Correlations of geological and biological elements in marine habitat mapping in glaciated areas; field tests from the coast of Møre and Romsdal County, western Norway.

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We describe a survey strategy for habitat mapping involving two cruises.. The first cruise was for multibeam acquisition, including a reduced ground truthing program based on automatic (unsupervised) or a semi-automatic (supervised) classification. The main part of the geological and biological ground truthing was performed on the second cruise. With this approach, habitat interpretation based on acoustic data, predictive models and, if possible, a few samples from the first cruise can then be used in between the cruises. This will delineate areas of special interest and complexity, where further geological sampling and visual inspection can be performed. The acquired data and interpretation results can be directly ”linked” to a classification scheme such as the one developed for marine sublittoral habitats in the Northeastern North America Region (Valentine et al., 2005). In the present case, a few minor adjustments in this classification scheme improved the survey strategy. The Valentine et al (2005) classification scheme was found reliable for use in a typical Norwegian coastal area dominated by glacial sediment, which has been problematic for other classification schemes due to the complexity of this sediment type. Good correlation between modelled tidal current strength, biology and the seabed sediment properties was found. Two sea pen species and one species of seastars displayed a strong correlation to specific tidal currents and sediment properties, while the correlations were weaker for most other species. Tidal current strength and the texture of seabed sediments seemed to have a great influence on the biological processes..

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Introduction

Today’s detailed swath bathymetry and backscatter obtained from multibeam sonar data, together with advanced ground truthing tools have opened up new possibilities for the characterisation and mapping of marine habitats. This has also triggered the need for robust habitat classification systems. Incorporating data and preliminary results in classification schemes can be problematic if the schemes do not explicitly address high-resolution information of seabed morphology and texture. Regional character has been difficult using well-established classifications schemes, e.g. EUNIS (http://eunis.eea.eu.int/index.jsp) which have problems coping with mixed substrates such as till normally found in glaciated areas (Rinde et al., 2004). This problem makes such classifications impractical to use in Norwegian waters, where glacial deposits dominate the seabed. Valentine et al. (2005) designed a habitat classification system for use along the repeatedly glaciated northeast coast of the USA and Canada. This system consists of eight individual and informal themes, organised in a non-hierarchical system, where each theme resides at a top-level position. The objective of this paper is to test the applicability of the chosen classification system in Norwegian waters and to explore correlations between seabed geology and the distribution of benthic species

Study area

The study area (Fig. 1) lies on the outer coast of Møre and Romsdal County, Western Norway. It covers parts of four sounds (fjords) surrounding three islands (Fig. 1). The water depths range from 15 to 150 meters. The area has been exposed to repeated glacial activity throughout the Quaternary. The last glaciation, the Weichselian, started c. 115 000 BP, and lasted until 10 000 BP with reduced glacial activity during interstadials. During the Weichselian, the ice margin reached the continental shelf at least three times and thus overran the study area several times (Larsen et al., 1988.) Features generated by repeated gla-

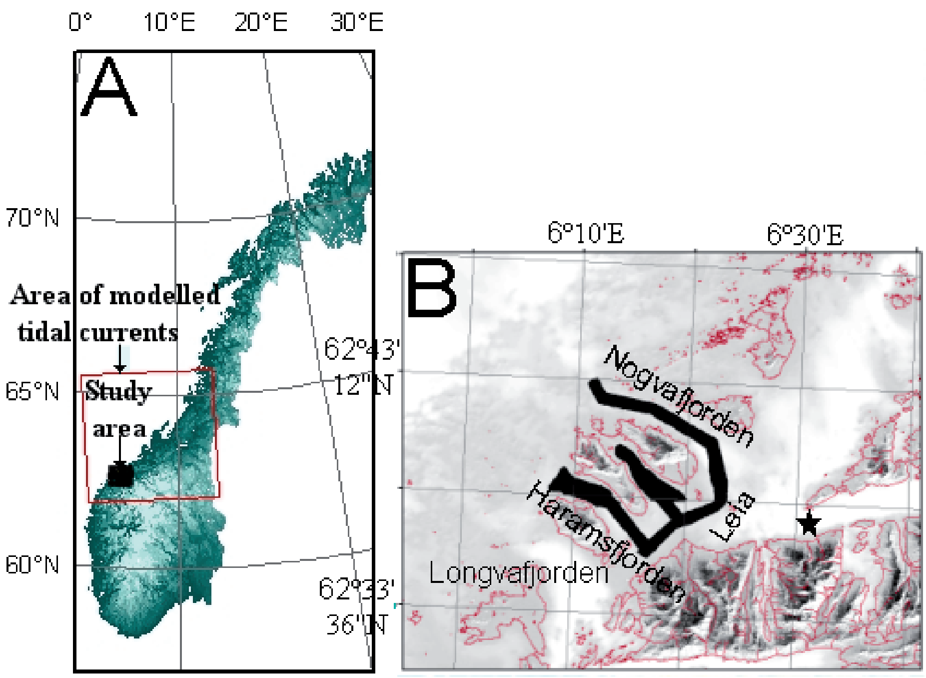


Fig. 1. A) Map of Norway showing the study area (small black square) and the area of modelled tidal currents (open frame). B) The mapped area (black) covers approximately 38.1 km², surveyed as a 38 km long corridor around three islands. East of the surveyed area numerous Lophelia pertusa coral reefs (black star), were mapped and confirmed using a video assisted grab sample.

ciations dominate the seabed morphology and have been modified by uplift, wave exposure, and currents throughout the Holocene.

Geology

Basement

The geological basement consists of metamorphic rocks formed along the Baltic shield during the Precambrian and deformed during the Caledonian orogeny (Tveten et al., 1998). The metamorphic bedrock is faulted and fractured in a pattern that has influenced glacial erosion forming sounds oriented both along and transverse to the coastline (Fig. 1). Bedrock is often exposed onshore and occasionally crops out below sea level.

Quaternary sediments

Sediments deposited during the Quaternary comprise mainly till, interlaid and overlain by marine sediments (Mangerud et al., 1981, Larsen et al., 1988). Till is found both as sheets, stoss side moraines, and moraine ridges (Larsen et al., 1988). Glacial striae indicate that the main ice-flow direction over the area during peak glaciations was towards the northwest. Till sheets are therefore best developed on the southeast sides of the islands and along the north-eastern sides of the north-east southwest oriented sounds. In areas where Holocene deposits do not cover glacial deposits, the seafloor morphology displays classic De Geer moraines formed during the last deglaciation (Larsen et al., 1991). Carbon 14 dating of shells (Larsen et al., 1988) have confirmed a very rapid deglaciation, with an estimated rate of up to 250 m/yr. The area west of the surveyed archipelago (Fig. 1B) became ice free between 12.370 to 12.270 years BP and the southwest part of the study area - 10 to 40 years later based on Carbon 14 dating (Larsen et al., 1988). The sea level in the area then lay between 30 – 40 m above the present sea level. During the Younger Dryas, i.e. 11.000-10.000 years BP, isostatic and eustatic movements were in balance, and the sea level was stable for more than one thousand years. During this period marine abrasion created a very distinct shoreline in the till beds and eroded silt and sand were transported into the fjords. At the same time lots of icebergs drifted along the coast, having calved from glaciers at heads of the fjords. Icebergs modified the seafloor by scouring and by rafting debris over it.

Sedimentation during Holocene

Continued isostatic uplift and the Tapes Transgression dated at 6.200 – 6.600 years BP (Hafsteen and Talletire, 1978, Larsen et al., 1988, and Svendsen and Mangerud, 1987) led to littoral winnowing of fine-grained sediments, mainly sand and silt. This has been the main form of transport of minerogenic matter into the sounds during the Holocene. The reduced width and water depth of the sounds have also led to increased current erosion and redistribution of sediments on the seafloor. During the Holocene, large amounts of organically produced carbonate have been generated in the form of shells. The carbonate debris is usually mixed with minerogenic matter, but is occasionally found as bioclastic sediments composedof almost pure carbonate sands and gravel. The study area has well oxygenated seawater and the primary organic production that settles as marine `snow´ is probably chemically dissolved, but fine-grained sediments in the sheltered Longvafjord and the deep basin off Nogvafjorden (Fig. 1B) has an elevated organic matter content.

Currents and waves shift sand in some of the sounds and along the shores and deposit silt in more sheltered locations. In the most exposed areas, the shores consist of boulders and cobbles washed out of till forming protective armour against further winnowing. Along these shores there are sandy bays and beaches, but the volume of sand varies seasonally. During winter storms the sand is usually washed offshore, but is slowly redeposited during spring and summer, thus creating a highly dynamic environment with large annual variations. Along the deeper parts of Haramsfjorden and Nogvafjorden (Fig. 1B) the seafloor is armoured with a lag of gravel and pebbles in a sandy matrix. Sand is found in sheets together with dunes in areas where sand is transported by storms and/or tidal currents.

Acoustic mapping and sediment classification

An EM1002 multibeam echo sounder was used to acquire backscatter and bathymetric data during the winter of 2002. The multibeam echo sounder operates on two frequencies, 98 kHz for the inner part of the swath and 93 kHz for the outer part of the swath and with three different pulse lengths. This survey is limited to shallow water, less than 200 metres, therefore only one pulse length, 0.2 ms, was used. The backscatter signal comprises both surface and volume scattering. Surface scattering is caused by seafloor roughness, which is a function of seabed sediments and seafloor morphology. Scattering from within the seabed sediments is termed volume scattering and is dependent on the impedance contrast between the seawater and the seabed sediment and the homogeneity of the seabed sediments. The recorded backscatter strength is dependent on the grazing angle, which is removed using normalisation software created by Robert Courtney, Geological Survey of Canada (Atlantic). After backscatter normalisation the seabed sediment boundaries can be mapped automatically using the backscatter strength. Classification of the seabed sediments is based on backscatter intensity from various grazing angles and on various ground truthing methods (Christensen et al., in 2007). Large sand waves in Haramsfjorden (Fig. 2) and Nogvafjorden were re-mapped in the summers of 2003 and 2004 using a GeoSwath interferometric sonar.

Ground truthing

Free fall gravity penetrometer

The Seabed Terminal Newton Gradiometer, STING Mk. II, is a lightweight free fall penetrometer that provides data about the bearing strength of the seabed in areas of soft sediments. The STING Mk. II acquires data on pressure, penetration and acceleration from a free fall impact on to the seabed. It is released for free fall 10 metres above the seabed, then raised to approximately 10 meters above the seabed and released again for a second impact. Several impacts can be performed at the same location within the two-minute recording time the system is capable of. Ten stations were tested within the survey area. Casts were performed in areas of clay to coarse sand. Results in till and bedrock have previously been poor, therefore, these sediment types were avoided in order to prevent damaging the instrument. During the series of measurements made at each station the average of seven repeated impacts were recorded. This increases the accuracy of the bearing strength estimates and provides an indication of the homogeneity of the seabed sediments.

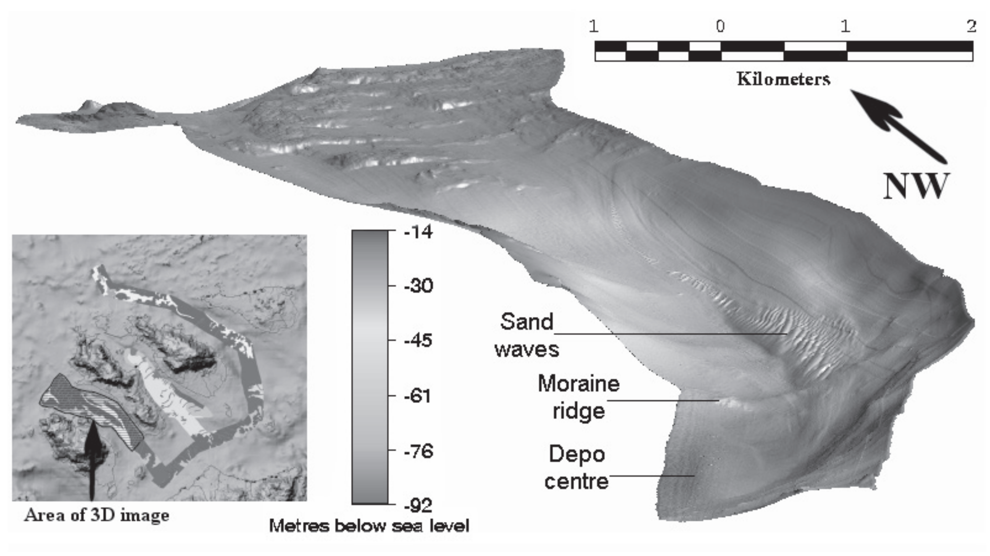


Fig. 2. Sand waves in Haramsfjorden (enlarged index map, see Figure 3) illustrating downslope and along slope sediment transport. Sediments are shown in a depocentre behind a morainic ridge shown in the lower part of the figure.

Grab samples and visual ground truthing

Ground truthing was performed using a Van Veen grab with a mounted video camera (Mortensen et al., 2000). The system was used as a drift camera to investigate sediment boundaries and coarse-grained sediments and for sampling fine-grained sediments such as clay, silt and fine sand. Visual inspection has proved to be the best method for differentiation between till and bedrock, as lightweight grab sampling in these areas often failed. In areas of fine-grained sediments, video inspections are of limited use, because the low image resolution of the camera makes it difficult to differentiate between these types of sediments (e.g. muddy sand from mud). Combining visual video camera inspection and analysis of grab samples has proved to be the most reliable and efficient method for ground truthing the seafloor. Grain size distribution of retrieved fine-grained sediment samples was determined by laser diffraction analyses using a Coulter LS 200 instrument, that has an analysis uncertainty of less ±3% on grains between 0.4µm and 2000mµ.

Twenty hours of video transect recordings covering nearly twenty-five kilometres were acquired to investigate sediment properties, sediment boundaries and biological identification. The resolution of these recordings was of the order of centimetres, compared to the obtainable resolution in millimetres from still photos. The broad-scale and continuous visual coverage of the seafloor obtained using video transects improves the large-scale understanding of habitat boundaries and to a certain degree compensates for the poor optical resolution. In addition, four video transects were undertaken east of the survey area, at the *Lophelia pertusa* reefs (Fig. 1B).

Video transects were sub-divided into segments according to changes in observed fauna and flora. Megafauna (animals >1 cm in size) was identified and the density of species estimated along the transect segments. The associations between benthic assemblages or single species with sediment types, water depth and current strength were established using an electivity index (Kostylev, 2001). Electivity indices for different habitat types were calculated for each assemblage as (Fh - Fa)/Fa, where Fh is a frequency of occurrence of the species in a given habitat and Fa is the average frequency of occurrence in any habitat. The index varies from –1 (complete avoidance of the habitat) through 0 (indifference) to indefinitely large positive numbers (indicating preferred habitat), (Kostylev, 2001).

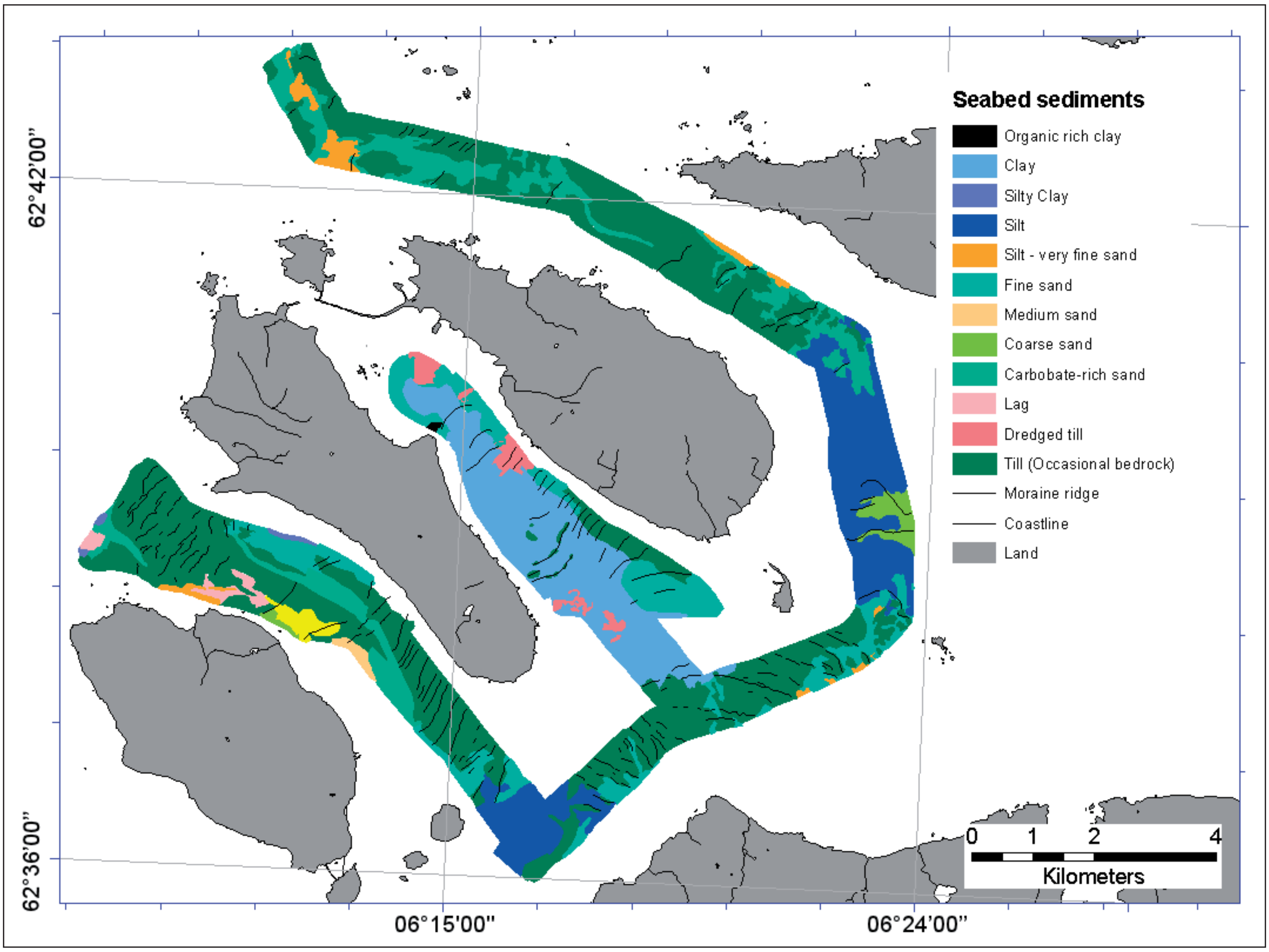


Fig. 3. Geological map showing 12 seabed sediment types interpreted and mapped from multibeam data, grab samples and video recordings.

Secchi disk

Algal production and other photosynthetic processes demand light, which is only present in the shallow photic zone. It is therefore important to map the base of the photic zone, in order to separate these two sub-classes. The depth of the photic zone was approximated using a white and black coloured Secchi disk. The disk was lowered into the sea until it was no longer visible. The observed depth, which indicates the depth of the photic zone, was adjusted according to the size of the disk. The "Secchi" survey was performed during the multibeam acquisition in early March. This is prior to the spring bloom of algae and the observed depth must be regarded as a maximum depth of the photic zone. Generally, it will be much shallower both during summer and as an annual mean.

Seabed sediment classification

Interpretations based on multibeam backscatter and bathymetric data, supported by the various ground truthing methods have been used to sub-divide the area into thirteen sediment classes (Fig. 3) (Fosså et al., 2005). These classes were merged according to acoustic analysis of the backscatter signal to form the basis for a rough classification comprising three classes:

- Bedrock and till, which are classified as hard sediments. This class, has a rough surface that covers barren rock, moraine ridges, gravel, pebbles and cobble-sized stones, winnowed areas, stones and gravel lags. The De Geer moraines are ridges from one to several metres high with a rough surface of gravel to block-size bedrock fragments. In between these fragments sandy patches occur locally.
- Sandy sediments, which are classified as coarse-grained. This class often has shells and shell fragments on the surface. In areas within Haramsfjorden (Fig. 2) and Nogvafjorden (Fig. 4) sand waves indicate mobile sand. Samples in these areas show that the sand is rich in carbonate, mainly from shell fragments.
- Fine-grained hemipelagic sediments, which are classified as fine-grained. This class is found in sheltered areas or in the deepest depressions and ranges from silt to clay.

Assessments: Effects of tidal currents on bottom substrate and biology

The study area lies on the outer part of the Norwegian coast and faces strong south-westerly winds from the North Atlantic lows that generate waves and wind driven currents during the autumn and winter. In addition,

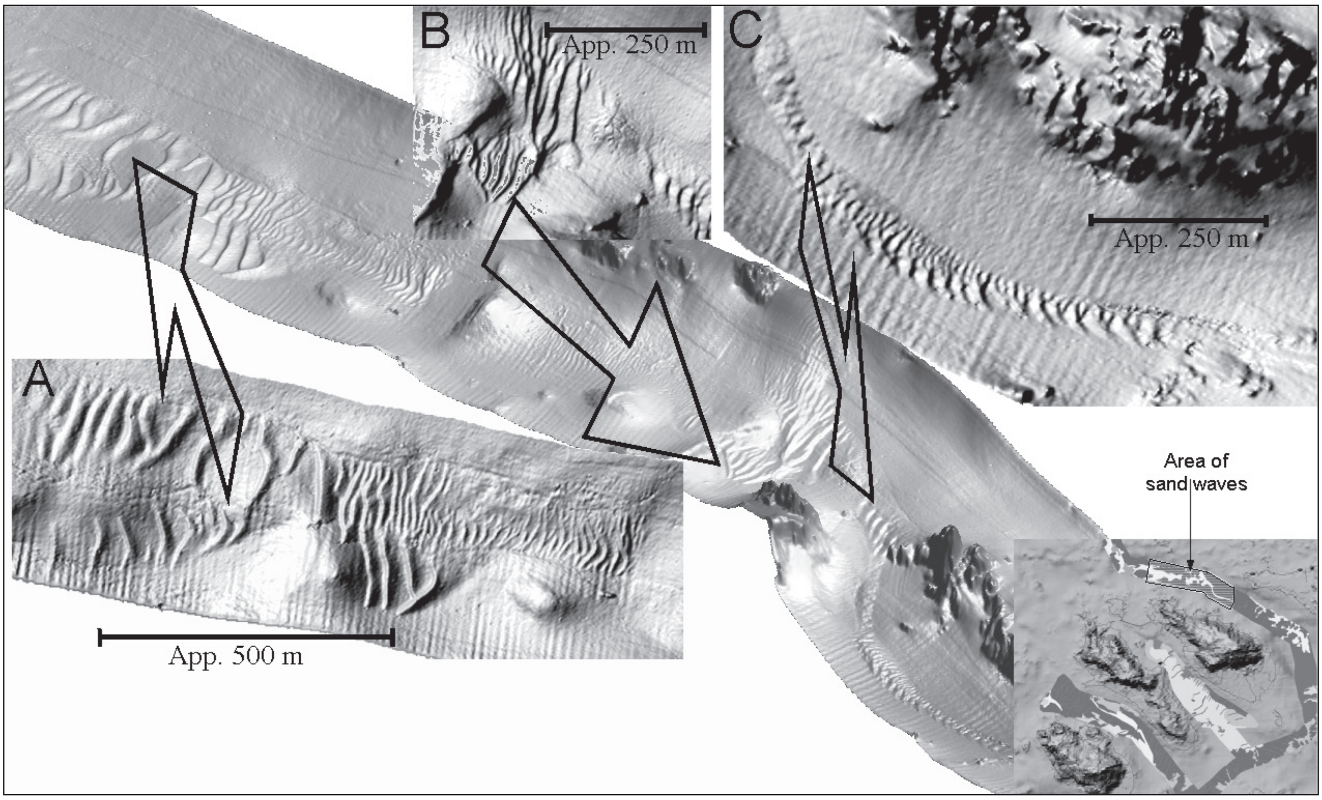


Fig. 4. Oblique and vertical view of sand waves in the central part of Nogvafjorden, index map in the bottom right corner (for enlarged index map, see Figure 3). Symmetrical sand waves in the upper part of inset image A are interpreted to be standing waves, while the sand waves in the lower part are interpreted as having moved eastward based on their morphology. The morphology of the sand waves in inset images B and C indicates eastward transport.

the tidal range in the area has a mean of 1.2 m causing fairly strong tidal currents (up to 162.3 cm/s). The tidal component from the Moon (M_2) and Sun (S_2) has been modelled in a 500-metre grid in part of the mid-Norwegian coastal area covering the study area (Fig. 1A), and calibrated using 28 tide gauge stations (Moe et al., 2003). This numerical model does not provide any information about wave energy or peak events that potentially have a large effect upon sediment transport. However, the model provides a good estimate of the tidal current strength and direction across the survey area and reveals a correlation between tidal current strength and various seabed morphologies.

The maximum current strength is achieved at mean spring tide conditions when the M_2 and S_2 tidal components are in phase. This maximum was compared with sediment types in order to investigate the likelihood of tide-generated sediment transport (Fig. 5). The critical shear stress for six of the dominating sediment types within the area was calculated (table 1) (Li and Amos, 2001, Paphitis, 2001 and Miller et al., 1977).

In most of the area, the maximum shear stress produced by the currents is considerably lower than the calculated critical shear stress. In two areas, the maximum current shear stress is close to, but not exceeding the calculated critical shear stress for the settling threshold for the sediment. This is the case in Nogvafjorden and Haramsfjorden, where sand waves are indeed present, oriented perpendicular to the dominant tidal current direction. Active sand movement has been independently documented by repeated surveys, showing inter-annual crest movements up to 7 metres. The tidal current at peak spring tide conditions can exceed the values at the mean spring tide by up to 40%. Storms and oceanic swells can introduce even larger deviations from mean spring tide conditions, and it is likely that the peak events, not accounted for in the tidal modelling, are the main cause of the sand transport.

There is a good correlation in the survey area between low current strength and the accumulation of fine-grained sediments, with the exception of the two areas outlined on fig. 5. Coarse-grained sediments dominate both areas, but finer sediment was expected due to the weak tidal current strength. However, the current in these areas is not dominated by the tidal current, but by current generated by wind and peak events.

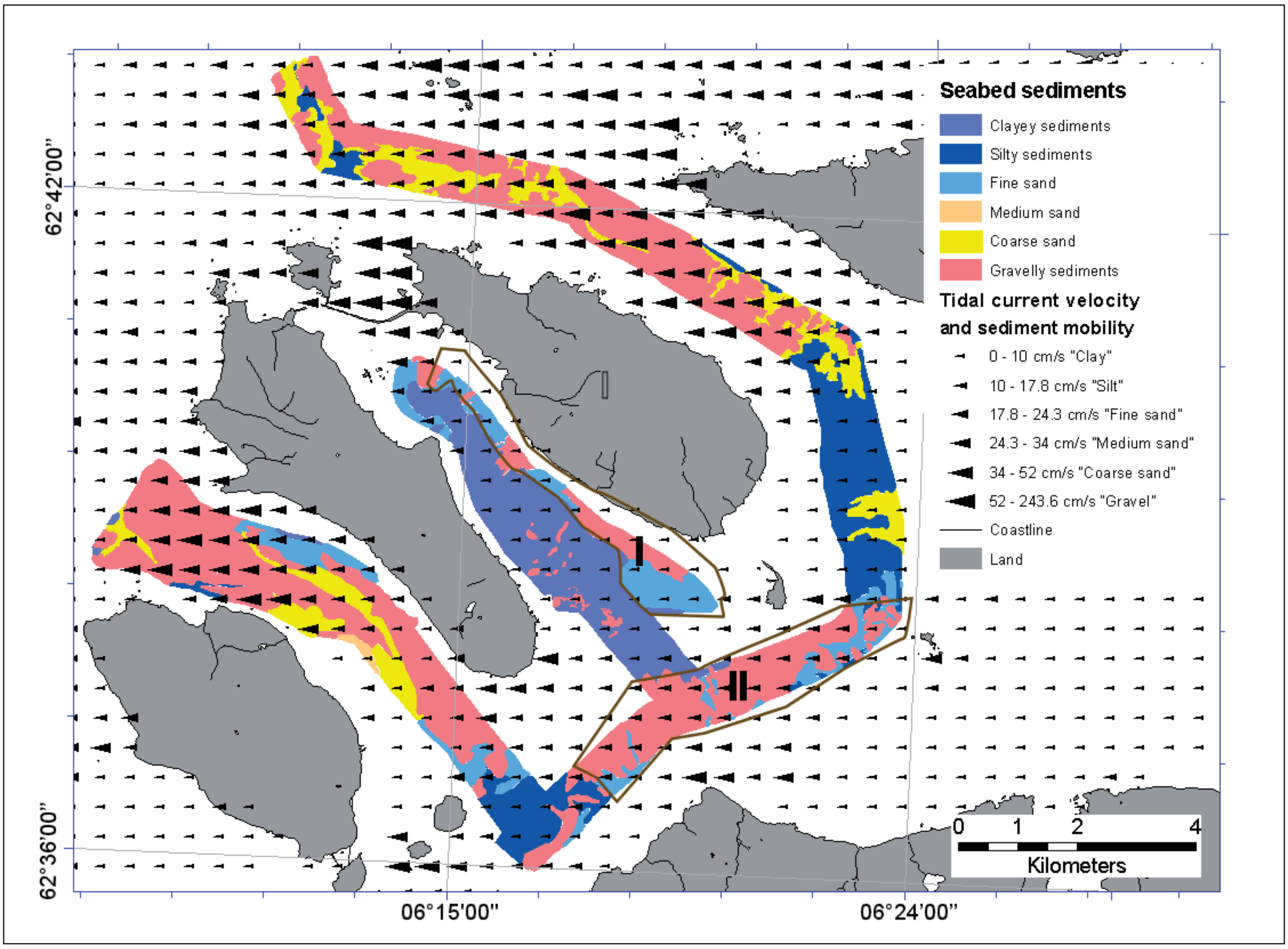


Fig. 5. Modelled mean spring tidal current strength shown when M_2 and S_2 tidal components are in phase and when superimposed on the sediment distribution map. The current strength is categorised according to the settling threshold of various sediments.

Habitat characterisation

The geological interpretation in combination with video recordings of the seabed was used to interpret the first six themes following the marine sublittoral habitat classification system for the Northeastern North America Region scheme (Valentine et al., 2005). The classification results of each of four themes are shown in Figure 6.
Theme 4 (grain size analysis) corresponds to the geological map shown in Figure 3.

Theme I, topographical setting, depicts the physical setting of the seafloor (major, natural and anthropogenic seafloor features, slope, and depth) in relation to assumed photic depth. The seafloor within the survey area is considered to be relatively flat, with occasional and locally steep slopes along the morainic ridges. Anthropogenic structures observed within the area are limited to a single water pipeline crossing Longvafjorden. Decades ago coarse-grained till was dredged on the seafloor within Longvafjorden, and could be considered anthropogenic. The till is now largely covered by fine-grained, naturally deposited sediments. Video surveys show a high abundance of sea pens, which dominate the fine-grained sediments in Longvafjorden. These areas have not been interpreted as anthropogenic structures, as the seabed seems to have returned to its former natural state.

Within the study area, theme I consists of two classes, a shallow photic zone from the sea surface down to approximately 25 meters and a deep aphotic zone (Fig. 6A). This paper is deals mostly with the deep aphotic zone, which comprises the majority of the surveyed area. The minor areas of seabed within the photic zone are excluded from further analysis.

Theme II, seabed dynamics and currents, depicts classification of the seafloor in terms of stability or mobility of the sediments. The theme consists of three classes, mobile sediments, immobile sediments and, infrequently, mobile sediments. Immobile substrate dominates the survey area, while minor areas of bedforms caused by sediment transport were interpreted as mobile substrate (Fig. 6B). The observed sand waves could be relict or active features. The calculated critical shear stress for carbonate-rich sand in Haramsfjorden indicates that the strength of the current is too low for generating sediment transport (Fig. 5). However, repeated surveys over the past three years show evidence of a significant sediment transport where individual wave crests have been shifted up to 7 m from their former positions.

Sandy sediments in the shallow areas are included in the infrequently mobile sediments class, as a certain mobility of the sediment surface can be expected during peak storm events. Although no morphological features such as wave or current ripples were observed to provide evidence for sediment mobility, the sediment grain size (sand) allows us to make such an assumption.

Theme III, Seabed texture, hardness, and layering in the upper 5-10 cm, addresses seabed texture and shallow lithological layering. The theme here has been separated into three classes; hard sediments, coarse-grained sediments and fine-grained sediments (Fig. 6C). In this area till has a large component of coarse sediments, stones and pebbles, which have been incorporated with bedrock into hard sediments. Coarse-grained sediments include coarse and medium sandy sediments, while fine-grained sediments are sediments with a grain size up to fine-sand. Initially, this subdivision was based on the geological map of theme IV (Fig. 3), but it has proved possible to subdivide this area automatically using the normalised multibeam backscatter strength, (Fig. 6D) (Fosså et al., 2005). The technique used is a supervised automatic classification method, as backscatter values used for defining the subdivision of the seabed are based on calibration using samples and/or video observations.

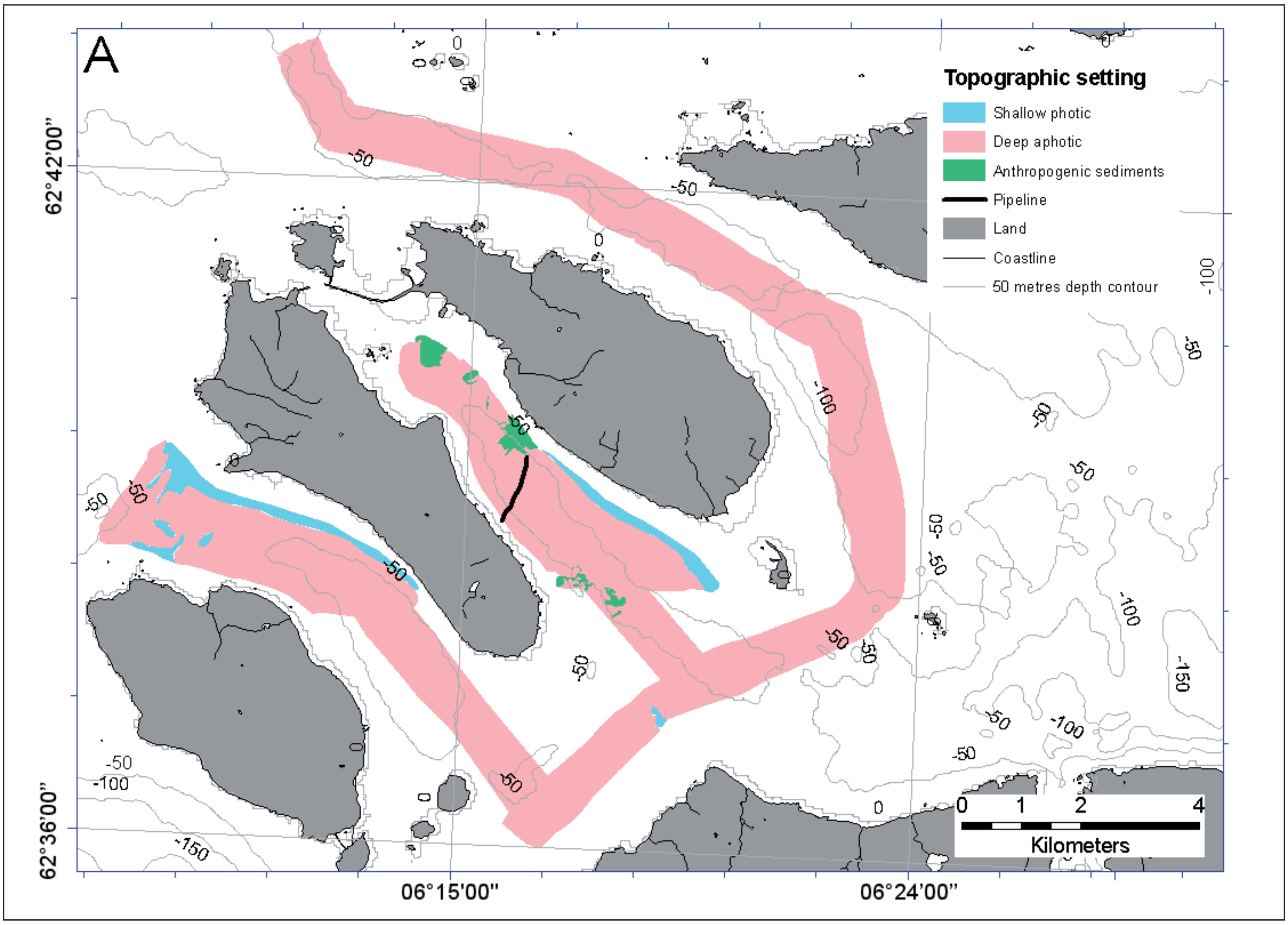
Theme IV, grain size analysis, is the geological map reflecting all interpreted details acquired through acoustic surveys, visual inspection and ground truthing (Fig. 3, Christensen et al. 2007).

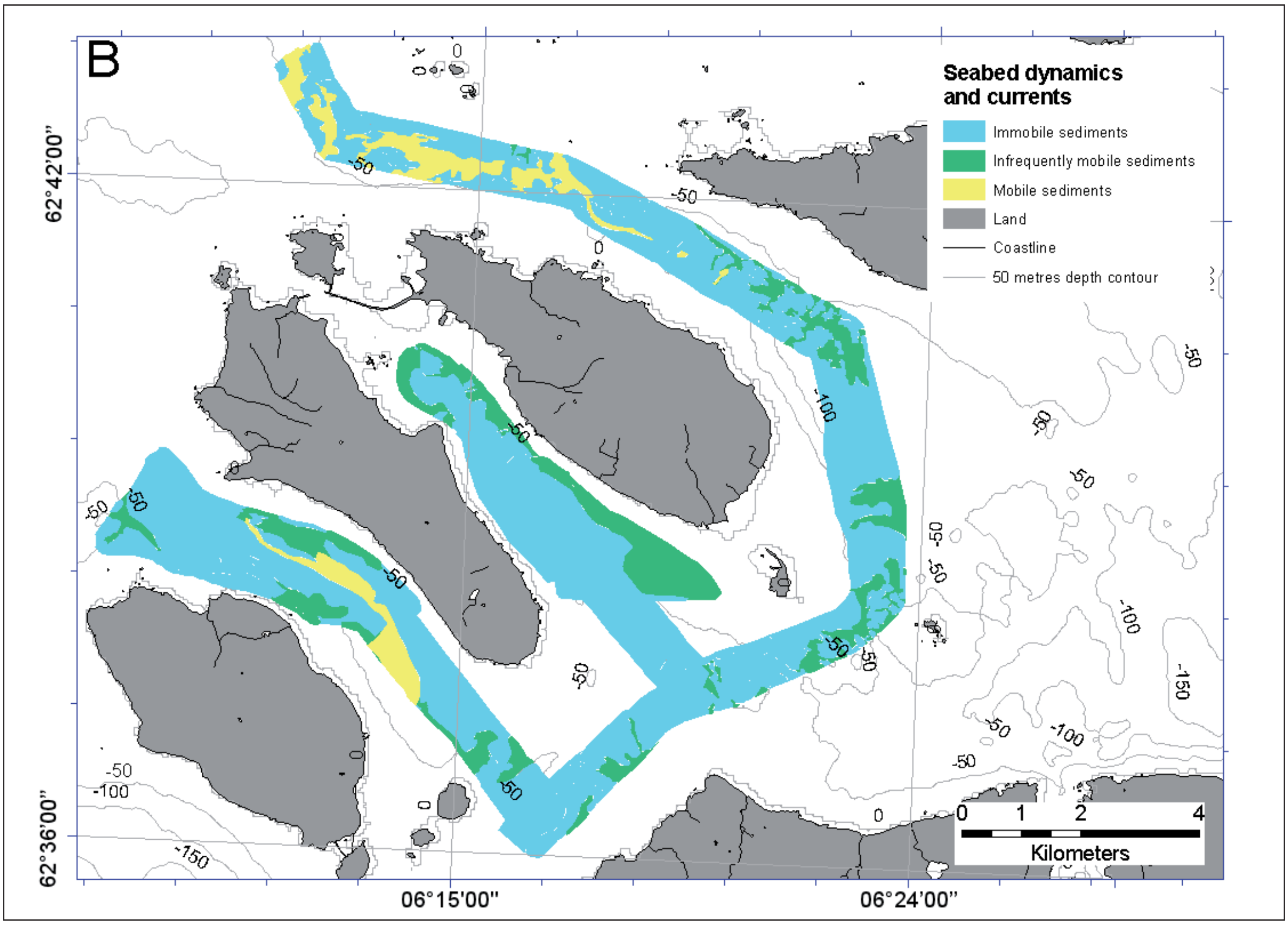
Theme V, seabed roughness, describes the seabed in terms of biological seabed roughness and geological seabed roughness. The former created by the presence of biological fauna and flora and the latter by geological and physical structures.

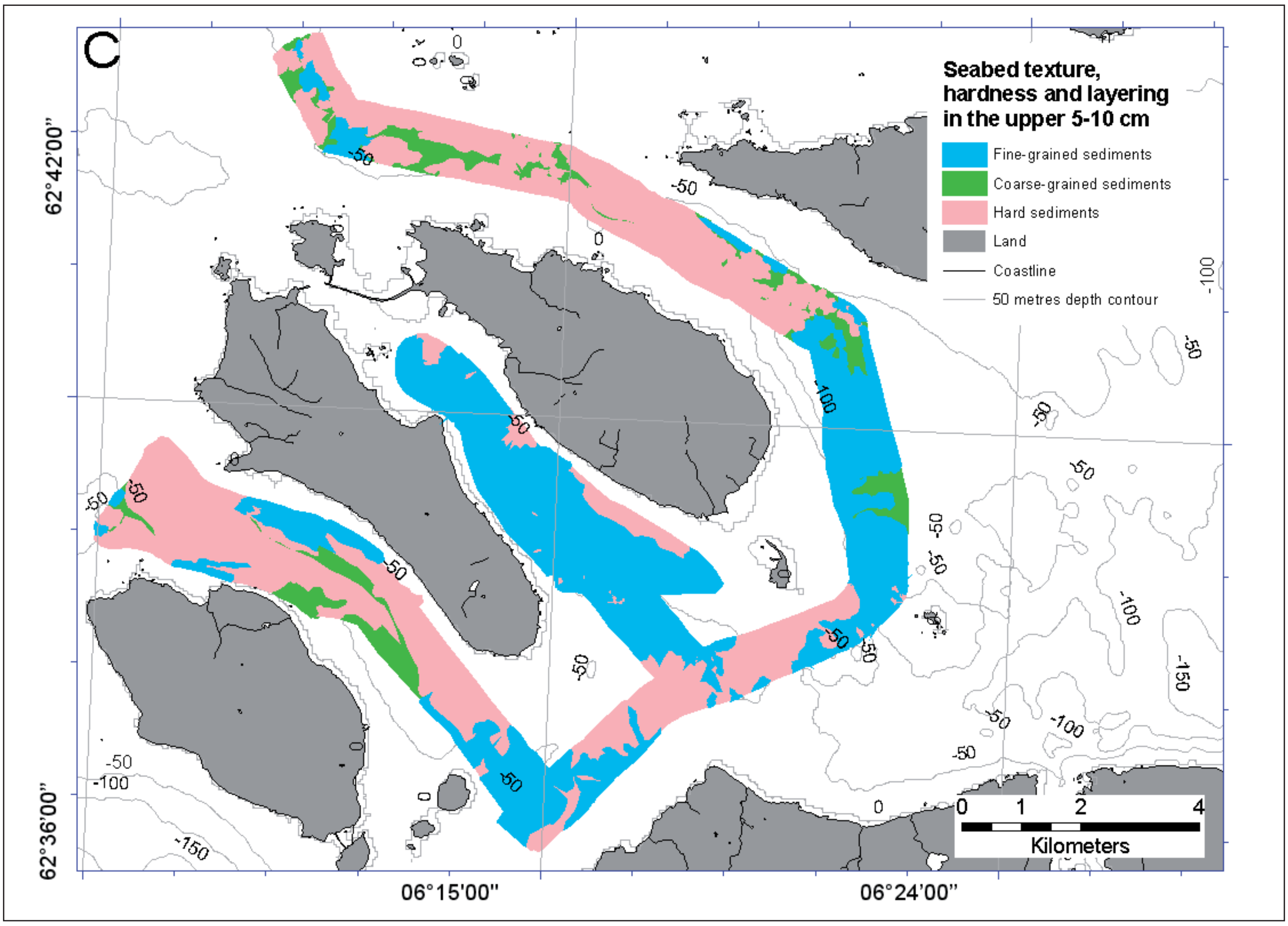
Biological seabed roughness is separated into four subclasses comprising sponges, sea pens, burrows and shells (Fig. 6E). A clear division is observed between distributions of sponges and sea pens. Sponges are observed within areas of hard sediments while sea pens are found in areas with soft sediments. Sponges, sea pens and bioturbation are not observed in areas with mobile substrata classified under theme II. These areas are dominated by shell material including large shell fragments as well as sand waves and ripples. Biogenic structures include evidence of active bioturbation, such as mounds, burrows and depressions generated by biological activity, which for the survey area are limited to areas of soft sediments, partly co-occurring with sea pens (Fig. 6E).

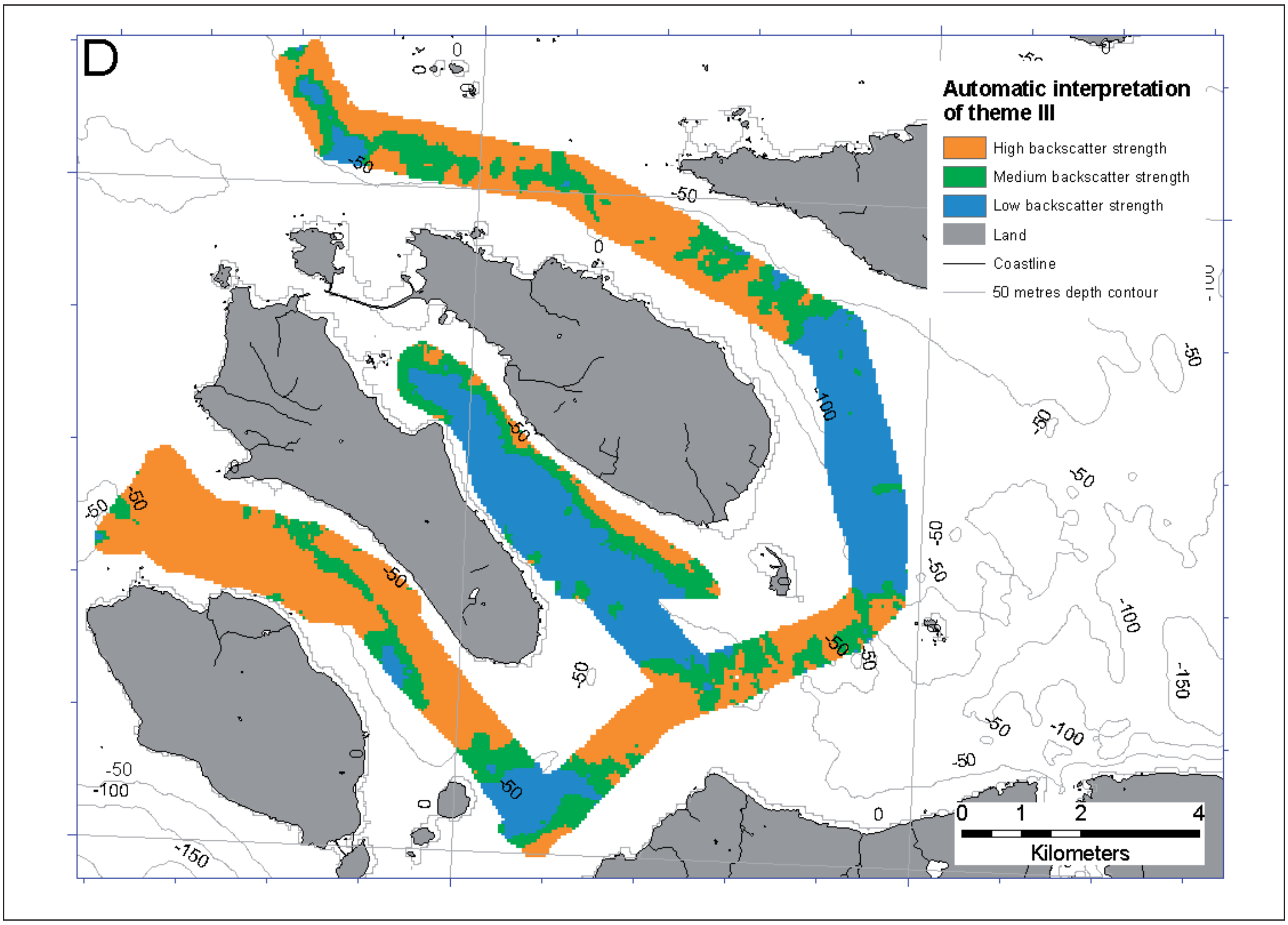
Geological roughness (Fig. 6F) is here defined as being larger than the roughness generated by grain size in coarse sand and gravel. Geological roughness is subdivided into three subclasses that include large, active sand waves, inactive bedforms and a sub-class comprising till, lag and other sediment types that generate a seabed roughness.

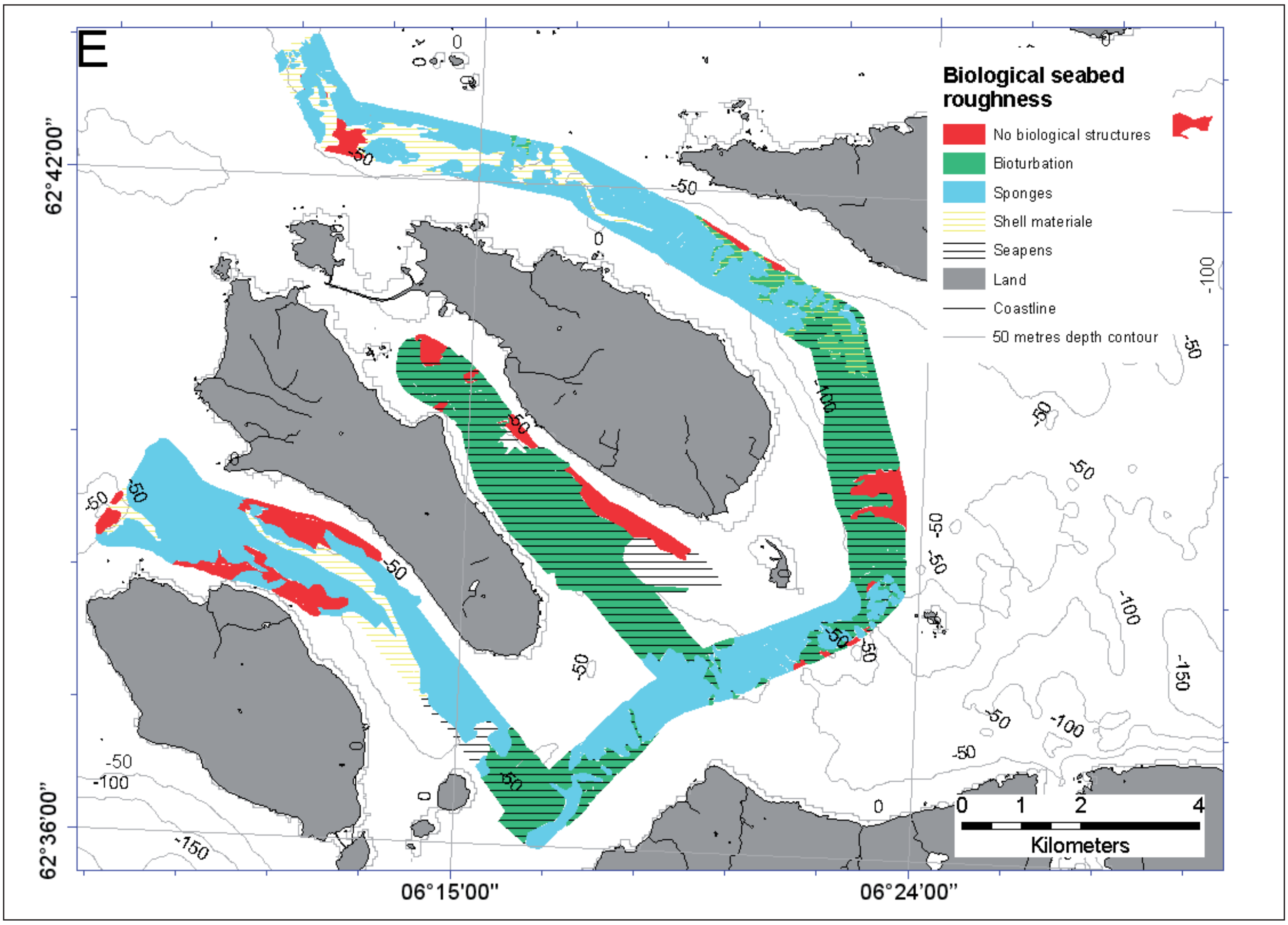
Carbonate-rich sand contains a large number of shells and shell fragments that could be classified as rough substrata. These sediments are however dominated by bedforms, either active or inactive and are therefore included as two physical structural subclasses. The low-density, coarse-grained shell fragments occurring in the


A
Topographic setting
Shallow photic
Deep aphotic
Anthropogenic sediments
Pipeline
Land
Coastline
50 metres depth contour
0
1
2
4
Kilometers
62°42'00''
62°36'00''
06°15'00''
06°24'00''


B
Seabed dynamics and currents
Immobile sediments
Infrequently mobile sediments
Mobile sediments
Land
Coastline
50 metres depth contour
0
1
2
4
Kilometers
62°42'00''
62°36'00''
06°15'00''
06°24'00''


C
Seabed texture, hardness and layering in the upper 5-10 cm
Fine-grained sediments
Coarse-grained sediments
Hard sediments
Land
Coastline
50 metres depth contour
62°42'00"
62°36'00"
06°15'00"
06°24'00"
0 1 2 4
Kilometers


D
Automatic interpretation of theme III
High backscatter strength
Medium backscatter strength
Low backscatter strength
Land
Coastline
50 metres depth contour
0 1 2 4
Kilometers


E
Biological seabed roughness
No biological structures
Bioturbation
Sponges
Shell materiale
Seapens
Land
Coastline
50 metres depth contour
0 1 2 4
Kilometers
62°42'00"
62°36'00"
06°15'00"
06°24'00"

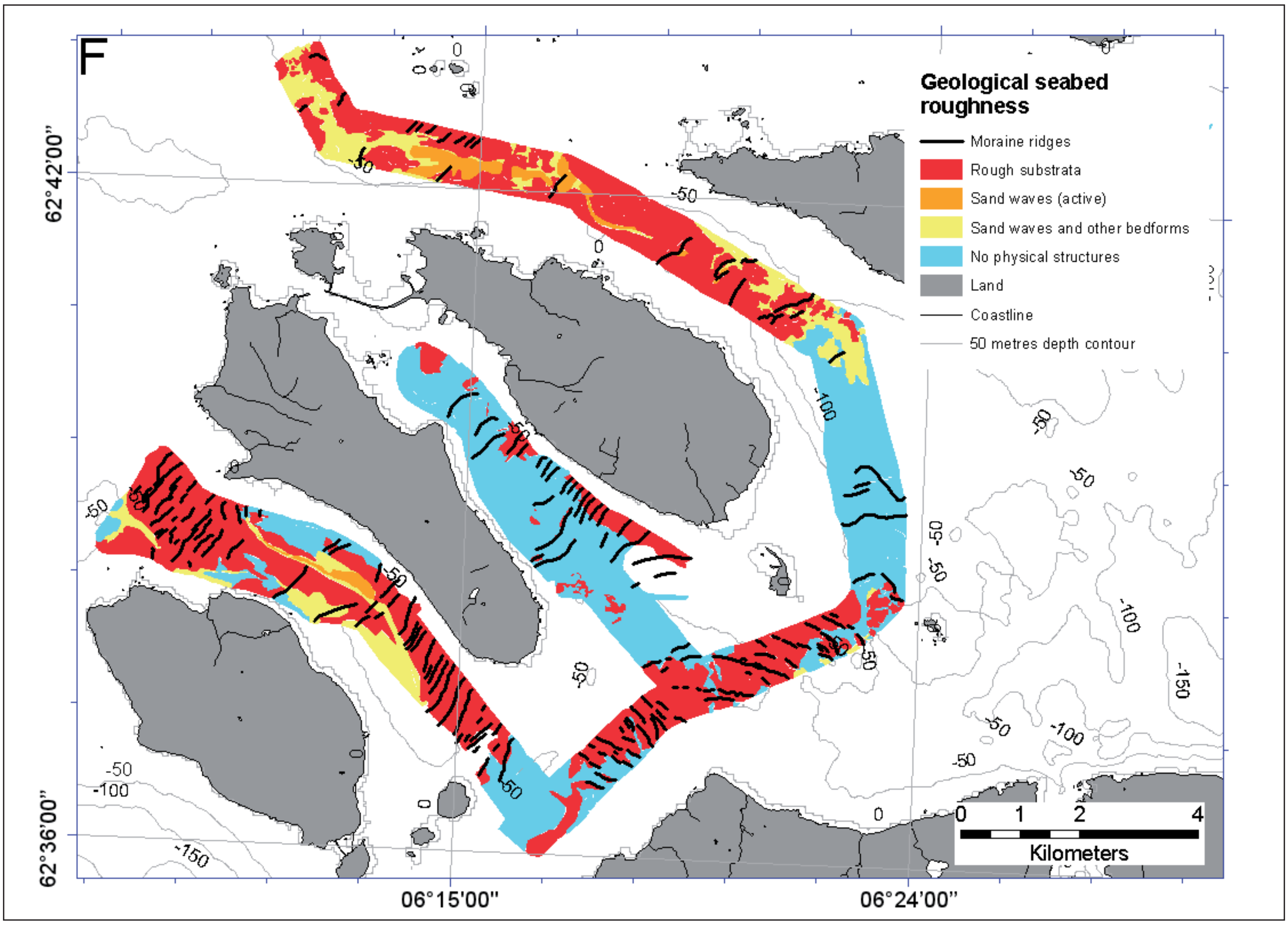

F
Geological seabed roughness
Moraine ridges
Rough substrata
Sand waves (active)
Sand waves and other bedforms
No physical structures
Land
Coastline
50 metres depth contour
0 1 2 4
Kilometers
62°42'00"
62°36'00"
06°15'00"
06°24'00"

Fig. 6. Interpreted habitat themes; 6A) Theme I, anthropogenic structures together with aphotic and photic areas. 6B) Theme II, areas of interpreted mobile and immobile sediments. infrequently mobile sediments are likely to have been transported, but seabed features or morphology do not suggest this. 6C) Theme III, three classes of seabed texture interpreted on the basis of the geological map. 6D) Version of theme III based on automatic interpretation of normalised multibeam backscatter strength. The classes of low, medium and high backscatter strength correspond to fine-, infrequently mobile- and coarse-grained sediments. The hard sediment class is till and bedrock, which has a roughness and hardness higher than the two other classes. 6E) Theme V, biological seabed roughness generated by fauna, flora and material of biological origin. Theme VI is not included in this figure, as the fauna and flora interpretation are based on single points or transects. 6F) Theme V, Geological seabed roughness, which is generated by physical structures and geologically generated seabed roughness interpreted using the geological information.

carbonate-rich sand is susceptible to significant sediment transport. The sediment mobility in these areas is a most important characteristic of a sandy habitat.

Theme VI, fauna and flora, addresses fauna and flora that characterize habitats. The biological information in the study area is extracted from observations along a number of video transects. These transects often cross sediment boundaries and allow biological boundaries to be distinguished within this habitat theme.

Biological classification

One of the goals of this paper is to investigate how fauna and flora, i.e. theme VI, relates to the other themes, especially the geological interpretation of theme IV. The analyses of video footage led to identification of forty-five species of fauna and flora, which were grouped into assemblages using cluster analysis (Fig. 7). Based on 80% within-group similarity in species composition we distinguished four typical benthic assemblages (referred to as A, B, C and D).

Assemblage A initially comprises twenty, mostly deep-water, megabenthos species associated with coarse sediments. Five of these species were excluded from further analyses because they were observed only at the *Lophelia pertusa* reef, which is outside the classification area. Unidentified brown algae are loosely associated with other species in the assemblage that are commonly present in deeper waters (Fig. 7). The records of brown algae in general and *Laminaria talloms* in particular in the aphotic zone are most likely observations of algal debris transported by gravity and currents into the deeper areas.

Assemblage B includes encrusting and fan-shaped (*Phakelia* sp.) species of sponges and a single species of sea anemone (*Utricina* sp.), all strongly associated with each other. This strong association between the species can be explained by the preference for a hard attachment substrate found on a seabed comprised of till or near the coral reef (Fig. 8).

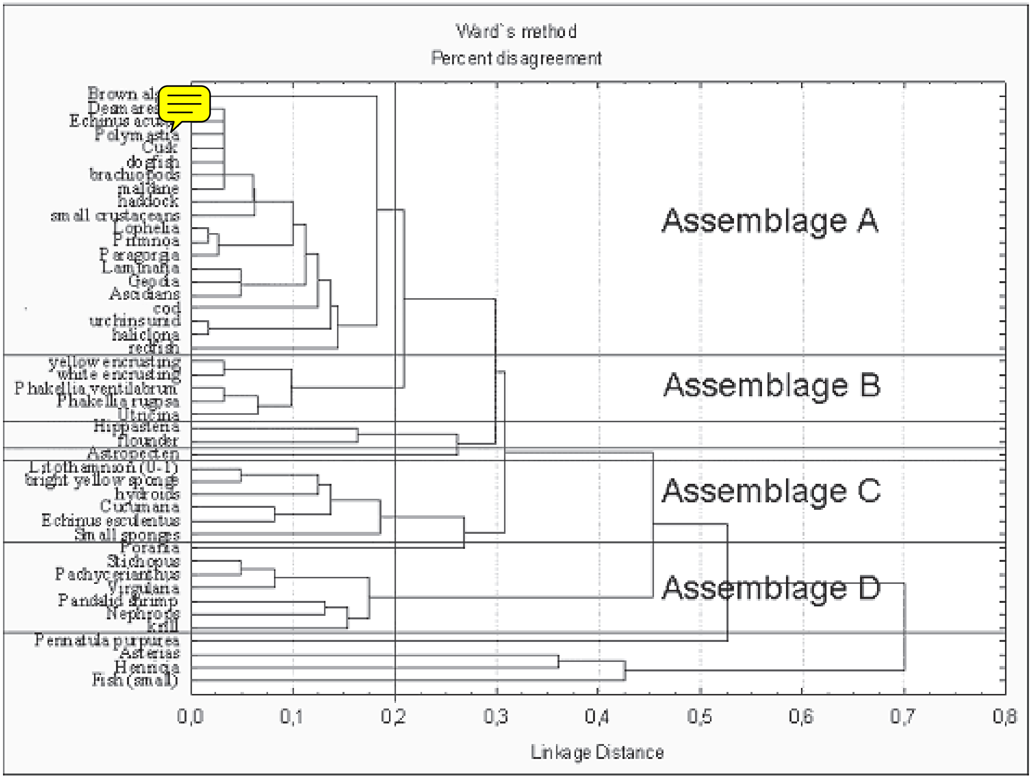


Fig. 7. Results of cluster analysis of all observed taxa performed on a Bray-Curtis dissimilarity matrix using Ward's method of linkage.

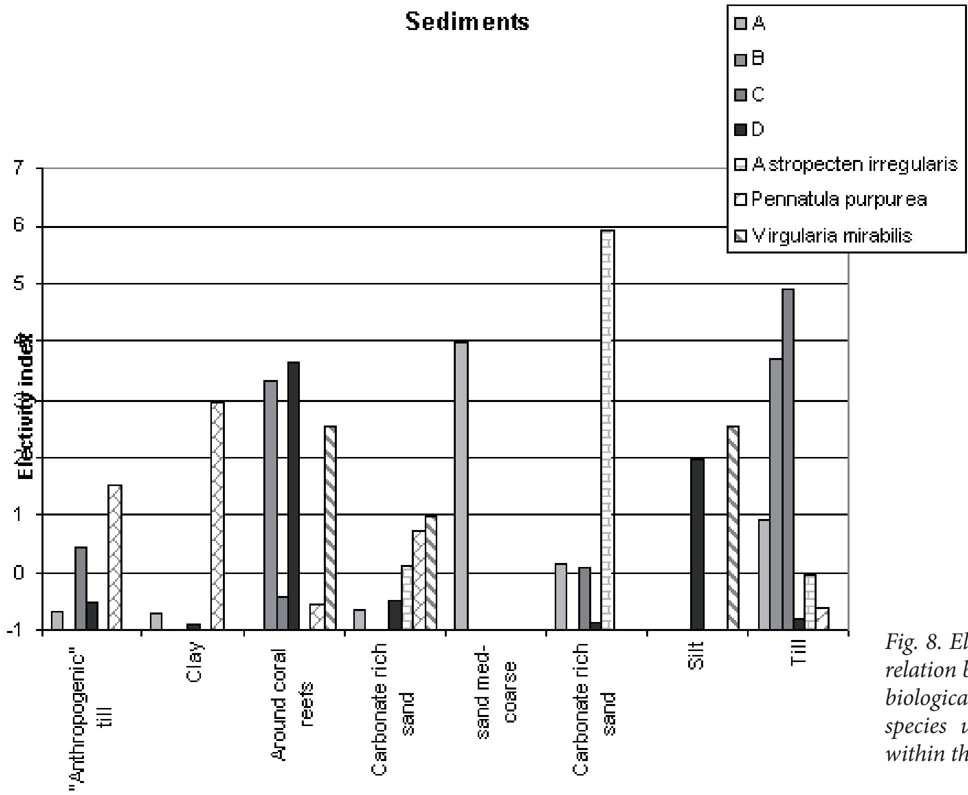


Fig. 8. Electivity index showing the correlation between sediment types and the biological assemblages and individual species used for habitat classification within the area.

Assemblage C is comprised of several species of sponges, sea cucumbers (*Cucumaria frondosa*) and sea urchins (*Echinus esculentus*), often co-occurring with encrusting calcareous algae. The assemblages have a large presence in the till habitat (Fig. 8).

Assemblage D is comprised of deep-water crustaceans, such as lobsters (*Nephrops norvegicus*) and shrimps (*Pandalus* sp.) as well as burrowing organisms such as one of the sea pen species (*Virgularia mirabilis*) and cerianthid anemones (*Pachycerianthus* sp.). All these species occur in areas around coral reefs, but are also very common in silty sediments (Fig. 8).

Sea pens (*Pennatula purpurea*), sea stars (*Asterias* sp. and *Henricia* sp.) and juvenile fish are vaguely associated, and stand apart from other groups of species at the 70% dissimilarity level. They were not distinguished as a separate assemblage.

Relationships between benthic fauna and physical factors

Several of the easily identifiable macrobenthic species exhibited strong relationships with the physical properties of seabed habitats. For example, *Astropecten irregularis*, the habitat preference of which is indicated by its common name "sand star" lives on clean sand or sandy mud where it can be found buried just below the seabed. Within the survey area, this species was mainly observed in carbonate-rich sand, where large-scale sediment movement is documented and characterizes this habitat. *Astropecten irregularis* is closely associated with another species of sea star, *Hippasteria phrygiana*. These two species are mainly observed in areas of bed forms (classified in theme II).

Two species of sea pens were observed in the survey area: the tall and thin *Virgularia mirabilis*, belonging to the assemblage D and the stouter and more fleshy sea pen, *Pennatula purpurea*,which is not included in any of the assemblages, due to very weak associations with other species (Fig. 7). *Pennatula purpurea* was observed in clay and in weaker currents than *Virgularia mirabilis*. These observations are similar to findings of Hughes (1998) made in Loch nam Madadh in Scotland.

Water depth

Using the electivity index we demonstrated variable distributions of the benthic assemblages through water depths. Because one of the objectives was to investigate the relationships between geology and benthos species, eliminating other physical factors (e.g. depth), it would have been helpful if no strong gradient in bathymetric distributions of benthic species existed, which was not the case (Fig. 9). The seabed sediments are also strongly correlated to water depth and may influence depth-related distribution of species. Fine-grained

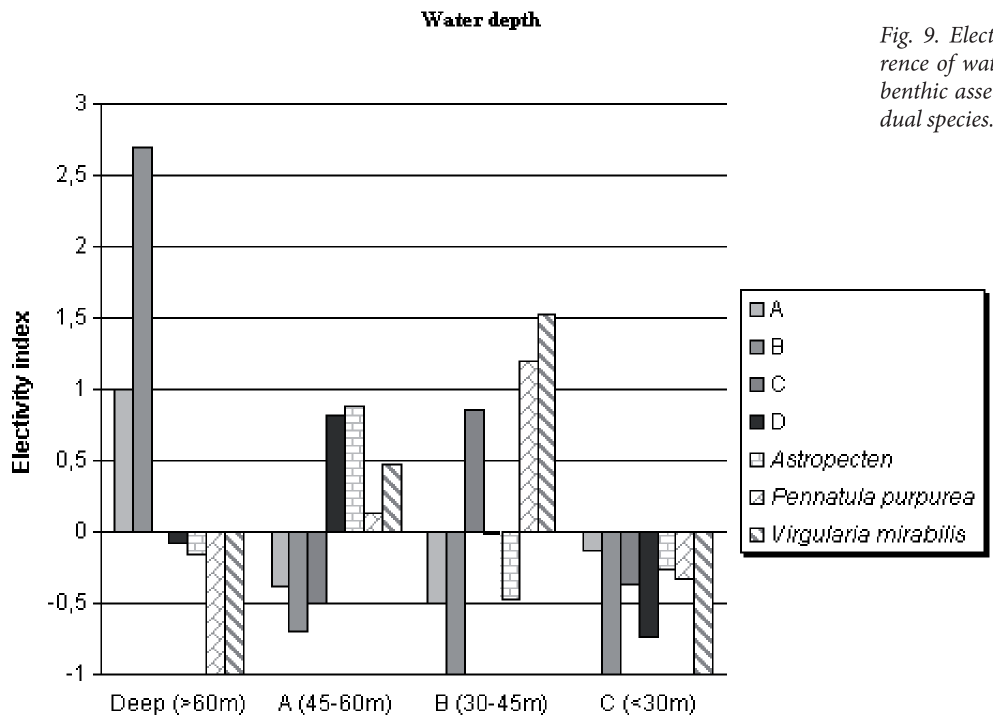


Fig. 9. Electivity index, showing preference of water depth ranges of the four benthic assemblages and several individual species.

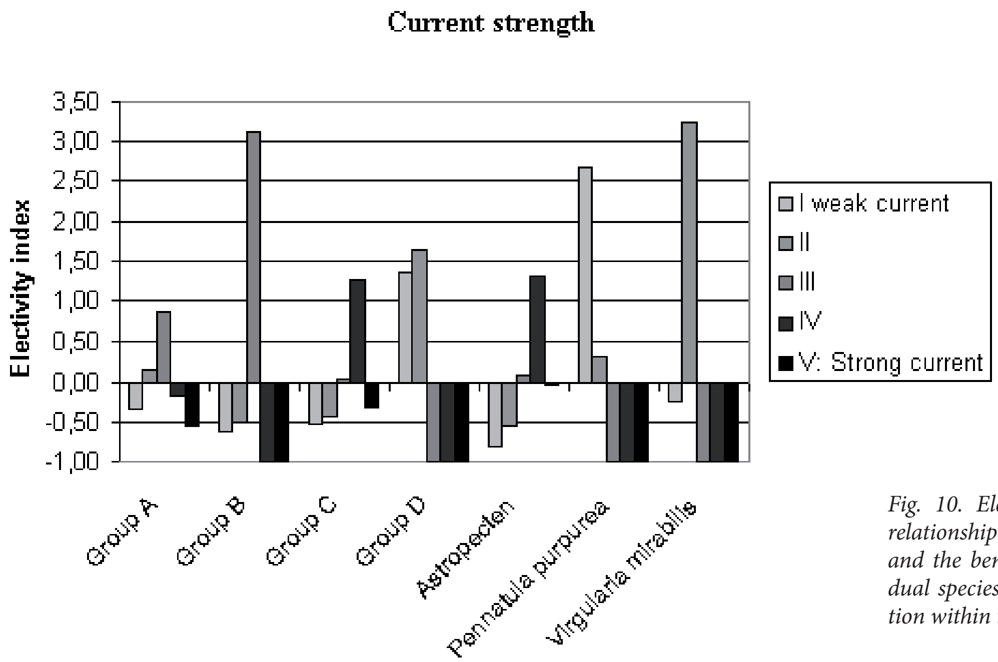


Fig. 10. Electivity index showing the relationship between current strengths and the benthic assemblages or individual species used for habitat classification within the study area

sediments, for example, such as clay and silt are mainly found in areas deeper than 45 metres. Fine sand appears in shallow areas between dredged and non-dredged till. Coarse sand and carbonate-rich sand appear mainly in the deeper water intervals. Till is the only sediment class observed throughout the entire depth spectrum.

Assemblages A and B are most common in deeper waters, with a general avoidance of shallow waters. Assemblage D as well as *Astropecten irregularis* mostly occur in the interval between 45 and 60 metres. Assemblage C, as well as *Pennatula purpurea* and *Virgularia mirabilis* prefer water depths between 30 and 45 metres (Fig. 9). None of the distinguished assemblages showed any association with shallow water (<30 meters).

Current strength

Analysis of the distribution of benthic species in relation to the current regime, using the electivity index, showed a weak correlation between the distribution of individual assemblages and current strength (Fig. 10). *Pennatula purpurea* prefers the weakest current, while the other sea pen, *Virgularia mirabilis*, occurs in the second weakest current regime. Assemblage D has an equal preference of both of these weak current regimes. Assemblages A and B typically occur in intermediate current strength regimes, and Assemblage C tends to prefer strong currents. *Astropecten irregularis* notably prefers the strongest currents, typical for coarse sand habitats.

Sediment type

For the eight sediment types analysed, the largest species richness was observed in till and in the area around the coral reefs (Fig. 8). Because acoustic data were limited in the area around these reefs, further analysis of the benthos-habitat relationship there was not carried out. Till has the largest textural diversity, creating heterogeneous habitats which are therefore expected to support the most diverse flora and fauna. Most of the observed species displayed a strong preference for one or two sediment types, tending to avoid other sediment types (Fig. 8). The two species of sea pens preferred fine-grained sediments, with *Pennatula purpurea* being mainly observed in clay and *Virgularia mirabilis* in silt and fine sand. Assemblages B and C have a strong preference for till. Assemblage A also occurs in areas of till, but has a larger preference for medium to coarse sand. Assemblage D occurs mostly in areas of silt. *Astropecten irregularis* prefers carbonate-rich sand, and observations indicate that this preference is most likely determined by the mobility of sediments. Numerous *Pennatula purpurea* were observed in between till outcrops in the areas of dredged till.

Discussion

Acoustic and geological data acquired in the area provided the basis for a detailed habitat classification. Biological observations were made from video recordings and were used to describe distribution of benthic life in relation to sediment type, tidal current strength, and water depth. Ideally, these video recordings should be complemented with still photographs in chosen areas to obtain better taxonomical resolution, and with grab samples for analyses of infauna.

Theme I is deemed essential for incorporating areas of anthropogenic structures and for separating the photic and aphotic zones. A pipeline crossing Longvafjorden was the only anthropogenic structure in this theme. At present, the classification scheme subdivides the water depth into two subclasses: photic and aphotic. While this classification relates to primary production in the water column and the on seabed, the subdivision is rather arbitrary and approximate. The depth of the photic zone may vary seasonally and geographically, therefore it can be questioned whether the boundaries of this zone on a 1:50 000 scale have any special meaning. It can also be affected by the interaction of seabed sediment with the current regime in the area through resuspension and transport of fine-grained sediment, further complicating the picture. We suggest that other, water depth-related subclasses could be added to this theme. For example, one of the boundaries could be located at the maximum wave base - water depth where the seafloor is not affected by water currents generated during peak storm events.

Theme II contains several information layers, which address the relationship between seabed sediment type and currents and the driving force behind the seabed dynamics. There is a good correlation between tidal current strength and the distribution of seabed sediments in the study area, which may make it possible to predict the occurrence of the finest possible grain size in the area from a tidal current model. This assessment can be done prior to any survey for making general assumptions of the seabed sediment distribution. However, in two areas we found sediments that were coarser than expected from the modelled current strengths (Fig. 5). Winds from the southwest dominate in Longvafjorden, generating waves that can rework sediments along the north shore of the fjord, the fine-grained sediments having therefore been washed out into the deeper parts of the fjord. The second encircled area on Figure 5 is located in Leia and is within a sound oriented northeast - southwest. Each peak storm event is likely to force water through this channel. The shallow water depth and the narrowness of the sound here could increase the current velocity, which could in turn transport fine-grained sediments. These resuspended sediments are likely deposited farther north, where the sound widens and the water depth increases, thus leading to reduced current strength. The increased water depth here is also expected to provide some protection for the currents. Thus, the peak storm events could clear the Leia site from fine-grained sediment, which is not replaced due to the pattern of tidal water circulation.

Biological observations confirmed that the active sediment transport has a large effect on the distribution of benthic fauna. Depending on whether the sediment transport is generated by occasional peak events or by continuous tidal currents, the effect on the benthos might be different. It is difficult to judge the relative effects of continuous current versus peak storm events on the benthic assemblages. However, strong tidal currents constantly transport suspended sediments in the benthic boundary layer, thus reducing the quality of food for suspension feeders and possibly limiting recruitment and survival of benthic larvae. On the other hand, the continuous current could provide oxygen and nutrients for the species that can tolerate the constant sediment movement. Peak storm events are likely to cause strong local effects for the whole community by physically removing organisms from the seabed or burying them in sediment.

The composition of observed fauna in areas of sand waves suggests a continuous sediment transport, but comparison of the modelled current strengths and the critical thresholds of motion for observed sediments in these areas do not support this. This could be explained by errors in the tidal current model, or errors in estimation of the sediment properties used for calculating the critical shear stress. More likely, the sand waves could have been generated by peak storm events, which are often the driving force behind the sediment transport.

The tidal current model used in this study (Moe et al., 2003) is based on a 500-metre bathymetry grid, which is significantly coarser than our sediment interpretation. A model based on a higher resolution bathymetric grid could predict a locally stronger current. Incorporating the spring tidal strength in the model, rather than the mean current tidal strength, could also increase the predicted tidal current strength. It is still worrisome that in some areas the modelled current strength appears significantly weaker than the strength needed to generate sediment transport. However the tidal model correlates well with sediment types elsewhere in the study area and has been calibrated by using twenty-eight stations. The uncertainties in the tidal model are not likely to introduce as large an error as the difference between the model current strength and the calculated sediment motion threshold.

The sediment properties were estimated from grab samples, where it is likely that some of the finer particles have been washed out. The carbonate content and density of the sampled sediments used for the sediment motion threshold calculations are possibly underestimated. The largest error could be introduced by disregarding the shape of sediment particles, which in this case are large, flattened, angular shell fragments (up to tens of millimetres in diameter). This shape is easier to transport than typical hemipelagic grains and therefore the sediment motion threshold estimate was too high. The calculation is based on the settling threshold and not the force required for re-suspension. Re-suspension in fine-grained sediment requires a significantly higher force, especially for clay particles.

Sediment movement caused by peak events, such as storms, is likely to be unidirectional. Bedforms in the sandy areas are also unidirectional, as expected if these were generated by storms. However, comparing the areas of sand waves shows a bi-directional sediment transport (Fig. 4). The direction of sand movement here is downslope. In Nogvafjorden this causes a nearly 180° local difference in transport direction of adjacent sand wave fields. Symmetrical sand waves dominate areas of the flat seafloor which are likely generated by a bimodal directional force, such as a tidal current. The unidirectional movement on the sloping seafloor is likely caused by gravity, where the tidal current can facilitate downslope movement. The strength of the tidal current is, however, possibly too weak to cause any upslope sediment transport.

The seabed texture, hardness and shallow subsurface sediment stratification influence remote sensing data and consequently interpretation of seabed geology. Full coverage surveys are essential for habitat classification in themes III and IV, whereas ground truthing is critical for theme IV. Theme III can be automatically interpreted using remote sensing data, with results similar to those from manual interpretation. As a matter of fact, such automatic classification can be performed during the acoustic survey in order to design a ground truthing program (Christensen et al., in 2007). However, an automatic acoustic classification reflects the overall seafloor texture, and does not distinguish the effects of sediment type or fauna and flora. Both themes represent geological interpretation, which is reflected in the terminology used. We believe that the geological information, both from remote sensing and ground truthing is best illustrated in one namely, theme, theme IV. To maintain a continuous workflow during data acquisition and interpretation, theme III should be based purely on automatic acoustic interpretation generated prior to ground truthing, while theme IV represents the next phase, which is augmented by ground truthing and regional information.

Theme IV should incorporate sub-bottom information (stratigraphy on millimetre or even centimetre scale). Shallow seismic data from sub-bottom profilers etc are not ideal for resolving the shallowest part (mm or cm scale) of seabed sediments due to acoustic "ringing" in the seabed pulse. Stratigraphic layering in the very shallow part of the seabed sediment can affect the overall acoustic scatter data, depending on sonar frequency and grazing angle. There is also the possibility of resolving layers using multibeam backscatter data (Talukdar et al., 1995). Thin layers are visible in unprocessed backscatter data, where the stratigraphic layers record near nadir data but not the backscatter data at large grazing angles. Such effects are difficult to remove and are not likely to be removed using standard backscatter processing. This is therefore likely to influence the automatic backscatter classification. The difference in the backscatter strength is relatively easy to detect by manual inspection of backscatter strength versus grazing angles. An effect should also be notable when comparing the automatic interpretation with the geological interpretation. Both manual inspection of the backscatter strength and comparing the automatic interpretation and the geological interpretation did not reveal any such effect within this area.

Fine and soft sediments are expected to have higher abundances of infauna, while hard and coarse sediments are expected to have more epifauna. The presence of bioturbation and burrowing organisms, such as *Cerianthid* anemones and sea pens in fine-grained sediments, and the presence of diverse benthic epifauna on coarse sediments confirmed these expectations. The greater structural complexity and heterogeneity of tills provide higher observed biodiversity than other sediment types.

Sea stars, with the exception of *Astropecten irregularis*, displayed a weaker relationship with physical factors than any other species or assemblage. *Astropecten irregularis* was the only echinoderm species observed in the mobile sediments, which could be a result of either competitive displacement of this species from other areas or unique adaptation to this habitat type. The latter seems to be more likely as *Astropecten irregularis* normally dwells in clean sand, and is often buried under a few centimeters of sand (Picton and Morrow, 2005). Burying by sediment movement might allow *Astropecten irregularis* to avoid predaciousness, and probably does not have such an adverse effect on it as it might have on other species (Sabatini, 2008 and Christensen, 1970). The strong correlation between the occurrence of this species and mobile substrata suggests that occurrence of *Astropecten irregularis* can be used as a proxy for defining mobile sediments.

Each identified biological assemblage had a distinct preference for a specific water depth range, current strength and sediment type. For assemblage D, sediment type seem to be the controlling physical factor, as the group has a strong preference for silt and a strong avoidance for other sediment types. Most groups and species exhibit a strong preference or avoidance for different sediment types. This is however not found in fine sand, for groups A and C in carbonate-rich sand or for *Pennatula purpurea* in till. Patches of fine sand are underrepresented in the study area, which can explain the lack of its correlation with different species. *Pennatula purpurea* has a strong preference for fine-grained sediments and weak currents. This environment can be expected to host sea pens, and can dominate locally in areas of till. However most of the till in the study area is exposed to stronger currents and consists of coarser sediments, which are unsuitable for sea pens. We believe that the observed depth distribution of sea pens is controlled by the presence of fine-grained sediments. *Pennatula purpurea* prefers weaker currents and finer sediment than *Virgularia mirabilis*. Epifauna, such as sponges (assemblages A, B and C) are abundant in coarser-grained sediments exposed to stronger currents.

A correlation between sediments and current strength is observed, but it is unclear whether s it is the current strength or the sediments that control the presence of the two species of sea pens. There is a weak indication that the current is the determining factor here, due to a strong and unique preference for a given current strength interval. There is also a strong preference, but uniquely so, for association with a single sediment type. *Pennatula purpurea* prefers clay and very weak current strength, while *Virgularia mirabilis* is found in slightly stronger currents and in silt to fine-grained sand. This can possibly be used to subdivide the fine-grained and weak current habitat. The presence of sea pens in the anthropogenic sediments was used as an indication of the return of these areas to a natural state.

Using sponges for further division seems more difficult. Larger sponges such as *Phakellia rugosa, Phakellia ventilabrum, Polymastia sp*., and *Geodia sp*., seemed to avoid areas near active sediment transport, but have a strong preference for areas exposed to medium to stronger current strength. Smaller sponges (Group C) seem to prefer higher current strength than larger sponges (Groups A and B). This contradicts some of the visual observations made. The preference shown by sponges can possibly be linked to water depth.

Comments and recommendations

- The tidal current strength has shown strong correlation with the biological activity and can be used to predict the sediment properties. It is recommended that this type of analysis be performed prior to survey activities so as to be useful for planning of habitat mapping.
- It was hoped that by incorporating modelled current strength an estimate of the driving force behind sediment movements could be established. This failed as the sediment model did not incorporate seabed slope and information about the shape of grains. The sediment model should be revised to take these factors into account. The failure can also be related to the coarse scale of the tidal model, the mean spring tide being used instead of the spring tide, and also to inadequate information about sediment properties.
- Sediments and current strength both affect the biology, while depth is less of a factor as long as the depth interval investigated is within the aphotic zone. It is recommended that the classification method should also incorporate the photic zone
- Tidal current-driven sediment movement (i.e. constant sediment transport) seems to create a habitat that favours some species. Constant water circulation will provide nutrient and oxygen, which will benefit the species that can survive constant sediment movement. Sediment movement caused by peak events might have less effect, depending on how often these peak events occur.
- Themes III and IV are at present two different levels of seabed mapping, a geological one and an acoustic one. Changing theme III to an automatic interpretation based on remotely sensed data would streamline the habitat scheme, as theme III can then be performed offshore. It can also be used to help design the ground truthing program. Theme IV will then incorporate the results of the ground truthing as well as other information. This interpretation is time-consuming and will most likely be performed onshore after the acquisition activity.

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