

Morphology and morphogenesis of a high-latitude canyon; the Andøya Canyon, Norwegian Sea

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Abstract

The morphology of the high-latitude Andøya Canyon in the Norwegian Sea was studied using multi-beam bathymetry data. The canyon excavation processes include sliding and slumping, axial incision and gullying. Sliding and slumping has most frequently occurred in muddy sediments of the western sidewall due to canyon axial incision and undercutting, and failures during infilling of a high-relief terrain by alongslope transported sediments. Axial incision is inferred to be due to turbidity current erosion, the turbidity currents were mainly the result of piracy of shelf sediments. The eastern sidewall is dominated by gullies speculated to be the initial forms generated on a steep slope constructed from stiff, poorly sorted glacial sediments. From the present canyon morphology including the overall convex-upwards form of the topographic long-profile with a steep (20–25°) upper headwall, we favour a “bottom-up” canyon development, i.e. mass wasting and subsequent piracy of alongslope transported slope and shelf sediments. In contrast to most other canyons, the development of the Andøya Canyon was not only a result of side- and headwall instability and axial incision, most active during periods of high sediment transfer, but also due to infilling of the canyon by sediments transported by alongslope flowing ocean currents and from the Fennoscandian Ice Sheet at the shelf break. There are little or no slide deposits covering the thalweg. This leads us to suggest that the most recent process dominating within the canyon is turbidity current flushing and erosion, inferred to have occurred during the Holocene.

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1. Introduction

Canyons are deep and narrow conduits for sediment transfer from the continental margin to the deep sea (Shepard, 1981). So far two main morphological types have been identified; large, mature canyons and smaller, numerous and clustered, straighter canyons (e.g. Goff, 2001).

Early investigations of the European Atlantic continental margin canyons found that the steepness of the slope was the most dominant factor in determining their morphology (Kenyon et al., 1978). Here, presently active canyons include the Capbreton Canyon in the Bay of Biscay where generation of turbidity currents following a major storm event has been documented (Mulder et al., 2001). Over a longer time span, the activity within this canyon was found to include periods of connection to fluvial systems and high sediment transfer that are responsible for the incision

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alternating with periods of sporadic activity. The incision was most active at the end of sea-level fall and sea-level lowstand (Mulder et al., 2004).

High-latitude continental slope canyons occur on both active and passive margins in both hemispheres. Detailed studies include the Labrador slope on the Canadian Atlantic continental margin which revealed numerous canyons with a dendritic pattern of downslope branching. They are inferred to be formed by headward gullying through small-scale slumping or turbidity current erosion (Hesse, 1992). The headward gullying was most active during glacial times but probably continued during interglacials as at present (Hesse and Klaucke, 1995). Although occurring in a different tectonic regime a somewhat similar slope morphology including numerous gullies merging into tributary canyons and eventually into one canyon have also been reported from the northern US Gulf of Alaska (Carlson et al., 1990). These systems probably owe their origin and development from sediment delivery from glaciers at the shelf

break during periods of sea-level lowstand (Dobson et al., 1998). Further west, in the Bering Sea some of the world's largest submarine canyons have been found. Their position and configuration was determined or strongly influenced by structural features of the margin and slumps and slides were found to be the principal mechanisms responsible for their cutting and shaping (Carlson and Karl, 1988). Although less studied, somewhat similar canyons have also been identified along the Antarctic continental margin (Fütterer et al., 1990).

To summarize, two morphologically different canyon systems seem to have developed on high-latitude continental margins: (1) numerous, generally smaller canyons with a dendritic pattern of downslope branching, and (2) single, commonly larger canyons with one or a few tributaries. The sedimentation rate and thus the angle of the slope is probably the first order control on their development, higher rate and lower slope gradient favouring type (1) (see also discussion by Nielsen et al., 2005).

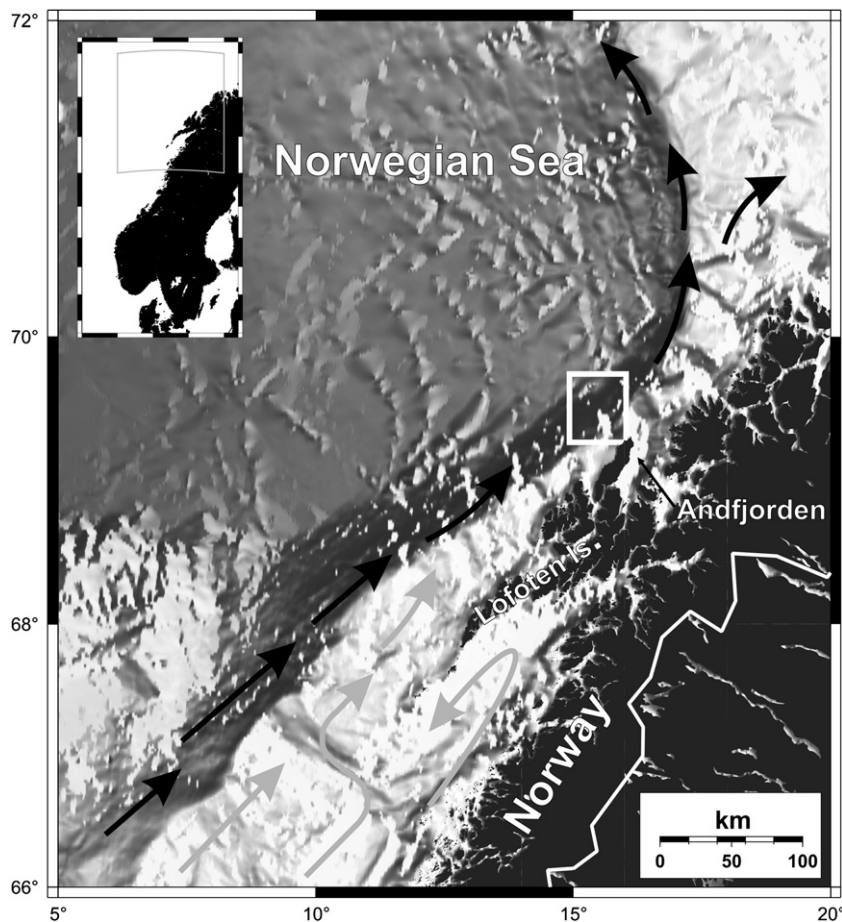


Fig. 1. Box outlines the location of the study area (see Fig. 2) on the continental slope of northern Norway. The circulation pattern of the Norwegian Current (black arrows) and Norwegian Coastal Current (light grey arrows) is also shown.

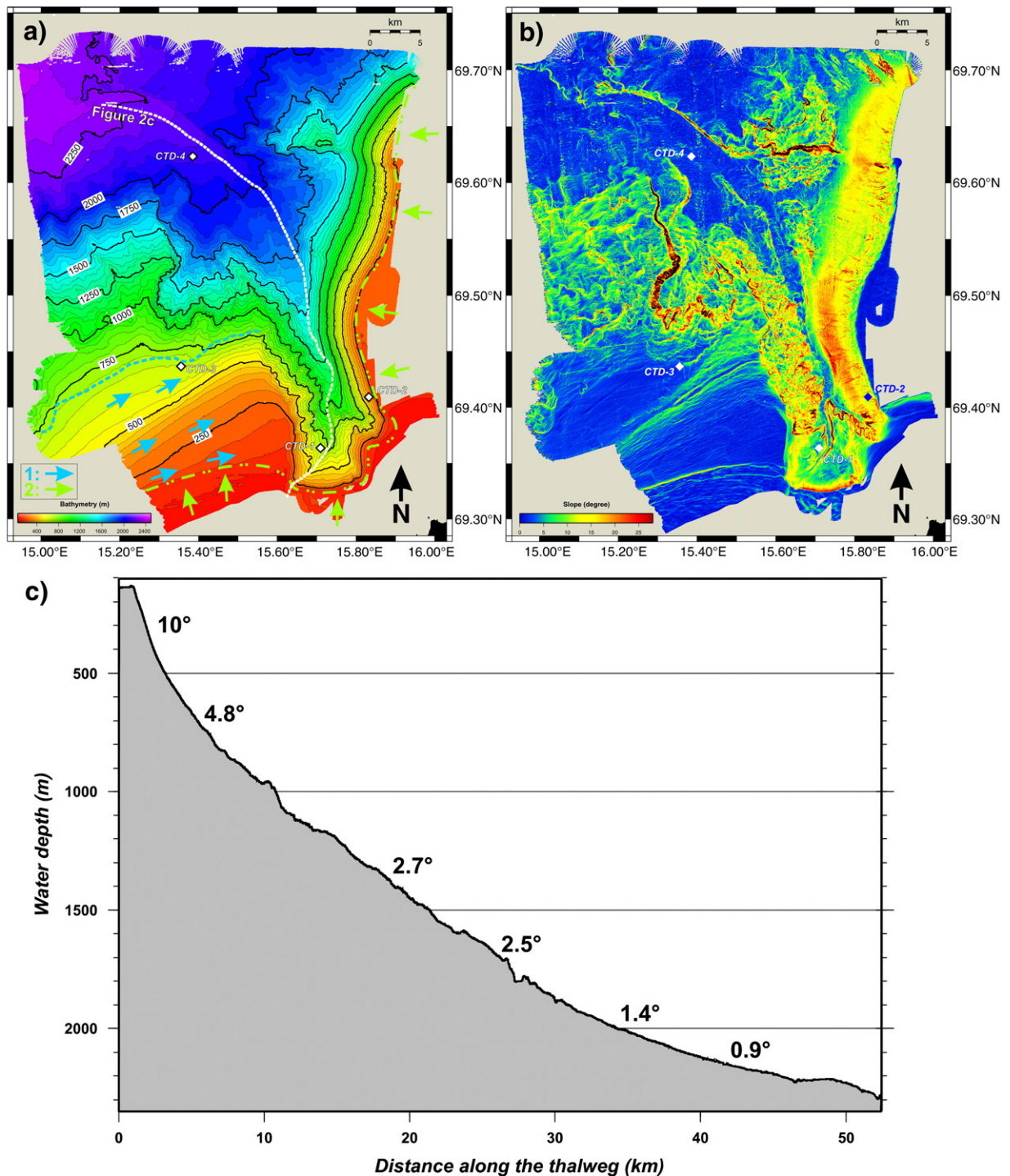


Fig. 2. a) Bathymetric map of the Andøya Canyon area, contour interval is 50 m. CTD- stations 1–4 and the location of Fig. 2c is given. 1: Norwegian Current flow direction (blue). Blue stippled line at 800 m water depth marks the downslope limit of the sea floor inferred to be affected by the Norwegian Current. 2: Flow direction of the Fennoscandian Ice Sheet during the last glacial maximum and the inferred maximum ice front position (green). b) Slope map covering the Andøya Canyon area. c) Topographic long-profile of the Andøya Canyon (location on Fig. 2a). See Fig. 1 for location of Figs. 2 a–b.

On the Norwegian continental margin a dozen single, large canyons with few or no tributaries extend from the upper slope or the shelf break to the base of the continental slope on the ~200 km long part of the margin from 68.5°–70.0°N (Bugge, 1983; Kenyon, 1987; Laberg et al., 2000; Taylor et al., 2000; Laberg et al., 2005). In this paper we present the first detailed description and discussion of one of these canyons, the Andøya Canyon (Figs. 1–3). From a morphological analysis based on multi-beam bathymetry data, the aim of the study was to identify the processes of canyon excavation, its initiation, growth and the relative timing of the most recent processes. Results from the distal sediment accumulation area in the Norwegian Sea were reported by Haflidason et al., 2007–this volume; Laberg et al. (2005) and Ó Cofaigh et al. (2006).

2. Geologic setting

2.1. Cenozoic evolution

Sea-floor spreading initiated in early Tertiary times resulted in the formation of the large and deep Norwegian–Greenland Sea basin bounded by the

Norwegian continental margin to the east (Eldholm et al., 1987). Subsequently, large sediment quantities were derived from the surrounding continents and deposited on the slope and in the basin (Vorren et al., 1991; Faleide et al., 1996). At the mouth of Andfjorden an up to 1.0 s (tw) thick prograding wedge comprises late Pliocene and Pleistocene glacial sediments although few details exist on the wedge evolution except for the LGM (Dahlgren et al., 2005). At that time the Fennoscandian Ice Sheet advanced through Andfjorden reaching the shelf break including the top of the eastern sidewall of the Andøya Canyon prior to 22 ¹⁴C ka BP (the Egga-I event) and during a readvance at about 16–15 ¹⁴C ka BP (the Egga-II event) (Vorren and Plassen, 2002). Sea-floor morphological studies combined with a detailed chronology shows that a fast-flowing ice stream occupied Andfjorden during these events (Vorren and Plassen, 2002; Ottesen et al., 2005).

2.2. Modern physiography

Offshore northern Norway the continental shelf narrows from being nearly 100 km wide at about

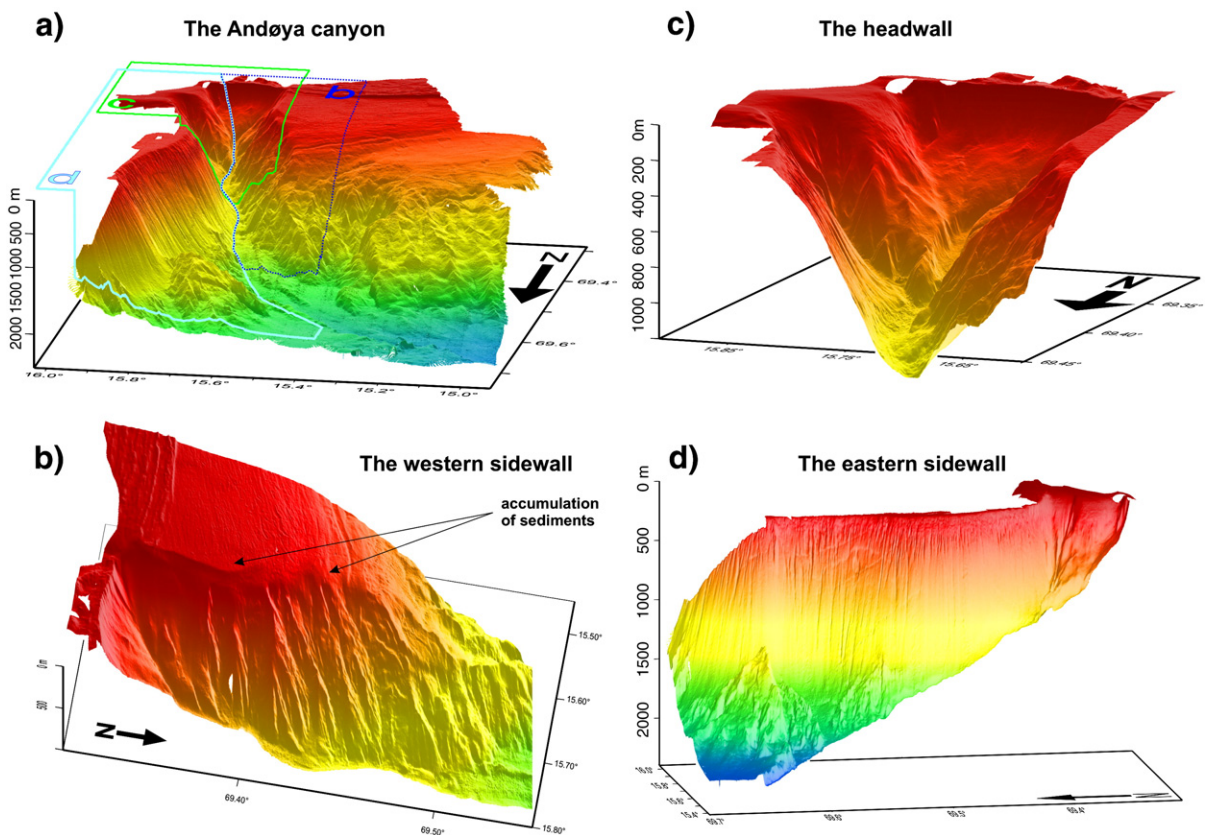


Fig. 3. 3D images of a) the Andøya Canyon, b) the western canyon sidewall, c) the canyon headwall, and d) the eastern canyon sidewall.

68°N to less than 10 km east of the Andøya Canyon headwall (70°N). The shelf morphology is characterised by troughs and banks. The troughs reach a water depth of 200–300 m while the water depth is less than 100 m on some of the banks. In general, the shelf water depth shallows from 68° to 70°N (Fig. 1). An average gradient of 4–5° makes the continental slope among the steepest on the Norwegian margin. The limited data available shows that the morphology is very irregular and is dominated by large canyons as well as areas of smoother relief corresponding to deposition from contour currents (Laberg et al., 1999, 2001, 2002a).

2.3. Interglacial–glacial ocean circulation and sea bottom sediment distribution

The Norwegian Current affects the upper ~800 m and brings warm and saline Atlantic water north-eastward along the shelf and upper slope (Figs. 1 and 4) (Orvik et al., 1995). Below, the intermediate water is

termed the Arctic Intermediate Water (Blindheim, 1990). The Norwegian Sea Deep-Water (below c. 2000 m water depth) circulates in topographically controlled anticlockwise gyres (Isachsen, 2003). Current measurements from 2035 m water depth and shallower on the continental slope at about 68.5°N show north-eastward, slope-parallel flowing water masses characterised by the highest velocity near the sea surface, low mean velocity in Arctic Intermediate Water at 1044 m water depth and a near sea-bed increase in mean speed (Heathershaw et al., 1998). Current velocities in excess of 110 cm/s at 15 m depth have been found in this area (Poulain et al., 1996).

Studies of the modern surface sediment distribution have shown a clear relationship between the water depth and the sediment texture (Holtedahl and Bjerkli 1975; Holtedahl, 1981; Sejrup et al., 1981; Vorren et al., 1984). The shallow areas (<200 m water depth) are to a large extent characterised by coarse lag deposits of boulder to sand sized material. On the deeper parts of the

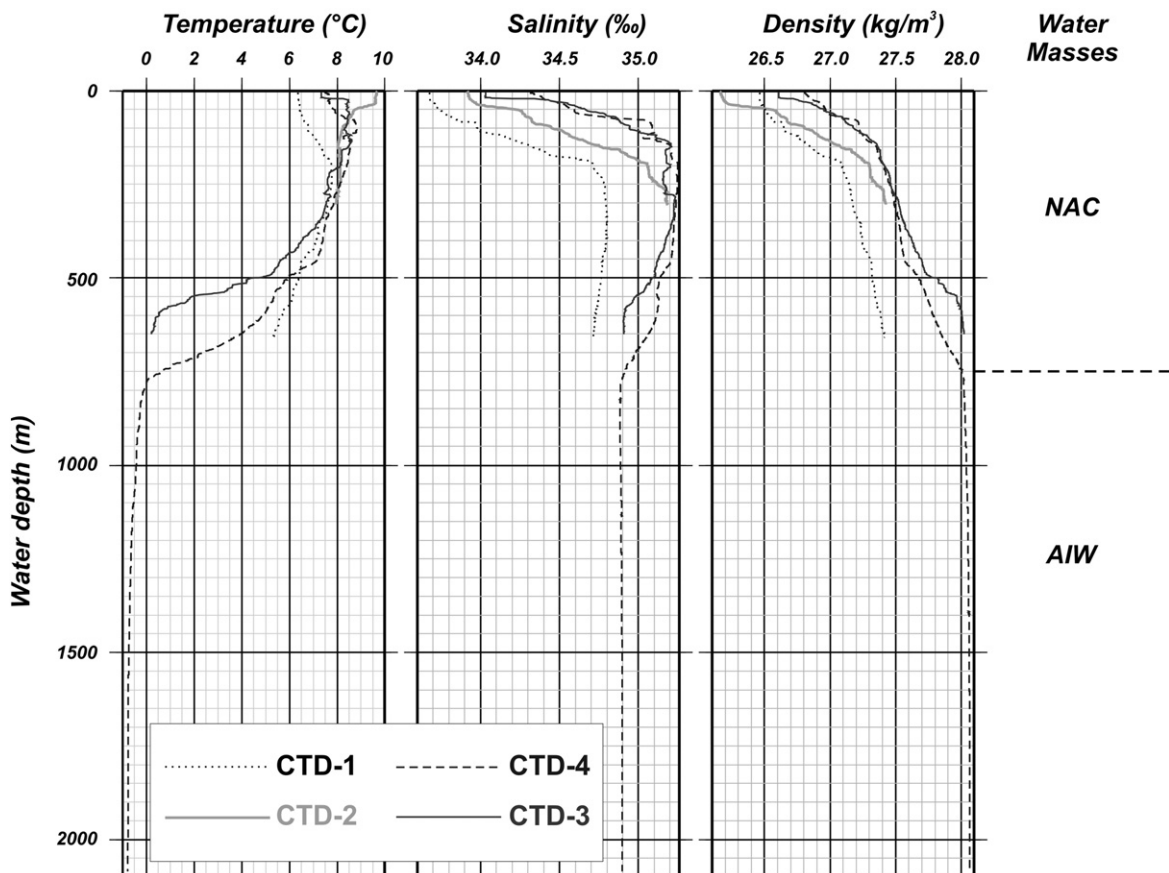


Fig. 4. CTD measurements (temperature, salinity and density) from the Andøya Canyon area from January 2005 (1), September 2004 (2), and November 2004 (3–4). The Atlantic water masses of the Norwegian Current (NAC) and the Arctic Intermediate Water (AIW) is indicated. See Fig. 2a for location.

continental shelf, as well as on the slope, silty clays are present, probably representing wash-out from tills in shallower water (Holtedahl and Bjerkli, 1975; Vorren and Vassmyr, 1991). The mud line, the upper boundary of the silty clay on the Norwegian continental slope occurs from 600–1000 m water depth (Holtedahl and Bjerkli, 1975; Kenyon, 1986; Dahlgren and Vorren, 2003). The position of the mud line is inferred to represent the transition from erosion or non-deposition upslope to deposition further downslope (Holtedahl and Bjerkli, 1975) as confirmed by results from deep-sea sediment traps measurements (Honjo, 1990).

During the Weichselian (including the late Weichselian glacial maximum (LGM)) a meridional current system similar to the present-day conditions, but affected by variations in strength and intensity, resulted in an almost permanent presence of at least some seasonally ice-free areas in the Norwegian Sea (Hebbeln

et al., 1998). Contourite drift growth on the North Norwegian continental slope shows that sediments were also transported by, and deposited from, this current system. The drift growth rate was an order of magnitude higher (190 cm/ka) during the late Weichselian compared with the Holocene (9 cm/ka); probably due to the high input of glaciomarine sediments from the Fennoscandian Ice Sheet (Laberg and Vorren, 2004).

3. Materials and methods

The sea floor of the study area (Fig. 2a–b) has been mapped during three surveys using two multi-beam echo sounders: the Kongsberg Simrad EM300 (data collected in September 2004 by the University of Bergen research vessel *G.O. Sars* and in November 2004 and January 2005 by the University of Tromsø research vessel *Jan Mayen*) and the EM1002 (data recorded in September

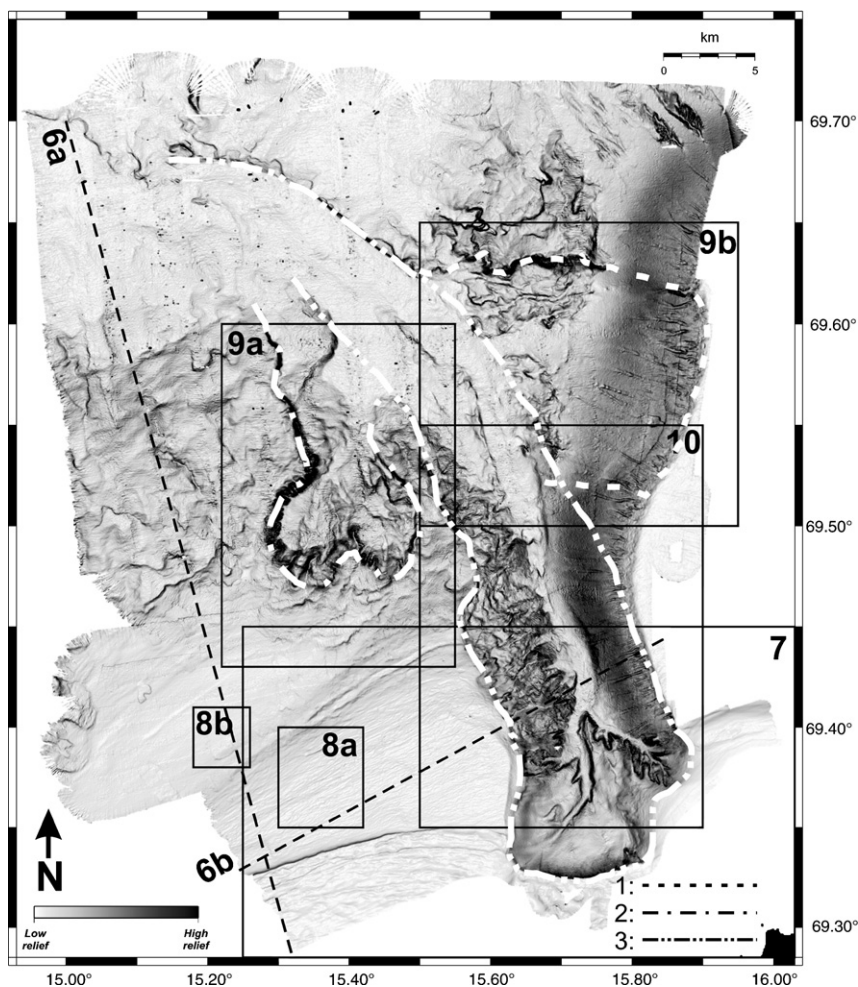


Fig. 5. Slope gradient map of the Andøya Canyon area. 1: a partly buried slide scar, 2: the western, lower slope slide scar, and 3: the Andøya Canyon. The location of Figs. 6a–b, 7, 8a–b, 9a–b and 10 is indicated.

2004 by the University of Bergen). The entire bathymetric map (Fig. 2a–b) covers an area of c. 2060 km². The EM300 has a nominal frequency of 30 kHz and is designed to map the sea floor from 10 m to 5000 m water depth while the EM1002 operates in shallower areas, typically between 2 m below the transducer to approximately 1000 meters. The operating frequency is 95 kHz.

During the acquisition, the coverage overlap was about 25%. The four different datasets have been merged and processed together using the *Neptune* software of Kongsberg Simrad. A first rough data cleaning was done by using a standard deviation limit of 2%, a noise limit of 2% and dropping the three outer beams. In a second step, areas with misfits and noise bursts were selected and then corrected or removed. Water depth was obtained integrating sea water sound velocity data from CTD measurements (e.g. Fig. 4). The gridding of the complete

and final dataset with a grid size of 25 m × 25 m and the bathymetric maps were created using GMT (Generic Mapping Tools) (Wessel and Smith, 1998).

4. The Andøya Canyon area

4.1. Morphology and morphogenesis of the adjacent continental margin

On the continental margin immediately west of the Andøya Canyon the continental shelf break is located at about 150 m water depth (Figs. 2a, 3a and 6a). It forms the outer limit of a shelf area characterised by small-scale (<10 m high) irregularities including parallel to semi-parallel ridges oriented E–W close to the canyon, towards the west gradually turning WSW–ENE. The shelf break is located on top of an up to 40 m high

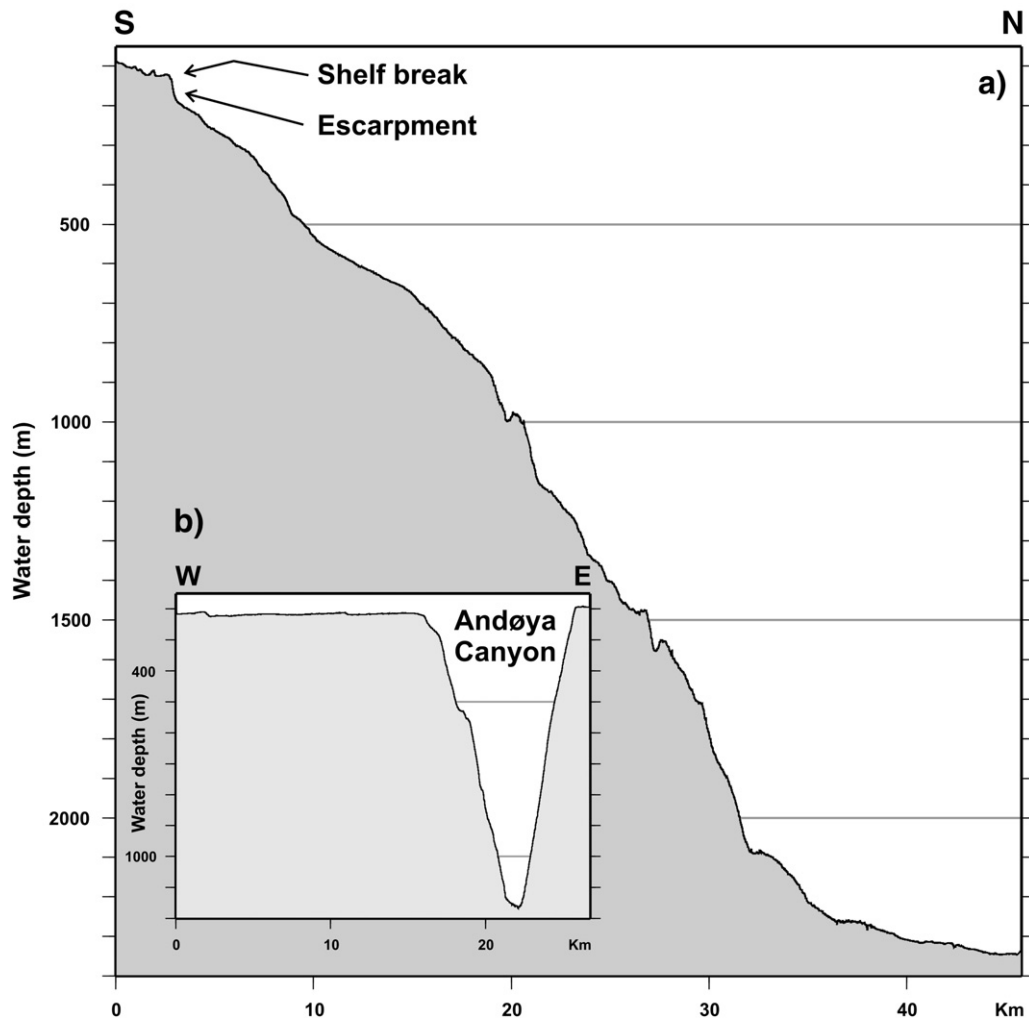


Fig. 6. Bathymetric profiles downslope west of the canyon (a) and along the upper slope across the canyon (b). For location, see Fig. 5.

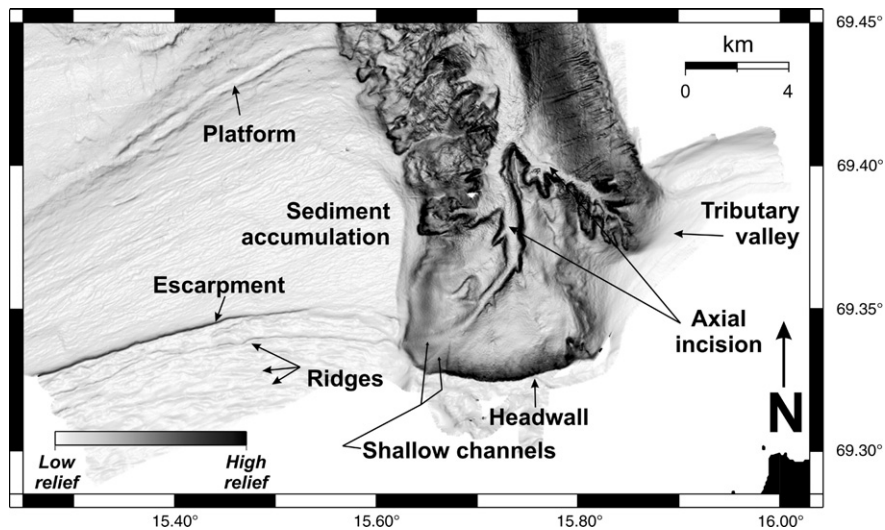


Fig. 7. Slope gradient map showing the morphological features of the upper slope immediately west of the canyon as well as the canyon headwall area. See Fig. 5 for location.

escarpment which defines the outer limit of the irregular area and the escarpment can be followed eastward to its intersection with the south-western canyon headwall (Fig. 7). We suggest that the shelf morphology was formed by subglacial and/or ice-marginal processes during a period of ice recession from the shelf break. If

correct, the ridges may represent De Geer moraines as described in areas with proglacial water depths in excess of 150 m in the coastal zone of northern Sweden (Lindén and Möller, 2005) or from the outermost coast in western Norway (Larsen et al., 1991). The age of these deposits is presently not known.

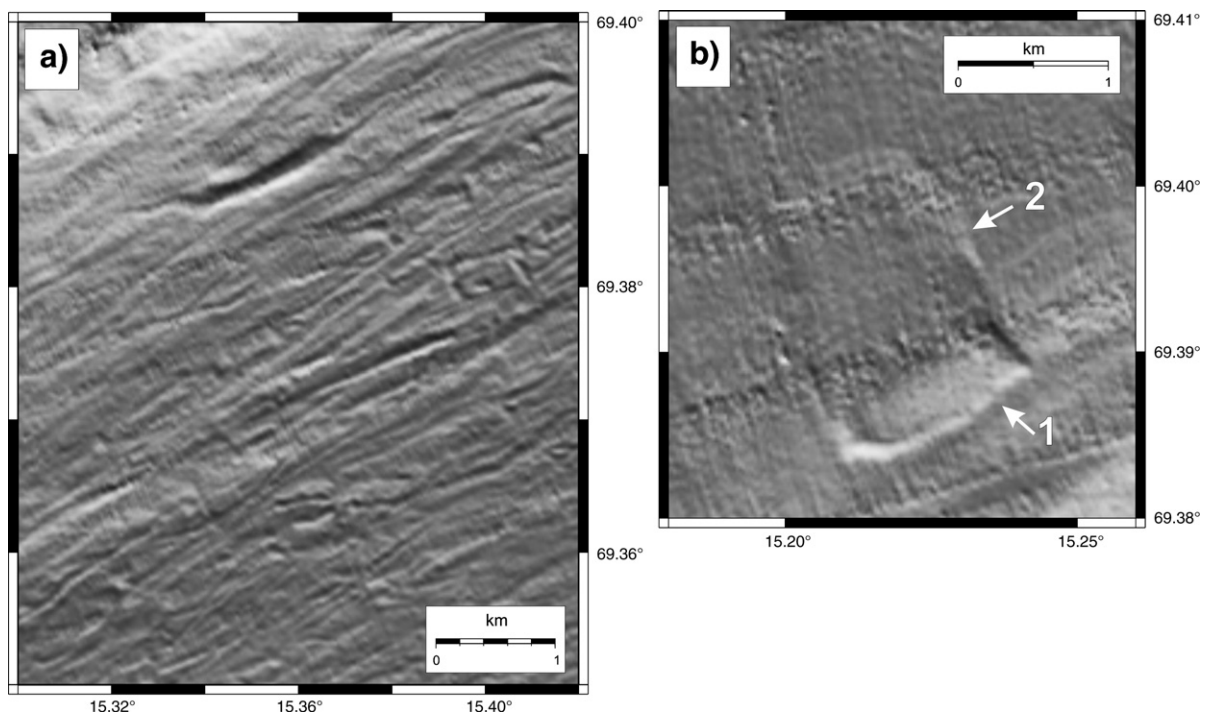


Fig. 8. a) Densely spaced, slope-parallel furrows inferred to be iceberg plough marks and b) a minor slide scar (1) and associated deposits (2) on the upper slope immediately west of the canyon. See Fig. 5 for location.

The sea floor from the escarpment to about 400 m water depth has a smooth, convex relief (Figs. 5 and 6a). Second-order sea-bed features include densely spaced, slope-parallel furrows (Fig. 8a), and a well-defined sediment accumulation. In some places these sediments can be followed into the western canyon sidewall (Fig. 7). Sediments also continue into the canyon where they partly bury slide scars (Fig. 3b). The furrows are inferred to be iceberg plough marks and their orientation is probably due to a strong ocean current controlled iceberg drift. The accumulation of sediments immediately west of the upper canyon, partly continuing into the canyon, is probably formed by sediments deposited from alongslope currents. When the Norwegian Current and the Norwegian Coastal Current were established in their present form in the early Holocene (e.g. Vorren et al., 1984), they probably eroded and redistributed glacigenic sediments on the slope including the study area.

From 400 to 600 m water depth there is a marked change in slope gradient: the slope steepens forming an escarpment locally reaching more than 10° separating a more gently dipping upper and lower slope (Figs. 2a–b and 5). Below the escarpment there is a slope-parallel, relatively flat and about 500–800 m wide platform. We speculate that the platform may have been formed or maintained by alongslope flowing ocean current erosion as it is located too deep to be formed by littoral processes.

In this area there are several slide scars and associated slide deposits, some located downslope of the platform. The largest slide scar is about 1 km wide and 500 m in length (Fig. 8b). The height is about 5 m. The slide deposits can be followed downslope for another 1.5 km and the deposits rise about 5 m above the present sea floor. Further downslope, the slope to 800–900 m water depth has a much smoother relief compared to the deeper area which is more irregular and dominated by a number of escarpments including the large and complex escarpment immediately west of the lower canyon (see description below) (Figs. 5 and 9a). The escarpments define the upslope limit of slide scars (Figs. 2a and 5). We ascribe this irregular morphology to the erosion, transport and deposition (infilling) of sediments upslope from 800–900 m water depth and little influence and slow hemipelagic settling further downslope.

The large and complex scar (Fig. 9a) includes the main headwall, smaller and headwall parallel escarpments further upslope as well as a number of smaller scars within the main scar, some of which have a channel-like continuation. Sediments from the western slide scar were fed into the Lofoten Basin Channel thus contributing to the sediment delivery to the deep sea (Fig. 5). The lower part of the western canyon sidewall has failed as a result of this mass wasting.

The continental shelf east of the canyon is relatively flat and the shelf break water depth ranges from 200 to 250 m water depth (Figs. 2a and 6b). The sea-bed

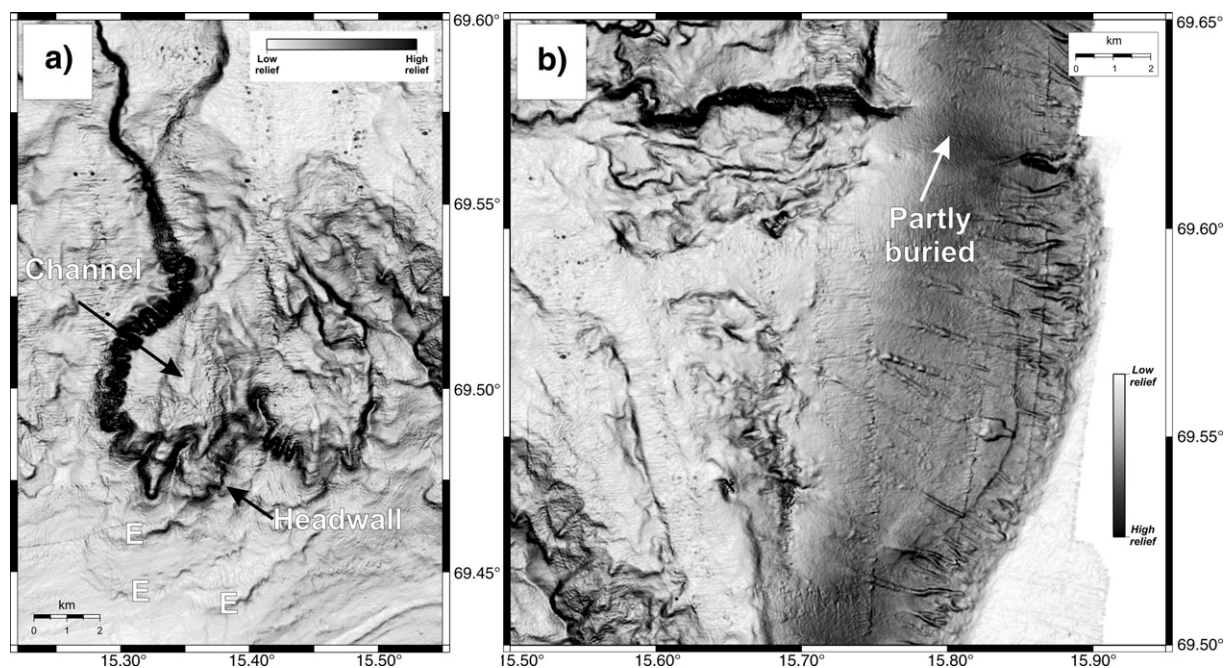


Fig. 9. a) The western, lower slope slide scar (E = escarpment), and b) a partly buried slide scar immediately east of the eastern canyon sidewall. For location, see Fig. 5.

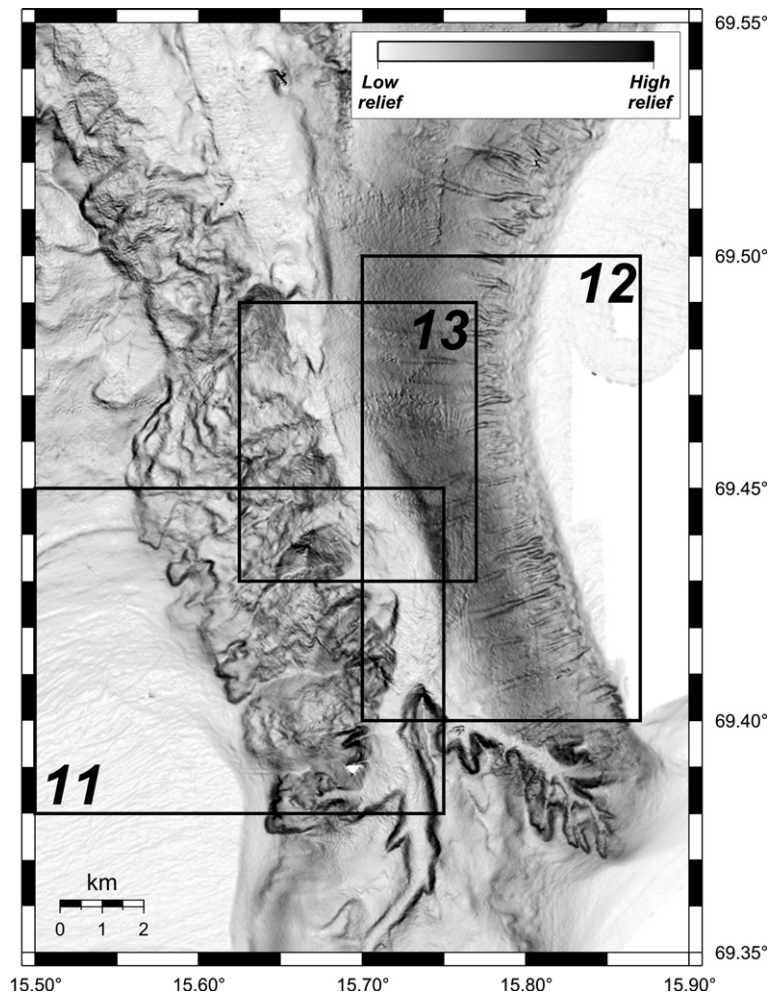


Fig. 10. A slope gradient map showing the western and eastern sidewalls of the canyon. The location of Figs. 11–13 are given. See Fig. 5 for location.

morphology is reported to be dominated by shelf edge transverse mega-scale lineations formed from subglacial processes (Vorren and Plassen, 2002; Ottesen et al., 2005).

At about 69.60° N a prominent escarpment can be followed from the uppermost part of the slope to about 2000 m water depth (Figs. 5 and 9b). The escarpment is partly buried, the parts not buried have a gradient of c. 20° and have a southward dip (Fig. 2b). The escarpment defines a concave part of the sidewall that can be followed for about 10 km. We interpret this part of the sidewall to represent a partly buried slide scar.

4.2. Canyon morphology and morphogenesis

4.2.1. Shape and dimensions

The Andøya Canyon is a c. 40 km long (from the headwall to 2100 m water depth) and gently curved feature incised into the continental slope and outer shelf (Figs. 2 and 5). Shelf-incised canyons represent a

mature phase in canyon evolution according to Farre et al. (1983). The upper half (headwall to thalweg depth of c. 1600 m) has a V-shaped cross-section, width between canyon shoulders is relatively uniform and about 9 km, and the maximum incision is 1100 m (Fig. 2a). Further downslope the canyon eastern morphology changes near the southern limit of the buried slide scar. Below its western boundary is defined by an up to 300 m high escarpment that can be followed from c. 69.50° N towards the north and then north-west. At the base of the slope it continues as the eastern wall of the Lofoten Basin Channel. The western sidewall is characterised by an overall westward shift in the order of up to 1 km upslope from about 69.45°–69.50°N (Fig. 5).

A topographic long-profile from the headwall along the thalweg to the mouth of the canyon shows an overall convex-upwards shape with the channel gradient declining away from the shelf edge (Fig. 2c). Headwall

gradients of 20–25° is as for the Storegga Slide headwall (Haflidason et al., 2004).

4.2.2. The headwall area

The main headwall is about 7 km long and has a gently curved convex shape. The uppermost part is at 150 m water depth where it forms the present shelf break and it can be followed to about 1150 m water depth where a tributary valley intersects (Figs. 3c and 7). The morphology is relatively smooth except for an axial incision. The incision originates at the shelf break in the south-west from where two shallow channels can be followed to 500 m water depth, where they join and continue as the main axial incised channel. Downslope, the channel gradually increases in width and depth to about 500 m and 100 m, respectively (Fig. 7).

The NW–SE oriented tributary valley is delineated by the uppermost part of the eastern sidewall (see below) and a western wall deeply incised by a number of downslope oriented, relatively straight channel-like features or second-order tributaries. The axial incision of the tributary valley is about 200 m wide; where it meets with the main axial incised channel it seems to be at a slightly higher level forming a “hanging valley” (Figs. 3c and 7).

4.2.3. The western sidewall

A complex morphology characterises the western sidewall (Fig. 10). Divides of knife-edged, steep-sided

spurs separate amphitheatre-formed escarpments of various dimensions which define the upslope limit of large scars. Some are single scars, other are more complex forms with scars within scars, sometimes forming a leaf-like pattern. Single, simpler scars dominate the upslope part of the sidewall while morphologically more complex forms are found further downslope (Fig. 10).

The largest single escarpment has a fresh morphology, is up to 150 m high and has steep side- and backwalls (20°). Others have back- and sidewall gradients of 10–15° and look less fresh due to sediment infilling and draping (Figs. 11 and 2b). With in some of the fresh scars the morphology is relatively rough, probably because of an incomplete sediment evacuation leaving blocks of sediment that may have moved only a limited distance (Fig. 11).

4.2.4. The eastern sidewalls

A steep slope (20–25°) forms the eastern sidewall of the upper half of the canyon, being steepest on the lower slope (Fig. 2b). The eastern sidewall slope forms part of the western slope of the Andfjorden prograding wedge of glacial sediments as identified by Dahlgren et al. (2005). The surface morphology is relatively smooth and intersected by numerous straight, narrow and shallow gullies. They display a very uniform width and depth, between 50–100 m wide and up to 10 m deep, respectively. Most of the gullies originate on the

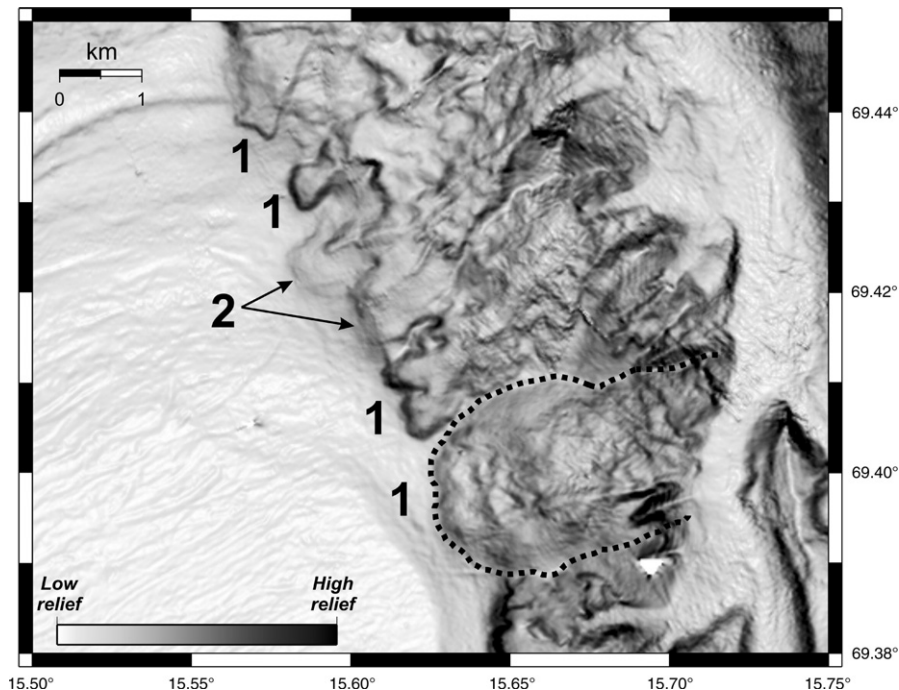


Fig. 11. Examples of fresh-looking (1) and sediment-draped and partly buried slide scars (2) of the western canyon sidewall. See Fig. 10 for location.

uppermost part of the sidewall. Some keep their width, others widen slightly upslope (Fig. 12). No connection to features on the outermost part of the shelf has been observed. Small, less fresh-looking depressions on the uppermost part of the sidewall are inferred to represent parts of older, partly buried and inactive gullies (Fig. 12). Similar gullies also characterise the continental slope immediately north of the canyon.

The lower, eastern canyon sidewall is defined by a 300 m high escarpment at about 15.70°E that can be followed from 69.50°N towards the north and then north-west where at the base of the slope it continues as

the eastern wall of the Lofoten Basin Channel. The upslope part is dominated by a relatively smooth relief being more irregular downslope due to small scars and/or gullies (Fig. 5).

4.2.5. The thalweg

The thalweg is a continuation of the main axial incision originating at the shelf break and can be followed to the canyon terminus at the base of the slope. In the upper part of the canyon the thalweg is about 1 km wide and relatively flat. At about 1100 m water depth it narrows and deepens which is probably a response to

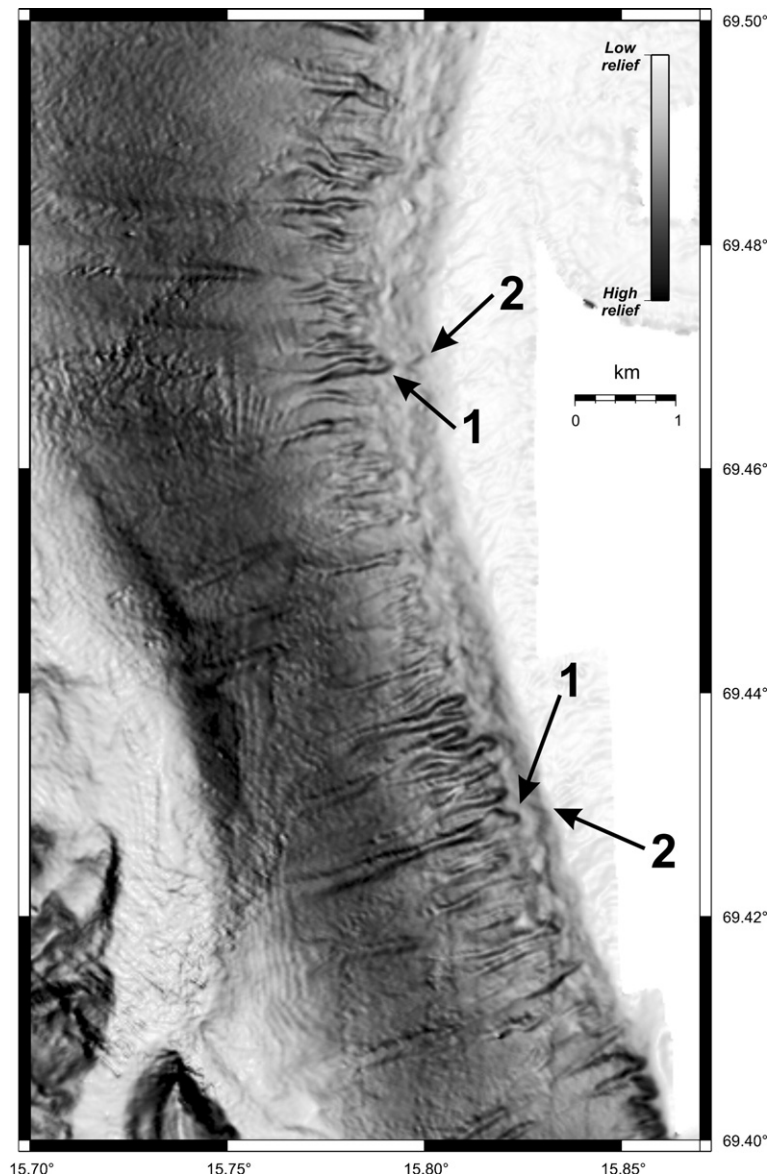


Fig. 12. Gullies (1) and sediment-draped and partly buried uppermost part of paleo-gullies (2) along the eastern sidewall. For location, see Fig. 10.

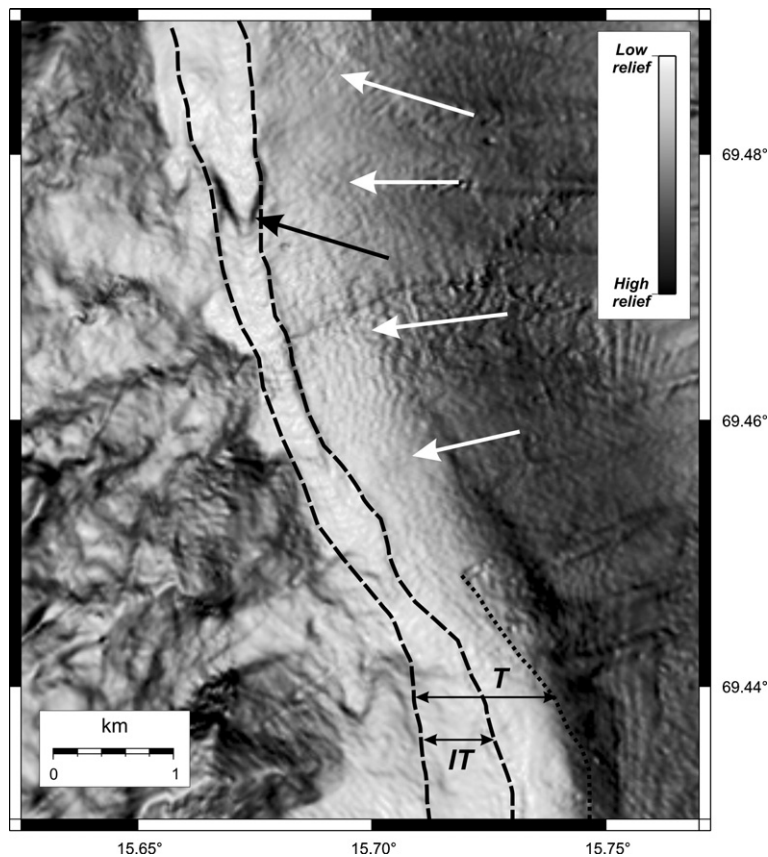


Fig. 13. Details of the canyon thalweg (T) and the inner, deeper thalweg (IT) that probably formed as a response to sediment progradation from the east (white arrows). The location of a V-shaped escarpment (or “waterfall”) is indicated by the black arrow. See Fig. 10 for location.

infill of sediments in to the canyon from the east (Figs. 5 and 13). The inner, slightly V-shaped deeper part of the thalweg keeps its identity to the canyon termination while the outer thalweg increases in width to up to 1.5 km from 1600 to 1800 m water depth to decrease to less than 1 km before it widens again where it intersects with the eastern, partly buried slide scar. The thalweg width increase at 1600 m water depth occurs immediately downslope from a marked slope gradient change (Fig. 5). Several downslope oriented, V-shaped escarpments or “waterfalls” also characterise the inner, deeper part of the thalweg. They occur in areas of increasing slope gradient and most likely formed due to enhanced erosion (Fig. 13).

5. Discussion

5.1. Canyon excavation processes

As pointed out by Shepard (1981) in his review of canyon forming processes, later confirmed by a number of studies including (Kenyon et al., 1978; Farre et al., 1983; Pratson et al., 1994; Kidd et al., 1998; Canals

et al., 2004; Popescu et al., 2004), canyons are formed by a complex interplay of processes acting over a long time period. The Andøya Canyon is no exception to this as will be further detailed below where the focus will be on the importance of sediment gravity flow processes. The canyon initiation, growth and the relative age of the most recent processes will be discussed.

5.1.1. Mass wasting

Mass wasting due to sliding and slumping has caused both headward and sideward widening of the canyon. The relatively smooth headwall morphology indicates sediment infilling and/or a more or less complete sediment evacuation. Two factors are important promoting mass wasting: 1) axial incision and thalweg erosion causing sidewall undercutting and failure, and 2) repeated infilling with ocean current transported sediments and subsequent failure in a high-relief terrain.

1) The axial incision is inferred to be due to the repeated occurrence of turbidity current erosion. The importance of this process for canyon evolution has previously been recognised in other settings as the Black

Sea (Popescu et al., 2004) and the western Gulf of Lion (Baztan et al., 2005). Baztan et al. (2005) found that axial incision was responsible for the triggering of mass wasting of various sizes along the canyon head and flanks and as such had a key influence on canyon evolution. 2) Modern erosion and reworking of shelf and upper slope sediments on the Norwegian continental margin have been shown by a number of studies (e.g. Høltedahl, 1981; Kenyon, 1986; Vorren et al., 1984) as well as the morphology of the continental slope immediately west of the canyon (see discussion above). Some of these reworked sediments probably infilled the western upper canyon which acted as a sediment trap in a similar way as the large slide scars on the Norwegian continental slope; the Storegga Slide (Haflidason et al., 2004) and the Trænadjupet Slide (Laberg et al., 2002b) (Fig. 7).

Together with axial incision and undercutting, infilling and subsequent failure has probably caused a morphology dominated by simpler slide scar forms on the upper, western sidewall while further downslope in the area of low sedimentation rate repeated failure due to undercutting has caused the development of a very complex terrain.

The evolution of the eastern sidewall was different for although the slope is steeper, sliding/slumping producing slide scars of comparable size to the western wall has not occurred. This is probably due to the sediment's physical properties. The eastern canyon sidewall forms part of the western slope of the Andfjorden prograding wedge (Dahlgren et al., 2005) and, as such, probably owes its present morphology to the processes operating during or after the LGM. Sampling on the outer shelf has shown that the youngest sediments are poorly sorted, stiff basal till (Vorren and Plassen, 2002) which probably dominate the prograding wedge. These sediments are less prone to failure compared to the muddy sediments transported along-slope and partly dumped into the western part of the canyon as shown by studies from other parts of the Norwegian continental margin (e.g. Laberg et al., 2003; Bryn et al., 2003).

5.1.2. Gullying

In the submarine environment gullies commonly lead into larger canyons (see references above) but they also occur as parallel features on continental slopes (Spinelli and Field, 2001) and their formation has been explained by turbidity current erosion (e.g. Izumi, 2004). Given the preconditions as discussed above we speculate that these are the first features to form on a steeply dipping slope composed of poorly sorted and stiff glacial sediments.

Their growth was probably initiated from small-scale mass wasting on the uppermost sidewall and they were not allowed to develop further because they were partly or completely buried by sediments delivered by the ice during the next glacial advance to the shelf break. Some support to this interpretation comes from studies of subaerial erosion on land where gullies are known to represent the first step in the fluvial dissection of landscapes (Bloom, 1991).

5.1.3. Axial incision

The canyon axis has deepened as a result of turbidity current erosion. As the axial incision can be followed upslope to the uppermost part of the south-western headwall we infer that at least the most recent turbidites have been initiated from piracy of shelf sediments. These sediments were probably transported along the shelf by the Norwegian Current and trapped into the canyon. Enhanced erosion and deepening is seen where the canyon thalweg narrows due to sediment infilling and in areas of increased slope gradient where “waterfalls” (Fig. 13) form due to enhanced erosion and headward growth.

5.1.4. Erosion from oceanographic processes

Very little is known on the details of the modern oceanography of the Andøya Canyon area. From other canyons tides, internal waves and upwelling are known to have an effect on the sea-bed sediments (see other papers in this volume as well as Shanmugam (2003) for a review) and we suspect this to be the case for the Andøya Canyon as well but so far no data exist to identify this effect.

5.2. Canyon initiation

Two hypotheses are considered most likely for the canyon initiation. 1) A slide produced scar that developed further by headwall and sidewall failure, later also by turbidity current erosion from shelf sediment piracy, the “bottom-up” alternative; 2) The canyon is located in the embayment where a north-eastward narrowing continental shelf meets the prograding wedge in front of Andfjorden. This morphological configuration may have affected the ocean circulation. When meeting the prograding wedge ocean currents may have been deflected seawards causing sediments transported along the shelf to spill over the shelf edge initiating turbidity current erosion and subsequent mass wasting, the “top-down” alternative.

Today there are no major rivers entering the nearby coastline, they all reach sea level in the inner fjords. Thus there was most likely no input of fluvial sediments to the upper slope in this area during sea-level lowstands contrary to what has often been the case for low-latitude canyon systems. However, if the canyon origin pre-

dates the evolution of the fjords, i.e. are of pre-glacial age, then river influence can not be excluded for the initiation of the canyon.

Based on the modern canyon morphology the “bottom-up” alternative is favoured. The topographic long-profile from the headwall along the thalweg to the mouth of the canyon shows an over all convex-upwards canyon shape with a steep upper headwall and a channel gradient declining away from the shelf edge (Fig. 2c), most likely due to the dominance of mass wasting processes. This shape is similar to linear canyons on the US Atlantic continental slope where slope failure around the canyon heads have been seen (Mitchell, 2005). Low-latitude, shelf-incised canyons, possibly connected to fluvial systems during sea-level lowstands (Twichell and Roberts, 1982), have uniform gradients landward of the shelf edge and a declining gradient seaward of the shelf edge (Mitchell, 2005).

A large and complex scar is located on the lower slope immediately west of the canyon (Fig. 9a). The scar includes the main headwall as well as smaller and headwall parallel escarpments further upslope indicating retrogressive failure (Fig. 9a). If this interpretation is correct, and if the retrogressive failure continues, this slide scar could finally reach the shelf edge. The accommodation space thus created could then cause piracy of alongslope moving shelf and upper slope sediments. When moving downslope, erosion from these sediments could then lead to the development of a canyon morphology similar to the Andøya Canyon. Slump-generated megachannels in glaciomarine sediments have also been identified from the rock record (e.g. Eyles and Lago, 1998).

5.3. Canyon growth

In contrast to most canyons so far studied, the growth of the Andøya Canyon is not only a result of the instability of the walls of a slope depression and undercutting due to turbidity current erosion. Infilling of sediments, from the south-west by alongslope flowing ocean currents and from the east and south-east by the Fennoscandian Ice Sheet during glacial maxima periods has also played a major role in controlling canyon growth. The former through more frequent failure along the western sidewall and subsequent deepening by the gravity flows generated, the latter through infilling, canyon narrowing and deepening but not complete burial. Input of glacial sediments occurred during glacial maxima (Vorren and Plassen, 2002) while sediments could have been delivered from ocean currents both during glacial and interglacial periods (Laberg and Vorren, 2004).

The similarity of submarine canyon morphology to that of terrestrial fluvial systems has been pointed out in a number of studies (e.g. McGregor et al., 1982; Mitchell, 2005). Thus, more can be learned about the morphological forming processes of the often inaccessible submarine canyons from the study of fluvial geomorphology. In a recent study from the Guadix basin, SE Spain, Azañón et al. (2005) showed that slide scars on both hillslopes of a river-incised canyon were formed by rotational slides. From the few multi-channel seismic lines available, Laberg et al. (2000) noticed underlying faults on the western sidewall. Taken together, this could indicate that in areas of undercutting, in particular on the downslope, western sidewall the slide scar morphology at least partly is due to rotational slides.

5.4. Relative timing of the most recent canyon processes

There are little or no slide deposits covering the thalweg. This leads us to suggest that the most recent process dominating within the canyon is turbidity current flushing and erosion, originating from instability within the canyon and/or piracy of shelf sediments. The former was probably an episodic process as shown by results from the distal accumulation area. Here Haflidason et al. (2007-this volume) identified two Holocene turbidites. Their age is coinciding with the Storegga and Trænadjupet Slides, two large submarine slides that affected the Norwegian continental margin, and it was suggested that in stability within the Andøya canyon was influenced by these large-scale failure events (Haflidason et al., 2007-this volume). The possible effect of tidal bottom currents, as reviewed by Shanmugam (2003), is presently not known.

6. Conclusions

1. Detailed morphological studies of one of the high-latitude canyons on the Norwegian continental margin using multi-beam bathymetry data has revealed excavation processes including sliding and slumping, axial incision and gullying. Sliding and slumping were most frequently occurring in muddy sediments of the western sidewall due to canyon axial incision and undercutting, and failures during infilling of a high-relief terrain from alongslope transported sediments. Axial incision is inferred to be due to turbidity current erosion, the turbidity currents were mainly from piracy of shelf sediments. The gullies of the eastern sidewall are speculated to be the initial forms generated on a steep slope constructed from stiff, poorly sorted glacial sediments.

2. From the present canyon morphology including the over all convex-up wards shape of the topographic long-profile with a steep (20–25°) upper headwall we favour a “bottom-up” canyon origin, i.e. mass wasting and subsequent piracy of alongslope transported slope and shelf sediments.
3. The development of the Andøya Canyon was not only a result of side- and headwall instability and axial incision, most active during periods of high sediment transfer, but also due to infilling of the canyon by sediments transported by alongslope flowing ocean currents (during interglacials and glacials) and from the Fennoscandian Ice Sheet at the shelf break (during glacial maxima).
4. There are little or no slide deposits covering the thalweg. This leads us to suggest that the most recent process dominating within the canyon is turbidity current flushing and erosion.

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