Sediment distribution and seabed processes in the Troms II area - offshore North Norway

Valérie K. Bellec, Margaret F.J. Dolan, Reidulv Bøe, Terje Thorsnes, Leif Rise, Lene Buhl-Mortensen, Pål Buhl-Mortensen

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As part of the MAREANO-programme, multibeam bathymetry and backscatter, sediment samples, pictures and video data have been interpreted to produce maps of geological terrain forms, seabed reflectivity, seabed sediments, Quaternary geology and modern sedimentary environment in the landward part of the Troms II area, Northern Norway. These maps form an important basis for mapping nature types and habitats. The area is dominated by a series of glacial banks in water depths of 50-200 m and intervening glacial troughs in water depths of 200-500 m. Banks are generally covered by coarse-grained lag deposits, while finer-grained sediments are deposited in the troughs. The banks represent areas of extensive erosion of glacial till. Less erosion occurs on bank slopes, particularly on north-facing slopes which are protected from the strongest currents. Glacial troughs are predominantly deposition areas, although we see evidence of local erosion in the southern parts of the troughs. Bottom current directions interpreted from sediment distribution in iceberg ploughmarks indicate that the erosion areas in the southern part of the troughs are due to bottom currents from the west (Norwegian Atlantic Current) whereas deposition areas in the northern parts of the troughs are due to current along the coast (Norwegian Coastal Current).

Valérie Bellec, Margaret Dolan, Reidulv Bøe, Terje Thorsnes, Leif Rise, Geological Survey of Norway, 7491 Trondheim, Norway (Valerie.Bellec@ngu.no).
Lene Buhl-Mortensen, Pål Buhl-Mortensen, Institute of Marine Research, 5817 Bergen, Norway (Lenebu@imr.no, Paal.buhl.mortensen@imr.no)

Introduction

Except for a few studies (Bugge & Rokoengen, 1976; Vorren et al., 1978, 1984), the bathymetry, seabed sediments, and sedimentary environment of the Norwegian continental shelf between the Lofoten Islands and the south Barents Sea have been poorly mapped. The MAREANO programme was initiated in 2005 to rectify this lack of knowledge. Its objectives are to survey and perform basic studies of the seabed's physical, biological and chemical environment. The information will be systematically archived in a marine area database that will cover Norway's coastal and marine regions and in particular the Lofoten - southern part of the Barents Sea area (Fig. 1A).

The nearshore part of the Troms II area presented in this paper is located on the continental shelf between Andfjorden and Nordvestbanken (Fig. 1B). The continental shelf of Troms II comprises two shallow banks (50-200 m depth; Malangsgrunnen and Sveinsgrunnen) and a deeper bank (110-250 m depth; Nordvestbanken) separated by two glacial troughs (150-500 m deep; Malangsdjupet, and a trough which we informally name Rebbenesdjupet).

The area has been surveyed under the MAREANO programme and data have been used to produce maps of bathymetry, multibeam backscatter, seabed sediments, Quaternary geology and modern sedimentary environment. These maps represent typical geological products from the MAREANO programme and provide the basis for understanding the sedimentation processes in the Troms II area, and for mapping habitats and depicting environmental status.

Study area

The Norwegian continental shelf has experienced several periods of glaciation (Ottesen et al., 2005), and much of the shelf is covered by glacial till. Moraines, glacial lineations (flutes) and iceberg ploughmarks reflect deposition and erosion during glacial periods. At present, two major currents control the sedimentation in the Troms II area. The Norwegian Atlantic Current (NAC) which runs along the continental slope towards the north, while the Norwegian Coastal Current (NCC) follows the coast from the southwest (Fig. 1). Both turn eastwards into the Barents Sea (Mosby, 1968; Ersdal, 2001; Ingvaldsen et al., 2004; Asplin et al., 2006). The direction of the NAC is strongly influenced by the broad-scale topography of the continental shelf (Gjevik, 2000). It follows the 500 m contour at this depth with a maximum speed of 1.17

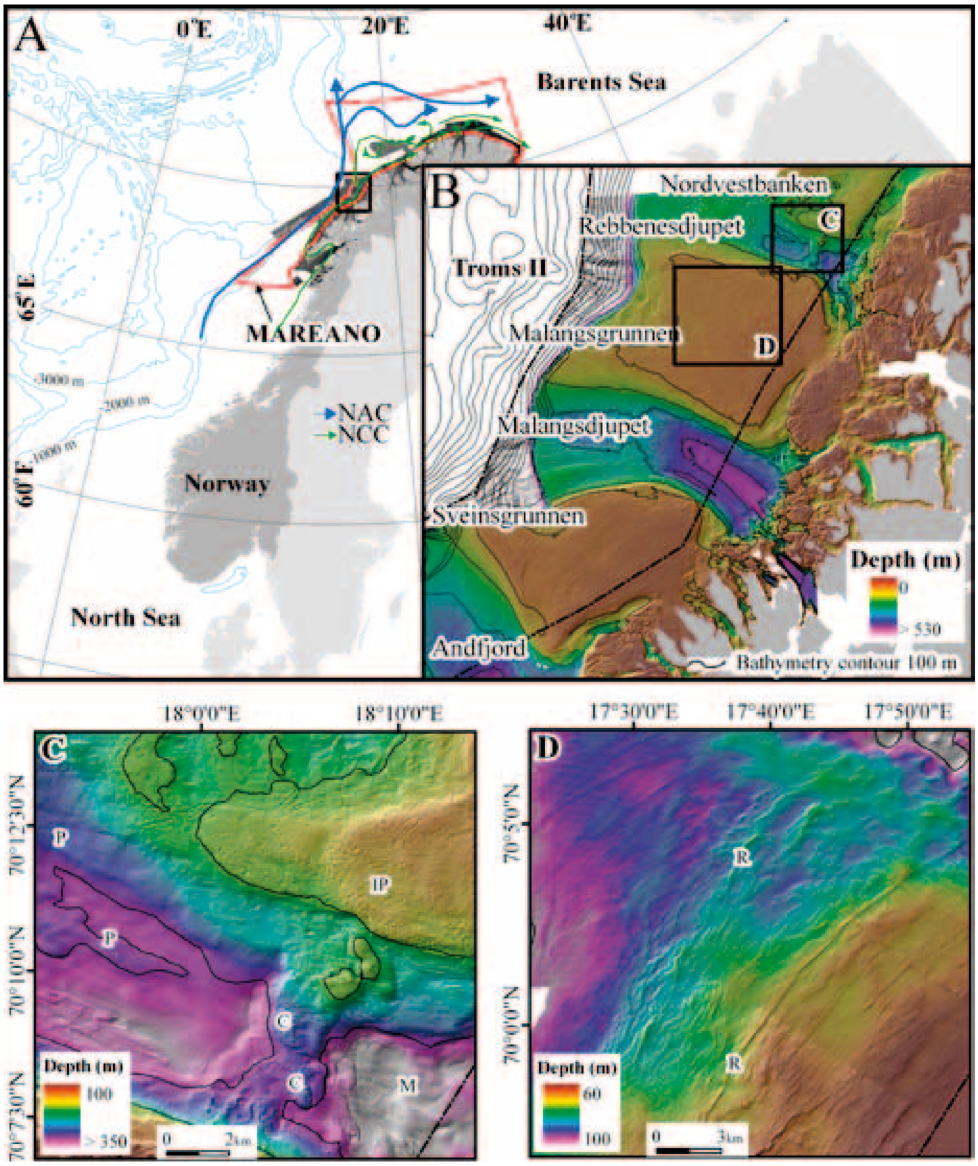

Figure 1. A) Location of study area. NAC: Norwegian Atlantic Current, NCC: Norwegian Coastal Current. 1B) Details of Troms II area. 1C) Detail from Rebbenesdjupet, showing location of coral reefs (C) on the bedrock ridge crossing the trough, pockmarks (P), moraine ridges (M) in deeper areas, and iceberg ploughmarks (IP) on Nordvestbanken. 1D) Detail from Malangsgrunnen, showing ridges (R) on the glacial bank.

m/s and typical bottom speeds of 0.2-0.4 m/s also occur (Gjevik, 1996). The velocity of the NCC is variable, and surface current speeds exceeding 1 m/s are frequently observed (Ersdal, 2001).

Materials and methods

Multibeam mapping

The study area was mapped by the Norwegian Defence Research Establishment (FFI) using a Kongsberg Simrad EM1002 (95 kHz) multibeam echosounder. Multibeam echosounding is used for detailed mapping of bathymetry, but gives additional information on the composition of the seabed through the amplitude of the returned sea-floor signal. The backscatter datasets were processed using Kongsberg Simrad Poseidon (correction and mosaicing of the data) to produce raster grids with cell sizes of 5 m and 10 m, allowing detailed study of seabed features. The data were further processed using a directional cosine filter in Geosoft (Geosoft, 2005). This technique is effective for reducing linear artefacts (nadir noise) associated with backscatter data, when line-spacing and direction are fairly uniform. The bathymetry data were processed by FFI using Kongsberg Simrad Neptune (data correction and cleaning). Data grid cell sizes presented are 5 m in the MAREANO area and 50 m between the MAREANO area and the coast (due to data restrictions inside the territorial boundary).

Video transects and sampling

Over the past 40 years, many institutions have acquired grab samples, gravity cores and pictures from the seabed in the Troms II area, e.g. the Norwegian Hydrographic

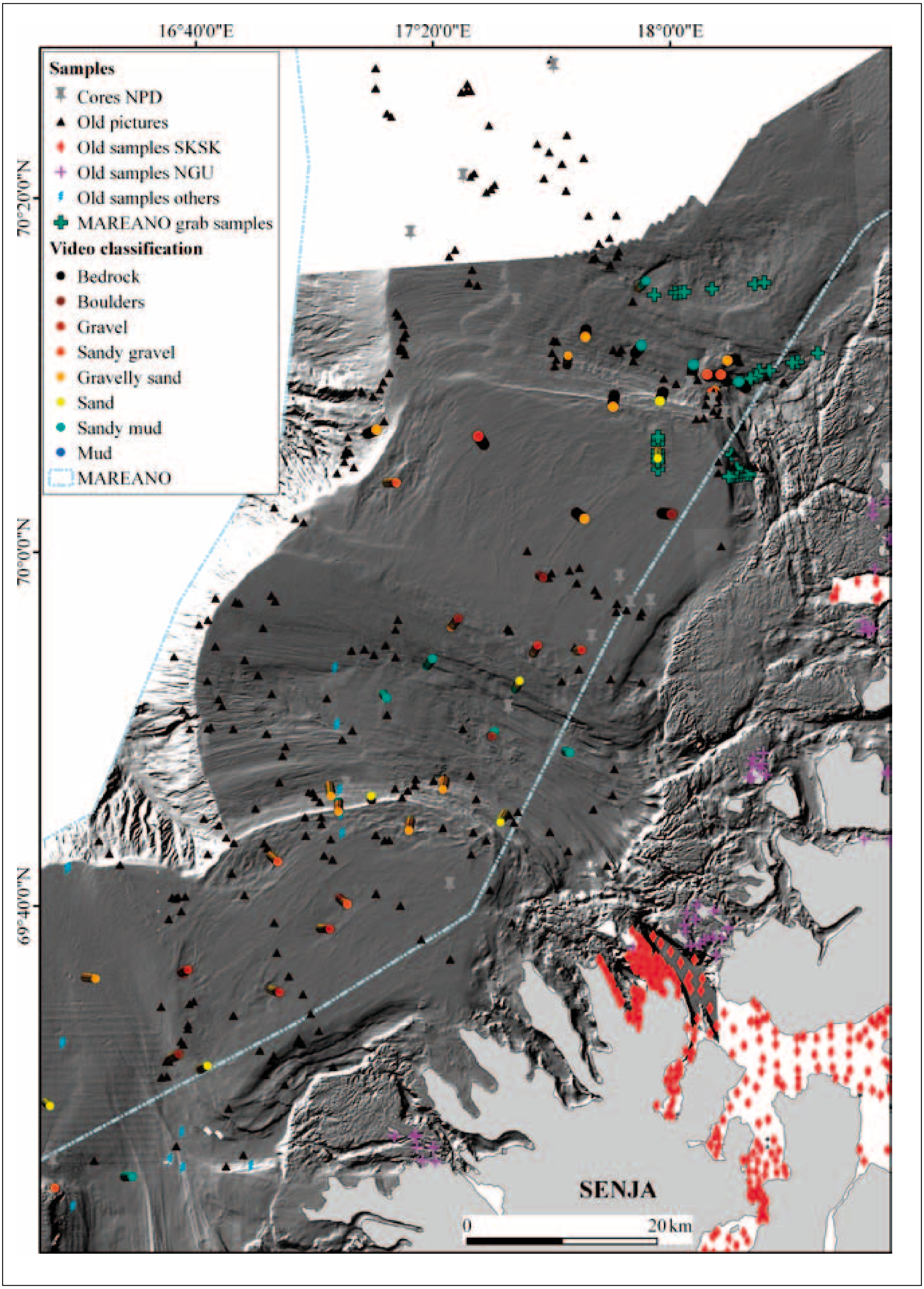

Figure 2. Location of ground-truthing information (pictures, videos, grab samples, cores).

Service (NHS) and the University in Tromsø (UiTø). This information has now been organized in GIS databases at the Geological Survey of Norway, along with new samples and seabed videos acquired during two cruises with *RV G.O. Sars* in April and October 2007, and one cruise with *FF Seisma* in June 2007 (Fig. 2). The aim of these cruises was to obtain data and samples, both for calibration of the multibeam backscatter, and for biological, geological, and geochemical analysis. A total of 41 video transects (each 0.5-1 km long), 42 Van Veen grabs, 8 multicores and 8 box-cores were collected in the study area (Fig. 2).

The video surveys were performed with the Institute of Marine Research's towed video platform CAMPOD, which is a metal-framed tripod equipped with low light CCD (forward-looking) and high definition (HD) video cameras. The lights (2 x 400 W HMI) are mounted on the sides close to the two front legs about 1 m above the "feet". The HD camera has manual zoom and focus, and is mounted on a pan-and-tilt device. The CAMPOD was used both "parked" on the seabed for detailed studies, and in a transect mode (drifting with the ship along a predefined survey line). The height above the seabed is maintained by a winch operator using visual observations from the forward-looking camera. Geopositioning of the video lines was obtained via a transponder, and is accurate to ca. 2% of the water depth.

Results

The nearshore Troms II area comprises 3 glacial banks and 2 troughs. A series of 5 geological maps has been produced for the area and these are described in turn here.

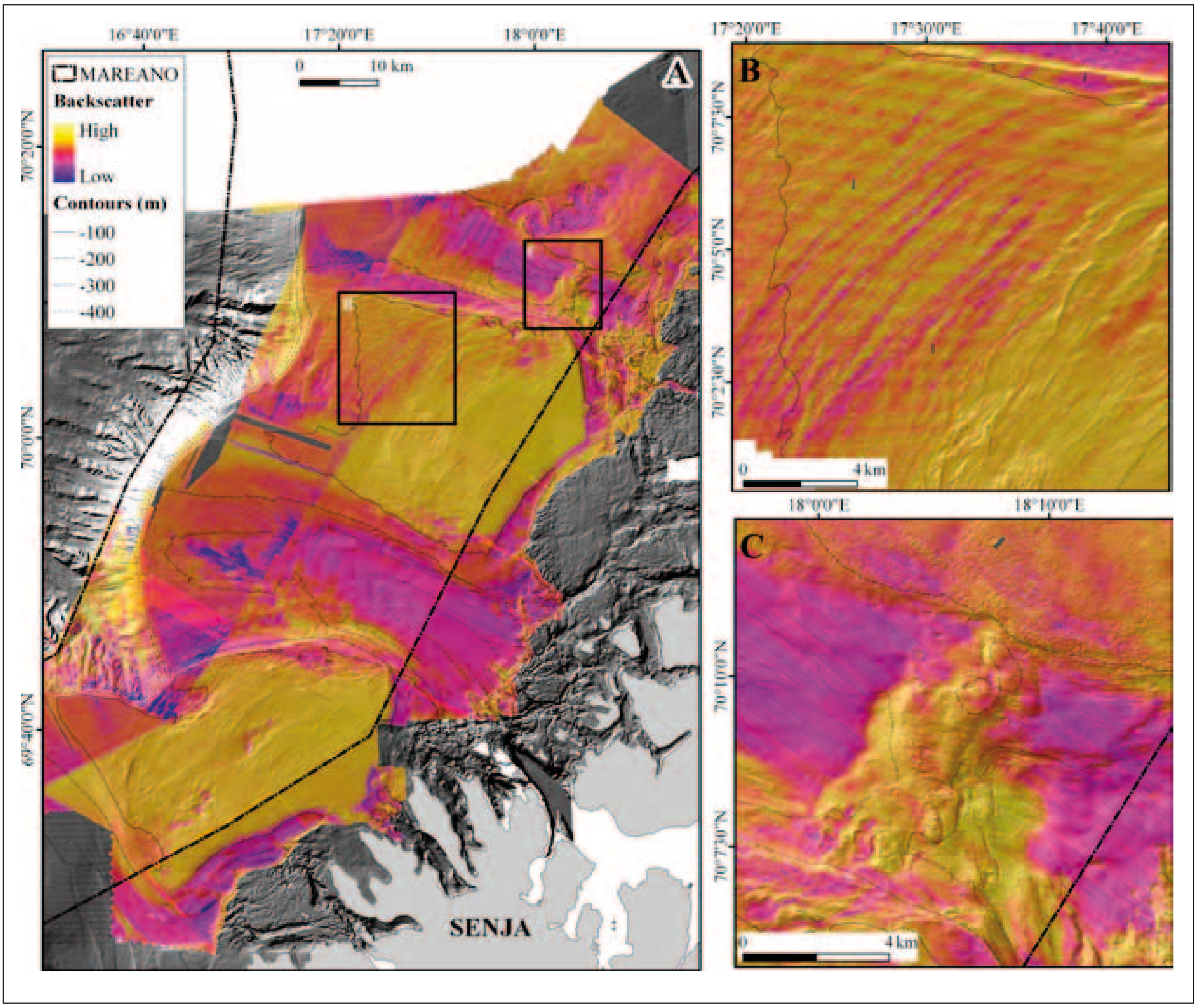

Figure 3. Multibeam backscatter. Figure 3. A) Part of Troms II with hard bottom on the banks and softer sediments in the glacial troughs, Figure 3. B) Detail from Malangsgrunnen, showing ribbons of finer-grained sediments, Figure 3. C) Detail from Rebbenesdjupet, showing a high backscatter ridge (bedrock covered by till) crossing the glacial trough.

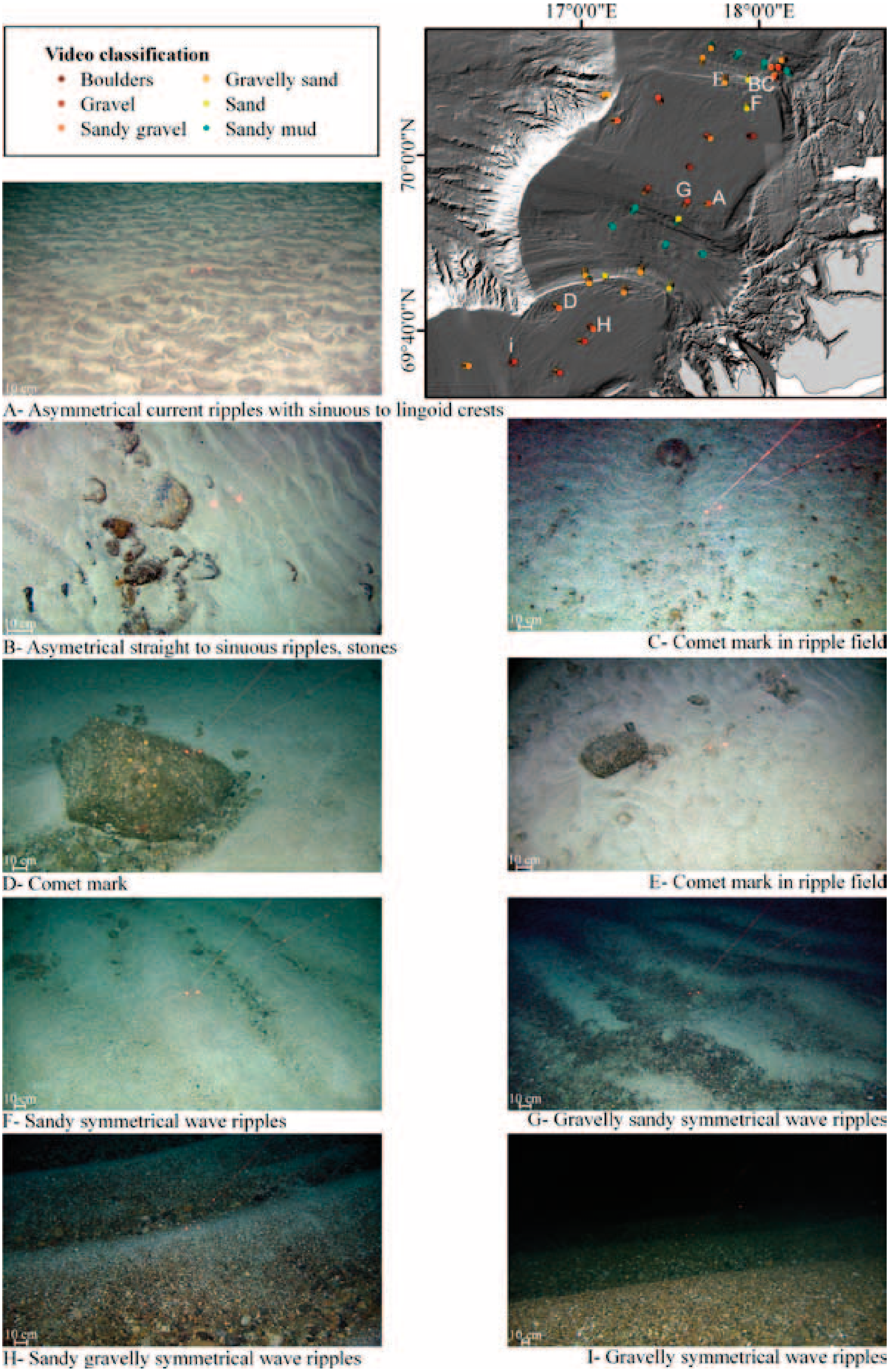

Figure 4. Campod pictures from video lines showing sandy ripples (A and B), comet marks (C, D and E) and symmetric ripples with different grain-sizes (F, G, H and I). There is 10 cm between the two red laser spots.

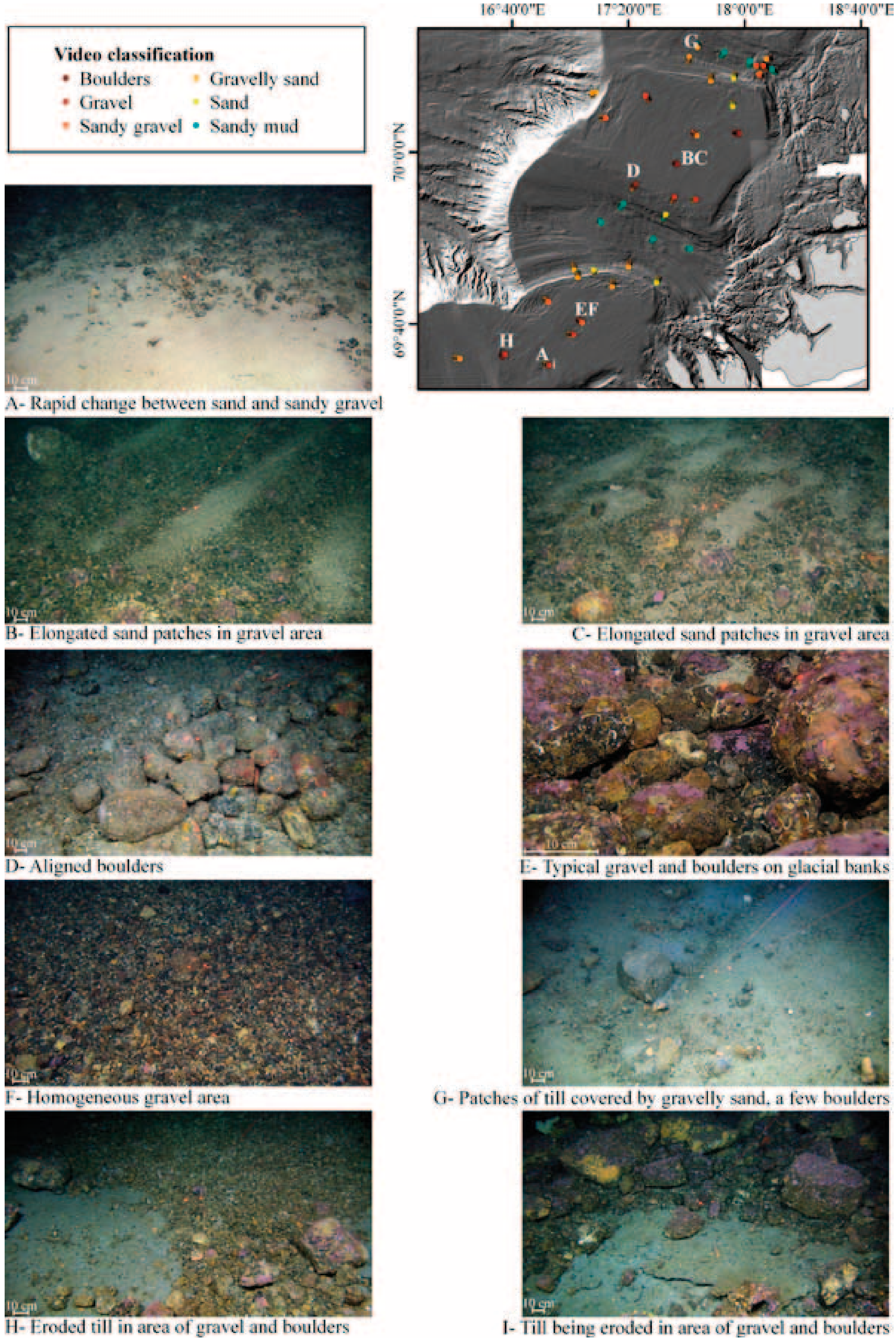

Figure 5. Campod pictures from video lines showing sharp contrast between sandy and gravelly areas (A, B and C), boulders (D and E), gravel (F) and till outcropping below superficial sediments (G, H and I). Note the strongly eroded till in 5I. There is 10 cm between the two red laser spots.

Seabed reflectivity (backscatter)

The map of hard and soft bottom (Fig. 3) is based on data collected by multibeam echosounder. Bottom reflectivity depends on several factors. A hard or coarse/gravelly bottom type generally gives strong backscatter, while fine-grained sediments on the seafloor give a weaker signal due to absorption. Other factors influencing bottom reflectivity include sorting of the sediments, and roughness of the seabed. By processing the reflectivity data and combining these with observations from ground-truthing (Figs. 2, 4 and 5), detailed maps of seabed sediments can be compiled.

Geological terrain forms

The terrain form map shows a combination of shaded relief, multibeam bathymetry and geological terrain forms (Fig. 1). The terrain form map is illuminated by an artificial sun from the NW (315°) with a sun angle 45° above the horizon. This illumination direction enhances many details of the seabed. Geological terrain forms include pockmarks, coral reefs, iceberg ploughmarks, mega-scale glacial lineations, glaciotectonic features such as hill-hole pairs, moraines and slide scars.

Seabed sediments (grain size)

For interpretation of grain sizes, several datasets have been used, including seafloor morphology (multibeam bathymetry), bottom reflectivity (multibeam backscatter), photos and videos, samples (grab, box corer, sledge, multicorer, gravity corer) and seismic data:

- Multibeam bathymetry (Fig. 1) helps to place grain-size boundaries as these generally follow morphological boundaries (banks, troughs, depressions, ridges).
- Multibeam backscatter (Fig. 3) provides information on the hardness and roughness of the uppermost centimetres of the seabed. Low backscatter generally corresponds to soft bottom (mud or sandy mud); high backscatter corresponds to hard bottom (gravel, stones or bedrock). Sand or shells may result in intermediate backscatter values.
- Observations from ground-truthing (samples, videos, pictures) (Figs. 2, 4 and 5) are used directly, and are also used to calibrate backscatter data.
- High-resolution seismic data are used to map vertical and lateral distribution of sedimentary units, especially the distribution of glaciomarine and Holocene fine-grained sediments.

The following seabed sediment classes (Fig. 6) have been applied in the areas mapped so far:

- Mud: fine-grained, homogeneous sediments comprising clay and silt. Mud is the dominating sediment type in deep areas with weak ocean currents, and in local topographic depressions. This class is found inside depressions on the Troms II continental shelf but in too small areas to be mapped at the chosen scale.
- Sandy mud: poorly sorted sediment comprising mainly clay and silt, but with varying contents of sand, gravel, cobbles and boulders. Sandy mud is common in iceberg ploughmarks, in pockmarks and in topographical depressions.
- Gravelly sandy mud: sediment dominated by mud, but contains also considerable amounts of gravel and sand. Gravelly sandy mud occurs in areas of weak bottom currents with poorly sorted sediments.
- Sand: sediment dominated by sand, but may also contain small amounts of gravel and/or mud. It is found on slopes where the current velocity drops and in glacial trenches.
- Gravelly sand: sand is the dominating grain size, but the sediment may also contain considerable amounts of gravel and cobbles. Gravelly sand is common in shallow areas with strong bottom currents.
- Sandy gravel: gravel predominates, but the sediment also contains considerable amounts of sand. Sandy gravel is common in shallow areas with strong bottom currents.
- Gravel, cobbles and boulders: dominated by gravel, cobbles and boulders, with only small amounts of sand and/or mud. This sediment type dominates areas of strong bottom currents, where fine-grained sediments are eroded away, or not deposited because of strong currents. In areas of coarse sediments, there is strong variation in grain size over short distances.

These classes are based on the video lines analysis and follow the SOSI standards (Statens Kartverk, 2006).

Earlier interpretations of seabed sediments in the Troms II area were mainly based on shallow seismic data and cores (Bugge and Rokoengen 1976, Vorren et al., 1984), and the maps showed only 2-3 lithologies on the continental shelf. The new maps, which are at a scale of 1:100 000 (Fig. 6), use seven sediment classes and show an improved level of detail.

The surfaces of Malangsgrunnen and Sveinsgrunnen are covered by sandy gravel, gravel and stones. Sandy gravel may occur in ribbons, following morphological structures such as ridges and furrows. Grain-size generally decreases with increasing water depth. Patches of finer-grained sediments (sand and gravelly sand) occur in depressions. The surface of Nordvestbanken exhibits some large depressions with sandy mud and sand. On this bank, old data (Vorren et al., 1978; Lien & Myhre, 1977) indicate winnowed deposits. Our data indicate that grain-size increase westwards, which is consistent with previous observations by Vorren et al. (1984). The shallow banks are usually covered by lag deposits of boulders and gravel with occasional patches of gravelly sand and sand.

The slopes of the banks are generally covered by sand or gravelly sand, while the deepest parts of the troughs dis-

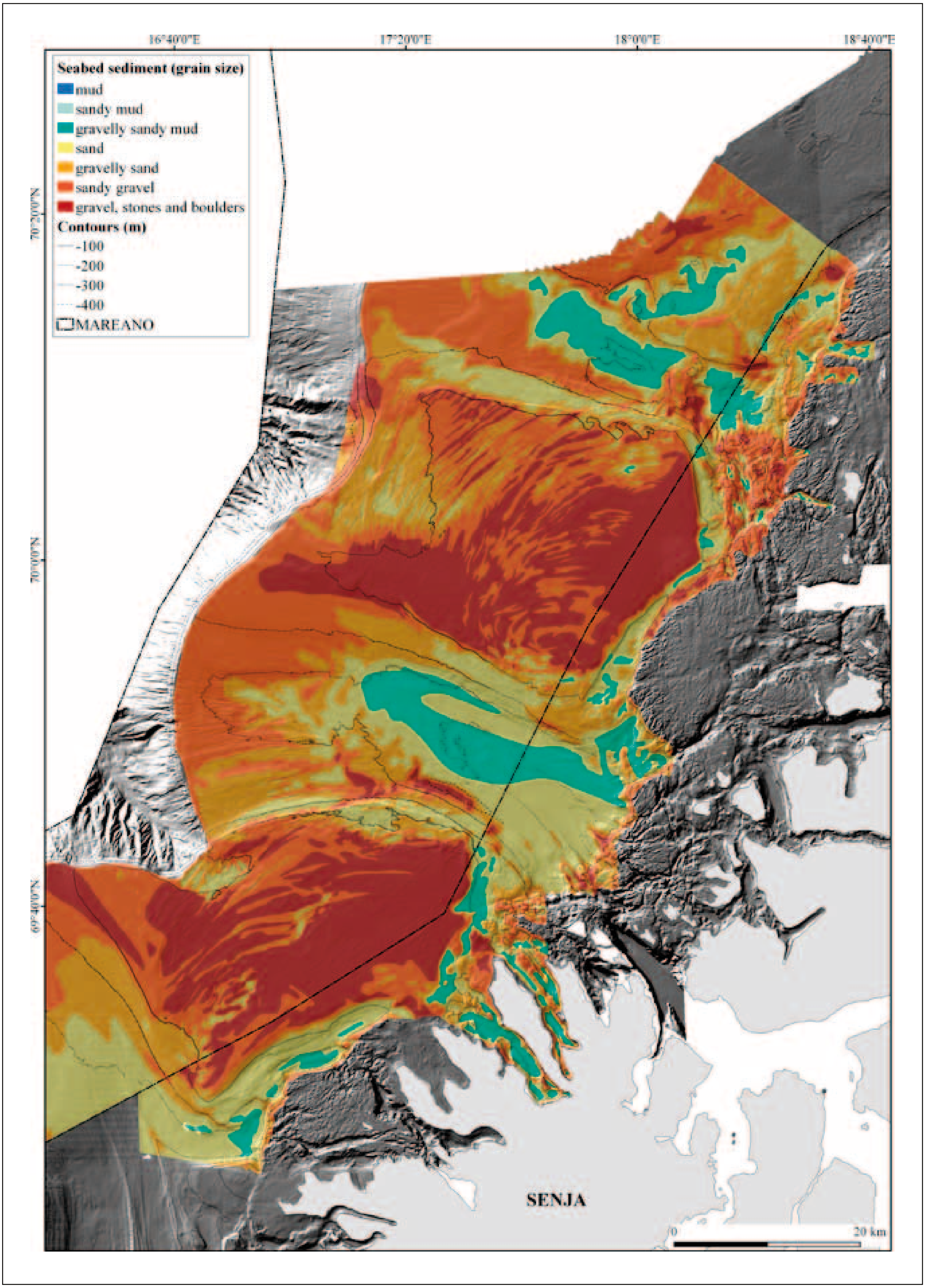

Figure 6. Seabed sediments (grain size), Troms II.

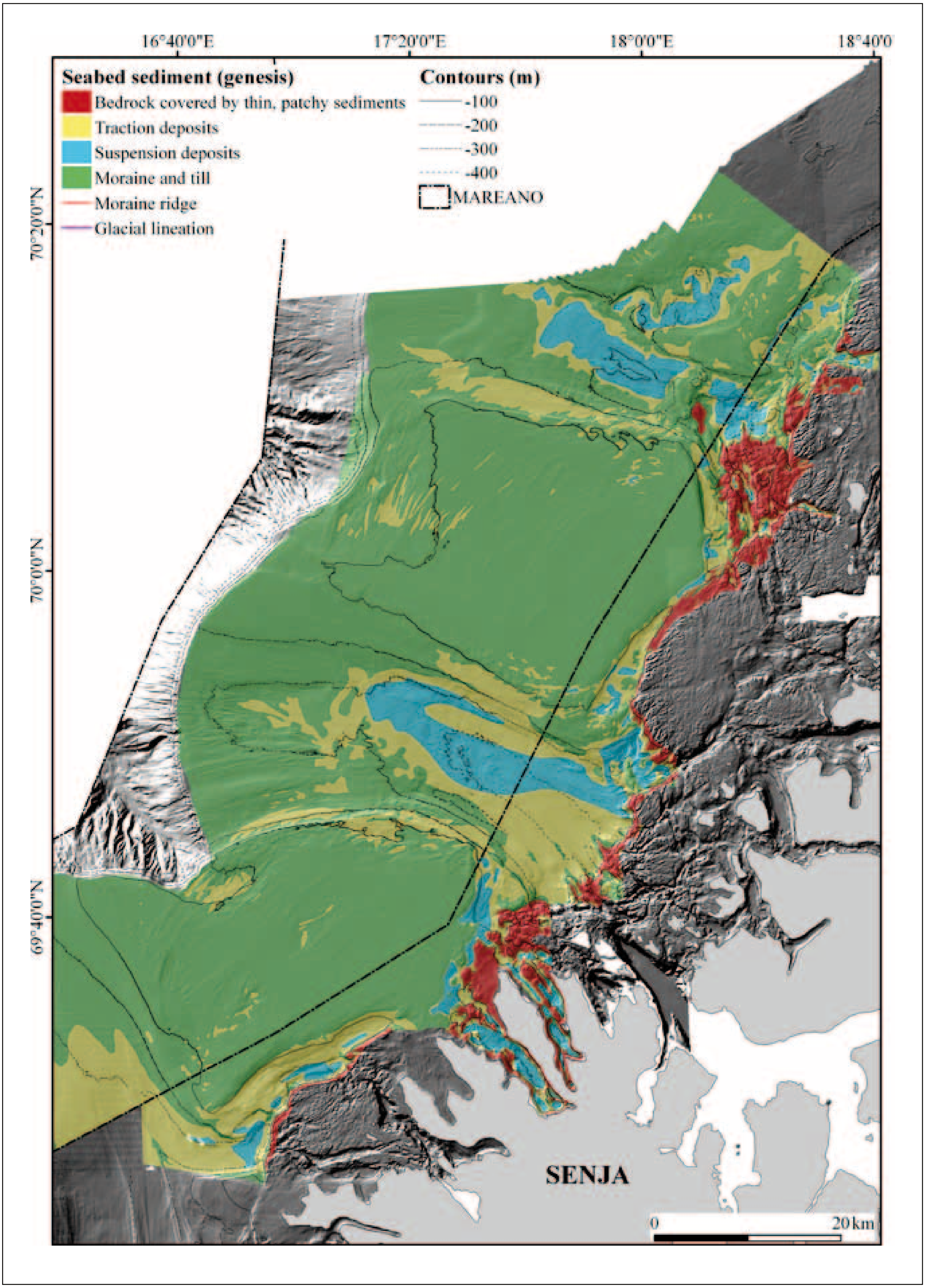

Figure 7. Quaternary geology, Troms II.

play sandy mud and sand. The interpretation of Bugge & Rokoengen (1976), from seismic profiles, was that the troughs are covered by soft clay. Vorren et al. (1984) interpreted the uppermost sequence of sandy mud to cover a muddier sequence below. Fig. 6 shows that fine-grained deposits predominantly occur in the northeastern part of the troughs, while the southeastern parts are covered by gravelly sand and gravel. The thickness of coarse-grained sediments is usually only a few centimetres as sometimes the till deposit can outcrop (Fig. 5G).

Quaternary geology

The seabed has been divided into three classes according to mode of formation. Classification has been performed on the same scale as for the seabed sediment map (1:100 000), and according to the level of detail of data available for interpretation and map production. For interpretation of Quaternary geology (Fig. 7), we have used seabed morphology, sediment grain size, photos and videos of the bottom, samples taken with grab, boxcores, gravity corer, sledge and multicorer and seismic data.

The main part of the mapped area is covered by till, frequently with a thin lag deposit on top. Areas of marine suspension and traction deposits are also usually underlain by till. Till was deposited by glaciers during several glaciations, either under the ice sheet or at/near the margins of the glaciers (marginal moraines). It is composed of sediments with varying grain sizes, from clay to boulders. Till with a top layer/lag deposit of sand and gravel is the dominating sediment type on the banks (Figs. 4 and 5; see also Bugge & Rokoengen, 1976; Vorren et al., 1984), but is also found in trenches with strong bottom currents. The top layer of the seabed may also contain ice-rafted material dropped from drifting icebergs at the end of the last glaciation.
Marine suspension deposits are fine-grained sediments which have settled through the water column. These sediments indicate calm conditions during sedimentation. Marine suspension deposits are found locally in trenches between banks and in deep areas, usually on top of till.
Marine traction deposits are dominated by sand transported by bottom currents (Fig. 4). Such deposits occur where the strength of the current drops, often on slopes, behind elevated areas, and locally as sand banks in trenches and shallower areas.

Modern sedimentary environment

The map of the modern sedimentary environment is based on seabed sediments (Fig. 6) and Quaternary geology (Fig. 7) maps, which are again based on all available data. The map in Fig. 8 shows areas of erosion and deposition together with interpreted bottom currents and surface currents from models.

Fine-grained sediments (mud and sandy mud) are deposited in topographic depressions, troughs and deeper areas. Banks and shallow areas are dominated by extensive current erosion of fine-grained sediments, especially on ridges. Sand is deposited where bottom currents become weaker. Gravel lag and boulders remain on the seabed where currents have washed away mud and sand. Lag deposits are typically a few centimetres to a few decimetres thick (Fig. 5G).

The outer part of Malangsgrunnen shows bottom currents coming from the south and turning eastwards in Rebbenesdjupet (Figure 8). Sundby (1984), Moseidjord et al. (1999), Skarðhamar and Svendsen (2005) and Skarðhamar et al. (2007) showed that, in general, the near coastal circulation has anticyclonic rotation over the banks and cyclonic rotation in the troughs. This corresponds to bottom currents coming from the west in the southern part of the troughs, and from the east in the northern parts. In Rebbenesdjupet, a counter clockwise gyre appears in the inner part of the threshold. The interpreted directions of the bottom currents on Nordvestbanken are variable. They come from the east in the inner part, then turn northwards in the north part. On the outer bank, the currents come from offshore.

Modelling of bottom currents shows large variations in current direction and strength depending on time of the year and tidal cycles (Vikebø & Ådlandsvik, 2005 using ROMS model). The strength of bottom currents is reflected in the grain size of the seabed sediments: mud indicates weak currents (less than 5 cm/s according to Hjulstrom's diagram, 1935, in Nichols, 1999), while coarser-grained sediments indicate stronger currents. The actual direction of bottom currents has been interpreted by studying the distribution of sediments relative to erosion and deposition areas. Fine-grained sediments deposited only on one side within an iceberg ploughmark indicate sediment transport from that direction (Bellec et al. 2008). In the area shown here, iceberg ploughmarks only occur along the margins of the glacial troughs and on Nordvestbanken (Fig. 8).

Ocean currents are strong on the shallow banks, probably more than 20 cm/s as little sedimentation occurs. Areas of till without a protecting lag deposit are exposed to erosion (Fig. 5). Symmetrical sand and gravel ripples testify to strong wave energy (Fig. 4). Comet marks and smaller, asymmetrical sand ripples occur where one current direction predominates (Fig. 4). Sedimentation occurs on the upper part of the northeast slopes of the banks, which are controlled by the NAC. This current is stronger on the lower part of the northeast slope and on the adjacent glacial trough than on the upper slope. The opposite occurs on the southwest slopes of the glacial banks, where erosion occurs higher on the upper part of the slopes, with sediments being deposited in deeper areas and in the glacial troughs. In the latter, the southern part is always more eroded than the northern part, where muddy sediment areas occur.

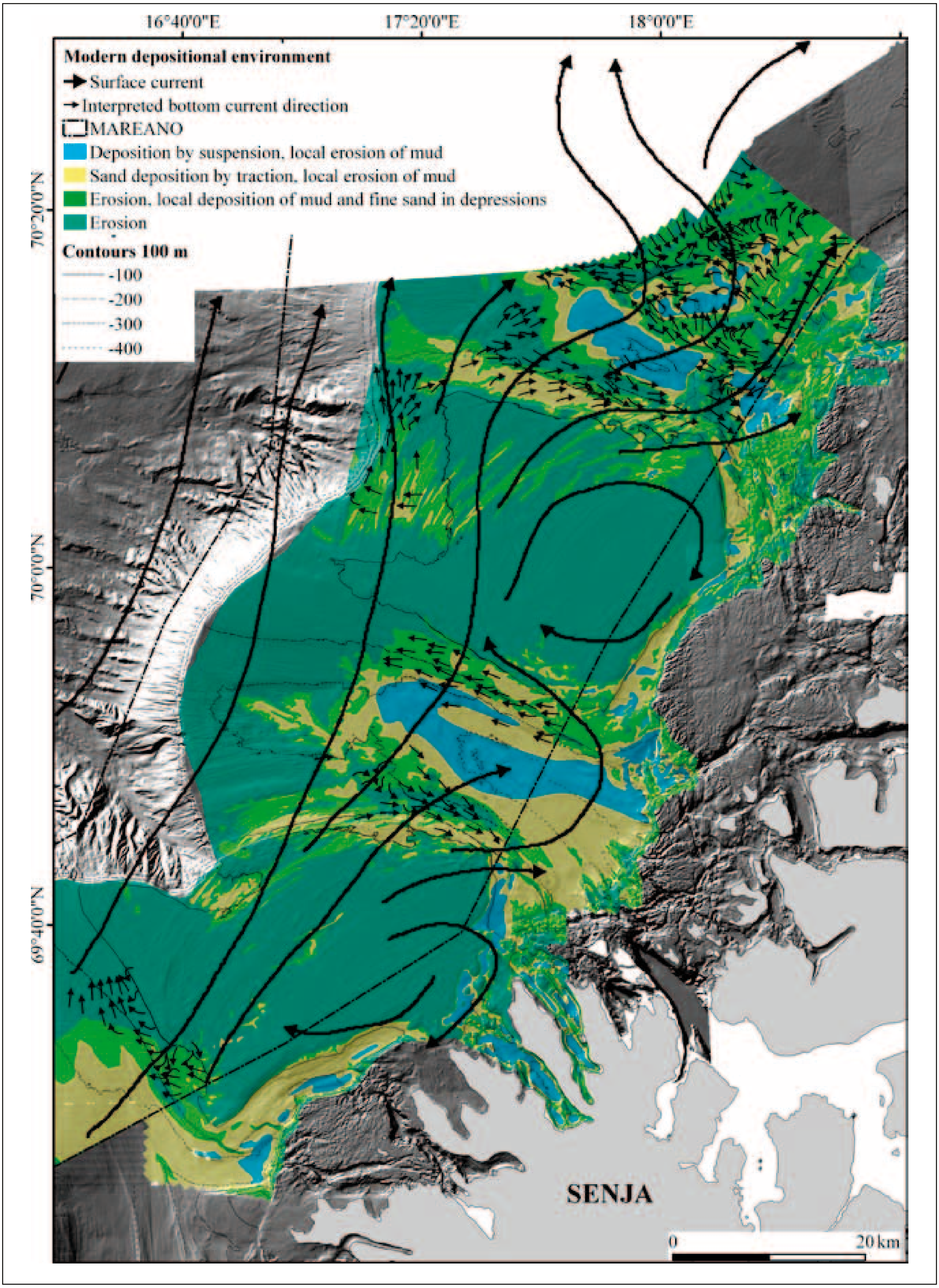

Figure 8. Modern sedimentary environment, Troms II. Bottom currents have been interpreted only within the MAREANO area. Surface currents are from Vikebø and Ådlandsvik (2005).

Summary

MAREANO provides five geological maps (geological terrain forms, seabed reflectivity, seabed sediments, Quaternary geology (seabed genesis) and modern sedimentary environment) which form an important basis for mapping of nature types and habitats. This work focuses on the Troms II area.
The main morphological features in the landward part of the Troms II area are glacial banks and glacial troughs. The banks comprise till undergoing wave erosion, and their surfaces are covered by sandy gravel, gravel and stones. Symmetrical ripples in sandy and gravelly areas testify to this wave action. Ribbons of gravelly sand occur, often following morphological features such as ridges. Sandy sediments are deposited in depressions on the outer part of the banks. On the deeper parts of the banks, large depressions allow deposition of sandy/muddy sediment. The shallow parts of the banks are subject to erosion by bottom currents from the west. On Nordvestbanken, currents on the inner part are from the east. These currents turn northwards in the northern part of the study area.

Southwest slopes of banks are covered by slightly coarser sediments than northeast slopes, indicating stronger erosion on the southwest slopes. In the glacial troughs, sand to sandy gravel occurs in the southwestern parts, which are affected by currents from the west. The northeastern parts of the troughs are covered by sand and sandy mud, indicating deposition. Bottom currents from the east are weaker than those from the west.

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References

Asplin, L., Budgell, P., Ingvaldsen, R., Lien, V., Loeng, H. & Skagseth, Ø. 2006: Comparison of modelled and measured fluxes at the western Barents Slope. *Deliverable D2.6, WP 2, ASOF-N (31.03.06).*

Bellec, V., Wilson, M., Bøe, R., Rise, L., Thorsnes, T., Buhl-Mortensen, L. & Buhl-Mortensen, P. 2008: Bottom currents interpreted from iceberg ploughmarks revealed by multibeam data at Tromsøflaket, Barents Sea. *Marine Geology 249* (3-4), 257-270.

Bugge, T. & Rokoengen, K. 1976: Geologisk kartlegging av de øvre lag på kontinentalsokkelen utenfor Troms. *IKU publication 85*, 51 pp.

Ersdal, G. 2001:. An overview of ocean currents with emphasis on currents on the Norwegian continental shelf. *NPD Preliminary Report*, March 2001, 40 pp.

GeoSoft 2005: Montaj MAGMAP Filtering. 2-D Frequency Domain Processing of Potential Field Data Extension for Oasis montaj v6.1 Tutorial. *GeoSoft Inc.* 72pp.

Gjevik, B. 1996: Hva driver golfstrømmen?. *Naturen 4*, 216-222.

Gjevik, B. 2000: Summary and assesment of the NDP metocean project, *Project report to the Norwegian Deepwater Project.*

Hjulstrom F., 1935. The Morphological activity of rivers as illustrated by river Fyris. *Bulletin of the Geological Institute*, Uppsala 25, 89-122.

Ingvaldsen, R., Asplin, L. & Loeng, H. 2004: The seasonal cycle in the Atlantic transport to the Barents Sea during the years 1977-2001. *Continental Shelf Research 24*, 1015-1032.

Lien, R. & Myhre, L. 1977: Undersøkelser av overflatelaget på kontinentalsokkelen utenfor Troms og Vest-Finnmark. *IKU publication 92*, 33 pp.

Moseidjord, H., Svendsen, H. & Slagstad, D. 1999: Sensitivity studies of circulation and ocean-shelf exchange off northern Norway. *Sarsia 84*, 191-198.

Mosby, H. 1968: Surrounding seas. In: A. Sømme (Editor), A Geography of Norden. Cappelens, Oslo, 18-26.

Nichols, G., 1999. Sedimentology and stratigraphy. *Blackwell*, Oxford, 355 pp.

Ottesen, D., Dowdeswell, J. A. & Rise, L. 2005: Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: The 2,500 km-long Norwegian-Svalbard margin (57°-80° N). GSA *Bulletin 117*, 1033-1050.

Skarðhamar, J., Slagstad, D. & Edvardsen, A. 2007: Plankton distributions related to hydrography and circulation dynamics on a narrow continental shelf off Northern Norway. Estuarine, *Coastal and Shelf Science 75*(3), 381-392.

Skarðhamar, J. & Svendsen, H. 2005: Circulation and shelf–ocean interaction off North Norway. *Continental Shelf Research 25* (12-13), 1541-1560.

Statens Kartverk 2006: Fagområde: Løsmassegeologi. SOSI standard – generell objektkatalog versjon 4.0. *Statens Kartverk*, 70 pp.

Sundby, S. 1984: Influence of bottom topography on the circulation at the continental shelf off northern Norway. *Fiskeridirektoratets Skrifter Serie Havundersøkelser 17*, 501-519.

Vikebø, F.B. & Ådlandsvik, B. 2005: Circulation and hydrography off northern Norway - a regional ocean model study. The impact of climate on early stages of Arcto-Norwegian cod - A model approach, PhD Manuscript, University of Bergen, Paper I, 15-49.

Vorren, T. O., Hald, M. & Thomsen, E. 1984: Quaternary sediments and environments on the continental shelf off northern Norway. *Marine Geology 57*, 229-257.

Vorren, T. O., Strass, I. F. & Lind-Hansen, O.-W. 1978: Late Quaternary sediments and stratigraphy on the continental shelf off Troms and West Finnmark, Northern Norway. *Quaternary Research 10*, 340-365.