1992: *Bedrock map of Norway and adjacent ocean areas.* Scale 1:3 million. Geological Survey of Norway.

Skardhamar, J. & Svendsen, H. 2004: Circulation and shelf-ocean interaction off North Norway. In: Skardhamar, J.: Variability in circulation and hydrography in North Norwegian coastal waters. Dr. Scient. Thesis, University of Tromsø, Norway.

Smith, R. & Möller, N. 2003: Sedimentology and reservoir modelling of the Ormen Lange field, mid Norway. *Marine and Petroleum Geology 20,* 601-613.

Vorren, T.O., Richardsen, G., Knutsen, S.-M. & Henriksen, E. 1991: Cenozoic erosion and sedimentation in the western Barents Sea. *Marine and Petroleum Geology 8,* 317-340.

Wynn, R.B., Piper, D.J.W. & Gee, M.J.R. 2002: Generation and migration of coarse-grained sediment waves in turbidity current channels and channel-lobe transition zones. *Marine Geology 192,* 59-78.

Wynn, R.B., Weaver, P.P.E., Ercilla, G., Stow, D.A.V. & Masson, D.G. 2000: Sedimentary processes in the Selvage sediment-wave field, NE Atlantic: new insights into the formation of sediment waves by turbidity currents. *Sedimentology 47,* 1181-1197.

Xu, J.P., Noble, M.A. & Rosenfeld, L.K. 2004: In-situ measurements of velocity structure within turbidity currents. *Geophysical Research Letters 31,* L09311, doi: 10.1029/2004GL019718.