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SUSHIMAP

Survey strategy and methodology for marine habitat mapping

Doctoral thesis
for the degree of doktor ingeniør

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Abstract

Bathymetrical mapping performed using multibeam sonar systems is widely used in marine science and for habitat mapping. The incoherent part of the multibeam data, the backscatter data, is less commonly used. Automatic classification of processed backscatter has a correlates well with three sediment classes, defined as fine- (clay-silt), medium- (sand) and coarse- (gravel–till) grained substrates. This relation is used directly as a theme in a modified habitat classification scheme, while a more detailed substrate classification is incorporated as another theme. This theme requires a manual interpretation and comprehensive knowledge of the substrate. This can partly be obtained by a newly developed technique using the backscatter strength plotted against the grazing angle. These plots make it possible to determine the critical angle and thereby calculate the compressional acoustic speed in seabed sediments. Marching a theoretical modeled backscatter curve to the measured backscatter strength at lower grazing angles provides estimates of four additional geoacoustic parameters.

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Content

1.0 Intro

The ocean covers more than 70% of the Earth's surface. It is not only the source of inspiration and reflection, but it is a major food supplier, a vital transportation link that has been used extensively since the early history of mankind. Recreation along the shorelines is for many the only direct contact with the ocean. However the seabed is the source of an important part of the consumed energy. It also supplies minerals and material to support a large industrial sector in the world. Despite its vast and “endless” extent, the pressure on the ocean’s shorelines for recreation and the rapid development of fish extracting and energy consumption can bring the natural ecosystem out of balance.

This can be observed along the most popular recreation sites, which typically are located near structures of great natural beauty, such as coral reefs. One example is in Hurgarda, Egypt, where many near-shore coral reefs are damaged by diving and construction activity. A valuable lesson was learned by the Atlantic Canadian fishing industry during the early 1990’s when many over-exploited fish stocks crashed and 40 to 50 thousand people were suddenly without work (Manson *et al*., 2000). This collapse was one of the factors that made industry and scientists realise that even the large ocean have to be sensibly managed so that future generations can also benefit socially and economically. The first step in the sustainable management of the ocean is the production of detailed maps of seabed habitats. These habitat maps comprise the bio-diversity as well as the sediment types that exist on the seabed. The economic reward of habitat mapping has already been demonstrated in Canada, where a similar quota of scallops was caught prior and post habitat mapping at Browns Bank. The quota was caught by trawling an approximately a quarter of the distance compare to the year prior to the habitat mapping. Not only were time and fuel consumption reduced significantly, but damage on the fishing gear was also reduced as obstacles and hazards were marked on the habitat maps (Pickrill *et al.*, 2002). Management of the ocean must be based on knowledge, which should be reflected in the habitat maps and habitat classification schemes.

The Sushimap (Survey and Methodology for Marine Habitat Mapping) project is a national project, funded by the Research Council of Norway. The partners in the project were

Havforskningsintituttet (Institute of Marine Research), Geological Survey of Norway (NGU), The Norwegian University of Science and Technology (NTNU) and Statoil. The project is a pilot project to investigate how habitat mapping of large areas in Norwegian waters can be best performed economically as well as scientifically.

Habitat mapping is a multidisciplinary task where various science disciplines, user-knowledge from fishermen, oil and gas exploration etc. as well as local knowledge has to be combined. Sushimap aims to integrate the knowledge from all these contributors in a test area, to see how this will benefit habitat mapping. This knowledge should be combined to define a protocol for habitat mapping that aids ocean management. Management will be provided with tools for habitat mapping designed on a habitat classification scheme.

The aim for this thesis is not to create essential habitat maps, as this requires continuous observation of fauna and flora. The purpose is to develop a survey procedure that can be utilised for rapid, reliable and cost-efficient substrate mapping and directly link this to a habitat classification scheme. The habitat classification must be chosen or designed to cope with the physical environment in Norwegian waters. Acquisition procedures, post processing and interpretation techniques must be developed to link the acquisition, processing, and interpretation to this habitat classification scheme.

1.1 Organisation of doctoral thesis

The introduction is a summary of five articles together with results that are not published and ideas that cannot yet be classified as firm results. The five articles in chapter 5 are the essential part of the thesis work.

Chapter 1 describes the focus of the work and gives a short summary of the terminology used. Chapter 2 is a description of equipment and interpretation methods used within this work. Chapter 3 is a summary of the work in each article and some of the results. Initial results of large-scale habitat interpretation of Norwegian waters are shown. This is followed by unpublished results showing that interferometric sonar provides as good if not better data for mapping substrates. This is followed by an example of large-scale habitat mapping, covering the entire Norwegian Exclusive Economic Zone (EEZ) and a short introduction of the chosen habitat classification scheme. Results of feature extraction, which have been used in various sub-projects but not been published, are also summarized in this chapter. Finally this chapter describes preliminary results of substrate classification using single channel seismic data and video assisted grab before finalising the results with a strategy section.

Chapter 4 contains a discussion of habitat classification schemes and utilisation of equipment. Automatic classification techniques tested during the project are then discussed as well as the resolution of the chosen methods. Methods for determining the nature of the substrate are discussed as well as the possibilities for resolving benthic life forms.

The main conclusion is listed in chapter 6, with a short summary of work not yet performed in chapter 7.

1.2 Definitions and terminologies

The term “habitat” has been used throughout this thesis and within the articles. Dictionaries define habitat slightly differently, but a habitat is generally characterised as a place where plants or animals grow or live and their typical place of residence. In this work habitat is restricted to the seabed substrate, if nothing else is mentioned. In Article 1 the term “geological facies” replaces habitat or substrate due to the review process of the Geological Association of Canada. Table 1 summarizes some of the terms associated to habitats used in this work.

Term	Explanation
Seabed habitat	The place where a specific fauna or flora lives, grows or its preferred residence on the seabed
Habitat classification scheme	The framework that is used for organising the results of various interpretation stages
Vulnerable habitat	A habitat that is easy to alter or destroy by changing the environment or by physical impact
Essential habitat	The ability to truly identify essential habitats for the sustainability of fish stock or other species demands that higher-level information must be acquired. This information must include rate of growth, reproduction and survival in relation to habitat variables of the fish stock (Noji *et al.,* 2005).
Mega-habitat	Large seabed features with dimensions from one km to tens of km (Greene *et al.,* 1999).
Meso-habitat	Seabed features with dimensions from tens of m to a km (Greene *et al.,* 1999).

Table 1, explaining the different habitats associations used in this work

In this work two scales of habitats are used: large- and medium-scale. Large-scale is defined as features that have dimensions from kilometres to tens of kilometres, similar to the definition of Mega habitats, which are defined by Greene *et al.,* (1999).

This work addresses the strategy of mapping medium-scale using multibeam data. Medium scale habitats are therefore defined according to the resolution of the acoustic data. This has been linked to the IHO S-44 – Minimum Standards for Hydrographical Surveys, as the capacity of most commercial equipment fulfils one or another criterion of the IHO S-44. This standard has been used to define the resolution of medium scale habitat according to water depth, as shown in table 2.

Water depth	IHO S-44 order	Detection Capabilities
< 35 m	Special Order	Cubic features >1.0 m detectable
35 - 200 m	Order 1	Cubic features >2.0 m in depths down to 40 m detectable or 10% of depth
> 200 m	Order 3	N/A

Table 2, separating the resolution of medium scale habitat into three according to water depth using IHO S-44 standard (International Hydrographic Bureau, 1998).

A water depth of 35 metres was chosen to separate Special Order from Order 1. This depth has been chosen, as the EM1002 multibeam echo sounder is capable of fulfilling Special Order to this depth (Haga *et al.,* 2003). A grid size of 1 metre was used in the shallowest area, while a grid size of 3 metres was used between 35 metres and 200 metres. In deeper areas the grid size was enlarged. Occasionally a smaller grid size was used, where an object or an area of special interest occurred. The water depth of 35 metres is generally used to subdivide shallow and deep water within this work.

1.3 Definition of the problem

The Sushimap project was designed to develop a rapid, reliable and cost-efficient procedure for the mapping and monitoring of seabed habitats. The institute of marine research in Bergen is addressing cost-benefit analysis of sampling in- and epi-benthos. This has shown that a high number of samples are required to provide a detailed biological picture, but for mapping the most common and largest species the number of samples can be reduced (Jørgensen *et al,* 2005). This Ph.D. project investigates the ability to integrate coarse regional bathymetry data as well as acquired acoustic bathymetry and backscatter data. This is integrated and utilised together with ground truthing data for habitat mapping. The Ph.D. work focuses on mapping seabed geology, which is believed to be one of the controlling factors of fauna and flora distribution. The Sushimap project tests and develops methods for using equipment and processing techniques, before suggesting a procedure for seabed habitat mapping of the Norwegian continental shelf, which is the second goal of the Ph.D. work.

The Ph.D. work shall also investigate survey strategy together with methods and procedures for extracting further information from acoustic data, acquired by multibeam systems. This part of the Sushimap project concerns geological substrate mapping as well as acoustic determination of the seabed sediment properties.

Habitat classification shall be tested and modified to form a template for further habitat mapping projects. The template shall cover the entire range of habitat mapping from acquisition to classification. New and more efficient technologies shall therefore be considered in all aspects of the classification, especially for mapping the coastal zone.

This Ph.D. work has evaluated the following subjects and improved methods where this is required and possible:

- Find an approach where multibeam backscatter can be used for habitat mapping in terms of:
  - Post-processing of multibeam backscatter data
  - Interpretation of multibeam backscatter data
  - Determine substrata from multibeam backscatter data
  - Automatic mapping using multibeam backscatter data
- Develop and test methods for mapping coral reefs efficiently and investigate the possibility of automatic mapping of the coral reefs
- Test habitat classification schemes to find an appropriate scheme that can be used systematically for larger areas, such as the mid-Norwegian continental shelf

Develop a survey procedure that is efficient, reliable and linked to a habitat classification scheme.

1.4 Focus of doctoral thesis

This doctoral study was commenced 15th November 2001 as a part of the Sushimap project, which shall propose procedures for cost efficient habitat mapping using acoustic data. The rugged seafloor in many Norwegian fjords and in larger parts of the coastal area is a potential hazard for sub-towed equipment. These areas as well as areas of prominent seabed features, such as coral reefs, are associated with the richest and most diverse habitats. Many of these habitats are vulnerable and a collision with sub-towed equipment could not only damage the equipment but also inflict significant damage on the habitat. Sub-towed equipment has therefore been disregarded and only hull-mounted equipment has been considered.

Various types of multibeam systems have been developed, making it possible to utilise multibeam in shallow as well as in very deep waters. Development of processing and interpretation routines has, in this thesis, been limited to Multibeam data, with the exception of Article 3, where results of other surveying methods such as side scan sonar have been compared to multibeam surveys. Interferometric sonar is shortly introduced in the introduction, as the use of this type of equipment in very shallow waters can be more efficient than multibeam systems.

A test site for acoustic and habitat mapping in a typical Norwegian coastal setting will be developed and is introduced in Article 1. Ground truthing techniques together with geologic and automatic multibeam interpretation techniques are also described in this article.

The data acquired within the test area are similar to data that are likely to be acquired in larger habitat mapping projects and therefore used for testing habitat classification schemes. Recorded video transects of the seabed were interpreted by Vladimir Kostylev and a tidal current model of the area was made available by Bjørn Gjevik (Moe *et al*., 2003). All this information was analysed for any cross-correlation between geology and biology (Article 2).

The work of this thesis has been focused on methods for mapping substrate, but a part of the work was addressed especially to mapping coral reefs. These are one of the richest special habitats within Norwegian waters. Methods for mapping coral reefs is an essential part of this thesis, as well as substrate mapping in shallow and coastal areas. Fishermen and scientists have reported numerous locations of expected coral reefs. Only a few locations have been investigated and confirmed to comprise coral reefs (Fosså *et al*., 2000). It has been investigated how multibeam data are most efficiently acquired, processed and interpreted for mapping coral reefs. Article 3 sums up this work as well as comparing different methods of mapping and sampling coral reefs.

Preliminary results of acoustic sediment determination using backscatter strength from various angles are presented in Article 1. These results were further investigated by acoustic modelling (Article

4) and further exploited for mapping coral reefs (Article 5). The advantage of an acoustic method for substrate determination is manifested in the reduction of the required ground truthing, which in turn is not very reliable especially when sampling fine-grained sediments (clay and silt). The results introduced in Article 1 were confirmed by acoustic modelling presented in Article 4, which also made it possible to determine five geoacoustic parameters of the substrate.

2.0 Material and methods

In the "*definition of the problem", 1.3,* the scale of habitat mapping was determined by describing the types of data that should be utilised. Habitat mapping should be based on large-scale bathymetrical data and data obtained by multibeam mapping. This defines two levels of habitat mapping; large–scale habitats mapped using regional data and a medium–scale habitat mapped using acquired acoustic data. This thesis does not address habitat mapping in a finer scale than the metre resolution of multibeam data or equivalent mapping methods.

2.1 Data acquisition, interpretation and mapping methods

Various methods for data acquisition, interpretation and mapping have been tested and used during the Sushimap project. Table 3 is a short summary of the most used hardware and software.

Hardware				
System	**Manufacture**	**Application**	**Data**	**Reference**
EM1002	Kongsberg-Simrad	Data acquisition between 2 and 1000 metres water depth	Bathymetry and backscatter	Kongsberg Simrad, 2004a
EM3002	Kongsberg-Simrad	Data acquisition between 1 and 150 metres water depth	Bathymetry and backscatter	Kongsberg Simrad, 2004b
GeoSwath	GeoAcoustics	Data acquisition between 0 and 200 metres water depth	Bathymetry and GeoTexture (side scan data)	GeoAcoustics 2004 & Bates *et al.,* 2001

Software			
System	**Manufacture**	**Application**	**Reference**
ArcGis	ESRI	Visualising, organising and interpretation	www.esri.com
ER Mapper	Earth Resources Mapping	Visualising and interpretation of data	www.ermapper.com
QTC	Quester Tangent	Single and multibeam classification	Preston *et al.,* 2001 & 2004
Triton	Kongsberg-Simrad	Multibeam classification	Huseby *et al.,* 1993
RoxAnn	SonaVision	Single beam classification	Chivers *et al.,* 1990
GS+	GeoAcoustics	Processing GeoSwath data (Bathymetry)	GeoAcoustics 2004
GeoTexture	GeoAcoustics	Processing GeoSwath data (GeoTexture data)	GeoAcoustics 2003
Matlab	MathWorks Inc.	Programming	www.mathworks.com

Table 3, summaries most used hardware and software during the Sushimap projects.

Habitat classification schemes are used to organise and produce a uniform habitat map and a uniform interpretation that can be correlated from location to location. These schemes often comprise numerous standard habitat types based on experience for various sites. Three habitat classification schemes have been evaluated in this thesis:

EUNIS (http://eunis.eea.eu.int/): The habitat types are hierarchically organised in EUNIS. Habitat type is defined for the purposes of the EUNIS habitat type classification as follows: 'Plant and animal communities as the characterising elements of the biotic environment, together with abiotic factors operating together at a particular scale.' All factors included in the definition are addressed in the descriptive framework of the habitat classification. The scope of the EUNIS classification is limited to its level 3 (level 4 for Marine habitat types), a typical example for the habitat level 1 to 4 is shown in table 4. At level 4 (5 for the Marine types) and below, the component units are drawn from other classification systems and combine these in the common framework.

Habitat level	Keyword	Examples
1	Location	Marine, coastal or woodland
2	Location	Littoral*, infralittoral* and sublittoral*and deep-sea bed
3	Sediment description	Coarse sediment, mud. Biogenic reefs
4	Sub-classification of sediments and environment	Solid rock (bedrock), strandline sand and mud, methane seeps in littoral sediments

*Table 4, summary and examples of the four upper levels in the EUNIS classification system. * The three littoral is sub-divided between sediment and rock and other hard substrata.*

Valentine *et al.*, 2002: This scheme is subdivided into 8 themes (informal units). Each of these themes contains one to many classes of habitat types. The classes and themes in the scheme are all unique, and all reside a top level, making it a non-hierarchical system. In this thesis, the themes are termed by their number in the classification scheme, Table 5, Valentine *et al.*, 2002 or Article 2.

Theme	Habitat themes according to Valentine *et al.,* 2002
I, Topographic setting	Location of the habitat in terms of seabed slope, major seabed features, and anthropogenic structures
II, Seabed dynamics and currents	Addresses the stability and mobility of seabed materials
III, Seabed texture, hardness, and layering in the upper 5-10 cm	Results of sediment texture, relative hardness by using visual observations
IV, Grain size analysis	Sediment texture analysis, such as particle shape and weight percent
V, Seabed roughness	Three dimensionality of the seabed surface, covering physical and biological structures
VI, Fauna and flora	Fauna and flora enumerates the dominant and typical biological elements that characterize habitats
VII, Habitat association and usage	Describes habitats in terms of faunal association, human usage, and state of disturbance
VIII, Habitat recovery from disturbance	Time required for the recovery of physical and biological structures from fishing disturbance

*Table 5, summary of habitat the*me *of Valentine et al., 2002*

Greene *et al*., 1999: Habitats in this scheme are classified into four categories after size, Table 6. This system subdivides the seafloor according to depth and physiography. Each class comprises a number of standard habitats and a list of modifiers.

Habitat term	Size	Typical features
Megahabitats	From kilometres to tens of kilometres and large	Continental shelf, slope and abyssal plain
Mesohabitats	Tens of metres to a kilometre	Canyons, banks reefs, pebble and cobble fields
Macrohabitats	One to ten metres	Boulders, blocks, reefs and sediment waves
Microhabitats	Seafloor material and features of centimetres in size and smaller	Sand, small cracks, crevices

Table 6, overview of habitat definition of Greene et al., 1999

2.1.1 Multibeam sonars

Multibeam echo sounder systems provide fan-shaped coverage of the seafloor, transmitting up to a hundred or more beams perpendicular to the vessel. These beams are narrower than a beam from a traditional single beam echo sounder. This is typically achieved using cross fan beam geometry generated by two transducer arrays mounted at right angle to each other either in an "L" or "T" configuration. These arrays are made up of a number of identical transducer elements that are equally spaced. The elements in the transmitter array are placed parallel to the vessel's keel and project a vertical fan beam that is narrow in the along track direction and broad in the across track (Farr, 1980). The typical beam widths for modern multibeam swath systems are a couple of degrees in the along track direction and up to or even more than 150 degrees. The receiver array is mounted orthogonal to the vessels keel, which is sensitive to the across track direction. Typically the receiver beam width is a few degrees across track, while the along track width is up to ten times larger. This geometry of the transmitter and receiver array allows area coverage of the seabed, with high resolution due to the reduced footprint size. The ability to resolve targets smaller than the footprint was utilised by Simrad, by introducing the "split aperture" or in-beam phase method in multibeam swath systems. This method relies on picking the zero differential phase point within the footprint. The ability to differentiate angles based on phase is better than half beam width (commonly ~0.1 degrees compared to ~1.7 degrees)(Miller *et al., 1997)*.

The ATLAS Fansweep 20 utilises the phase detection for the outer part of the swath, this relies on the differential phase (Miller *et al., 1997*). This is also utilised on the outer beam in the SeaBat multibeam swath systems produced by Reson (personal communication; Pawel Poćwiardowski, Reson). The design of the multibeam is slightly different, as the central beams are often orthogonal to a semi-cylindrical transducer and the other beams are steered non-orthogonal. The steered beam requires a more precise knowledge of the sound speed at the transducer, which is often obtained by a mini-svp mounted near the transducer.

Each type of multibeam is manufactured for a certain working range. Shallow water multibeam has a wider swath and utilises higher frequency than deep-water multibeam swaths. The differences between commercial brands are difficult to assess, as new technology is often not well documented by the manufacturers, in order to maintain a competitive advantage. The techniques that have been documented are often adopted and incorporated in other systems.

The Simrad EM1002 was the chosen multibeam echo sounder for all areas surveyed in this work. In the main test area, where the water depth is less than 200 metres, it could probably have been an advantage to utilise a shallow water multibeam, for example the Simrad EM3002 or SeaBat 7125. This was not practically possible, however, since the EM1002 performed very well, and the data have fulfilled other aspects of the mapping requirements.

2.1.1.1 EM 1002

The predominant multibeam system used during the Sushimap project, was the EM1002 with a barrel type transducer array. The inner beams are transmitted orthogonal to the transducers, while the outer beams must be electronically steered. For an EM1002 beams at a larger angle than ±50º from the center of the receiver array are electronically steered (Beaudoin *et al.,* 2004). This is the same angle where a frequency change occurs. The EM1002 transmits a narrow along-track, wide across-track beam and then receives backscattered energy with 111 receiver apertures (2° × 2°) that are distributed across track (Kongsberg Simrad, 2004a). The bathymetry is calculated from the two way travel time that is corrected for the traveling patch and measured properties of the seawater.

Tests have shown that the EM1002 meets the Special Order of IHO S-44 for object detection with a speed up to 5 knots in depth between 15 and 31 metres (Haga *et al.,* 2003). When properly compensated, the depth accuracy of the EM1002 system is 0.2% of water depth or 10 cm, whichever is greater (Bacon *et al.,* 2002).

Most modern multibeam sonars including the EM1002 also acquire backscatter data, which are influenced by three factors: local geometry of ensonified area, the morphological characteristics of the seafloor and the intrinsic nature of the seabed sediments. The latter is the composition, density and relative importance of volume versus surface scattering (Blondel, *et al.,* 1997). Scattering can be broken into two parts: one part due to interface roughness and the other part due to sediment inhomogeneities (Jackson *et al.,* 1992). Roughness scattering dominates the outer beams, and is the only scatter component at grazing angles lower than the critical angle (for grazing angles smaller than the critical angle, no energy is refracted into the layer below, in this case the seabed). At high grazing angles more energy penetrates the seabed and in general the volume scattering contributes becomes more significant.

In this thesis, the term ”multibeam backscatter” covers the mean centre backscatter strength acquired by sampling an individual time series for each beam. The side scan data, which are also available from newer multibeam sonar, are not considered in this thesis. The sampling is only performed in a small window near the seabed detection; unlike the interferometric sonar and side scan sonars. To ensure that the hydrographical data are of high quality, the systems changes pulse length, sampling rate, beam width, and even sonar frequency to match the survey conditions. This is anathema for classification systems (Preston, *et al.,* 2001) and for general interpretation of the backscatter data. Corrections for these changes are often problematic and the effects of these changes are not always completely removed. This easily leads to misinterpretation; something that has been experienced in the Sushimap project. In order to avoid frequent changes between the different modes and thereby pulse length changes, acquisition of multibeam data in latter surveys was performed using manual settings. The absorption coefficient is kept constant for the entire survey. Backscatter data acquired using equidistant mode of acquisition were noticed to have higher quality than data acquired with equiangle or in-between mode.

2.1.2 Interferometric sonar

Interferometric sonars provide bathymetry and a sonar picture of the seabed. The transducers are basically side scan staves (Cloet *et al.,* 1986) and therefore often referred to as bathymetrical side scan sonar. A few very similar commercial interferometric sonars exist. The GeoSwath, produced by GeoAcoustics, is used to describe these types of systems. Other brands might be slightly different, but are based upon the same principles. Interferometric sonar records a time series of relative phase on several receiving transducer staves. For the GeoSwath system the number of receiving staves is four. Each of the receiving staves records a time series of the ensonified area. The amplitude of the times series is used to determine the relative phase and phase difference between the four staves. The time from transmitting to receiving is used to determine the distance to the scatter location. Multiple staves ensure that the angular measurement and the overall phase resolution are measured with high precision. By receiving the acoustic signal on a pair of acoustic transducers, both range and phase measurements can be made (Cloet *et al.,* 1986).

The range and the phase angle pair enable us to determine the location of the ensonified seabed patch relative to the sonar transducer (Bates *et al.,* 2001). This can be used to calculate the water depth at numerous locations within the swath. The interferometric system also provides a detailed sonar image of the seafloor.

The GeoSwath interferometric system was used to acquire bathymetry and a sonar image of the seafloor in shallow water, from the coastline to 180 metres water depth. The sonar records a series of echo amplitudes as a function of time, like traditional side scan sonar. These data are used to map the texture of the seabed and are referred to as GeoTexture data. The GeoTexture data are first processed in a similar manner as side scan sonar data, for each stave individually. Time varying gain can be applied but it is found more efficient to normalise each trace by applying a normalisation factor. The normalisation is performed on the basis of a normalisation curve, which is derived from an area with a flat and featureless seabed. This curve will reflect effects of the system as well as reduction in power due to spherical spreading and propagation loss. The normalisation curve is applied to all data in the region. The bathymetry data is then incorporated for slant range correction, to obtain as clear a sonar picture of the seabed as possible.

The GeoSwath system comprises two major physical components that are linked together: the sonar head and the processing unit. The sonar head is composed of two transducers, a single beam echo sounder and a sound speed sensor that are all mounted on a V-plate. Each of the two transducers is equipped with five elements. The bottom element on each transducer is a transmitter, while the remaining four elements are phase differencing interferometric and side scan receivers. Two sets of transducers were tested; the 250 kHz where reliable data can be acquired to a depth of 80 metres and the 125 kHz that can acquire data to a depth of 180 metres, but with a reduced resolution (GeoAcoustics, 2004).

Interferometers are now accepted as providing data to the standards of IHO S44 Special Order *(*International Hydrographic Bureau, 1998) (Hiller *et al.,* 2004). For the GeoSwath, this accuracy is accomplished out to 6 times the water depth. The GeoSwath offers wide swath coverage of up to 12 times the water depth, but only to a maximum of 600 metres width. The across track resolution is 1.5 cm for both used frequencies, while the along track resolution is depending on the rate of the swath and the vessel speed. A higher range will reduce the pulse rate. The resolution of the range is one wavelength, approximately 6 mm and 12 mm for the two frequencies. The accuracy of the range is depending on the transmitted frequency (0.01%), angular resolution (0.04º) and accuracy of determination of the acoustic speed of water (GeoAcoustics, 2004).

2.1.3 Lidar

Airborne Lidar (Light Detection and Ranging) was considered in the Sushimap project. The system is normally mounted on a small plane or a helicopter and has a very wide coverage compared to acoustic methods presented earlier. Lidar is a laser transmitter/receiver, which transmits pulses towards the water surface. The laser pulses that are transmitted are a green (e.g., a wavelength of 532 nm) and an infrared (e.g., a wavelength of 1064 nm) pulse. One of several receiving channels measures the Raman return (645 nm), which emanates from molecular excitation of the water by the green laser (Irish *et al.,* 1998). In calm conditions, the infrared laser is not reflected by the surface, but by the seabed. The time difference between the two arrivals is used to determine the water depth.

Typically, Lidar returns are received to a depth ranging from 2 to 3 times the Secchi depth (Irish *et al*., 1998). The Secchi depth is the depth where light can penetrate. This is a measurement of the water's clarity and transparency. In Norwegian waters this means from less than 20 metres to more than 40 metres, depending on the season and physical factors.

It was not possible to test such a Lidar system during the Sushimap project, due to mobilisation costs. The sensitivity to clouds and rain is likely to disrupt an efficient use of the system along the Norwegian coastline. It is unlikely to be as economically efficient as the GeoSwath, due to the steep slopes typically observed in Norway. The Lidar would then only cover a narrow strip, which could easily be covered using shallow water multibeam or interferometric sonars. Such a system would be necessary in any case, to map from the base of the Lidar survey to a depth where a medium- or deep-water multibeam is efficient.

2.1.4 Parametric sub-bottom profiler

Parametric sub-bottom profiler utilises the non-linear interaction of two high-frequency plane waves in the near-field. This creates a highly directional wave with low frequency wave (Westervelt, 1963). Westerveld's model assumption that this non-linear interaction only takes place in the near-field is not realistic, as this would require very large directional transducers (Hovem 2005). Measurements by Bartram (1972) show that the beam width is broader at higher levels. It was therefore suggested to improve the model by incorporating the attenuation of a shock sound wave (Bartram, 1972). This does not, however, change the underlying assumption in Westerveld's model. A proposed model by Moffett et al. (1971, 1977, 1981) takes into consideration not only the effects of non-linear attenuation, but also the fact that the interaction may be in both the near- and far-field (Hovem, 2005).

Generation of low frequency sound is accomplished by using a conventional transducer that simultaneously transmits a primary wave composed of the sum of two sinusoidal waves with relatively high frequencies. The non-linearity will cause the two primary waves to interact and thereby generate a sum and a difference frequency component. The difference frequency source distribution then resembles a continuous end-fire array with an exponential taper (Pettersen *et al.,* 1977). The difference frequency will be a low frequency secondary wave, if the two primary frequencies are almost equal. This will experience a low absorption and a narrow beam width. The Topas system is based upon this principle.

All vessels used during the Sushimap project have a parametric sub-bottom profiler (Topas, which is produced by Kongsberg) installed. The seismic data from the Topas is also considered for sediment classification, to support results from multibeam data. Topas is capable of generating different types of low frequency pulses. Normally survey lines are run using Burst pulse, which puts a large amount of energy into the water and has a larger penetration into the seabed than the Ricker pulse. To test the possibility of sediment classification, lines in one area were run twice, using both Burst and Ricker pulses. The Ricker pulse has a more regular shape and power spectrum than the Burst pulse (Berntsen, 2001). In this test the Ricker pulse data were acquired with a low gain to avoid clipping the seabed pulse. Technical problems with the system made it impossible to test the Chirp pulses. The Chirp can be distinguished from short-pulse single frequency profilers by the nature of its wavelet. A chirp wavelet is transmitted by computer-generated, swept- frequency pulses, which are amplitude- and phase- compensated (Quinn *et al., 1998)*.

The idea behind the sediment classification test was to use the seabed roughness as the classification parameter. A seabed comprising coarser-grained sediment produces a higher roughness compared to a seabed comprising fine-grained sediments. The acoustic signal will be scattered partly due to roughness, with higher frequencies being scattered more than lower frequencies at a certain roughness. The centre of gravity of the frequency is a measure for how high this is in a spectrum on average, and this should reflect such a change in roughness. This was tested for seabed classification, by sampling Topas data in a small window around the seabed. The data was transformed from time to frequency domain, where the effect of the signal was calculated by squaring the amplitude. Filters were used to remove vessel noise, prior to calculating the centre of gravity for individual traces (Ellingsen, 2002).

2.1.5 Seabed sediment determination

When a geologist segments the seabed using acoustic data, the different segments will be annotated with geological terms. The geological names will normally contain information of the seabed properties. Automatic classification segments the seabed into areas of similar acoustic response. The acoustic response will have to be translated to obtain information of the seabed sediments properties. The sediment properties can be determined from ground truthing, which is then extrapolated to areas with the same acoustic response.

2.1.5.1 Ground truthing

Sampling is in most cases performed by grabbing or coring, but also by visual inspection or direct measurements. The free fall gravity penetrometer is an example of the latter, which primarily determines the relative hardness and consistency of the seabed (Spooner *et al.*, 2004). All of these methods require instruments to be deployed at the seafloor, which is time consuming. Not only the process of deployment/recovery, but the time for positioning of the vessel is often substantial. Acoustic sediment determination using multibeam backscatter was considered for reducing vessel time used for ground truthing.

2.1.5.2 Acoustic determination of seabed sediment properties

Multibeam backscatter data has been acquired and is used for mapping habitat boundaries. The data has been processed and available. If this data can be used for sediment determination, it will then be possible to reduce the ground truthing time considerably. Using this data will also allow sediment determination to be performed at all locations within the survey area that might be of interest. Most of the classification methods do not extract physical information of the seabed, but classify areas of similar acoustic response, which are linked to the samples. Comparing grain size to multibeam backscatter data shows that gravel has high backscatter strength and silt has lower backscatter strength. Backscatter strength from the grazing angle interval from 50º to 55º confirms that gravel has high backscatter strength and silt has low backscatter strength (Unger *et al.,* 1998). This work shows a relation between mean grain size and backscatter strength, but the variation is so significant that it will be difficult to determine the mean grain size from the backscatter strength.

Many consider interpretation of substrate boundaries easier when the data are post-processed, and artefacts as well as other physical effects, such as the angular response in the data are removed. Correcting the angular dependency of the backscatter data often fails, because the shape of the angular response curve (backscatter versus grazing angle) is highly variable. A new method that relies on the variation in shape of the response curve was utilised to separate lithologies that exhibit similar mean backscatter (Hughes-Clarke *et al.,* 1997). The results were not very successful, as most of the investigated areas comprised more than one substrate. The high survey speed and large areas analysed for each sediment determination test might explain why the test was unsuccessful. Chakraborty *et al*, 2000, Fonseca *et al*., 2005 and Beyer *et al*., 2005, tested methods of similar ideas with more success.

A similar method was developed in this work, but with a different focus by using the outer beam and avoid the near nadir region. This was partly to avoid problems with backscatter acquired near nadir (Hughes-Clarke *et al.,* 1997) and partly trying to resolve the critical angle. The critical angle is the smallest angle where energy is penetrating into the seabed when flat. Theoretical models of the angular response show a minor local maximum at the critical angle, which could be used to determine the speed of sound in the seabed sediments (Hovem, 2005). Interpretation of the scattered signal behaviour at low grazing angle could provide a method for determining the critical angle and hence extracting the compressional speed of the seabed sediments, which in turn could be used for sediment classification.

Further parameters of the seafloor should then be extracted by fitting a modelled response to the seabed. The composite model (Jackson *et al.,* 1992) was first considered. This model comprises both the Rayleigh-Rice and Kirchhoff model.

The Helmholtz-Kirchhoff model provides a good prediction for backscatter using high frequency at near normal incidence (Medwin *et al.,* 1998). This is however not the region of interest here and the first part of the classification is based on the critical angle. The best-suited model for testing the AVA classification is considered to be the Rayleigh-Rice model demonstrated by Essen, 1994. Despite the unreliable results near nadir, this model does provide reliable results at smaller grazing angles, and it reveals the characteristic cusp at the critical angle.

2.2 Interpretation

Interpretation is the translation of data to a specific theme, in this case acoustic signature to geological substrate. Unprocessed backscatter data have been used successfully for mapping marine facies (Article 1). The backscatter strength is influenced by the physical properties of the seafloor. Seafloor with high acoustic impedance will reflect more energy than regions with lower acoustic impedance (Barthelemy *et al.,* 2002).

Post processing that removes the angular dependency removes information that could be useful during interpretation. The post processing provides a more uniform sonar picture of the seafloor, and enables fishermen and many others to use the backscatter data. Trained and experienced people will obtain more information from these processed sonar data than a map that has translated the backscatter data into a few classes. Maps generated by automatic classification are much faster to produce compared to a geological interpreted map.

2.2.1 Automatic classification

Automatic classification has been explored for a long period of time and several classification applications using multibeam data have been commercialised. A few of these were tested during the Sushimap project.

Triton was extensively tested. This software is based on statistical analyses of multibeam backscatter (Huseby *et al*., 1993). Five different statistical features describe the classes. These features are the quantile, pace, standard deviation, and contrast together with the mean value (Kongsberg-Simrad, 2001).

QTC have developed a suite of software that is able to classify most acoustic data, from single- and multi-beam echo sounders to side scan sonar data. This software extracts numerous features, using principal components analysis (PCA) to select those combinations of features that are best suited to particular data sets for classification (Preston *et al.,* 2001 and Preston *et al.*, 2004).

Classification based purely upon the mean backscatter strength derived from post-processed data was also tested. An empirical method based on local statistics developed by Robert C. Courtney (Geological Survey of Canada) was used to remove the angular effect (Figure 1). In this case the boundary between the different classes was chosen in areas where extensive video inspection and sampling were conducted.

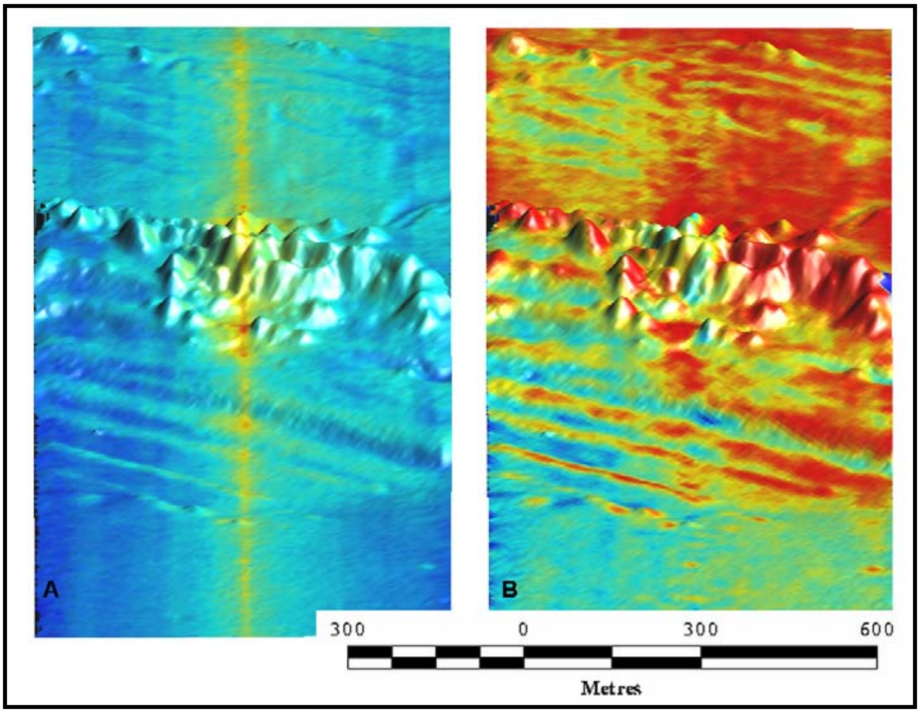

Figure 1, A) Single swath unprocessed gridded backscatter data from the coral reefs at Sula. B) The same multibeam line as figure A, processed using Robert C. Courtney's software. The resolution of the images is similar, but the backscatter strength in figure A is clearly largely affected by the grazing effect that is removed in figure B.

Shallow water interferometric sonar data were classified using GeoTexture software, which performs a supervised classification using the seafloor texture. Texture is however an intuitive notion, which is defined differently. In general texture definition can be subdivided into two groups; one that describes a sample by statistical parameters and one that uses pattern reorganization. GeoTexture uses the latter, it is very amplitude dependent, and therefore rely strongly on the normalisation of the image. An expert user trains the software by defining a uniform area or a line, where the nature of the seabed is known or estimated. Areas with similar characteristic are then interpreted as the defined class. The operator then decides upon a texture recognition threshold level. The lower the threshold, the more exact the match has to be, while too high a threshold setting may classify inappropriate areas (GeoAcoustics, 2003). A single patch can also be used to find areas of similar texture. This is similar to feature extraction.

The features used in the GeoTexture software are amplitude dependent. This makes it rely strongly on the normalisation of the data. The software generally provides more consistent results than a manual interpretation, as the human eye is poor to recognise texture that gradually changes. The results from the software are however entirely depended on the training of the software.

2.2.2 Feature extraction

Feature extraction addressed two issues, firstly detection of specific habitats and secondly mapping the extent of these habitats. The purpose of developing a detection method is to locate the presence of a specific habitat using unprocessed data acquired during transit or on passages.

The work in this thesis has mainly consisted of pursuing a method for mapping the extent of different habitats by characterising their acoustic or morphological signature. These methods are mainly based upon processed data, where a specific characteristic signature can be linked to a specific substrate or a specific habitat. The entire data set has been analysed for areas with similar character. These areas have been classified and mapped, while the remaining area is left unclassified. Multibeam backscatter and single beam data were used for extracting areas coral reefs (Article 3). Bathymetry data were used to define areas of outcropping bedrocks (Christensen *et al.*, 2005A) and moraine ridges.

2.2.2.1 Feature extraction of coral reefs

Single and multibeam data were specifically used for detection and feature extraction of coral reefs. Single beam data acquired by calibrated echo sounder were analysed in the RoxAnn software. RoxAnn extracts two indices: one from the first echo and one from the second echo (first multiple). Only the tail part of the first echo (E1) is integrated, to remove the initial normal back reflection that is often 10 to 20 dB above the level of other signal of interest. This permits the dynamic range of the system (Chivers *et al.,* 1989) to be more effectively used for ground discrimination. The E1 can be related to roughness (in combination with hardness). The whole of the second echo (E2) is thus integrated, which is primarily related to hardness (moderated by roughness) (Chivers *et al.,* 1990). Entering an area of coral, the roughness signature rises sharply and the hardness signature decreases. This can also be observed on online echo sounder monitors, where the seabed amplitude increases and the first multiple disappears.

2.3 Survey procedure

The methods for data acquisition, interpretation, sediment determination, ground truthing, classification and feature extraction have been used to define a procedure for an efficient and reliable survey strategy. This resulted in proposing a two-cruise strategy (Article 1). The first cruise is conducted with a larger survey vessel with expensive acoustic equipment and a survey crew for both acquiring and processing acoustic data. A limited ground truthing program based on automatic interpretation is suggested. It is therefore essential to improve the resolution of the automatic interpretation (Article 1 and 5).

The second cruise performs a larger ground truthing program, which only requires a small vessel with a reduced crew. This cruise commences during the later stage of the interpretation, when areas of special interest and complexity have been found together with locations where acoustic interpretation is not conclusive. Methods for extracting physical information of the seabed have been developed, such as the AVA classification method (Article 4). This method is developed to be used in-between the cruises, prior to ground truthing, where the information obtained shall improve the acoustic seabed classification. Interpretation results shall be incorporated into a habitat classification scheme, which ensures that all results from various stages of the interpretation are used directly in the scheme.

2.4 Habitat classification

Sushimap aimed to find or develop a suitable classification scheme for Norwegian waters. The European Environment Agency has developed a classification system, EUNIS (European Nature Information System), which is a comprehensive pan-European system to facilitate the harmonised description and collection of data across Europe. This system covers all types of habitats from the natural to artificial, from terrestrial to freshwater and marine environment (http://eunis.eea.eu.int/about.jsp). EUNIS is hierarchically organised, to enable user and managers to choose the appropriate level of information. The system is difficult to implement in large parts of Norway, as the substrate is subdivided into hard or soft at a high level. Glacial till dominates the substrate in Norway and is geologically defined as soft, while it can function as hard ecologically (Rinde *et al.,* 2004). This scheme was therefore not applied in the Sushimap project. Instead, the classification was performed using two other schemes. The classification scheme developed by Greene *et al*., (1999) was used for large-scale habitat classification, which was mainly based on regional bathymetrical data. This classification scheme mostly addresses deeper water habitats. Medium-scale habitat classification was performed by the classification scheme developed by Valentine *et al*. (2002), for regional habitat classification as applied to the marine sublittoral of northeastern North America. The scheme is not restricted to deep waters and has been developed in areas of recent glacial activity, using multibeam and side scan sonar surveys, video and photographic transects as well as sediment and biologic sampling. The physical environment and the methods are similar to the methods defined in "*definition of the problem*" (section 1.2). This scheme can, without major difficulties, be implemented into ArcGis or other database systems for storing and organising the results.

2.5 Data management

Interpretation and results must be accessible; able to be viewed, used and modified to the users demand. This thesis has not described this subject in larger detail. However the data, interpretation and results for the test area are accessible in an ArcGis project. This is stored on a shared server and can be accessed from all computers within the NGU system. This is however the first step, which had been developed further in the MareanoWeb (http://www.mareano.no). This has enabled everybody with an Internet connection to access habitat maps in Norway and related information, provided by various institutions.

3.0 Results

The results of the five enclosed articles illustrate the progression and development of using acoustic data for interpretation of marine habitats within the Sushimap project. The status of these articles is summarised in Table 7, followed by a short summary of the articles and then by results not yet published.

Article	Status
1. Marine facies mapping using multibeam backscatter	Accepted by the "Marine Benthic Habitat mapping", ed. Brian Tood and Gary Greene
2. 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	Submitted to Limnology and Oceanography, Methods (In black and white and some minor changes compared to the article in chapter 5)
3. Mapping of *Lophelia* reefs in Norway: experiences and survey methods	Printed in Freiwald A, Roberts JM (eds), 2005, Cold-water Corals and Ecosystems. Springer-Verlag Berlin Heidelberg, pp 359-391.
4. Sediment classification using multibeam backscatter amplitude versus grazing angle	Submitted to Marine Geology.
5. Multibeam backscatter classification of seafloor properties – examples using response on e.g. deep-water coral reefs	Printed in not peer-reviewed conference proceeding (1st International conference on underwater acoustic measurements: Technologies and results

Table 7, status over the five enclosed articles that comprise most of the work of this PhD thesis.

3.0.1 Summary of Article 1.

The purpose of this article is to investigate the possibilities of using multibeam backscatter data for interpretation of seabed substrate, here termed geological facies. The interpretation was performed using three-dimensional visualization software, where bathymetry and backscatter could be combined.

Automatic classification of the backscatter data was tested offshore and used for a small-scale ground truthing survey. Comparison of this classification with the geologic interpretation showed a reduced resolution as well as locally incorrect classification. This is specifically linked to the software. Further investigation and recommendations, are presented in Article 5 and Christensen *et al.* (2005B). It is not ideal to design the entire ground truthing on the basis of automatic classification only. It is however beneficial to perform a minor ground truthing survey on the basis of the acoustic interpretation, and delay the major part of the ground truthing to a later stage.

Numerous standard ground truthing methods were tested, which showed that the video assisted grab had some clear benefits compared to grab sampling. The video assisted grab was very efficient in distinguishing bedrock from till, but in fine-grained sediments it only worked for investigating the homogeneity of the seabed. The option of grabbing was largely used in these locations. Initial acoustic sediment determination based on multibeam backscatter data was tested. Plotting backscatter strength against the grazing angle showed a good correlation at more than fifty locations where the sediment properties were confirmed by ground truthing. These results were the basis for further developing sediment determination using backscatter strength from various grazing angles.

Combining bathymetry and backscatter data in a three-dimensional interpretation environment, made it possible to increase the number of mapped classes. This is due to the extensive colour manipulation and image enhancement of the backscatter data that allows minor geomorphologic features to become visible.

3.0.2 Summary of Article 2

The purpose of this article is to test the suitability of habitat classification schemes in the physical environment of the Norwegian coast and for handling the data and the survey strategy suggested in Article 1. This paper also compares biological, geological and tidal current models to find any correlation that can be useful for further habitat mapping projects.

The classification scheme developed by Valentine *et al.* (2002) was tested, as it has been established in an area with geology similar to Norway. The first six themes in this classification were interpreted from acoustic data and ground truthing data. Theme III was interpreted geologically as well as automatically on the basis of the mean backscatter strength. The results of automatic classification and a geological interpretation where some of the classes were merged produced a very similar result. It was therefore suggested to change theme III to become the automatic classification. Theme IV will be the geological interpretation, incorporated ground truthing, results from analysing samples, geological knowledge and other relevant information.

Dependency between modelled tidal current strength, biology and the seabed sediment properties was investigated. Two observed types of seapens have a strong correlation to specific tidal and sediment properties. Similar strong correlation was observed for one type of seastars, while the correlation was broader or weaker for most other species. Tidal current strength and the seabed sediments seem to have a high influence on the biological activity. It was hoped that the modelled tidal current strength could enable us to predict sediment properties prior to survey activities. The model used for calculating the sediment properties was somewhat inaccurate, as slope and grain shape is not incorporated into the model used for calculating the sediment threshold. This reduced the correlation between sediment types and the tidal current model.

The tested habitat scheme could cope with the complex physical environment and was well adapted to the used data. Only minor changes to the scheme would make it adaptable to the proposed survey strategy.

3.0.3 Summary of Article 3.

The purpose of this paper is to review existing interpretation, processing, acquisition and sampling methods used on Lophelia-reefs in Norwegian waters, and to suggest an effective mapping procedure.

Single beam echo sounder data can be acquired at significantly higher survey speed than multibeam data and demand much less post-processing. These data are efficient for regional reconnaissance surveys for coral reefs. RoxAnn was particularly useful, as post processing was not required. The software analysed acquired data and translated the results into a map view. When RoxAnn was calibrated correctly the acoustic signature from coral reefs, such as *Lophelia Pertusa,* was highlighted automatically. Single beam systems, however, are not ideal for interpreting the extent of the reefs.

Interpreting coral reefs using multibeam bathymetry data has been successful in some areas, but the confidence of such an interpretation is low in areas of complex morphology. In these cases the high backscatter response from coral reefs enabled a more detailed mapping and made automatic extraction possible.

Large variation in the interpreted extent of coral reefs was discovered when comparing multibeam bathymetric interpretation with side scan sonar interpretation. The shadow from the coral reefs on the side scans records makes it difficult to define the coral reefs exactly. Position of the side scan fish was calculated from layback, which introduces uncertainties into the interpretation.

Seismic data, as well as most other acoustic data acquired for mapping the seafloor, can be used for interpretation of coral reefs. All acoustic methods have their advantages and disadvantages, as do the various ground truthing methods. The video assisted grab cannot be steered as an ROV and provides only pictures from above. Due to the grabbing option, the minimum requirement for operating the system, the fast deployment and recovery, the video assisted grab seems much more efficient than an ROV. The ROV can provide pictures from various regions of the coral reefs, which is not always possible using a video assisted grab.

3.0.4 Summary of Article 4.

The purpose of this paper is to demonstrate earlier results, which suggested angular response curves could be used for sediment classification. In this paper the possibility of extracting physical parameters of the seabed sediments using AVA (Amplitude Versus grazing Angle) curves is investigated. This is performed using theoretical models and multibeam data acquired using an EM1002 multibeam echo sounder.

A perturbation model with the Rayleigh-Rice approximation was used to produce the best possible results at the outer beams, where the critical angle results in a minor cusp, a local maximum. Resolving this cusp could be used to determine the compressional speed in seabed sediments. The perturbation model was modified to incorporate shear waves, so a better correlation to multibeam backscatter data can be obtained. The modelled response was fitted to multibeam data acquired from three typical Norwegian sediment types. By modifying the input parameters in the model, it was possible to estimate four additional geoacoustic parameters of the seabed sediments. For the coarse-grained sediment the results were not convincing, but the results in fine-grained sediments (Clay) was encouraging. The results in clay were confirmed in a second test and had a good correlation to published geoacoustic values. The AVA or any other remote sensing measurements are believed to be more accurate, especially in fine-grained sediments. Sampling will alter the structure of the sediments and water will be drained from the samples during recovery and analysis. This will increase the measured density. It is therefore believed that the AVA will provide a more accurate estimate of some of the geoacoustic parameters.

3.0.5 Summary of Article 5.

The purpose of this paper is to demonstrate the ability to perform an automatic classification on the basis of multibeam backscatter that has good similarity to the geological properties. It also shows the possibility of using the acoustic data to determine the seabed properties, including coral reefs.

The classification based on the geological interpretation was compared with the automatic classification, which is based on the mean backscatter strength. The number of classes possible to classify was investigated from the backscatter plot of the angular response for typical Norwegian sediments, as well as for coral reefs.

Automatic classification and geological interpretation had large similarities, when using three broad geological classes. Plotting the angular response from these three geological classes indicated that it would be rather difficult to resolve for further classes using only the backscatter data. Coral reefs seem to have a special acoustic response with higher backscatter strength at low grazing angle, but they are also similar to most other sediment types at Nadir.

3.1 Large-scale habitat classification

Large-scale habitat classification was mainly interpreted using the existing regional bathymetry. These data vary in quality, with a maximum resolution of 50 metres in the coastal areas. In deeper water the regional data are even coarser. The classification scheme published by Greene *et al.* (1999) was applied. This classification scheme defines three categories; Mega-habitats that refer to large features that have dimensions from kilometres to tens of kilometres and larger; Meso-habitats are those features having a size from tens of metres to a kilometre; Macro-habitats range in size from one to tens of metres. The latter cannot be resolved using the regional data.

Many of the features listed as meso-habitats in the schemes, such as coral reefs and slides, are so extensive in Norwegian waters that according to the classification they should be defined as mega-habitats. Two examples of how such large-scale maps are shown in figures 2A and 2B. Data used in these maps are from an early version of the Mareano project database, which does not yet comprise all published information. Pockmarks are for example only shown in the southern part of the Norwegian trench and in the Barents Sea. Pockmarks have however been confirmed in muddy sediments in the northern North Sea and in Norwegian fjords (Hovland and Judd 1988). With time all published information will be incorporated into this database and it might be possible to confirm or find new correlations between different habitat themes.

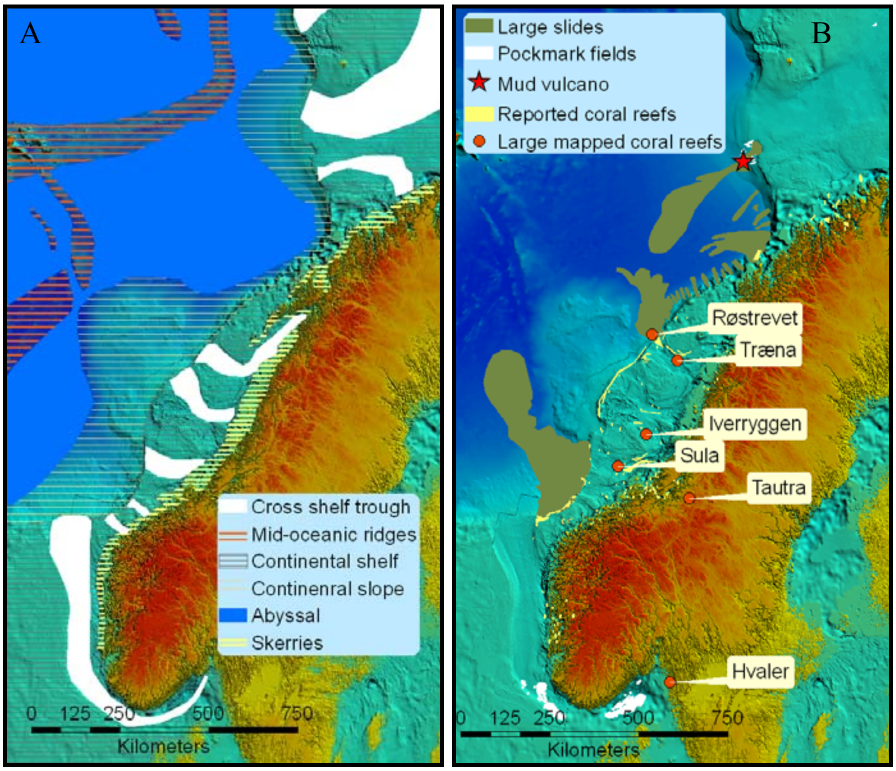

Figure 2, large-scale habitat maps for the Norwegian waters, modified after Thorsnes et al., 2005. A) Mega habitats according to habitat classification of Greene et al., (1999), interpreted from regional bathymetry. B) Meso habitats partly interpreted from regional bathymetry and partly from data of higher resolution.

Skerries have been added as a new mega habitat. Skerries are the translation of the Norwegian concept "Skjærgården", a highly valued coastal archipelago consisting of many islands varying in size. The large biodiversity and the economic revenue created in this habitat from fishing, aquaculture as well as a recreation site and tourism magnet, makes this habitat one of the most exploited habitats in Norway.

Meso-habitats in figure 2B, such as the Storrega slide, can be observed using regional data, but interpretation was performed using seismic and multibeam data (Bugge, 1983). Three large cold-water coral reefs, all mapped using multibeam data in the Sushimap project, are shown together with reported and confirmed coral reefs (Fosså *et al.,* 2000). The Sula reef is a long linear structure of several kilometres, which cannot be resolved by the regional bathymetry due to the small width of the coral reef. The Træna reef is also invisible on the regional data, as the reef complex is not a single structure. The Træna reef complex comprises more than a thousand reef colonies that have a length of between 100 and 150 metres (Lindberg *et al*., in prep). The individual reef would be separated and treated independently in a medium scale habitat classification.

3.2 Medium-scale habitat classification

Medium-scale habitat classification was performed in the test area, according to the classification scheme developed by Valentine *et al.,* 2002. This scheme could cope with the complexity of glacial sediments and is well adapted to the data used and the survey procedure. The scheme is subdivide into themes, which have been modified in order to make the survey procedure and the classification better linked. This also makes the classification and interpretation process more efficient. The original and changed themes are summarized in Table 8.

Theme	Habitat themes according to Valentine *et al.*, 2002	Habitat themes according to the changes in this work
I, Topographic setting	Location of the habitat in terms of seabed slope, major seabed features, and anthropogenic structures	Location of the habitat in terms of seabed slope, major seabed features, and anthropogenic structures
II, Seabed dynamics and currents	Addresses the stability and mobility of seabed materials	Add tidal current models, information on current systems*
III, Seabed texture, hardness, and layering in the upper 5-10 cm	Results of sediment texture, relative hardness by using visual observations	Automatic seabed interpretation based on acoustical data, which can be performed during or shortly after acquisition
IV, Grain size analysis	Sediment texture analysis, such as particle shape and weight percent	Geological interpretation, incorporating all details based upon all available data. The results of this theme will have to be updated as new information becomes available
V, Seabed roughness	Three dimensionality of the seabed surface, covering physical and biological structures	No changes recommended
VI, Fauna and flora	Fauna and flora enumerates the dominant and typical biological elements that characterize habitats	No changes recommended
VII, Habitat	The fauna association,	Not been considered

association and usage	human usage, and the stage of disturbance.	in this work
VIII, Habitat recovery from disturbance	Time required for the recovery of physical and biological structures from fishing disturbance	Not been considered in this work

*Table 8, summarizes the individual themes within the habitat scheme developed by Valentine et al., 2002 and the changes suggested within this work. * Information concerning hydrographical conditions could possibly be separated into new separate themes.*

Comparing the different themes, such as substrate interpretation, the biological observations from the grab and tidal model showed a fairly high correlation (Article 2). An essential habitat map was not created, as only biological distribution data were available. The ability to truly identify essential habitats for the sustainability of fish stock or other species demands that higher-level information must be acquired. This information must include rate of growth, reproduction and survival in relation to habitat variables of the fish stock, (Noji *et al.,* 2005). The acoustic data, however, have been successfully used for interpretation of physical parameters. These parameters seemed to have a large influence on the distribution of many observed species. This scheme can be well adapted to the survey procedure and could reduce the workload of habitat classification significantly by applying minor modifications. This would enable automatic classification to be incorporated directly, as an individual theme.

3.3 Automatic classification

To use the automatic classification directly, demands a good correlation between the geological and automatic classification. Statistical classification performed in Triton showed some similarity. The resolution, however, was too low to be acceptable for medium scale habitat classification, as minor areas of outcropping sediments would not be resolved (Article 5 and Christensen *et al*., 2005B). These results are, however, significantly better than the results provided by the classification in the QTC classification software. Classification boundaries produced by the QTC software were largely parallel with the survey direction, which was suspicious and believed to be associated with the effects of the difference in grazing angle.

Subsequent ground truthing confirms the error in QTC software classification.

The highest similarity between the geological interpretation and automatic classification was achieved using the mean backscatter strength of post-processed data (Article 5). This result reflected the geological interpretation and ground truthing data very well and was therefore suggested to be incorporated directly into the scheme as theme 3. This method was also fairly successful for interpretation of coral reefs (Article 3).

In shallow water very good results were achieved for the interferometric data. However, the clear image of draping the GeoTexture over bathymetry (Figure 3A) probably provides as good an indication of sediment types as the classified images (Figure 3B). Colour manipulation of the GeoTexture data in a three dimensional environment can provide even a better tool for classifying the seabed (Figure 3C). Adjusting the colour was performed so special habitats are highlighted, which is a primitive form of feature extraction. In this case the classification was performed by adjustment. The possibility of balancing the colour and filtering in the visualization/interpretation software helps improve the classification.

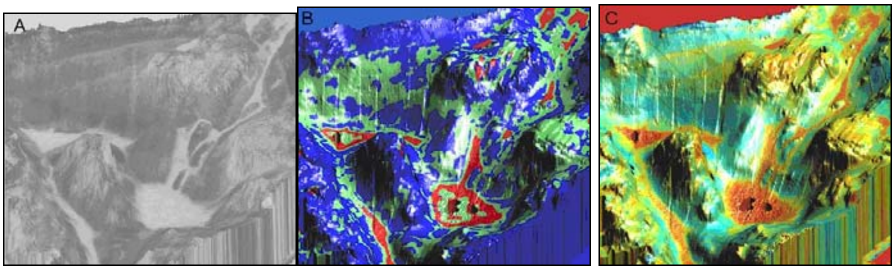

Figure 3, A) Geotexture draped over bathymetry. B) Automatic classification of the GeoTexture data. C) Colour manipulated backscatter draped over bathymetry.

3.4 Feature extraction

Feature extraction during the Sushimap project has been limited to moraine ridges, coral reefs or bedrock. The variation of slope direction in large cells provides poor results for extraction of moraine ridges, compared to the results achieved for feature extraction of the coral reefs.

3.4.1 Feature extraction of coral reefs

The acoustic signatures used for feature extraction of corals using single beam and multibeam data are related to roughness. The RoxAnn parameter that has the strongest response to coral reef is the roughness parameter, which increases significantly over coral reefs (Article 3). Multibeam backscatter strength from the outer beams, which is largely a function of the roughness, shows similar increase in backscatter strength. The other single beam signature used in RoxAnn is related to hardness, and shows a soft response. The single beam E2 response is not similar to the nadir response from the multibeam echo sounder. The hardness is based on the first multiple, which is high when the seabed is hard and little or no energy is transmitted into the seabed. RoxAnn classifies the coral reefs as soft. This could be due to energy being transmitted into the open structure of the coral reefs. It is, however, more likely due to the large scattering caused by the extreme roughness of the coral reefs. Higher backscatter strength from coral reefs compared to other sediments is noticed at all angles, except at nadir (Figure 4).

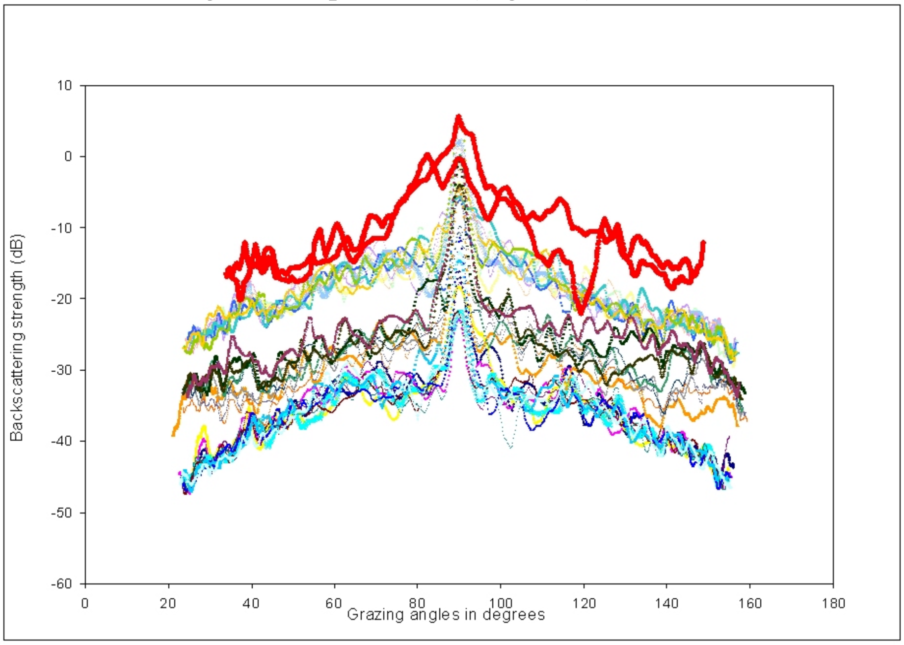

Figure 4, AVA curves, which is a plot of the backscatter strength as a function of grazing angle (port 0-90º, starboard 90-180º). Ten AVA-profiles from each of the substrate types and two from coral reefs were analyzed.

Feature extraction of coral reefs using post-processed multibeam backscatter was successful as the normalisation was performed at the outer beams. Normalisation at nadir would not resolve the different seabed substrate, and the data would not have been useful for extraction of coral reefs.

3.4.2 Feature extraction of bedrock

It has previously been demonstrated that it is possible to distinguish between rock and sediments using a 50 m grid bathymetry data set by using a combination of convexity (Bekkby *et al*., 2005). The best approach for extracting bedrock appears to be the Terrain Elevation Index (TEI) when tested against other methods such as TRI (Terrain Ruggedness Index) (Riley, *et al.,* 1999). The TEI is obtained by subtracting the mean depth value in a window from the value at the centre. TEI was tested using various window sizes on the original 50-metre grid and was found best when applied on a 500 by 500 metre window. Areas with TEI>1 have a generally positive topography, and we tentatively infer that 5-50% of these areas may contain exposed bedrock in the Norwegian skerries (Christensen *et al*., 2005A). TEI seems to work even better when applied to multibeam data in a 3 metres grid, but due to a significant quality difference between the multibeam data and the regional data it is not possible to determine whether the scale or the quality that improves the TEI results. It is likely that the quality of the data will affect the results significantly. Utilising the best possible interpretation method for a given habitat is essential for obtaining a good result.

3.5 Comparison of data acquisition methods

The data from the EM1002 and GeoSwath are combined for habitat interpretation and therefore it is essential to compare the resolution of the systems, with respect to both bathymetrical and backscatter data.

3.5.1 Bathymetry

The accuracy of the 250 kHz GeoSwath system was compared to the shallow water multibeam system, EM3002, at the Norwegian Hydrographic Office's test site. The results are comparable with those of NOAA (Table 9), even when the cell sizes are different. The difference in cell size should not affect the values significantly. The standard deviation of the GeoSwath data tended to be between 3 and

6 times as high as the multibeam systems (Gostnell, 2004). The data density of the GeoSwath can be 40 or more soundings per meter slant range, but when the distribution of individual soundings is inspected, it appears to have a high standard deviation compared with beam formed data. The feature definition from interferometric bathymetric images is equivalent or better than from multibeam sonars. This excellent feature definition arises from the fact that the data collected has a very high density, giving many data points per bin and thus a very accurate bin mean depth (Hiller *et al.,* 2004).

Survey	**Survey system**	**Standard deviation (grid size)**	**Mean difference (between systems)**
NGU	GeoSwath (250 kHz)	40.1 cm (2 x 2 m)	5.3 cm (GeoSwath/EM3002)
NOAA	GeoSwath (250 kHz)	23.5 to 41.1 cm (5 x 5 m)	
NOAA	Reson 8125	7.5 to 8.9 cm (5 x 5 m)	9 cm (GeoSwath/Reson 8125)
NOAA	Simrad EM3002	5.3 to 13.6 cm (5 x 5 m)	5 cm (GeoSwath/EM3002)

Table 9, Results comparing GeoSwath 250 kHz with multibeam system, NGU survey performed by Norwegian Hydrographic Office and the NOAA results described in Gostnell (2004).

Further analysis of the comparison performed by NGU, showed that the difference increased with seafloor slope, while sediment types and water depth did not show any significant correlation to the difference. Annual surveys over the sand waves showed that the GeoSwath provides similar details as the EM1002 (Figure 5).

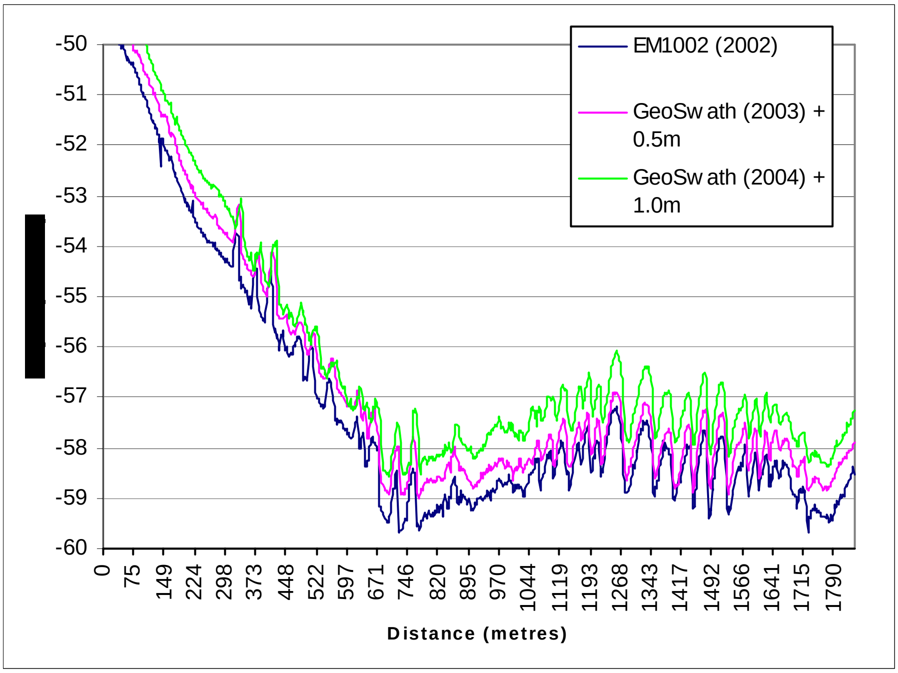

Figure 5, Three bathymetrical profiles over the sand waves, Article 1, where the GeoSwath bathymetry was added 0.5 metre for 2003 and 1.0 metre for 2004. The sand waves are moving up to 7 metres east (up distance at x-axis) each year, which explain why the sand waves crests do not line up for the different surveys.

The sonar images from interferometric systems are in general of better quality than multibeam backscatter images. The multibeam bathymetry should probably be considered more accurate than the interferometric bathymetry, but for habitat interpretation where the absolute depth is of less interest than images of seabed features, both systems are very adequate.

3.5.2 Backscatter data

In shallow waters, GeoTexture data provides details of the seabed with much higher quality compared to multibeam backscatter data. In deeper waters the slant range correction reduces the quality of the GeoTexture data and the multibeam backscatter data becomes more useful. The quality of GeoTexture and Multibeam backscatter data for interpreting seabed substrate is similar in water depth from 50 to 100 metres water depth, depending on the GeoSwath frequency used and the multibeam system used.

Shallow water GeoTexture and multibeam backscatter data must be interpreted together to obtain an overall understanding of the processes taking place. Combining the data sets prior to the interpretation, as shown in Figure 6, is found to be most suitable.

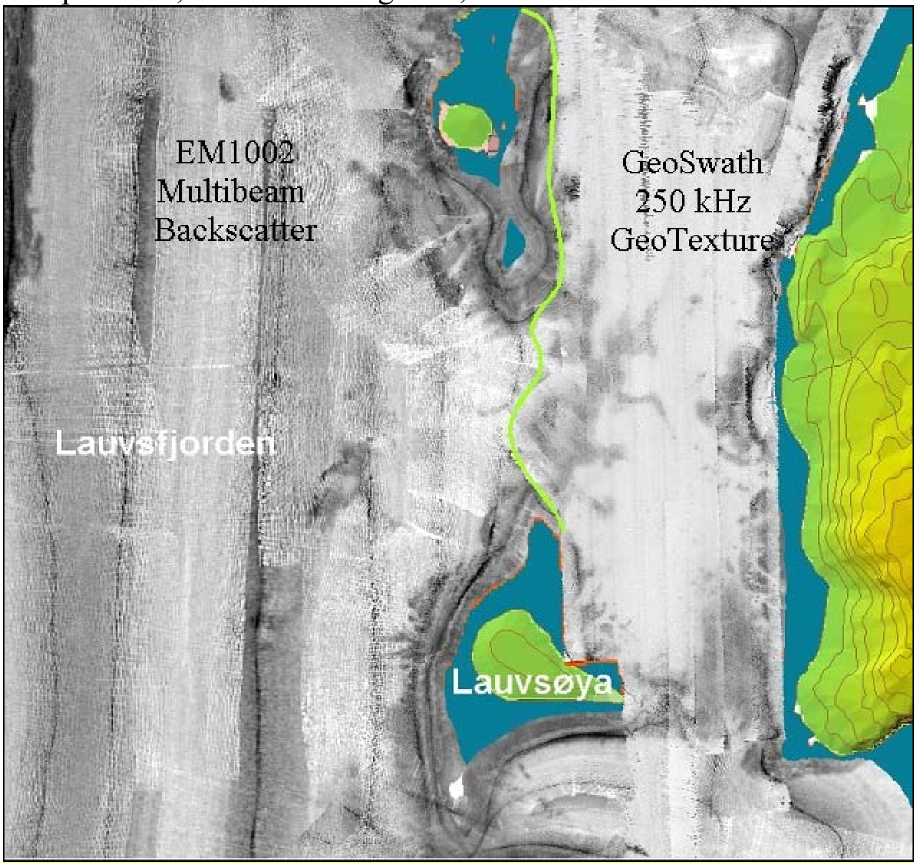

Figure 6, Data on the left side is gridded standard processed mean backscatter strength acquired using an EM1002, where the depth is from more than 150 metres to less than 50 metres. The area to the right is mapped with a 250 kHz GeoSwath, where the GeoTexture shown is processed by the GeoAcoustics software. The water depth is generally less than 80 metres.

Multibeam backscatter from the entire survey is often processed and mosaiced. This procedure has occasionally been used for GeoTexture data as well, however this will reduce the resolution of the GeoTexture data. A topographical structure will have a strong return from the side facing the transducer and be followed by a shadow. Mosaicing two parallel lines might obscure the structure or at least reduce the characteristic of topographical structures. High-resolution interpretation should be performed prior to mosaicing (Figure 7).

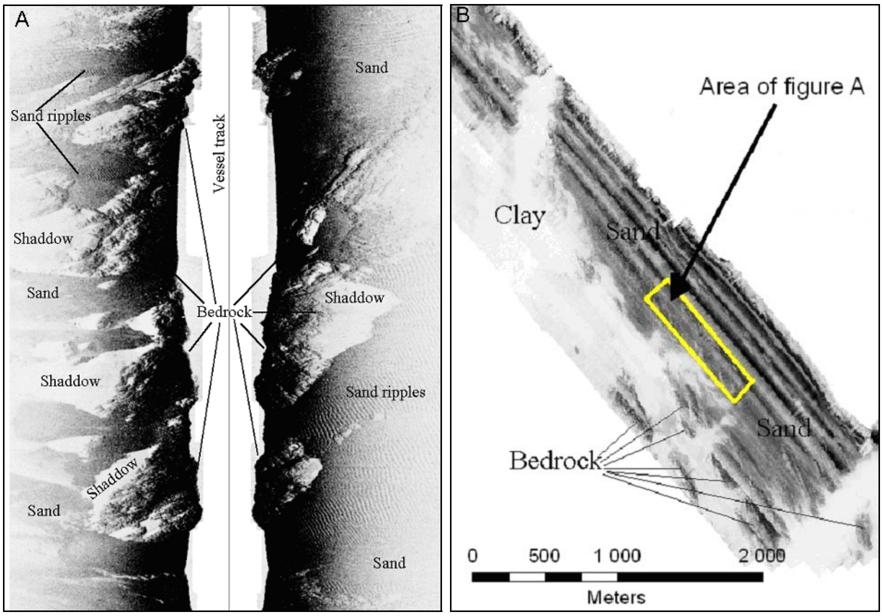

Figure 7, A) Unprocessed GeoTexture data from a single GeoSwath line, showing minor sand ripples that were not resolved by the bathymetry. B) Mosaic from the same area, clearly illustrating how prominent features on the single line GeoTexture become difficult to observe in a mosaic. Post processing of this area is not complete, which will also remove the stripe effect in the coarser sediment (darker GeoTexture).

It is occasionally very difficult to differentiate between bedrock and till outcrops using multibeam or interferometric data. High-resolution single channel seismic data provide a better understanding of the geological setting, especially when attempting to differentiate between these two substrates.

3.6 Seismic data

Analysis of the Topas data did not provide any results regarding the differentiation of till and bedrock (Ellingsen, 2002). The same algorithms were tested in areas of fine-grained sediment, where a sharp change in the Centre of Gravity between clay and fine sand was observed (Figure 8).

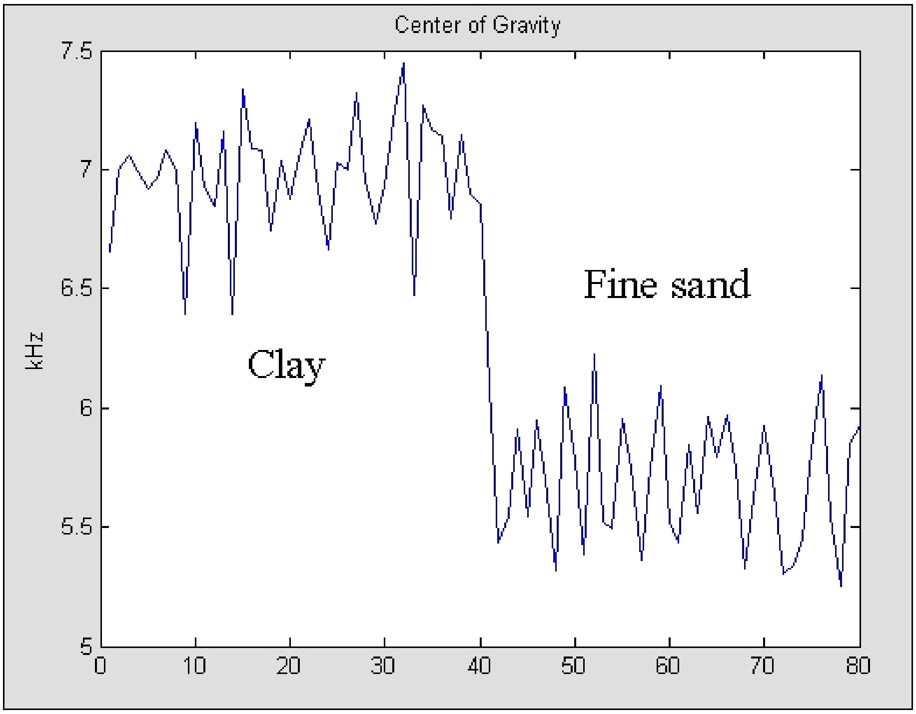

Figure 8, The centre of gravity calculated over 80 traces (x-axis). A clear difference is observed at trace 40, which is acknowledged as the boundary between fine sand and clay.

This boundary was confirmed by grab samples, as visual inspection does not resolve the difference between these fine-grained sediments.

3.7 Video assisted grab

The visual information from the video assisted grab was very useful for determining the seabed properties in areas of gravel and till, where grab samples are difficult to obtain. The video recording could not be used for determination of fine- to medium-grained sediments (clay, silt and sandy sediments), where the grabbing option was possible. However in all sediment types, the large visual footprint was very useful for defining the homogeneity of the seabed, which grab samples do not help determine.

These video recordings also showed how fine-grained sediments were dispersed, as the grab was lowered towards the seabed. This dispersion results in samples where fine-grained material is under-represented. It might, therefore, be more accurate to determine the sediment properties prior to the sampling, possibly by using acoustics.

3.8 Acoustic determination of sediment properties

Plotting the backscatter strength from Nadir versus the critical angle sub-divided the seabed into three categories (Article 1). Interpretation of the critical angle made it possible to calculate the compressional speed. Fitting a theoretical model to these AVA curves allowed four additional physical parameters to be estimated (Article 4).

Being able to determine or at least get a reasonable estimate of the sediment properties prior to grabbing will fit very well the proposed survey strategy.

3.9 Strategy

Through the Sushimap project and other related activities such as Marmodell (Longva *et al.*, 2003), models for predicting the distribution of sediment and kelp forest have been tested (Rinde *et al.,* 2004). This makes it possible to determine areas of special interest prior to survey activity. This knowledge is essential when one species or habitat type is addressed, and it is also important for mobilisation of personnel and equipment when a specific area is to be addressed. These models suit the EUNIS system, but this system has been fairly problematic in Norway, due to the complex nature of glacial sediments that dominate the seafloor. Incorporating new classes could have solved this problem, but instead it was decided to use the scheme developed by Valentine *et al*. (2002). This scheme was tested and works well along the Norwegian coastal line. Seabed texture, hardness and layering in theme III and grain size analysis of theme IV were based on geological interpretation, which is evident from the terminology of the scheme. Seabed texture and hardness as well as layering affect multibeam backscatter. It has also been proved that automatic classification based on multibeam backscatter has a good similarity to geological interpretation. Reconfiguration of the scheme, so that the automatic classification in theme III and ground truthing and geological knowledge are incorporated in theme IV, will make the survey procedure suggested in Article 1 and the interpretation process better linked to the habitat classification scheme.

4.0 Discussion

This work does not contain any detailed comparison between multibeam swath systems. The brands and types of equipment used have all been chosen partly for practical reasons and partly from experience. The data quality or resolution was not found to be a limiting factor during processing or interpretation. A higher frequency system might have provided further information, but this is only a speculation. No documentation was found to show other brands of echo sounder might provide better or worse results than the ones used. It is, however, likely that the experience of using a certain system rather than changing systems will improve the data quality and reduce problems of non-conformity. No information has indicated that other systems should perform better than the Simrad EM1002 multibeam swath system for habitat mapping at this resolution. Other multibeam echo sounders were therefore not considered. The focus has been to extract as much information as possible during acquisition, as well as during processing and interpretation. Finally, it has been important to link the habitat classification scheme more directly with the data and survey strategy.

4.1 Strategy

It is essential that a habitat scheme is adapted to the survey strategy and the physical environment to reduce the workload. The EUNIS scheme has not yet been adapted to the physical environment in Norway, nor has it been streamlined with the survey strategy. The predictive models are well adapted in the EUNIS classification, which should be addressed in further modification of the classification by Valentine *et al.* (2002). The suggested changes to the scheme developed by Valentine *et al.,* will link the proposed survey and interpretation strategy directly to the classification scheme.

The two-cruise strategy that was found best economically and scientifically was very closely linked to the equipment used. The economic benefit would disappear if a larger vessel had to be utilised for the second cruise. Therefore the use of a large and more manoeuvrable ROV was not included in the proposed survey strategy. The scientific reward of the two-cruise strategy is only maintained if grab sampling and video inspection is carried out during the second cruise. The video assisted grab is therefore essential for the survey strategy, even if it does not provide the same opportunities as ROV inspection. The system can be significantly improved by mounting a still camera as well as the video recording on the video assisted grab. A still camera often provides a higher resolution than a video camera, thus enabling a better biological interpretation. Mounting a transponder would increase the positional accuracy and allow higher speed when using the system as a drift camera. The transponder would also allow the position of the camera to be plotted online over the interpretation results of the first cruise in ArcGis.

4.2 Survey methods

Combination of multibeam and interferometric sonar data is essential, as most multibeam systems are too inefficient in the shallow areas. Shallow water multibeam could replace the interferometric system, which would make data comparison easier. The interferometric sonar is, however, recommended for substrate interpretation, as it produces better sonar images of the seafloor. The reduced quality of the bathymetry is not problematic for substrate interpretation. The limited survey periods due to weather conditions, and the danger associated with surveying in the skerries at very shallow waters makes it essential to use a very efficient sonar system with largest swath width. The interferometric sonar is such a system.

Smaller vessels perform shallow water surveys best. These vessels typically have limited space for additional processing crew. It can therefore be essential to consider the workload of processing the data. The interferometric sonar produces quantities of data many orders of magnitude higher than multibeam sonar, due to the increased data density. It has been proven during the Sushimap surveys that one person can acquire and process interferometric data in near real time. Multibeam data processing, which traditionally takes significantly longer time than the acquisitions, often requires further processing personnel. The fast processing of the interferometric sonar data is possible due to the high data density, which makes it possible for filtering algorithms developed in the GeoAcoustics software to run semi-automatically. A few minutes of user interaction for setting filters is required and the same operator can perform the post-processing parallel with acquisition of new data. Newer processing methods such as Combined Uncertainty Bathymetric Estimation (CUBE) (Calder *et al.,* 2003) provide more efficient methods for multibeam processing. The development of these advanced algorithms is likely to be implemented in interferometric processing systems. Interferometric data have the benefit of co-located side scan sonar imagery with the bathymetry. This makes it feasible to perform quality control of the bathymetrical processing, in order to ensure that objects have not been filtered out. Automatic classification of multibeam data is so efficient that it can be performed shortly after acquisition, when the various classes have been determined.

4.3 Classification methods

Classification using the morphological complexity of special habitats has been partly successful in some areas. The conclusion of Bekkby *et al (*2005) was based on a specific area northeast of the test area used in this thesis. The seabed in this area generally comprises clay to coarse sand, with bedrock outcrops. Using the curvature of the seabed to distinguish bedrock was found to be suitable, but the results might have been different if an area comprising glacial features had been used. Classification using the morphological character is likely to be a very useful tool, but is not likely to work on a regional or global scale. The methods developed should be tested locally prior to using the classification results.

Automatic classification is often simple and usually has larger uncertainties than classification performed by a geologist. The test results from some of the automatic classification software were rather poor. The results obtained using the QTC software were of no use for habitat interpretation. QTC was not tested as extensively as for example Triton. An operator error could be the explanation for the poor results and the data was therefore reclassified by QTC. They experienced similar problems, which suggested the errors were within the data due to poor acquisition (personal communication; Glenda J. Rathwell, QTC). This was, however, not confirmed in any other classification or processing software.

Automatic classification using the Triton software was fairly good, but the reduced resolution due the statistical analysis was based on cells that contain four thousand data points (Christensen *et al.*, 2005B). This large number seems inappropriate; there should at least be an option for the user to reduce the number to increase the resolution. The method behind the software, however, is well documented both by Kongsberg and by independent authors, such as

Huseby *et al.* (1993). The lack of information concerning the resolution and a few post-classification filters together with the poor operator control also reduced the confidence.

The automatic classification that provided the best result was based on post-processed mean backscatter strength. It is likely that more information can be extracted using statistical analysis by extracting further parameters from backscatter data. However disregarding the mean amplitude or energy in each sonar trace, and only relying on the shape differences within unit-scaled data, neglects over 80% of the resolving power in the trace (Courtney *et al.,* 2005). This can explain why the simplest method provides better results than the two other methods tested, which disregard the mean backscatter strength.

Fairly good correlation was observed between the geological classes and species such as seapens in softer sediments. The details provided by automatic classification software might be sufficient for most habitat mapping projects.

In Article 5 it was concluded that increasing the number of substrates classified based on multibeam backscatter to more than three would be difficult. Four classes were, however, defined in Article 1. The classes in both articles have a similar geological width. The conclusion should have been concerning the geological width of the classes and not the final number of classes. It will be difficult to reduce the width of the classes due to the stochastic nature of backscatter data.

In general, automatically interpreted boundaries always separate neighbouring classes, which is not the case in the geologic interpretation. It is rare that a change of seabed sediments occurs abruptly, rather than as a gradual transition. Till outcrops in areas of clay is one example of an abrupt change in seabed composition. The automatic classification systems have medium classes in between the fine- and coarse-grained classes. This is an artefact created during the post-processing, when removing the effects of the grazing angle. Backscatter data in this process are averaged over an area. The post-processed backscatter data near sediment boundaries will therefore be an average of two different substrates.

The difference between geologic and automatic classification does not always have to be explained by software error or the software method used. One example is in Haramsfjorden (Article 1 and 5), where the automatic classification shows fine-grained sediments on top of the dune in the deepest part. The geological interpretation did not discover this, although geologically logical. The sand wave field shows a transportation of sand sized material, from west to east, with the large dune in the deeper part of the fjord as the final deposition centre (Article 2). Fine-grained material will be transported through the sand wave area and directly into the deeper basin. As the deeper fjord seems to function like an eddy, the materials deposited in the dune will contain finer grain sediments than the sand dunes to the west. This is clearly missed in the geological interpretation. Side scan sonar data might better resolve sediment changes like these as well as minor features.

The conclusion in Article 3 was different, however, as it was concluded that the multibeam interpretation was more correct than the side scan sonar interpretation. The difference between the two interpretations is most likely caused by the difference of interpretation strategy. The side scan interpretation overestimates the presence of corals, while the multibeam interpretation is conservative. The shadows and poor positioning of the side scan fish, reduced the confidence of the side scan sonar interpretation. The higher resolution of the side scan sonar compared to multibeam data makes it likely that areas comprising minor coral reefs or a thin coral cover can be interpreted using side scan sonar. These features are not likely to have a topographical expression that can be resolved using multibeam bathymetry data.

The results of detecting coral reefs using RoxAnn have proven ideal, but as the software has to be calibrated the usability of the methods might be limited. The methods of calibrating the software are based upon a certain transect located outside Bergen harbour, where the system is adjusted to obtain certain values along this transect. It should be possible to obtain a less area-specific calibration technique.

The use of the centre of gravity of the Topas frequency for differentiating between till, bedrock and coral was probably a poor strategy. These three seabed types were characterised by a large roughness. The preliminary results indicate that the methods may prove useful in differentiating between different fine-grained sediments. Differentiating between these sediment types has been problematic using other methods. Many newer sub-bottom profiler systems utilise the Chirp pulse and it is possible that the broader frequency band also could be utilised to improve seabed classification.

4.4 Amplitude Versus grazing Angle method for seabed determination (AVA)

The comparison between the backscatter strength versus grazing angle in this work (e.g. Figure 4) and in some of the published articles (e.g. Beyer *et al.,* 2005) was significantly reduced at nadir. This does not affect the AVA model significantly, as this model was designed to predict the backscatter strength at low grazing angles. The observed difference could be attributed to errors in removing the beam pattern effect or/and to acquisition- or processing errors. This has been investigated, but no such errors were found to be associated with the data used in this work. The correctness of the backscatter in this paper is supported by publications that have similar shape and values (e.g. Hughes-Clarke *et al.,* 1997 and Novarini *et al.,* 1998).

The correlation between grain size and backscatter strength at grazing angle interval between 50˚ and 55˚ shown by Unger *et al.* (1998), showed a significant variation of the backscatter strength. It is likely that extraction of the backscatter strength at a certain grazing angle rather than from an interval, will reduce the variance and thereby improve the result. Extraction of the backscatter strength from a predetermined angle is simpler than determining the critical cusp first, as used in the AVA method. The determination of the grazing angle is, however, used to calculate the compressional speed directly. Combining this with theoretic models made it possible to extract four additional geoacoustic parameters of the seabed sediments.

Parameters estimated from a model using the backscatter strength are sensitive to corrections of attenuation, gain, area coverage of various beams and pulse length variations. Significant changes in backscatter strength with respect to plankton depth have also been noticed (Van Holliday, BAE Systems, ICES study group on Acoustic Seabed Classification, Bergen meeting 2003). To resolve the presence of large amounts of plankton or other minor species requires very high frequency echo sounders, especially designed to acquire information about the water column. These are very rarely used for surveys designed for seafloor mapping. Plankton and other fauna or sediment particles in the water-column can therefore add a significant error to the backscatter strength.

The similarity between the model and the measurements used to determine four Geoacoustic parameters was not ideal for coarse-grained sediments (Article 4). The results for finer sediments (clay) was however encouraging and showed good correlation to published geoacoustic parameters. Sampling and handling of cores and grabs introduces some significant changes to the samples, which in turn introduces errors to the laboratory results. This led to the conclusion that AVA methods might be more accurate than laboratory measurements. The backscatter data used in Article 5 are of very high quality and the geological conditions favoured the AVA method.

The position of the cusp is not affected by the backscatter strength, but only by the acoustic speed of the substrate and the seawater. The determination of the compressional speed is, therefore, not as dependant upon the post-processing of the backscatter as the other parameters. It should be possible to develop an algorithm that can extract the compressional speed automatically. There are, however, some problems with acquiring data over the critical angle, as it demands a relatively large swath. This makes the AVA method difficult to use in deep waters, where the swath width is normally reduced to maintain the high resolution of the bathymetry data.

The overall backscatter strength allowed the classification of three substrates, which represent fine-, medium- and coarse-grained sediments (Article 5). The AVA technique does not resolve any further substrate classes at present (Article 4). The method showed a different AVA response from corals, which were also resolved from the normalised backscatter as the normalisation was performed from 45°. However, the AVA technique will increase the certainty of sediment classification, and possibly enable the resolution of special biota, such as sponges. Backscatter strength from sponges is distinctly low at nadir (Figure 9; Longva *et al*., 2003). It has been speculated that the increased roughness due to the presence of sponges will generate high backscatter strength at low grazing angles.

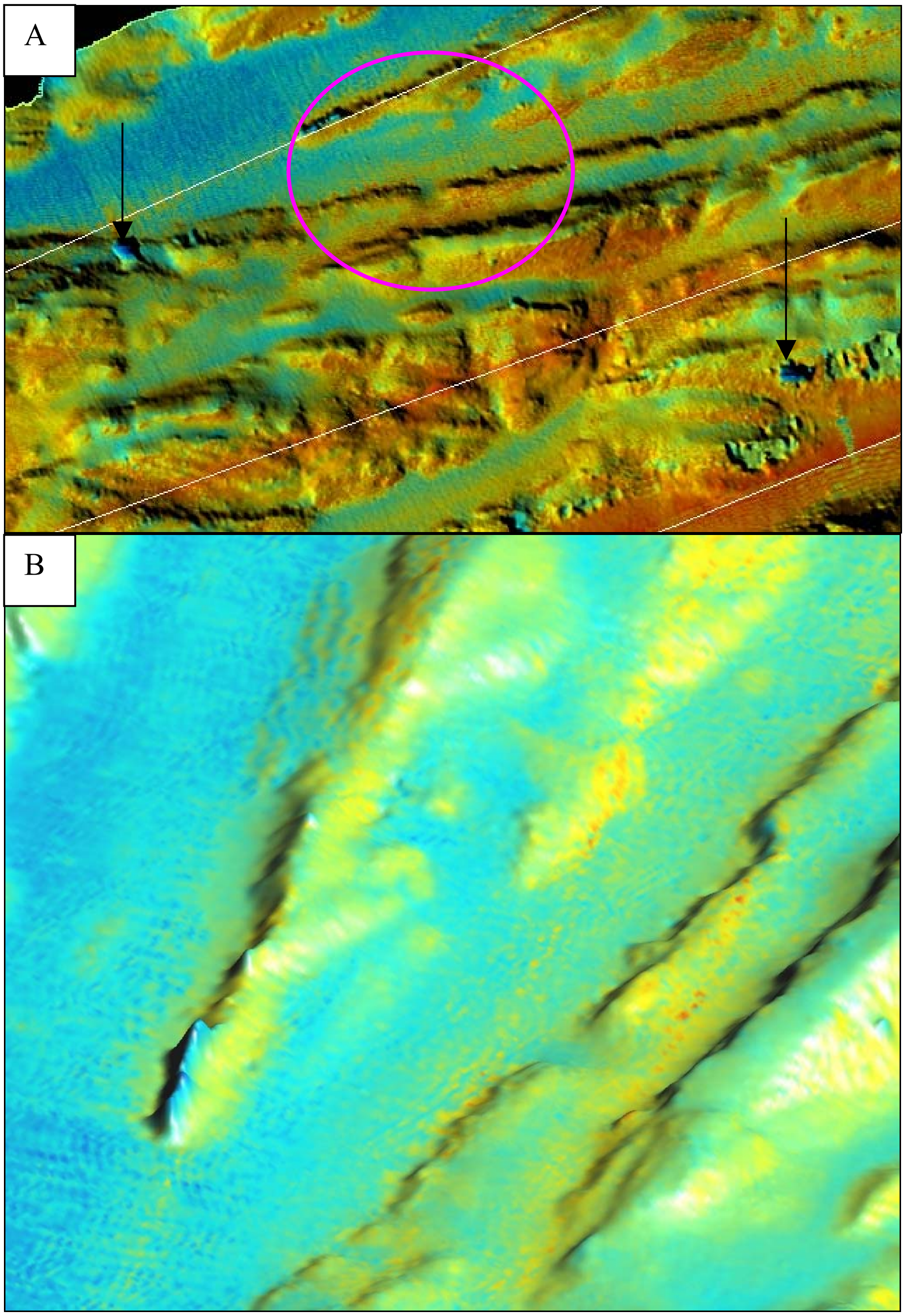

Figure 9, A) Unprocessed gridded backscatter data North of Jøa, Norway. White lines show nadir response. Several locations showed very low backscatter strength. The two locations marked with arrows are interpreted as spikes, due to the bathymetrical nature and the very low backscatter strength. Combining backscatter and bathymetry can possibly be useful during acquisition and processing *for quality control of multibeam processing. B) A pseudo 3D view of approximately the area shown in figure A. This shows that the low backscatter is related to the clay between the outcropping bedrock ridges and at a minor part of a bedrock crest, which is confirmed to comprise sponges.*

The AVA methods can be very useful, when applying the suggested survey strategy. The geological interpretation commences on a reduced ground truthing program. Any information that can help classify the substrate, prior to the larger ground truthing cruise, would be very useful in the habitat interpretation and for planning the second cruise.

A similar method for determining sediment properties was proposed by Chakraborty *et al.* (2000) and Beyer *et al.* (2005). Chakraborty *et al*. also avoided using backscatter data near nadir and fitted data from around 80˚ to 45˚ grazing angle to the composite model from Jackson *et al.* (1992). The two models in the composite model were spliced at the 70˚ degrees grazing angle, utilising Helmholtz-Kirchhoff from nadir to the splicing point and the Rayleigh-Rice at lower grazing angles. This method is very similar to the work in this thesis, but the main difference is that the region near nadir data is completely ignored here and only the backscatter strength from the low grazing angle was taken into account. In order to resolve the critical angle this work considered lower grazing angles than in Chakraborty *et al.* (2000) and Beyer *et al.* (2005). The first step by Beyer et al. is similar to this work, i.e. processing backscatter data to obtain a homogenous image of the seafloor. The normalised backscatter strength is then linked to grab samples. Beyer *et al.* tested a semi-empirical approach using angular backscatter response. A regression fit to the mean angular backscatter response and the slope of the regression fit are used together with an estimation of a predicted backscatter response at the 20˚ incidence angle and the average ratio of the standard deviation to the mean (i.e. the coefficient of the variation). The application of the semi-empirical approach employed to the angular backscatter data provides three major parameters to classify the seafloor provinces (Beyer *et al.,* 2005). The increased number of parameters compared to the processed (normalised) backscatter is likely to improve the classification. The classification is a relative classification and from this work it is not possible to extract physical properties of the substrate directly. The model used by Beyer *et al. (2005)* is dependant upon accurate backscatter measurements near nadir. The near nadir region is in general the hardest place to acquire estimates of the backscatter strength. Given the amplitude detection methods generally employed (weighted mean time), the estimate may not correspond exactly to the peak intensity and thus underestimates of the backscatter strength can occur. Another problem that occurs close to normal incidence is the effect of sidelobe interference and sub-bottom reflections, which both alias the estimate of slant range and contribute to the received intensity, thereby giving false estimates of the backscatter strength (Hughes Clarke *et al.,* 1997). Fonseca *et al.* (2005), also made an attempt, but their idea was based on results obtained by multi channel seismic data. Rather than cross-plotting values from different offsets, backscatter strength from near nadir and medium and low grazing angles were cross-plotted.

The method developed in this work emphasized obtaining geoacoustical parameters of the substrate directly and is not only to be used as a relative classification technique. Only backscatter data from low grazing angles were used to avoid the uncertainties at near nadir.

4.5 Habitat maps

This thesis does not contain a habitat map, but only maps showing physical, geological or biological distribution. The results from these maps show that many of these themes are closely linked. The biological distribution of individual species is important for understanding habitats, but not enough. The mobility of the species, growth rate and mortality must be incorporated. Continuous monitoring either acoustically or by marking a large number of each species is strongly recommended. This would show which physical or geological habitats are attractive for the different activities and in different life stages for individual species. Feeding and breeding grounds are probably the most critical habitats to locate. If these locations are vulnerable for mechanical disturbance, which can be caused by fishing activity, it might be beneficial to relocate fishing activity to other habitats where the species are located in other stages of their life cycle.

A better understanding of the fish behaviour could possibly locate the habitat where fishing activity makes the smallest impact on the environment as well as the life stock.

5.0 Publications

5.1 Article 1

Marine facies mapping using multibeam backscatter.
Accepted to the "Marine Benthic Habitat mapping", ed. Brian Tood and Gary Greene

MARINE FACIES MAPPING USING MULTIBEAM BACKSCATTER

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Keywords; EM1002 Multibeam, Multibeam backscatter, Bathymetry, AVA sediment classification, Acoustical seafloor mapping,

Abstract

Marine facies mapping was performed automatically and manually using multibeam bathymetry and backscatter data. The automatic classification was based on backscatter data and provides the most sensible result, using a few broad geologically classes. Minor details are not revealed in the automatic classification, due to difficulties correcting for angular dependency and reduced resolution. Backscatter mosaics reveal more details, but the automatic classification provides valuable information for the untrained eye, and for generating facies charts.

Manual interpretation using a combination of backscatter mosaics, bathymetry and regional knowledge in pseudo three-dimensional environment, made it possible to map more than twice as many facies classes. This is however a time consuming process, which is not likely to be performed offshore during multibeam acquisition, unlike the automatic classification.

Sediment properties were extracted from video-assisted grab, samples and STING (free-fall penetrometer). Acoustic analysis using backscatter strength from two beam angles had a strong correlation to the different sediment types.

These data were acquired for testing a cost cutting two-cruise strategy. The first cruise included acoustic acquisition and a reduced

ground truthing program based on automatic classification. The second cruise utilised a smaller vessel, performing a larger ground truthing program based on manual interpretation.

Introduction

The fjords and the coastal areas of Norway have a very rugged topography, due to repeated phases of tectonism and glacial erosion (Holtedahl, 1960). This rugged topography represents a safety hazard when using deep-towed equipment, such as side scan sonars. The introduction of commercial hull mounted multibeam echo sounders in the 1980s made it possible to acquire accurate information of the seafloor morphology and acoustic properties, even in areas with a very rough seafloor.

The last decade has witnessed an increasing use of multibeam swath systems, primarily for bathymetric mapping. These systems have been in a constant development, improving accuracy, resolution and coverage for the bathymetric data. Minor attention has been paid to the backscatter data and the use of these data for seafloor classification. This is partly related to problems processing multibeam backscatter data, such as correcting the angular dependence (Parnum *et al*., 2004). This paper will investigate how much information can be extracted automatically using multibeam backscatter and manually using a combination of backscatter data with bathymetry for geological facies mapping. The object was to test and improve procedures for mapping and classification using multibeam data, with existing algorithms and software.

Survey area

The survey area consists of parts of four fjords surrounding three islands, Figure 1. in a coastal setting in the Møre area, western Norway.

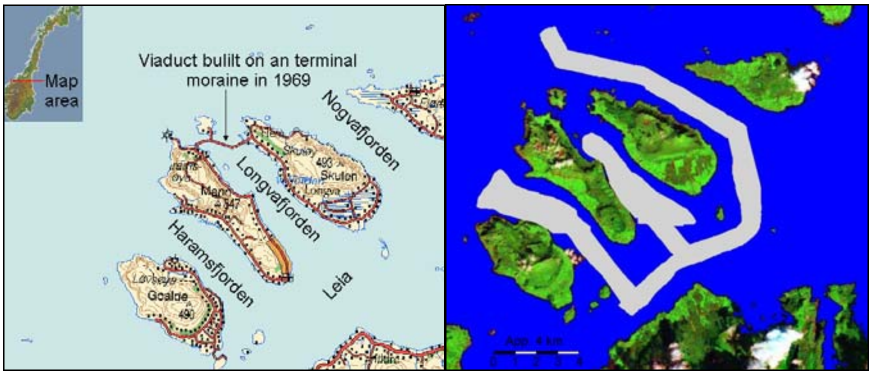


Figure 1, A) Geographical map, showing names and setting of the survey area B) The survey area (grey), showing the 38 kilometre long multibeam corridor superposed on a NASA satellite image.

The seabed is dominated by sediments deposited during and since the last glaciation, with local outcrops of crystalline bedrock. Glacial sediments termed till has a mixed grain size, ranging from clay to cobbles. Post-glacial, hemipelagic sediments in the area range from clay to coarse sand (Larsen *et al.,* 1988). Stronger tidal currents in Haramsfjorden and Nogvafjorden (Moe *et al*., 2003) have given rise to coarser sediments compared with the sediments found in Longvafjorden which is partly blocked towards the open sea by a viaduct built in 1969, figure 1. The viaduct was built on a terminal moraine. The moraine led to a restricted circulation since c. 9.000 BP, when the sea level dropped to approximately the level of the moraine threshold, except for a period of improved circulation during the Tapes transgression in Mid Holocene time (Larsen *et al*., 1988). The fjord has therefore acted as a sediment trap for fine-grained, hemipelagic deposits covering a number of glacial ridges. Nearly buried moraine ridges are outcropping within the soft sediment (Larsen *et al*., 1988).

Methodology

An EM1002 multibeam echo sounder was used for acquiring bathymetry and backscatter data. These data are the basis for the geological facies interpretation, which was performed automatically using the Kongsberg-Simrad software Poseidon and Triton as well as manually interpretation. Ground truthing was performed using a STING seabed penetrometer and a Van Veen grab, which was rigged up as a video assisted grab (Mortensen et al., 2000). Grab samples and STING data were analysed onboard.

Multibeam acquisition

Multibeam data were acquired using a Simrad EM1002 system hull mounted on H. U. Sverdrup II. This system utilises 111 beams with a ping rate of more than 10 Hz. Compensation for heave, roll, pitch and heading was performed using the integrated MRU5 motion sensor and the Seapath 200 system. Equidistance beam setting and a constant absorption coefficient were maintained throughout the survey.

The EM1002 operates at two frequencies, 98 kHz for the inner part of the swath (beam angles less than 50º) and 93 kHz for the outer part of the swath (beam angles higher than 50º) (Mosher *et al*., 2002). This is likely causing a change in the backscatter strength (O. Christensen *et al.,* Geological survey of Norway, in prep.).

Water column sound speed data were calculated from measured conductivity, depth and temperature acquired using a Neil Brown MK 2 CTD. Several stationary casts were performed through the survey. These results were fed into the Simrad processors for instantaneous beam forming and ray tracing of individual beams.

The survey area was restricted to water depth shallower than 200 metres, to avoid a change of the pulse length. The pulse length increases from 0.2 ms to 0.7 ms at 200 meters using an EM1002 (Hare, 2001). These pulse length changes are likely to improve the bathymetrical resolution, but also change the acquired backscatter strength and thereby the mosaics (Preston *et al*., 2001).

Multibeam processing

The mean backscatter for each beam was used for both automatic and manual interpretation. The data were corrected for signal strength, source level, and transmission loss during acquisition. No correction for the slope was performed, as this was not an option within the used software. A manual correction could have been performed using one of many published methods, but this might introduce artefacts and was therefore avoided. The data were used for the manual interpretation, with no further processing or correction. For the automatically classification, further processing was performed using the Poseidon mosaic and Triton classification software.

Multibeam data were processed onboard using a Kongsberg-Simrad software suite. Backscatter mosaics were created using Poseidon that corrects variation of the backscatter strength due to the beam angle, using a combination of logarithm scale for the centre beams and Lamberts law for outer beams (Kongsberg-Simrad, 2000). Data from beam angles higher than 67° were removed in Poseidon, but smoothing filter was avoided to maintain maximum resolution. Poseidon also offers contrast filters and histogram correction, but neither of these were used. The contrast filter is used to detect objects that have a stronger reflectivity than the background (Kongsberg-Simrad, 2000), but only lead to an increased stripe affect within the survey area. The histogram correction contains information about the average beam reflectivity (Kongsberg-Simrad, 2000), which should reduce the stripe effect. Several attempts were performed, without any significant improvement of the mosaics.

Triton is Kongsberg-Simrad software's module for seafloor classification, which uses a statistical method for seabed classification from backscatter data. The classification rule is derived from Bayes decision rule and involves a probability model of the features extracted from the multibeam data (Husby *et al*., 1993). The software uses predefined classes for the classification, where five different extracted statistical features describe the classes (Kongsberg-Simrad, 2001). The seabed within the survey area was initially subdivided into seven classes on the basis of four statistical features (quantile, pace, contrast and the mean value). This was reduced to four classes to obtain a more sensible classification.

Video assisted grab

Ground truthing was performed using a Van Veen grab and free-fall penetrometer, during the first cruise. A video camera was mounted to the cable, approximately 1 metre above the grab (Mortensen *et al*., 2000), during the second cruise. The system was then used as a drift camera over facies boundaries, which made it possible to both investigate the position of facies boundaries and the sediment properties (Figure 2). Layback was calculated using water depth and cable length and manually applied. Position of facies boundaries was plotted and used in the manual interpretation, and for validation of the automatic classification.

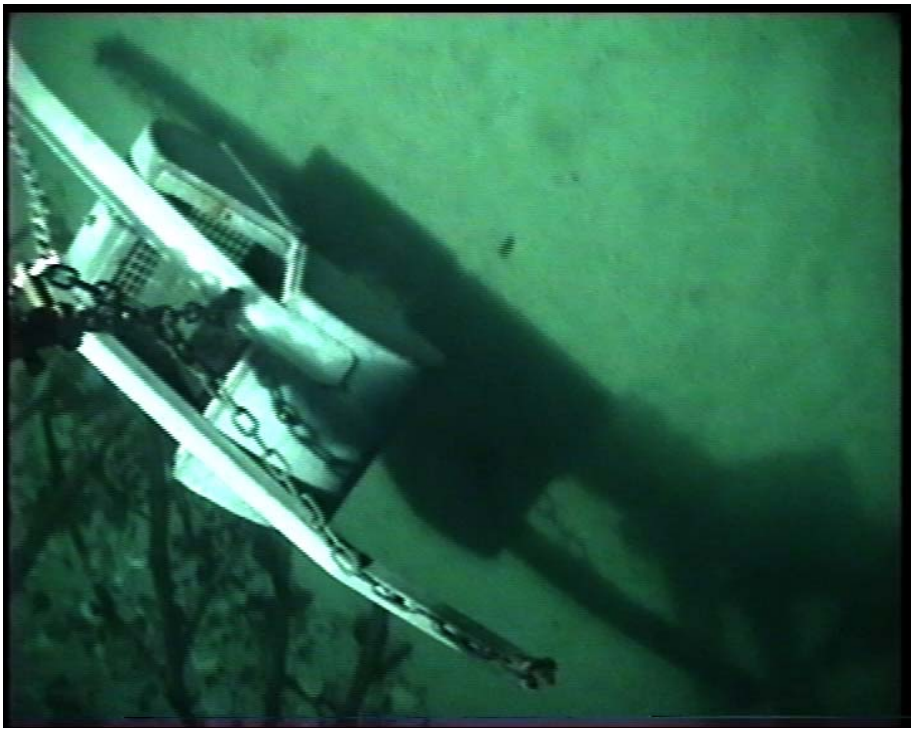


Figure 2, visual inspection of a sediment boundary in Nogvafjorden, between till to the bottom left and shell sand in the upper right. Width of grab is 25 centimetres.

In areas of till and bedrock, video inspection was used as the main ground truthing method, as these bottom types are difficult to sample using a small grab.

Seabed penetrometer

A free-fall penetrometer, STING MK II, was used to measure the bearing strength of the seabed. The STING consists of a one metre long shaft with a diameter of 19 mm and a replaceable foot wider than the shaft. The foot can be changed to match anticipated bearing strength. An instrument house that contains an accelerometer to record the deacceleration as the shaft enters the seabed tops the shaft. Logging commences when the STING is at a pre-selected water depth. Data is then logged for up to two minutes, which allowed a sequence of up to eight impacts to be recorded. The STING software calculates bearing strength versus depth for each of the impacts, together with statistical variance between the impacts completed during the sequence.

Manual interpretation

The first step was to manually sub-divide the seabed into a maximum number of polygons, representing different acoustic or morphological properties. In order to avoid any artefacts from processing algorithms, unprocessed backscatter data were used. The stripe effect was recognised during the manual interpretation, but had very little effect on the result, as the interpretation scientist was aware of this effect.

Extensive colour and image enhancement of the backscatter data were used to bring forward the difference in both texture and backscatter strength (Blondel and Murton, 1997). The interpretation was performed in a pseudo three-dimensional environment. This allowed the seafloor morphology from the multibeam bathymetry to be integrated with the backscatter data in an optimal way. This allowed a combined use of bathymetry and multibeam backscatter strength as shown in figure 3. Features such as sand waves can be observed using the bathymetrical data. In this case sand waves have low backscatter strength, which indicates softer sediments compared to the surrounding sediments (Figure 3). Video inspection and grab samples confirmed the sand waves to comprise shell sand and the surrounding areas to comprise till

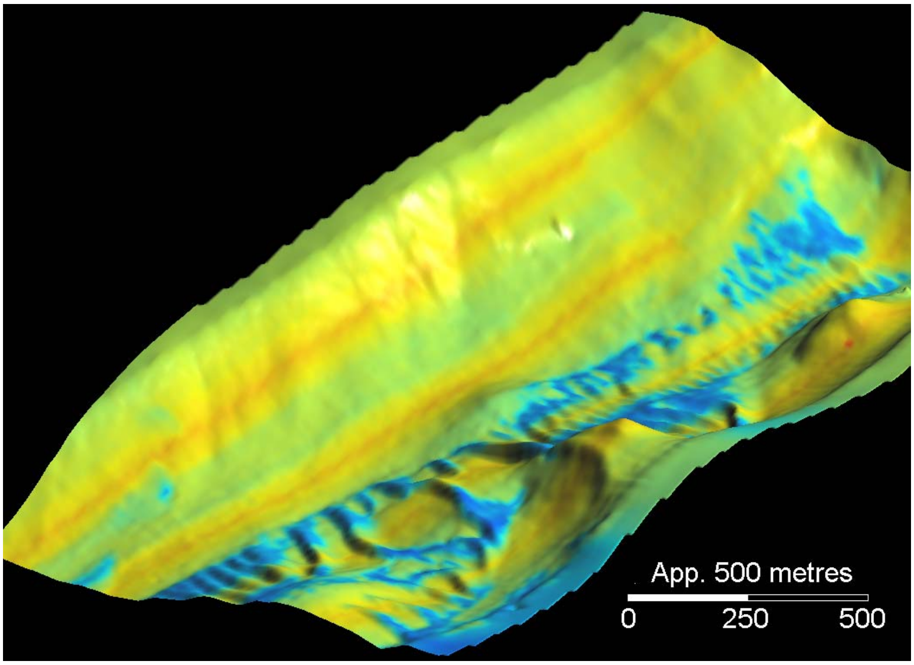


Figure 3, 3D model with unprocessed backscatter data draped over bathymetry, with a manual adjustment of the colour-scale for the backscatter strength. Sand waves comprising shell sand have low backscatter strength (blue). Shell sand is deposited on a till surface, which has high backscatter strength (yellow to orange). Water depth ranges between 26 metres to 54 metres.

Acoustic sediment classification

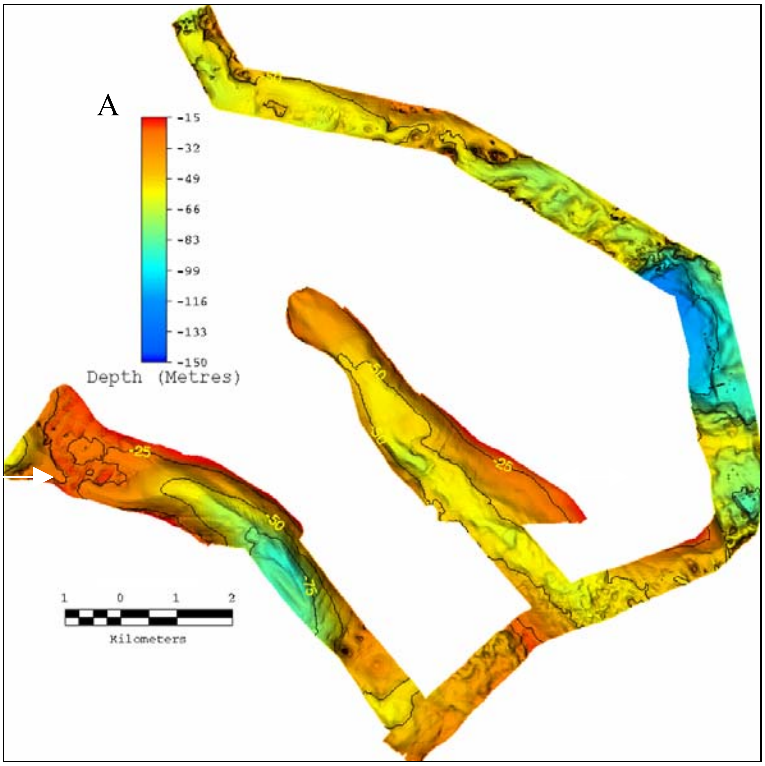
To test acoustic sediment classification using multibeam backscatter data, AVA (Amplitude Versus Angle) analysis was carried out. Fifty locations with known sediment composition, based on grab samples, video inspection and STING measurements were used for this test. The analysis is based on cross plotting the backscatter strength from normal incidence (nadir) versus the backscatter strength at the critical angle. Backscatter strength along the swath was extracted from grids, produced for individual survey lines, using the mean backscatter strength for each beam. Beam angle and grazing angle was calculated using distance to vessel track and bathymetry.

Maximum backscatter strength is observed at normal incidence, which correlates to nadir where the seabed is flat. In practice scattering strength is observed to increase rapidly at high beam angles (low grazing angles), which is within the pure surface scattering domain (Jackson and Briggs, 1992). The critical angle is located at the position where the overall backscatter strength is no longer a function of pure surface scattering, but a mixture of volume and surface scattering. This angle is associated with a distinct cusp (local maximum) in backscatter strength (Hughes Clarke, *et al*., 1997). This angle has been suggested to give an estimate for the seafloor sediment velocity (Hovem, 2000).

Results

The water depth in the survey area varies from 15 to 150 metres (Figure 4A) with the seafloor slope between 0 and 21 degrees (Figure 4B). The steepest slopes are located along the margins of moraine ridges, but the larger part of the surveyed area is relatively flat (Figure 4B). The slope effect on the backscatter strength is assumed minimal for the larger part of the survey area, but more significant near moraine ridges. Bathymetry data within Haramsfjorden and Nogvafjorden indicate a rougher seabed compared to Longvafjorden. This indicates the presence of coarser sediments within these fjords compare to Longvafjorden. This was expected due to the restricted circulation within Longvafjorden caused by the presence of a terminal moraine and the viaduct (Figure 1). The restricted circulation is also confirmed by tidal current modelling, which shows a weak tidal current in Longvafjorden and stronger tidal currents in both Haramsfjorden and Nogvafjorden (Moe *et al*., 2003).

In general high backscatter strength within the survey area is related to glacial sediments, while low backscatter is related to post-glacial, hemipelagic sediments. This is clear within Longvafjorden, where moraine ridges outcrops in areas of softer sediments (Figure 4C). High backscatter strength also reveals dredged till within three locations in Longvafjorden, marked by circles in figure 4C. This till was dredged in this area during harbour constructions in the 1970s.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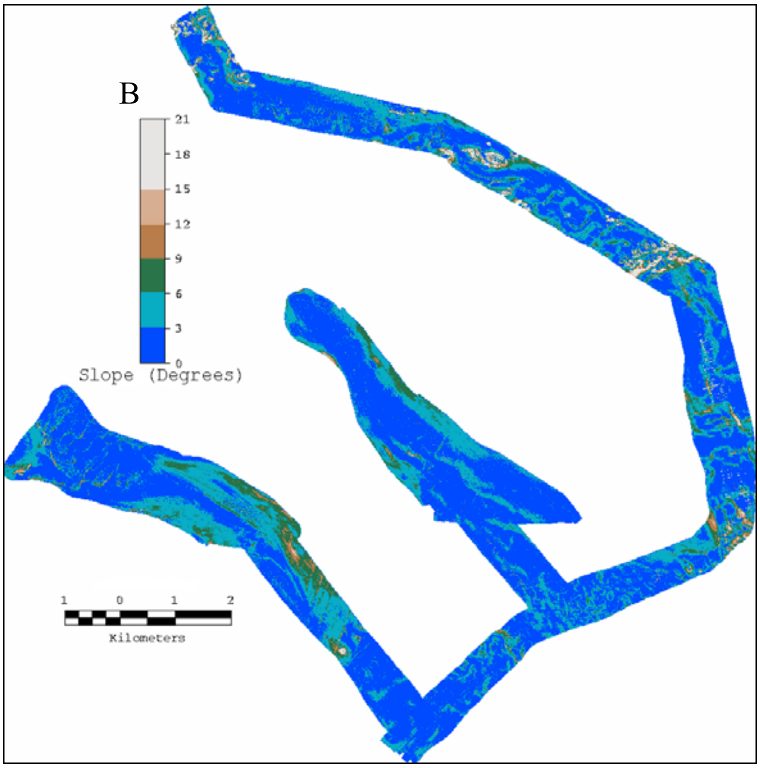
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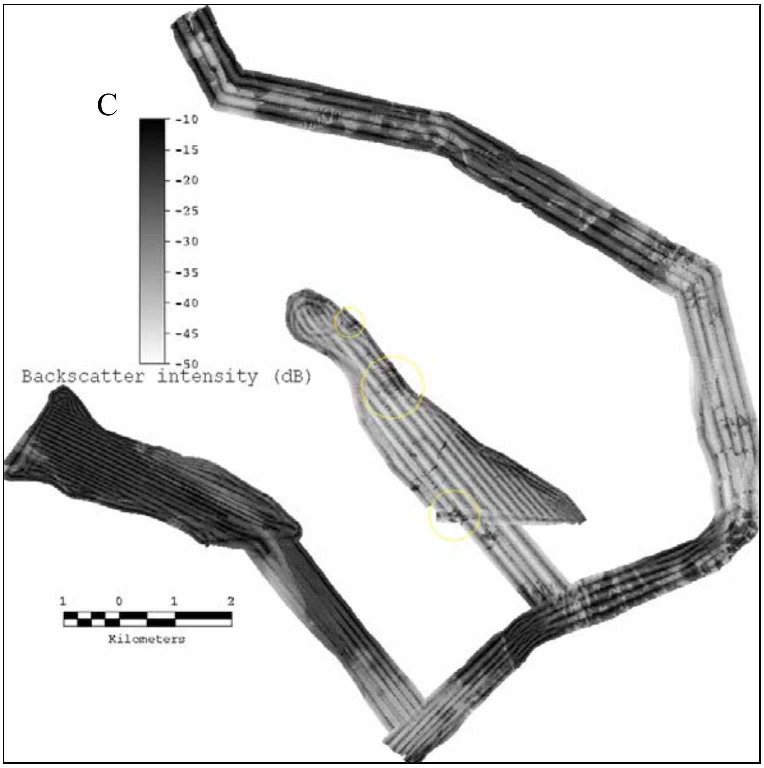

Figure 4. A) Sun shaded bathymetry data with 25 metres contours, showing the smooth seafloor in the Longva fjorden and many of the larger glacially created features through out the area. B) Slope of the seafloor in degrees. C) Gridded unprocessed multibeam backscatter, darker tones are associated with higher backscatter strength. Circles surround areas where dredged coarse-grained material was observed.

Automatic classification

Automatic classification was performed using Kongsberg-Simrad software, Triton. A probability value of 0.05 was used to classify. Pixels with a membership probability less than this were classified as outliers. Tests within the area showed that this value provided the best result. However, the initial classification using seven classes made no sense, as ground truthing using video-assisted grab and Sting seabed penetrometer, showed similar sediment types across sediment boundaries suggested by this classification. In order to avoid this, the number of classes was reduced. The best results were achieved by reducing the number of classes to four. This gave a unique sediment type for each class. Minor outcrops and smaller areas of sediment could not be resolved in Triton. These areas occur in different classes and occasionally resulted in classification errors.

The sediment boundaries were segmented and linear. These boundaries were therefore smoothed, using a smoothing filter with a size that equals 15 cells (Figure 5).

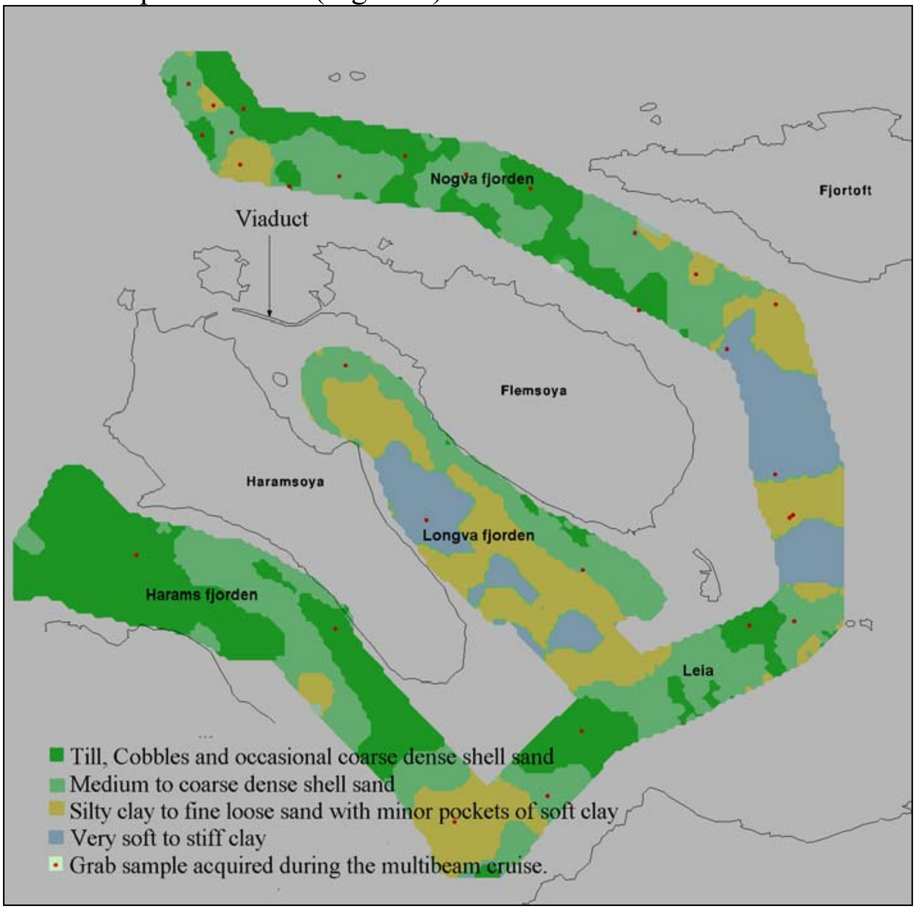

Figure 5, Triton generated sediment classification chart. This chart was used to design a reduced ground truthing program using a Van Veen grab and STING during the multibeam acquisition cruise.

Manual interpretation

All data and methods described in this paper combined with local knowledge from both scientists and fishermen were used to perform a manual geological facies interpretation (Figure 6). This map is the first step in producing a wider habitat map where biological diversity, as well as geological and oceanographic processes shall be included.

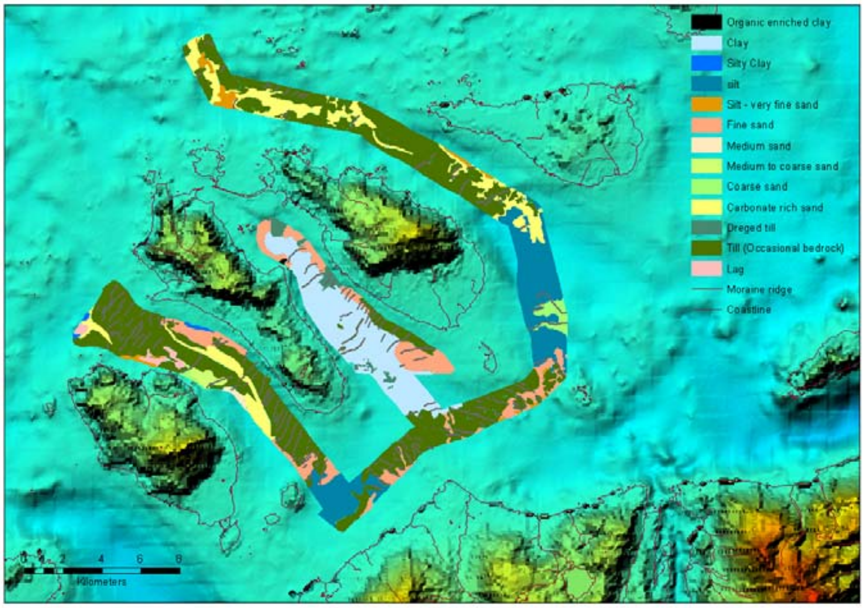

Figure 6, manual interpreted geological facies map using all available information and techniques described in this paper.

Multibeam bathymetry can be used to differentiate between bedrock and till. There is however significant possibility that a morphological interpretation of this is not correct. Ground truthing is therefore recommended, using visual inspection that has proven the most efficient method. This will still be a major task. Outcropping bedrock is mainly observed in areas of till with limited Holocene sediments. The only exception found in the survey areas is located within Longvafjorden (Figure 7). It was therefore decided to integrate these two types of substrata into one single class (Figure 6).

The central part of Longvafjorden will serve as an example to illustrate the increased resolution of facies achieved by combining bathymetry and backscatter data (Figure 7). Manually backscatter interpretation made it sensible to sub-divide the seabed into three classes according to backscatter strength. High and low backscatter strength units dominate the area, while units with medium backscatter strength are visible only in the top right corner of figure 7A. Using the multibeam bathymetry made it possible sub-divided areas of to high backscatter strength into three classes (Figure 7B). The elongated high reflectivity areas in the central part of figure 7A are morphologically distinct ridges (Figure 7B). The ridges are typical moraine ridges, comprising till. The irregular shape of the high reflectivity area in the lower right corner of figure 7A does not have the same distinct morphological signature. Local people confirmed that till were dredged in these areas for construction purposes. The last high reflectivity class occur in the upper left corner (Figure 7A). The irregular outline, high backscatter strength and steep slopes led to bedrock as the preferred interpretation, which was confirmed by video.

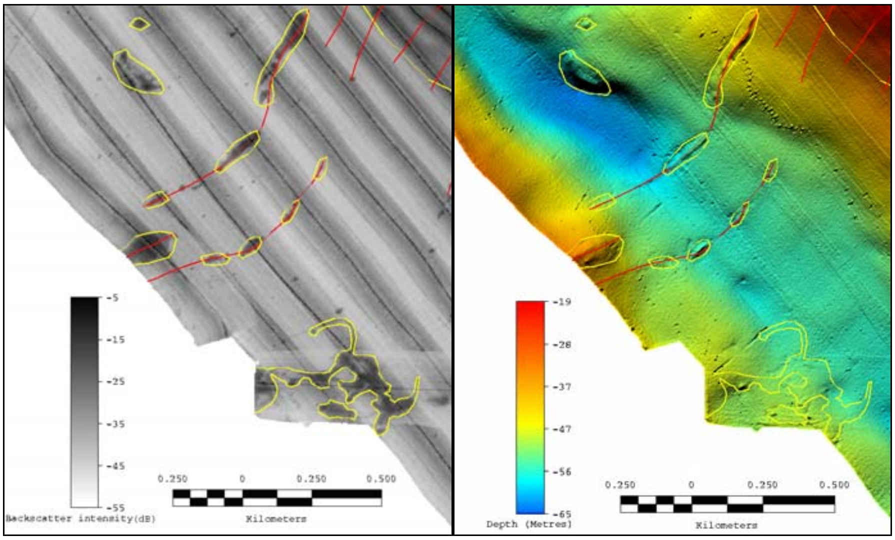

Figure 7. A) Multibeam backscatter image from the central part of Longvafjorden. Low backscatter strength - clayey sediments; medium backscatter strength (in the north-eastern part) – fine sand; high backscatter strength - Till and bedrock. Red lines - the crests of moraine ridges. B) Multibeam bathymetry shaded relief image of the same area. B – bedrock; DT – dredged till. Red lines – moraine ridge crests.

Acoustic sediment classification

Cross plotting of backscatter strength from the nadir and the critical angles makes it possible to separate the substrata into three sediment classes (Figure 8). These classes comprise clay, coarse sand and till + lag deposits and are separated using both hardness (Y-axis, Figure 8) and roughness (X-axis, Figure 8). Other sediment types like carbonate rich sand displayed variable backscatter strength.

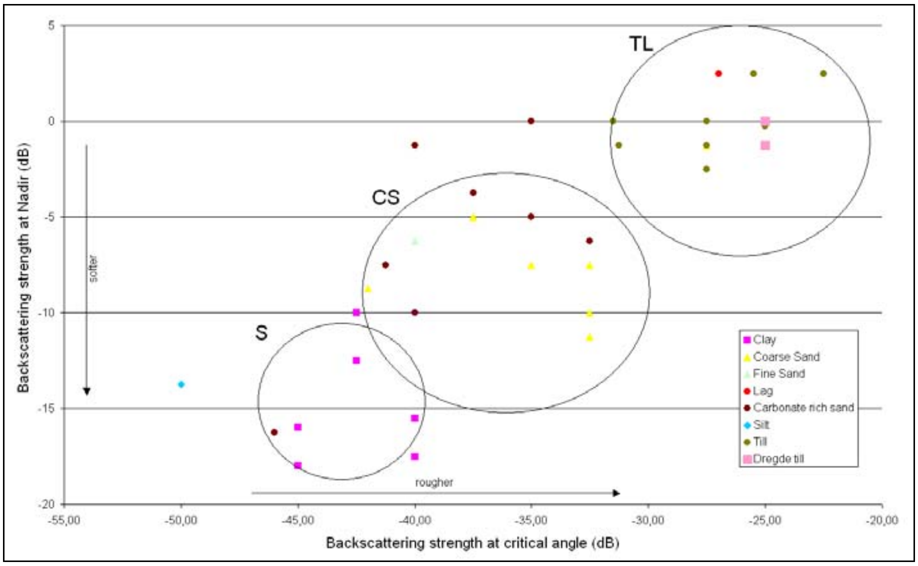

Figure 8. Cross plot of multibeam backscatter strength from nadir and critical angle, from fifty locations where sediment types were confirmed by ground truthing. This was used to test acoustic sediment classification. Circle codes: C – clay; CS – coarse sand; TL – till and lag deposits.

Video assisted grab

Facies boundaries between coarse- and fine-grained sediments could be determined using visual inspection (Figure 3). These recordings made it possible to separate till and bedrock. In areas comprising fine-grained sediments, visual inspection was of limited use for determining sediment properties. Instead, grab samples were used.

Discussion

Video assisted grab

The video assisted grab is an efficient tool, as the visual inspection is useable in areas of hard and coarse-grained substrata where grab sampling normally fails. In areas of fine-grained sediments, grab samples provide the essential information. The visual recordings would often resolve the homogeneity of the seabed, and thereby reduce the chance of linking samples located in minor pockets of substrate to larger areas.

Recording from video assisted grab have documented how fine-grained sediments and low-density carbonate is suspended and removed as the grab is lowered. Fine-grained sediments or low-density components sediments in grab samples are therefore likely to be underestimated.

Seabed penetrometer

Within the upper parts of the seabed sediments, boulders or harder inhomogeneities can be analysed using the bearing strength data. Strong correlation between bearing strength, grain size and porosity has been documented (Preston *et al*., 1999). Neither porosity nor an accurate measurement of the grain size was performed in the survey area and the use of STING data was limited. It is believed that combining bearing strength data and other sediment parameters will show a strong correlation with backscatter data.

Poseidon mosaicing software

Mosaics created using Poseidon are very useful for trained geologists, and a detailed geological interpretation can be performed using these. High backscatter strength at nadir is observed in all created mosaics. This is caused by an incorrect angular correction, which is based on a combination of a logarithm correction and Lambert's law. Lambert's law rests on a particular assumption concerning the redistribution of scattered energy in space, (Urick, 1996). The general simplicity of Lamberts law makes it difficult to fit real data to the modelled data, especially at higher grazing angles, and it is inappropriate for near-specular scatter (Novarini and Caruthers, 1998). Correcting for angular dependence of backscatter is a problem still not resolved (Parnum *et al*., 2004). It is recommended that the angular dependency problem should be addressed prior to further development of automatic classification tools.

Triton classification software

The resolution in Triton is lower than the resolution in Poseidon, as data points are merged into cells for extraction of statistical parameters. Each swath is sub-divided into four sectors (Figure 9), which is a reduction from 111 data points acquired within each swath. Along track merging occurs, as each cell in Triton comprises 4000 data points (J.O. Bakke, Kongsberg-Simrad, personal communication, 2005). This gives an impression of a reduced stripe effect, but is in reality is due to a reduced resolution. It would appear that smaller cells would be more appropriate for seabed classification. A reduced cell size is likely to generate a more accurate lateral interpretation, but also introduce numerous sporadic classification points. This could possible be removed by using smoothing or more advanced filters. It is however important that the user can control the size and the use of cells and filters so that the accuracy for the classification can be clearly documented.

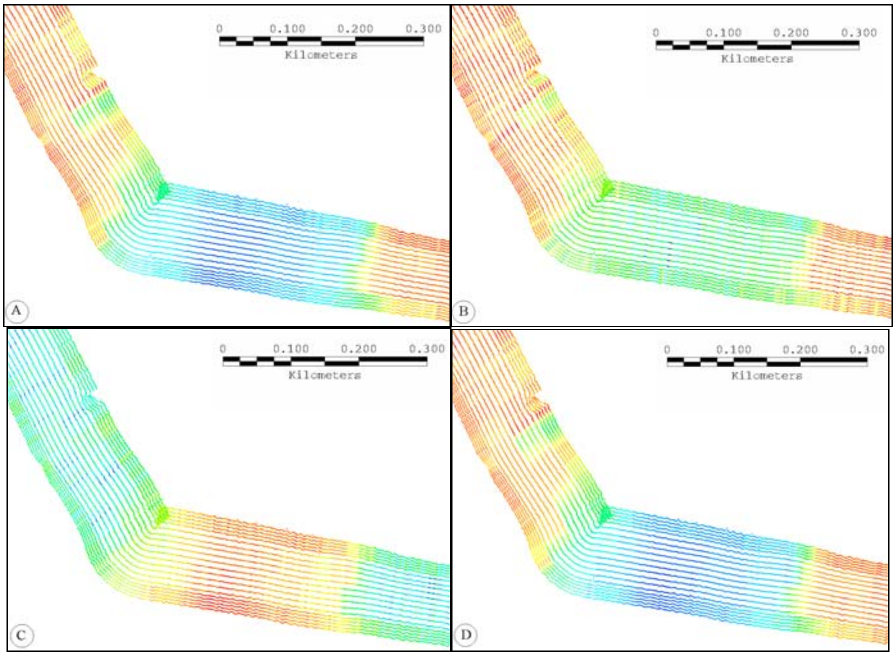

Figure 9. Extracted statistical features used for the automatic classification of the survey area. Here shown for a single line located northwest in NogvafjordenA) Quantile, 80% of the mean reflectivity. B) Pace, the variation in measured frequency. C) Contrast, the variation in measured strength. D) Mean value

The automatic generated sediment boundaries are linear and blocky, which can be smoothed by applying smoothing filters, figure 10. This will however further reduce the resolution of the automatic classification. The small area classified and coloured blue within the pink area disappears as the filter size is being increased from 5 to 15 (Figure 10B, C).

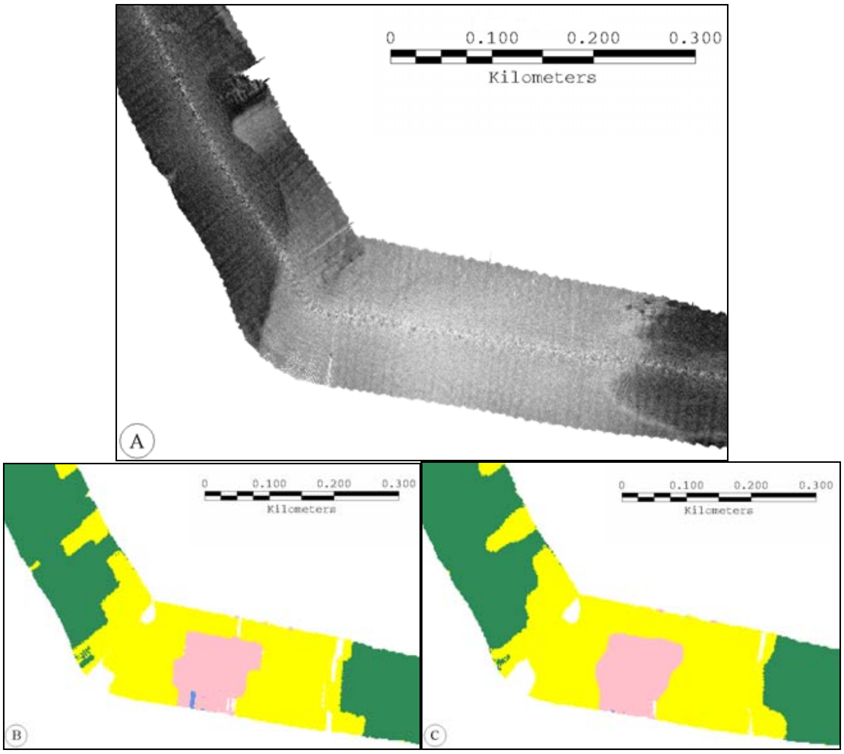

Figure 10, Backscatter mosaic and automatic classification from the same area as shown in figure 9. A) Backscatter mosaic created using Poseidon. B) Triton classification using a smoothing filter with a size equals to 5 cells. C) Triton classification using a smoothing filter with a size equals to 15 cells.

Automatic interpretation software is traditionally using a single physical parameter, such as multibeam backscatter strength. To achieve a successful automatic classification the variation between the different classes must exceed the noise level and other parameters which influence the data. Otherwise these effects will dominate the results and the classification will be useless. This should be taken into account when performing an automatic classification. Before increasing the number of classes, it should be investigated whether individual classes comprise similar sediment types. It is therefore suggested that a few broader geological classes should be used, to avoid similar sediment types within several classes. This will make the automatic classification more sensible. Outcrop or minor sediment pockets, smaller than the size of cells used in Triton, will not be resolved and can cause errors in the classification. It is not recommended to use Triton in areas where such features can be anticipated or observed using backscatter mosaics. Triton classification is ideally used together with Poseidon mosaic to clarify such features.

Manual seabed interpretation

The manual interpretation allowed an increased number of classes to be interpreted, compared with the automatic classification. This is partly related to the combined use of bathymetry, backscatter data and regional knowledge (Figure 7), but also due to the possibility of observing minor variation in the backscatter strength. A lag deposit in the southwestern part of the Haramsfjorden serves as an example of this (Figure 11A). Lag deposited is a residuum of coarse-grained rock particles left on a surface, after finer material has been removed. The area marked with an X (Figure 11A), was confirmed to comprise a lag deposit using visual inspection (Figure 11B). This area reflects higher backscatter strength than the surrounding area marked with S, C or T. The Triton classification only recognised two classes in this area, with the area comprising lag is classified as medium coarse shell sand (Figure 5). This is due to the relatively small area comprising lag and the large cell size used within Triton. In this case, the cells that contain lag also contains sandy sediments, with weaker backscatter strength. This affects the overall backscatter strength within the Triton cells and thereby also the automatic classification.

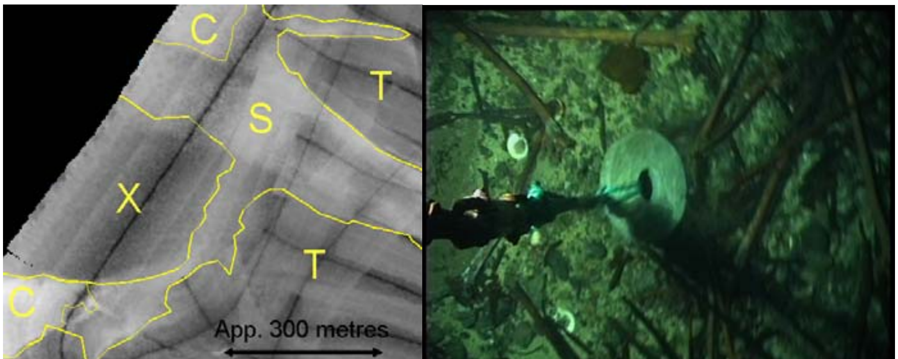

Figure 11, A) Unprocessed backscatter strength of the south-western part of Haramsfjorden. The outlined area marked by X, was manually interpreted as a new sediment class, with higher backscatter strength than other areas shown in this figure. The other areas were interpreted as clay (C), shell sand (S) and till (T). B) Video footage of the area marked by an X in figure A, revealing a typical lag deposit.

Automatic classification versus manual interpretation

Manual interpretation of the central part of Longvafjorden resolved several outcropping moraine ridges in areas generally comprising clay (Figure 6 and 7). These were not resolved using Triton (Figure 5). Triton classified the central part of Longvafjorden into two classes - neither of these comprise till (Figure 5). This classification was probably a result of cells comprising both till and clay. The size of till outcrops was smaller compared to the size of cell used in Triton and the size of smoothing filters used. This area clearly shows the limitation of automatic classification compared with manual interpretation, comparing figure 4C, 5, 6. There is however a moderate correlation between automatically generated boundaries and the manual interpreted sediment boundaries. The automatic classification can therefore be useful as a starting point for the manual interpretation, even though most of the automatically generated sediment boundaries and polygons will have to be adjusted and sub-divided during the manual interpretation.

The use of Triton generated charts is limited for a detailed geological facies mapping, but might be useful for large-scale studies. The charts have been very useful for choosing sampling locations offshore, as the charts can be produced shortly after data acquisition. The charts should however be treated with care, due to the uncertainties of the position of the sediment boundaries due to smoothing filters and the reduced lateral resolution.

Poseidon generated mosaics might provide the same or even more information for a trained geologist than the automatic classification. It is therefore appropriate to ask the question: "Why use automatic classification?" An automatic classification will assist less experienced geologists as well as support people with more experience. The classification parameters can be stored and used in several areas, which will aid a homogenous interpretation. The automatic classification can be directly transformed in seabed sediment charts, which can be read by personal with little or even no knowledge of acoustic data. Such charts should however have clear indications of the uncertainties around the position of sediment boundaries and possible errors in the sediment classification.

Survey strategy

Ground truthing programs are best using all available data and knowledge, which is incorporated into the manual interpretation. This will however demand a two-cruise strategy, due to time involved in making the manual interpretation. The most efficient strategy is for acoustic data to be acquired together with a reduced ground truthing program based on automatic classification or Poseidon mosaics during the first cruise. These data will be used for manually interpretation on-shore before commencing a second cruise. The second cruise can then include an extensive ground truthing program. Performing a second ground truthing cruise after commencing the manual interpretation opens the possibility of investigating areas with special features or areas found complex during the interpretation.

Two-cruise strategy provides economical benefits of reducing man-hours and large vessel equipment with expensive equipment, as the second cruise can be performed using a small vessel with a reduced crew.

Acoustic classification

AVA classification is a very powerful tool, but significant testing must be performed to support these initial test results. The backscatter strength at the distinct cusp is used as one of the parameters for the AVA classification, but the cusp is often difficult to observe using data from an EM1002. The stochastic nature of the backscatter data and therefore performing running average is an other process that increases the difficulties locating the cusp, as averaging will smoothen the AVA profiles. The cusp might also be reduced as an effect of extracting the AVA profiles from gridded backscatter data rather than extracting the values beam by beam. This method was chosen to ensure that the best profile location was used according to seabed slope and uniformity of the seabed sediments. The backscatter strength drops significantly at lower grazing angles than the cusp. The cusp has not been proven to be located at the critical angle. The cusp could be either a consequence of the EM1002 using 93Khz for the outer beams and the 98 kHz for the inner beams (Mosher, *et al.,* 2002), or where the phase detection performs better than the amplitude detection. A larger cusp is observed at a constant beam angle of 50º (40º grazing angle), which correlates to the position of the frequency change (Figure 12). The cusp interpreted to be associated with the critical angle is smaller and observed at a higher beam angle (lower grazing angles, figure 12), which is used for determination of the values for cross plotting.

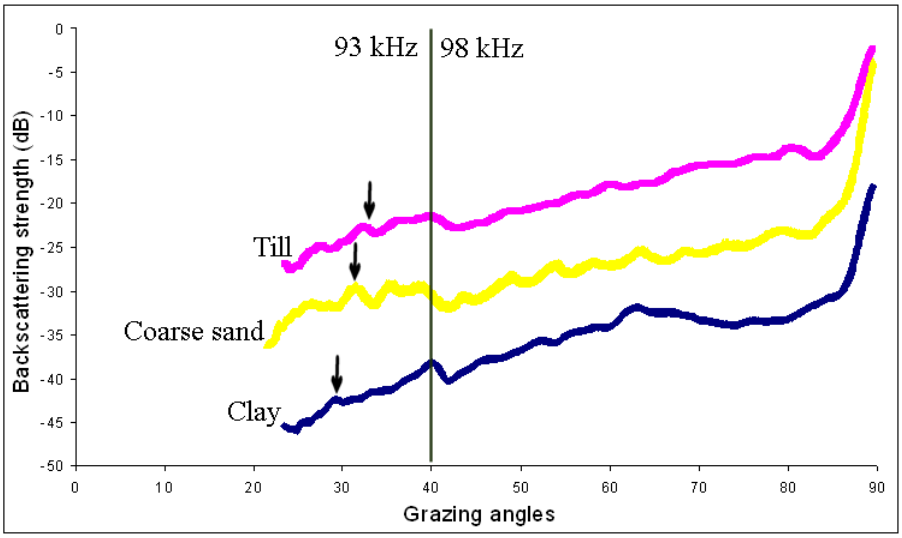

Figure 12, Mean of the ten AVA curves for each sediment group. The vertical line at a grazing angle of 40° corresponds to a frequency change, which is believed to cause the cusp observed on all three curves. The arrows marks the cusp interpreted to correspond with the critical angle.

Simrad acquisition software uses the best detection method, if the detection method should cause the variation in backscatter strength it is also an effect that might be linked to the seabed composition. The authors do not see the logic in the detection methods should cause a variation in the backscatter strength. We believe that the drop in backscatter strength is associated with the critical angle.

Carbonate rich sand has a varied acoustic response (Figure 8), which is likely related to the presence of sand waves in this area. AVA curves were extracted along the sand wave crests, where the slope was smallest and the thickness of carbonate rich sand largest. Even if till is outcropping between the crests, it is inferred that the thickness of the sand waves was sufficient to not influence the backscatter strength. It is more likely that the topography influences the backscattered strength to such an extent that it overrides the sediment properties. The number of ground truthed locations for the silt and fine sand was not large enough to provide a sensible interpretation concerning these sediment types.

Conclusions

- Automatic seabed classification, using a statistical method in Kongsberg-Simrad software module (Triton), yielded a sensible classification comprising four sediment classes. These are geologically rather broad, but it was not possible to increase the number of classes without having similar sediment types within the different classes.
- Poseidon generated mosaics reveal more details of the seafloor than the Triton classification. The quality of these mosaics is reduced due to insufficient angular correction, which is especially visible at nadir.
- Manual interpretation was performed in a pseudo three-dimensional environment combining bathymetry, unprocessed backscatter and regional knowledge. This made it possible to sub-divide the seabed into thirteen different classes.
- Visual assisted grab used as a drift camera was an efficient tool for ground truthing large areas and to differentiate between coarse-grained sediment types. Visual inspection was less useful to determine the nature of fine-grained sediments, where the grabbing option had to be used.

- Cross plotting backscatter strength from nadir and critical angle, makes it possible to differentiate between clay, coarse sand and lag + till.
- Automatic classification is useful for supporting manual interpretation, but the largest advantage of automatic classification is the short time needed from acquisition to chart
- Manual interpretation is rarely finalised offshore, as this is time consuming process. Ground truthing can be performed on the basis of automatic classification. Improved results can be achieved using a two-cruise strategy. The first cruise shall then acquire acoustic data and possibly a few samples from locations determined using automatic classification. The second cruise shall commence when manual interpretation and AVA classification have been performed. This opens the possibility of ground truthing areas of special interest or complexity, discovered during the manual interpretation.

Further work

The survey area is being developed as an acoustic test area. Annual surveys have been performed in an area of rapid sediment transport and accumulation. The biological diversity have been analysed for generating the wider scale habitat maps for the area. Mathematical models of currents have been performed on a large scale and is currently being re-modelled to a fine-scaled grid. The area will be re-visited to improve the understanding of physical processes taking place and the effect on the bio-diversity.

Automatic classification based on bathymetry has been performed using published algorithms (Riley *et al.,* 1999), without significant results were achieved. Combining these results with automatic backscatter classification might improve the automatic classification and make it possible to increase the number of classes.

Theoretical modelling of the AVA response is currently being performed to investigate the possibilities using this method further. The possibilities for extracting physical parameters from the seabed sediments, that can be used for sediment classification and for geotechnical assessment are considered good.

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5.2 Article 2

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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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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SUSHIMAP (SUrvey Strategy and Methodology for Marine HabItat MAPping)
Ole Christensen

Abstract

In habitat mapping a survey strategy of two cruises is suggested. The first cruise is multibeam acquisition, including a reduced ground truthing program based on automatic (unsupervised) or a semi-automatic (supervised) classification. The main part of geological and biological ground truthing will be performed on the second cruise. Habitat interpretation based on acoustic data, predictive models and if possible a few samples from the first cruise will be used in between the cruises. This will indicate and bring forward 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 of Northeastern North America Region (Valentine et al., 2002). A few minor adjustments in this classification scheme improve the survey strategy.

The Valentine et al (2002) classification scheme was reliable in a typical Norwegian coastal area that is dominated by the 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 the 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 texture of seabed sediments seemed to have a high influence on the biological processes.

Introduction

Today's detailed swath bathymetry and backscatter obtained from multibeam sonar mosaics, together with advanced ground truthing tools have opened 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 are not explicitly addressing high-resolution information of seabed morphology and texture. Regional character has been difficult in well-established classifications schemes, e.g. EUNIS (http://eunis.eea.eu.int/index.jsp) that have problems coping with mixed substrates, such as till, normally found in glaciated areas (Rinde et al., 2004). This problem makes such classifications unpractical to use in Norwegian waters, as glacial deposits dominate the seabed. Valentine et al. (2002) have designed a habitat classification system for the repeatedly glaciated northeast coast of the USA and Canada. This scheme 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 to Norwegian waters and to explore correlations between seabed geology and 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 multiple times (Larsen et al., 1988.) Features generated by repeated glaciations dominate the seabed morphology, these features have been modified by uplift, wave exposure, and currents throughout the Holocene.

Geology

Basement

The geological basement consists of metamorphic rocks generated along the Baltic shield during the Precambrian and deformed during the Caledonian orogeny (Tveten et al., 1998). The bedrock is faulted and fractured in a pattern that has influenced glacial erosion that has formed sounds oriented along and transverse to the coastline (Fig. 1). Bedrock is often exposed onshore and occasionally outcrops 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 is towards the northwest. Till sheets are therefore best developed on the south-eastern sides of the islands and along the north-eastern sides of the north-eastern – south-western directed 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). Carbon14 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. 1C) 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 lies 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 balanced, and the sea level was stable for more than one thousand years. During this period marine abrasion created a very distinct shoreline into the till beds and eroded silt and sand were transported into the fjords. At the same time lots of icebergs drifted along the coast both from calving glaciers at heads of the fjords and from the Skagerrak. Icebergs both scoured the sea floor and rafted debris and thus modified the seafloor.

Sedimentation during Holocene

Continued isostatic uplift and the Tapes Transgression (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 transport of minerogenic matter into the sounds during the Holocene. The reduced width and water depth of the sounds has also led to increased current erosion and redistribution of sediments on the sea floor. During the Holocene, large amounts of organically produced carbonate have been generated. The carbonate debris is usually mixed with minerogenic matter, but it is occasionally found as bioclastic sediments composed of 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 broken down, but fine-grained sediments in the sheltered Longvafjord and the deep basin off Nogvafjorden (Fig. 1A) can have 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 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, creating a highly dynamic environment with large annual variations. Along the deeper parts of Haramsfjorden and Nogvafjorden (Fig. 1C) the seafloor is armoured with a lag of gravel and pebbles in a sandy matrix. Sand is found in sheets with dunes in areas where sand is transported by storms and/or tidal current.

Methods

Acoustic mapping and sediment classification

An EM1002 multibeam echo sounder was used to acquire backscatter and bathymetric data during the winter of 2002. Automatic acoustic mapping of sediment boundaries was performed using normalised multibeam backscatter data. The backscatter normalisation was done using software created by Robert Courtney, Geological Survey of Canada (Atlantic). Acoustic sediment classification was based on backscatter intensity from various grazing angles and on various ground truthing methods (Christensen et al., in press). Large sand waves in Haramsfjorden (Fig. 2) and Nogvafjorden (Fig. 4) were re-mapped in the summers of 2003 and 2004 using an 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 of the bearing strength of the seabed in areas of soft sediments. The STING acquires data on pressure, penetration and acceleration from a free fall impact with 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 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. In average seven replicate impacts was obtained on each station, during on measurement series. This increases the accuracy of the bearing strength estimates and to provide an indication of homogeneity of the seabed sediments.

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 sediments and for sampling fine-grained sediments, such as clay, silt and fine sand. Visual inspection has proven to be the best method for differentiation between till and bedrock, as lightweight grab sampling in these areas often fails. In areas of fine-grained sediments, video inspections are of limited use, because the low image resolution makes it difficult to differentiate between these types of sediments (e.g. muddy sand from mud). Combining visual inspection and analysis of grab samples has proven to be the most reliable and efficient method for ground truthing of the seafloor.

Twenty hours of video transects covering nearly twenty-five kilometres were acquired to investigate sediment properties, sediment boundaries and for biological identification. The resolution of these recordings is within the centimetre scale, compared with the millimetre resolution that is obtainable using still photos (Kenny et al., 2000). 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. The video survey also included four lines east of the survey area, at the *Lophelia pertusa* reefs (Fig. 1C).

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 was 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).

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 relates to 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, corresponding to hard sediments in habitat theme III. This class, has a rough surface that covers barren rock, moraine ridges, gravel, pebbles and cobbles 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, corresponding to coarse-grained sediments in habitat theme III. 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, corresponding to fine-grained sediments in habitat theme III. This class is found in sheltered areas or in the deepest depressions and ranges from silt to clay.

Results

Effects of tidal currents on bottom substrate and biology

The study area lies on the outer 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, 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 across the coastal area of Møre and Trøndelag (Fig. 1A), and calibrated using 28 tide gauge stations (Moe et al., 2003). This numerical model does not provide any information of 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 condition 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 I) (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, but not lower exceeding the calculated critical shear stress for settling threshold for the sediment. This is the case in Nogvafjorden and Haramsfjorden, where sand waves are indeed present, 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 accumulation of fine-grained sediments, with exception of the two encircled areas (Fig. 5). Coarse-grained sediments dominate both areas, finer sediment were however expected due to the weak tidal current strength.

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 Northeastern North America Region scheme (Valentine et al., 2002). 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 relatively flat, with occasional and local steep slopes along the moraine ridges. Anthropogenic structures observed within the area are limited to a single water pipeline crossing Longvafjorden. Dredged coarse grained till within Longvafjorden could be considered anthropogenic, but in this case fine-grained natural deposited sediments have largely covered these areas. Video surveys showed a high abundance of sea pens, which dominate the fine-grained sediments in Longvafjorden. Because dredging took place decades ago and seabed seems to have returned to it’s a somewhat natural state these areas have not been interpreted as anthropogenic structures.

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 dealing 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 the further analysis.

Theme II, seabed dynamics and currents, depicts classification of 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 preserved, relict or active features. The calculated critical shear stress for carbonate rich sand in Haramsfjorden indicates that the currents strength 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 with 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 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 has here been separated into three classes; a class comprising bedrock and till is termed hard sediments, a class of coarse and medium sandy sediments is termed coarse grained sediments and a class of fine-grained sediments with grain size up to silty sand (Fig. 6C). Initially this subdivision was based on the geological map of theme IV (Fig. 3), but it has proven possible to subdivide this area automatically using the normalised multibeam backscatter strength, (Fig. 6D) (Fosså et al., 2005).

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., in press).

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 later by geological and physical structures.

Biological seabed roughness is separated into four sub-classes 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 or 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 mainly based on distribution of coarse-grained components of till, bedrock and bedforms. Bedforms are 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 therefore included as two physical structural subclasses. The low-density coarse-grained shell fragments occurring in the 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 transect 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 of 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 the 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 to hard attachment substrate found on seabed comprised of till or near the coral reef (Fig. 10).

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 has a large presence in the till habitat (Fig. 10).

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 area around the coral reefs, but are also very common in silty sediments (Fig. 10).

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 70% dissimilarity level. They were not distinguished as a separate assemblage.

Relations between benthic fauna and physical factors

Several of easily identifiable macrobenthic species exhibited strong relationship with the physical properties of seabed habitats. For example, *Astropecten irregularis* which habitat preference is indicated in its common name "sand star" lives on clean sand or sandy mud where it can be buried just below the seabed. Within the survey area, this species had mainly been observed in carbonate rich sand, where large-scale sediment movement is documented and is characteristic for 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 association 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, while influences of other physical factors (e.g. depth) were eliminated, it would have been helpful if no strong gradient in bathymetric distributions of benthic species existed, which was not the case (Fig. 8). The seabed sediments are also strongly correlated to water depth and may influence depth-related distribution of species. The fine-grained sediments, for example, such as clay and silt are mainly found in areas deeper than 45 metres. Fine sand appears in in shallow areas together with dredge till, medium sand (in the middle two classes), coarse sand and carbonate rich sand appear mainly in the deeper water intervals. Till is the only sediment class observed throughout the entire depth interval.

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* have the preference of the water depths between 30 and 45 metres (Fig. 8). None of the distinguished assemblages showed association with shallow water (<30 meters).

Current strength

Analysis of distribution of benthic species in relation to the current regime, using the electivity index, showed a weak correlation of distribution of individual assemblages with current strength (Fig. 9). *Pennatula purpurea* prefers the weakest current, while the other sea pen, *Virgularia mirabilis*, occur 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. 10). Because acoustic data were limited in the area around the coral reefs, further analysis of benthos-habitat relationship there was not carried out. Till has the largest textural diversity, creating heterogeneous habitats which therefore are expected to support the most diverse flora and fauna. Most of the observed species displayed a strong preference for one or two sediment types and avoidance of other sediment types (Fig. 10). The two species of sea pens prefer fine-grained sediments, with the *Pennatula purpurea* mainly observed in clay and the *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 defined by the mobility of sediments.

Dredged sediments also contain numerous *Pennatula purpurea* where they occur in the areas of clay between the till outcrops.

Table 2 sums up habitat preference of the four biological assemblages and the individual species that have been analyzed in this paper.

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 the analyses of infauna.

Theme I is deemed essential for incorporating areas of anthropogenic structures and separating the photic and aphotic zone. 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 water column and on seabed, the subdivision is rather arbitrary and approximate. The depth of photic zone may vary seasonally and geographically, therefore it is doubtful that the boundaries of this zone on a large-scale map (e.g. 1:50 000) have any strict meaning. It can also be affected by the interaction of seabed sediment with 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 the 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 building 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, which generate waves that are likely to rework sediments along the north shore of the fjord. The fine-grained sediments have therefore been washed out into the deeper parts of Longvafjorden. The second encircled area located in Leia (Fig. 5) is within a sound oriented northeast - southwest. Each peak storm event is likely to push water through this channel. The shallow water depth and the narrowing of the sound here could increase current velocity which could transport fine-grained sediments. These resuspended sediments are likely deposited farther north, where the sound widens and the water depth increases, thus reducing the 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 being 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, the strong tidal currents constantly transport suspended sediments in benthic boundary layer, thus reducing 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 of the whole community by physically removing organisms from seabed or burying them in sediment.

The composition of observed fauna in areas of sand waves suggested a continuous sediment transport, but comparison of the modelled current strengths and the critical threshold 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 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 higher resolution bathymetric grid could predict 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 he 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 disregard of the shape of sediment particles, which in this case are large, flattened, angular shell fragments (up to tens 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 resuspension. Resuspension in fine-grained sediment requires a significant 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 down-slope. In Nogvafjorden this causes nearly 180° local difference in transport direction of adjacent sand wave fields. Symmetrical sand waves dominate areas of flat seafloor, which are likely generated by a bimodal directionality force, such as a tidal current. The unidirectional movement on the sloping seafloor is likely caused by the gravity, where the tidal current can facilitate downslope movement. The strength of the tidal current is possibly too weak to cause an upslope sediment transport.

The seabed texture, hardness and shallow subsurface sediment stratification influence remote sensing data and consequent 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 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 press). However, an automatic acoustic classification reflects the overall seafloor texture, and does not distinguish 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 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 will also consider sub-bottom information (stratigraphy on millimetres or even centimetres scale), which is obscured by acoustic “ringing” in the seabed pulse in sub bottom profiler data. This stratigraphic layering can affect the overall acoustic scatter data, depending on sonar frequency and grazing angle. While there is the possibility of resolving layers using multibeam backscatter data (Talukdar et al., 1995). Thin layers are visible in unprocessed backscatter data, which is not likely to be removed during standard backscatter processing. This is therefore likely to influence the automatic backscatter classification, and could be notable when comparing the automatic interpretation with the geological interpretation.

Fine and soft sediments are expected to have higher abundance of infauna, while hard and coarse sediments - 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 high structural complexity and heterogeneity of tills are related to higher observed biodiversity than other sediment types.

Sea stars, with exception of the *Astropecten irregularis*, displayed a weaker relationship with physical factors than any other species or assemblages. *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 more likely as *Astropecten irregularis* normally dwells in clean sand, where they are often buried under a few centimeters of sand (Picton and Morrow, 2005). Burying by sediment movement might allow *Astropecten irregularis* to avoid predation, and probably does not have such an adverse effect on it as it might on other species. The strong correlation of occurrence of this species with the 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 types. For assemblage D, sediment types 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 the different sediment types. This is however not found in fine sand, for group 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 to different species. *Pennatula purpurea* has a strong preference for fine-grained sediments and weak currents. This environment, which is expected to host the sea pens, can dominate locally in areas of till. However most of the till in the study area is exposed to stronger currents and consist 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 current 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 uncertain if the current strength or the sediments 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 strong and unique preference for a given current interval. There is also a strong preference, but not as a unique preference for a single sediment type. *Pennatula purpurea* prefers clay and very weak current strength, while *Virgularia mirabilis* is found in slightly stronger current and 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 recovery to a natural state for these areas.

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 (Group A and B). This contradicts some of the visual observations. The preference of sponge can possibly be linked to the water depth.

Conclusions

- The tidal current strength has shown strong correlation with the biological activity and can be used to predict the sediment properties. These estimations can be performed prior to survey activities and can therefore be useful for planning habitat mapping.
- It was hoped that incorporating modelled current strength could provide an estimation of the driving force behind sediment movements. This failed as the sediment model does not incorporate seabed slope and information of the shape of grains. The failure can also be related to the coarse scale of the tidal model, that the mean spring tide was used rather than the spring tide, and also to the poor information of sediment properties.
- Sediments and current strength both effect the biology, while depth is less of a factor as long as the depth interval investigated is within the aphotic zone.
- Tidal current driven sediment movement (i.e. constant sediment transport) seems to create a habitat where very few species can survive. The constant water circulation will provide nutrient and oxygen, which will benefit the species that can survive the constant sediment movement. Sediment

movement caused by peak events might have less effect, depending on how common these peak events occur.

- After forty years, the biological habitat of the dredged sediment within Longvafjorden have returned to near normal, due to natural deposition of fine-grained sediments.
- Themes III and IV are at present two different levels of seabed mapping, a geological and an acoustic. 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 design the ground truthing program. Theme IV will incorporate the results of the ground truthing as well as other information. This interpretation is time-consuming and is most likely to be performed onshore after the acquisition activity.
- Glacially derived influenced sediments, essentially mixed sediment type are typical within Norwegian waters. The classification scheme was used here developed in areas of similar sediment types and can therefore be applied in typical Norwegian waters better than many other tested classification schemes.

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Table 1, upper part shows a comparison of calculated critical shear stress for samples and the modelled tidal current strength at the sample locations. Lower part a summary of critical threshold and required current velocity for maintain sediment transport for various sediment types for sediment transport occurs.

Sediment type	Sample ID	Particle diameter (cm)	Dimensionless grain diameter	Yalin Parameter	Dimensionless critical Shields parameter	Critical shear stress	Critical shear velocity	Tidal current velocity (cm/s)	Bottom shear stress, from tidal current	Calulated mean velocity at 1 metre above seabed required for sediment transport
Calculation based on parameters extracted and estimated from chosen samples										
Carbonate rich sand	P0209002	0,08	14,241	53,741	0,03387	4,32068	2,05212	24,3	1,81753	37,4663652
Clay	P0209003	0,005	0,8901	0,8397	0,11227	0,89519	0,93408	4,8	0,07092	17,053902
Fine Sand	P0209004	0,009	1,6021	2,0278	0,08271	1,18714	1,07567	8	0,19699	19,6388802
Fine Sand	P0209005	0,012	2,1361	3,122	0,07195	1,37683	1,15842	6,4	0,12607	21,1498156
Clay	P0209006	0,007	1,2461	1,391	0,09393	1,04862	1,01096	9	0,24932	18,4575739
Fine Sand	P0209009	0,008	1,4241	1,6994	0,08774	1,11937	1,04451	6,6	0,13408	19,0701009
Lag	P0209010	0,08	14,241	53,741	0,03387	4,32068	2,05212	11,8	0,42858	37,4663652
Carbonate rich sand	P0209012	0,03	5,3403	12,341	0,04823	2,30744	1,49966	9,8	0,29561	27,3798677
Calculation based on estimated parameters relating to standard sediment types										
Clay	N/A	0,0002	0,0356	0,0067	0,9774	0,31175	0,55122	N/A	N/A	10,0639014
Silt	N/A	0,006	1,0681	1,1038	0,10181	0,97421	0,97444	N/A	N/A	17,7906856
F.Sand	N/A	0,02	3,5602	6,7176	0,05709	1,82094	1,33221	N/A	N/A	24,3227932
M.Sand	N/A	0,06	10,681	34,906	0,03727	3,56599	1,8643	N/A	N/A	34,0373434
C.Sand	N/A	0,2	35,602	212,43	0,0261	8,32324	2,84821	N/A	N/A	52,0010345
Gravel	N/A	6,4	1139,3	38454	0,01789	182,611	13,3411	N/A	N/A	243,573153
Carbonate rich sand	N/A	0,2	19,673	87,256	0,03066	1,64969	1,26803	N/A	N/A	23,1508705

Table 2. A summary of the preference for the four assemblages and individual species observed within the test area

	A	B	C	D	*Astropecten irregularis*	*Virgularia mirabilis*	*Pennatula purpurea*
Typical species	Deep-water Megabenthos	Fan-shaped sponges	Sponges, sea cucumbers and sea urchins	Deep-water crustaceans, shrimps and burrowing organisms			
Water depth	Deep	Deep	30-45 m	45-60 m	45 – 60 m	30 – 45 m	30 – 45 m
Current strength	Medium (II)	Medium (II)	Stronger (IV)	Weak (I + II)	Stronger (IV)	Weak (II)	Very weak (I)
Sediment type	Medium to coarse sand and till	Till	Till	Silt	Carbonate rich sand	Silt and fine sand	Clay

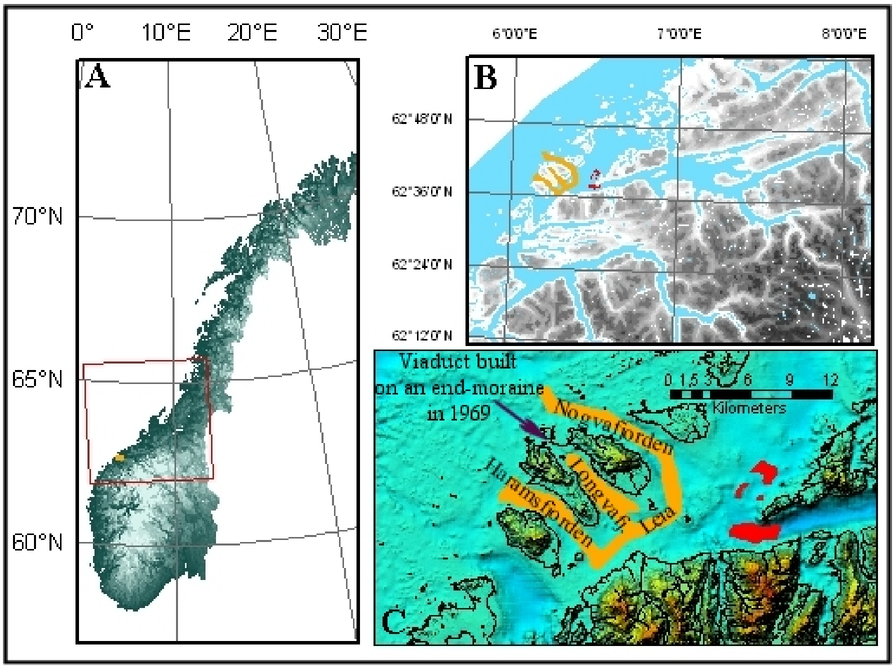


Fig. 1. A) Map of Norway showing the study area (yellow) and the area of modelled tidal currents (red square). B) The survey area (yellow) is situated in a typical Norwegian coastal setting. C) The mapped area (yellow) covers approximately 38.1 km^2, surveyed as a 38 km long corridor around three islands. East of the survey area numerous Lophelia pertusa coral reefs (red), were mapped and confirmed using a video assisted grab sample.

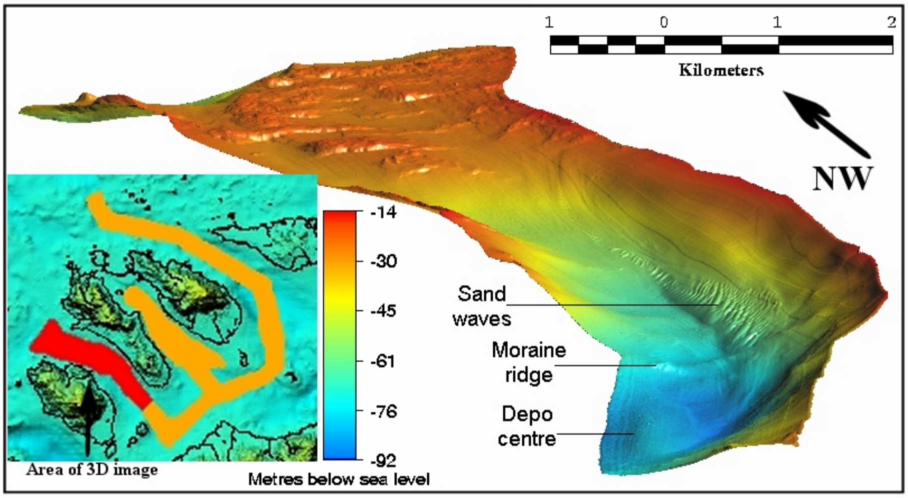


Fig. 2. Sand waves in Haramsfjorden (indicated by red area in the lower left corner) illustrating downslope and along slope

sediment transport. Sediments are deposited in a depocentre behind a moraine ridge shown in the lower part of the figure.

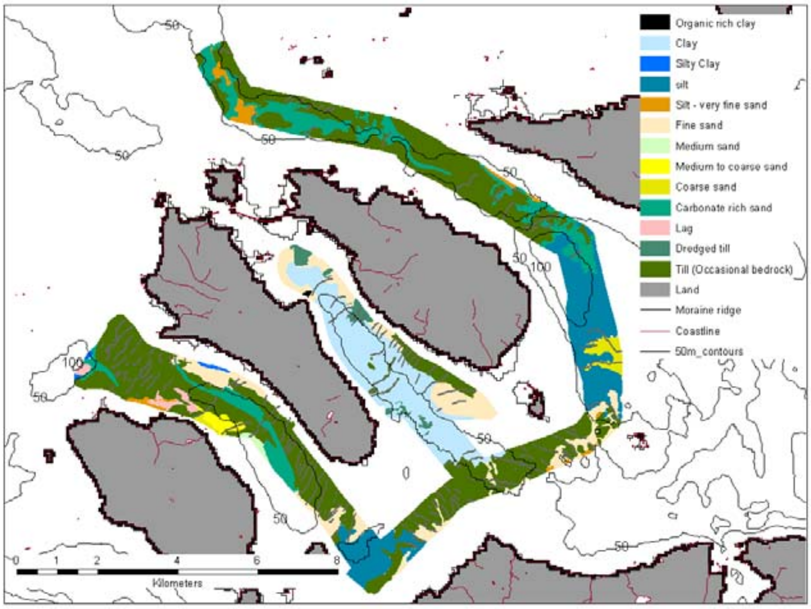


Fig. 3. Geological map showing thirteen sediment types interpreted and mapped from multibeam data, grab samples and video recordings.

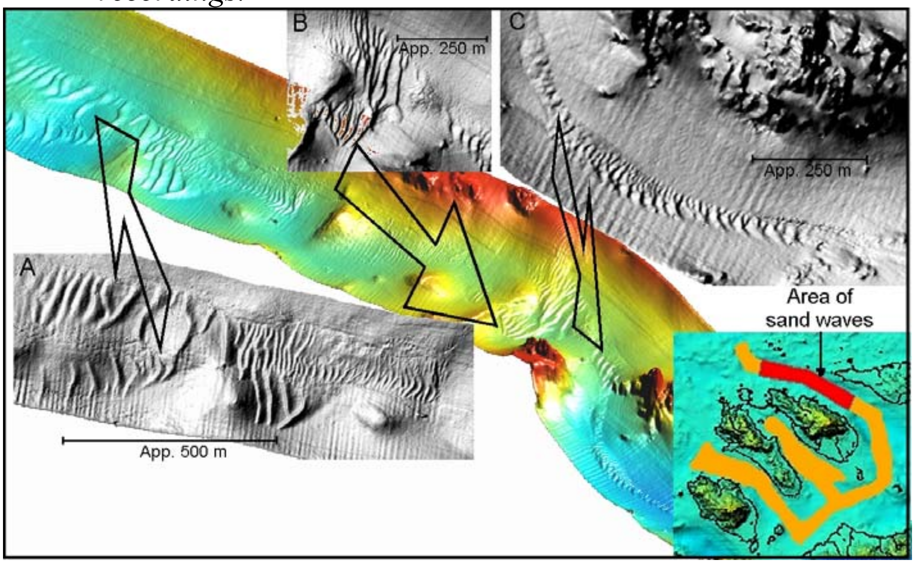


Fig. 4. Oblique and vertical view of sand waves in the central part of Nogvafjorden, index map in the bottom right corner. Symmetrical sand waves in the upper part of inset image A are interpreted to be standing waves, while the sand waves in

the lower part are interpreted to move eastward based on their morphology. The morphology of the sand waves in inset images B and C indicates eastward transport.

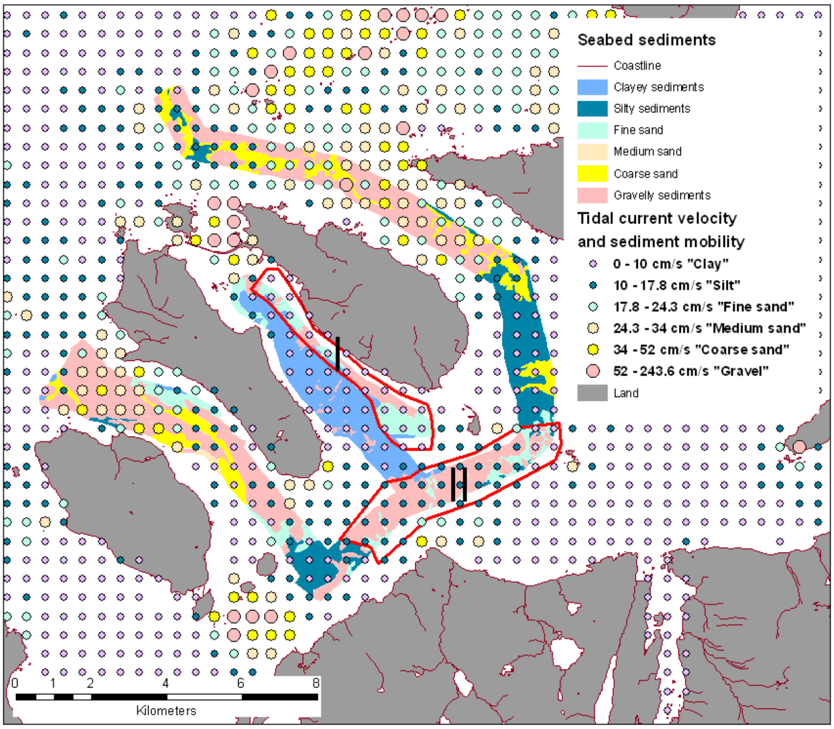
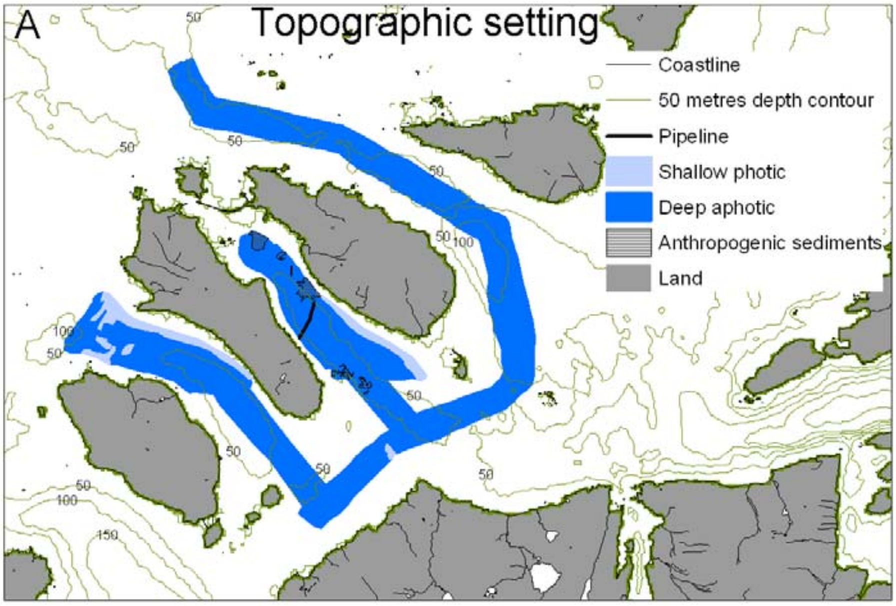
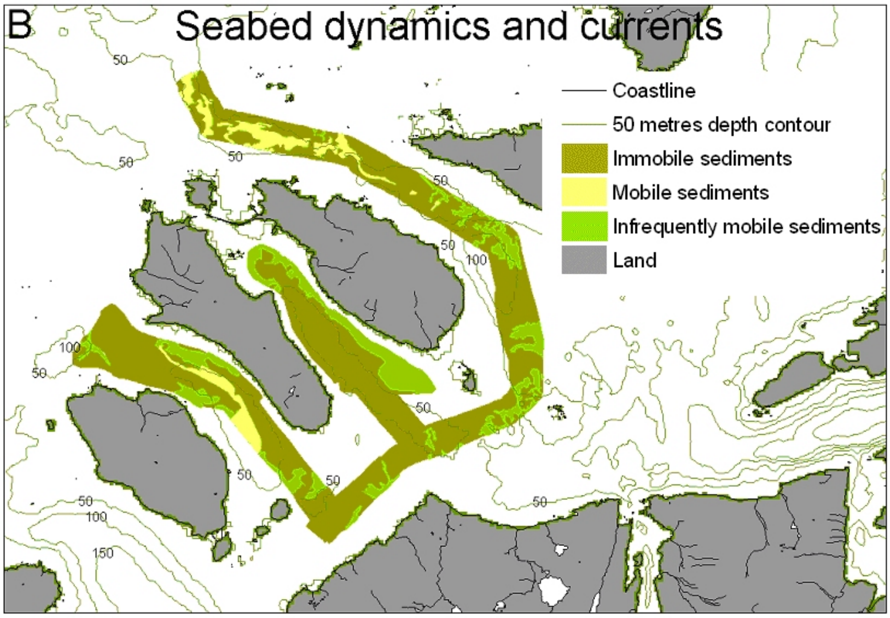
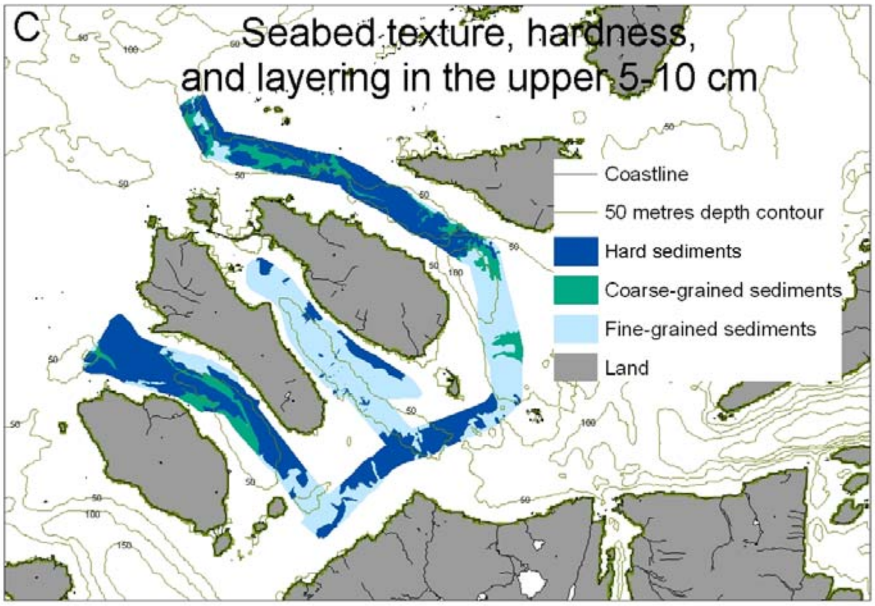
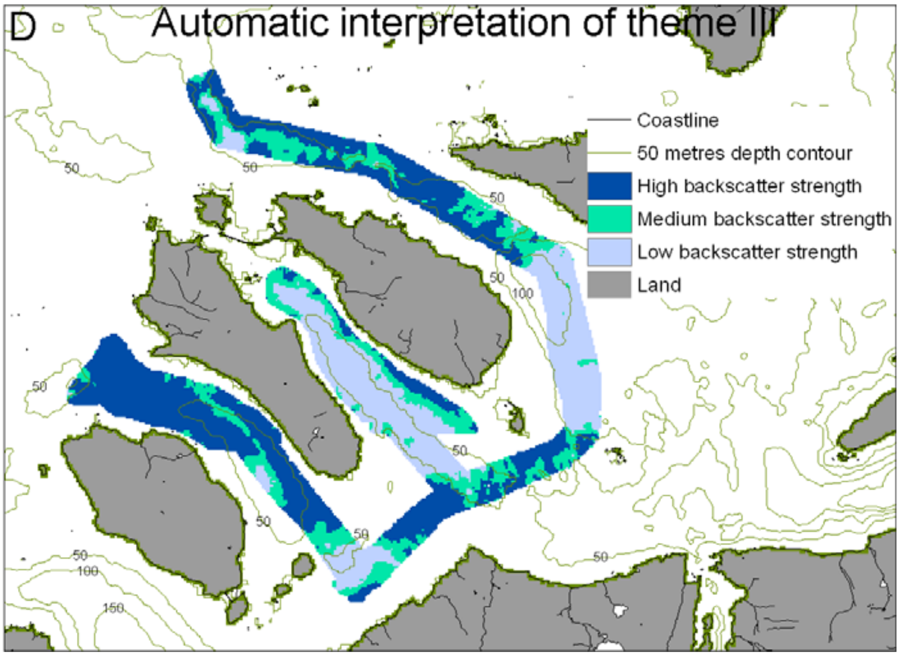


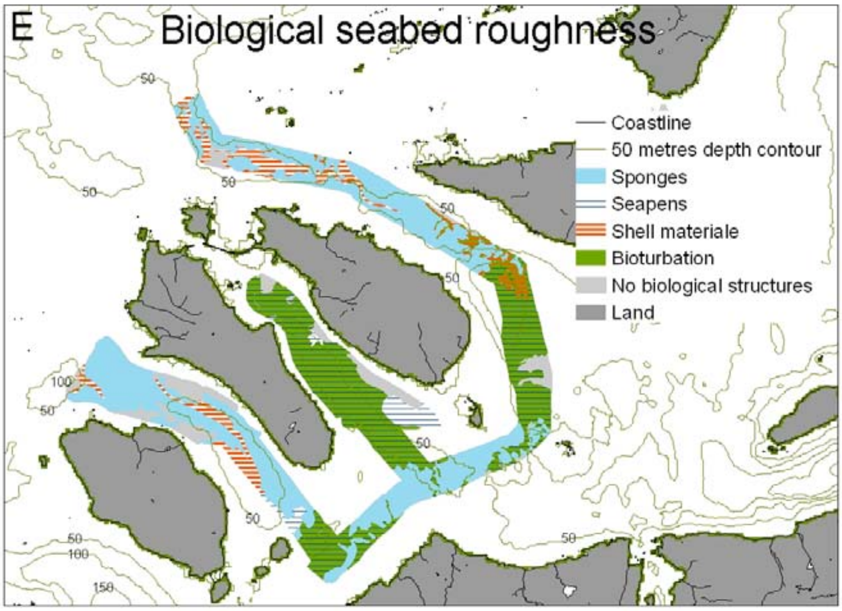
Fig. 5. Modelled mean spring tidal current strength when M_2 and S_2 tidal components are in phase superimposed on the sediment distribution map. The current strength is categorised according to the settling threshold of various sediments.


A
Topographic setting
Coastline
50 metres depth contour
Pipeline
Shallow photic
Deep aphotic
Anthropogenic sediments
Land
50
100
150


B
Seabed dynamics and currents
Coastline
50 metres depth contour
Immobile sediments
Mobile sediments
Infrequently mobile sediments
Land
50
100
150


C
Seabed texture, hardness, and layering in the upper 5-10 cm
Coastline
50 metres depth contour
Hard sediments
Coarse-grained sediments
Fine-grained sediments
Land


D
Automatic interpretation of theme III
Coastline
50 metres depth contour
High backscatter strength
Medium backscatter strength
Low backscatter strength
Land



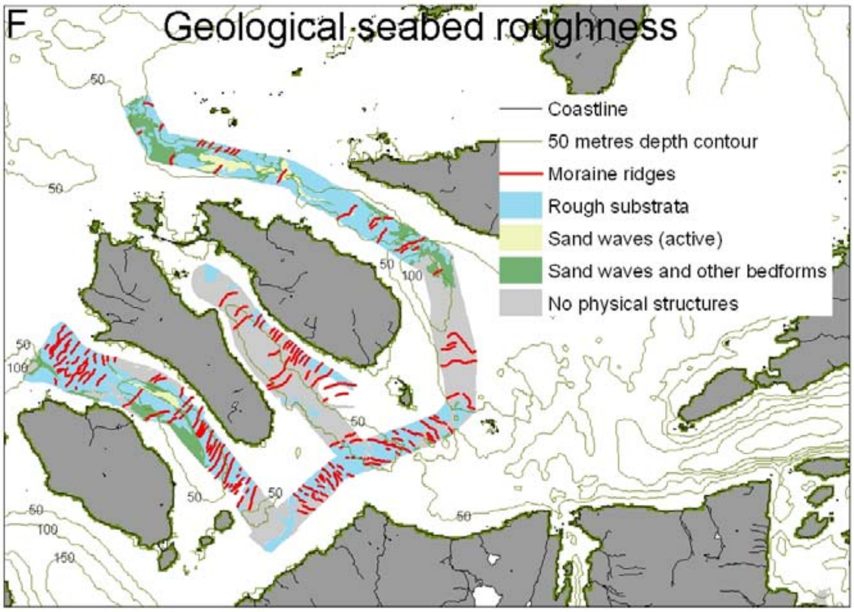


Fig. 6. Interpreted habitat themes; A) Theme I, anthropogenic structures together with aphotic and photic areas. B) Theme II, areas of interpreted mobile and immobile sediments. infrequently mobile sediments are likely to have been transported, but seabed features or morphology do not suggest this. C) Theme III, three classes of seabed texture interpreted on the basis of the geological map. D) 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 E) 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. F) Theme V, Geological seabed roughness, which is generated by physical structures and geologically generated seabed roughness interpreted using the geological information.

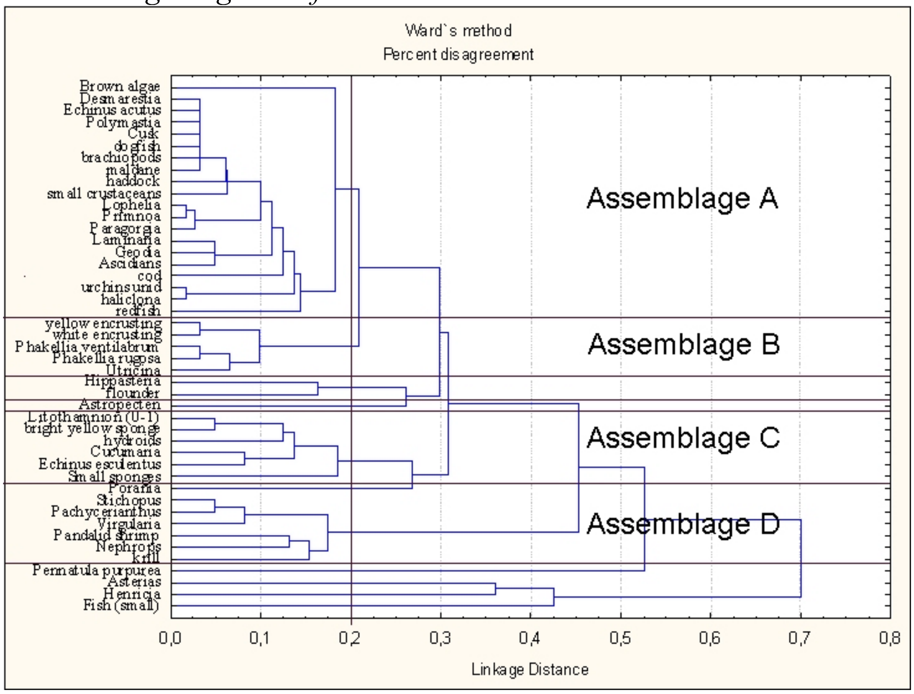


Fig. 7. Results of cluster analysis of all observed taxa performed on a Bray-Curtis dissimilarity matrix using Ward's method of linkage.

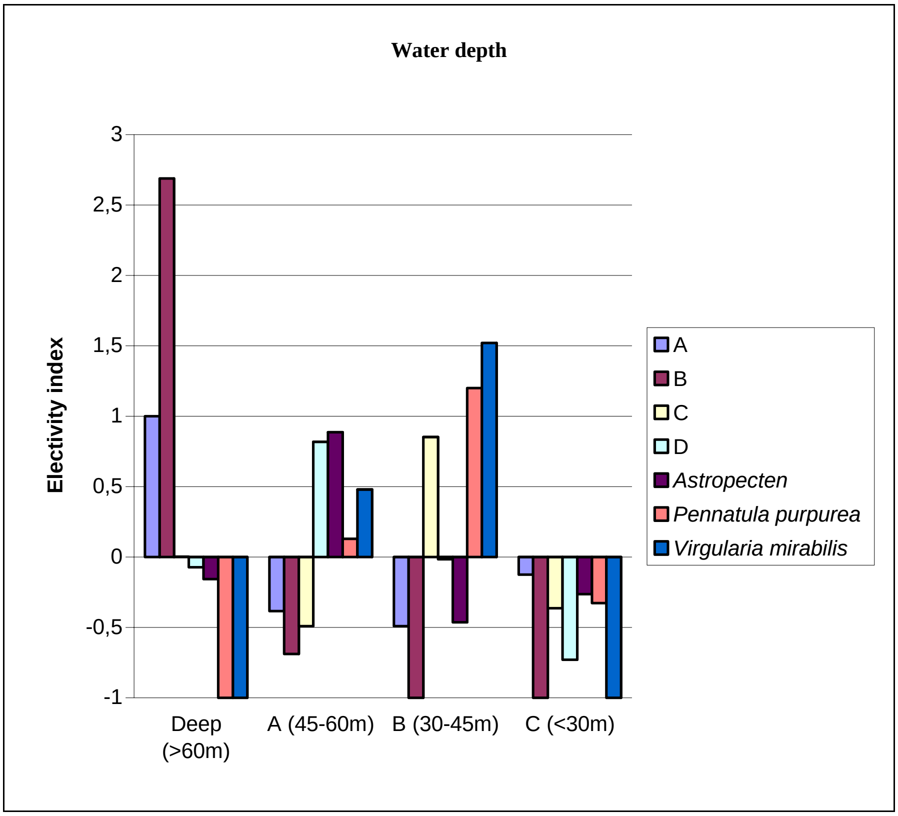


Fig. 8. Electivity index, showing preference of water depth ranges of the four benthic assemblages and several individual species.

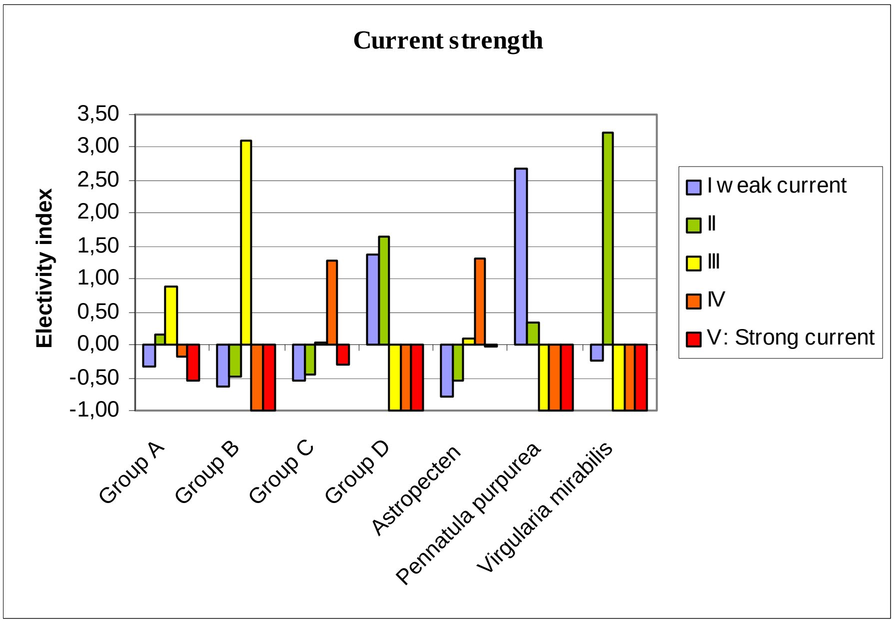


Fig. 9. Electivity index showing the relationship between current strengths and the benthic assemblages or individual species used for habitat classification within the study area.

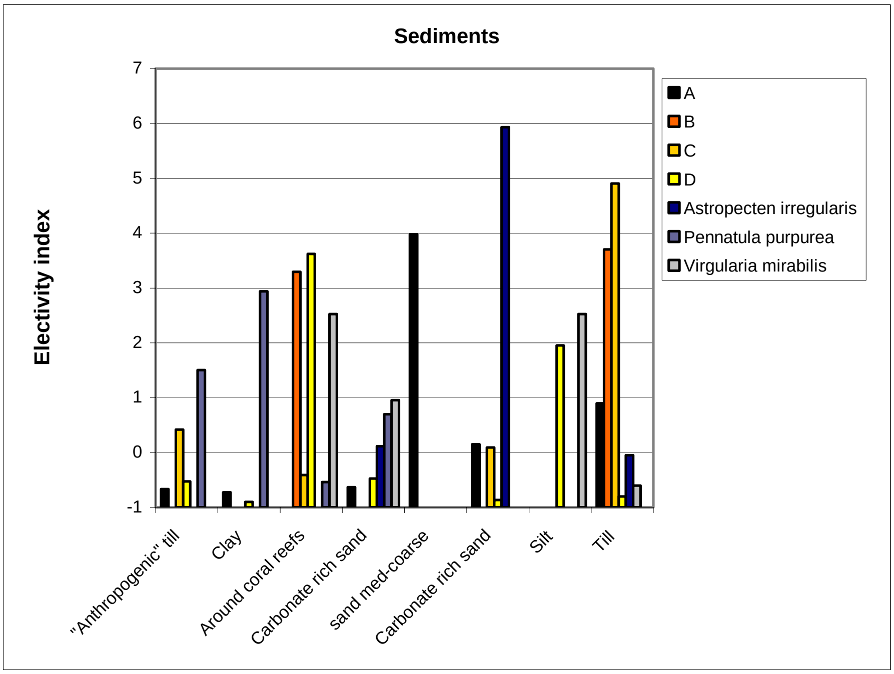


Fig. 10. Electivity index showing the correlation between sediment types and the biological assemblages and individual species used for habitat classification within this area.

5.3 Article 3

Mapping of *Lophelia* reefs in Norway: experiences and survey methods.

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Mapping of *Lophelia* reefs in Norway: experiences and survey methods

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Abstract. The Institute of Marine Research commenced a program for mapping and assessment of *Lophelia* reefs in 1997. It was initiated by reports from fishermen claiming that bottom trawling damaged deep-water coral reefs. The strategy was to survey coral sites reported in the literature and by the fishermen. This has provided an extensive database of coral occurrences, both damaged and undamaged sites. A number of major coral reefs have been identified, which has provided a better understanding of the morphology of *Lophelia* reefs and where they are likely to occur. We are now able to identify potential coral areas by analysing seafloor topography on maps. Fast and reliable ground-truthing methods using simple and inexpensive systems have been developed. Mapping and quantification of corals demand more advanced instrumentation, such as singlebeam and multibeam echo sounders in combination with data processing software allowing coral reefs to be detected in real time. Systems providing real time presentation of multibeam data are especially useful in combination with Remotely Operated Vehicle (ROV) positioned with acoustic navigation systems. We suggest the following mapping procedure: 1) acoustical reef detection followed by multibeam mapping, preferably along with collection of seismic reflection data. 2) ground-truthing with a tethered video camera platform or an ROV. The position of the observation platform is plotted online and draped on the multibeam maps, either in 2D or 3D mode. Examples from the reefs on Sula, Røst, Træna and Fugløy are given.

Keywords. Deep-water corals, cold-water corals, reefs, Lophelia, mapping, detection, ground-truthing, monitoring.

Introduction

Deep-water coral reefs formed by *Lophelia* pertusa (Linné, 1758) are widely distributed along the shelf and coast of Norway (Dons 1944; Hovland and Mortensen 1999; Fosså et al. 2000, 2002). Although there has been a number of studies of the distribution of *Lophelia* in the North East Atlantic (e.g., Dons 1944; Wilson 1979a; Mortensen et al. 2001; Fosså et al. 2002), information about the precise location of the reefs and their size and abundance was largely lacking until modern technologies enabled more detailed mapping (Hovland et al. 1997; Freiwald 1998; Mortensen et al. 2001).

The Institute of Marine Research (IMR) in Bergen, Norway, commenced investigations and mapping of deep-water corals in 1997. Information on the presence of corals comes from a number of sources (fishermen, oil companies and older literature). Since then, IMR and other institutions such as the University of Tromsø and the Geological Survey of Norway, have carried out dedicated research cruises to map reef occurrences along the continental shelf and in the fjords (Fig. 1).

Lophelia polyps have a growth rate of about 7 mm a year and are able to form massive reef complexes several km long and up to 30 m high (Wilson 1979b; Mortensen et al. 1995; Fosså et al. 2002; Freiwald et al. 2002). They are generally found on elevated features on the seafloor such as ridges and moraine structures formed since the last glaciation. Coral debris in the Sula area has been dated to be about 9000 years old (Hovland and Mortensen 1999). There are several definitions of what a coral reef is (see references in Mortensen 2000). Here we use the term in the following meaning: a reef is an individual seabed feature consisting of an accumulation of coral skeleton. A reef may consist of a single or several coalesced coral mounds. A reef-complex is an area consisting of closely located coral reefs that are separated by other seabed substrates.

Reefs are fragile structures easily damaged by bottom trawling fishing gear. Based on information from fishermen and other sources, it has been estimated that between 30 and 50 % of the Norwegian reefs have been impacted by bottom trawling (Fosså et al. 2000, 2002). Therefore the Norwegian Ministry of Fisheries passed legislation in March 1999 to protect reefs from fishing activities. This legislation prohibits wilful damage or destruction of coral reefs, and fishermen are required to exert caution when fishing in the vicinity of known reefs. The legislation also provides a means for closing areas with corals to fishing activities. So far five reefs have received this special protection: the Sula Reef, Iverryggen Reef, Røst Reef, Tisler

Reef and Fjellknausene Reef. In addition, the Selligrunnen Reef in Trondheimsfjorden has been temporarily conserved by the environmental authorities through the Norwegian Nature Conservation Act (Fig. 1).

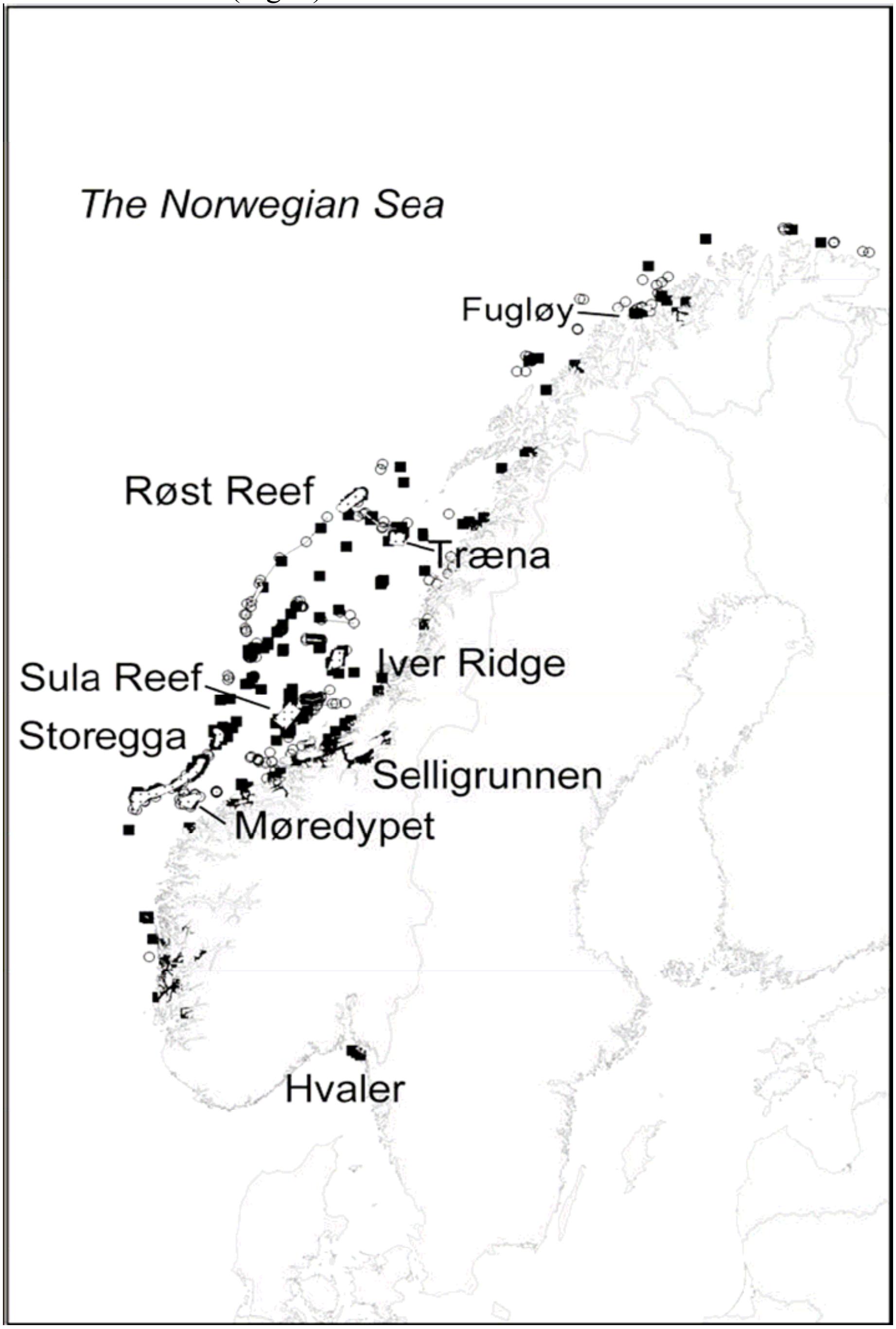

Fig. 1 *Large-scale distribution of Lophelia in Norway. Grey shaded*

areas indicate major coral areas. The Røst Reef, Iver Ridge, Sula Reef, Selligrunnen, and Hvaler are protected areas (squares = confirmed occurrences; circles = unconfirmed information from fishermen)

A reef is a complex structure that forms a habitat for a range of other marine organisms (Fig. 2). More than 1300 species of animals have been recorded living on, or in association with, the *Lophelia* reefs in the northeast Atlantic (Roberts et al. 2003). Redfish (*Sebastes* sp.) in particular are found in high abundance in reef areas. Also demersal species such as ling and tusk seem to be more common around corals than on the surrounding seabed (Husebø et al. 2002; Costello et al. 2005). The reefs are therefore important both from a general biodiversity perspective and as a habitat for commercial fish. At present there is a growing understanding of the ecological importance of the deep-water corals and the need for further mapping and research and management plans (Freiwald et al. 2004).

Fig. 2 *Model of a Lophelia-reef. Due to poor light conditions and abundant particles in the water it is difficult to present an overview photo of a Lophelia-reef. Therefore we have combined several photos taken from ROVs to illustrate a "representative" reef. On the top of the reef the hemispherical living colonies are found. Below this zone living colonies of varying size are found with dead corals in*

between. At the base of the reef there is a zone characterised by smaller fragments of coral (rubble) mixed with sand and mud. Paragorgia arborea and other gorgonians are common on the reefs. Sebastes spp. are often seen in considerable numbers in connection with the reefs. The reef is about 10 m across. From Fosså et al. (2000)

Deep-water coral reefs are difficult to map and sample. However, seabed mapping techniques are rapidly developing and methods based on modern technologies are now available. The majority and the most efficient methods are based on acoustics, while the most accurate and reliable are based on visual observation such as video and photograph. The purpose of this paper is to review existing mapping and sampling methods used on Lophelia-reefs in Norwegian waters, and to suggest an effective mapping procedure.

Large-scale mapping

Single split-beam echosounder

Acoustic reef recognition

IMR has developed an acoustic method to detect *Lophelia* reefs (Svellingen et al. 2002). The systems used are the Bergen Echo Integrator (BEI) (Foote et al. 1991; Korneliussen 1993) and the RoxAnn bottom classification system (Burns et al. 1989; Anonymous 1995). BEI is connected to a Simrad EK500 multi-frequency echo sounder, equipped with vertical looking split-beam transducers operating at 18, 38, 120 and 200 kHz respectively. The RoxAnn system is connected to one of the pairs of the 38 kHz split-beam transducer cable.

Bergen Echo Integrator

Acoustic sample data are stored in files as volume backscattering coefficients (sv), together with spatial data with a resolution of 500 sv per ping for each frequency. In addition, 150 values are recorded around the automatically detected seabed in order to increase the resolution. Horizontal data resolution varies with water depth and the EK500 processing speed, but a typical value is 1 ping per second (for more details see Knudsen 1990).

Data acquired using an EK500 is processed by the BEI, where the entire duration of the first bottom echo is integrated for all acoustic frequencies. This gives the frequency response r(f), defined in Korneliussen and Ona (2002) as $r(f) \equiv s_v(f)/s_v(38\ kHz) \equiv s_A(f)/s_A(38\ kHz)$, where f is the acoustic frequency. Since different bottom habitats and sediments will return different amounts of acoustic energy at the various frequencies, the frequency response can be used to classify the seafloor based on return energy (for further explanation see Korneliussen and Ona 2002; Svellingen et al. 2002).

RoxAnn

The two parameters used by the RoxAnn are roughness (E1) and hardness (E2). E1 is a measure of the energy in the tail of the first acoustic bottom return and E2 is a measure of the total energy of the complete second acoustic bottom return (Burns et al. 1989). The combination of the two parameters is used to distinguish coral reefs from the surrounding bottom, and the resolution is higher than for the BEI as a result of integration distance. The calculations of E1 and E2 are stored in a database together with time, depth and navigational data every five seconds.

The Leksa Reef – case study

The Leksa Reef is situated in a fjord system outside Trondheimsfjorden (63°36.40'N, 09°22.60'E). *Lophelia* colonies grow on a pronounced high in the fjord at water depths between 190 and 140 m with the surrounding bottom mostly deeper than 250 m. The site was studied with four ROV-dives 14-16 May 1999. We found three summits (Fig. 3); two western summits, about 500 m apart, and one eastern summit about 1 km to the east. The westernmost summit is the shallowest one and supports the highest densities of *Lophelia* corals. Between the two western and the eastern summits, the seabed consists mostly of sand. Below the areas with living *Lophelia* colonies, there is a steep hill with a spectacular coral rubble zone with high densities of gorgonians and soft corals.

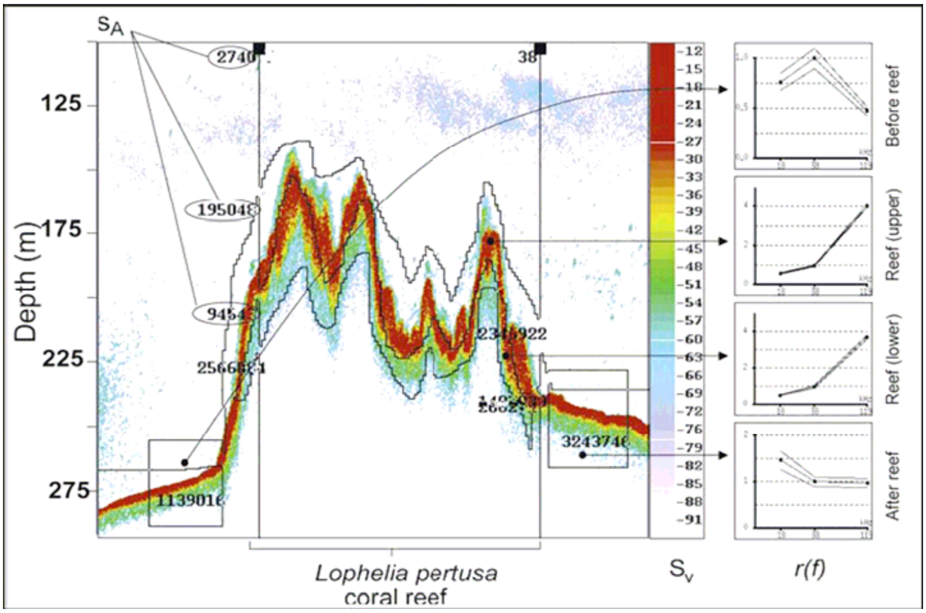

Fig. 3 *The Leksa Reef west of Trondheimsfjorden. A 2.0 nautical mile echogram taken at 120 kHz across the reef for about 17 minutes. The panel to the right shows the relative frequency response, r(f)≡s_v(f)/s_v(38 kHz), where f is the acoustic frequency, just before the reef, the first and last received backscatter from the reef, and just after the reef has been passed. From Svellingen et al. (2002)*

Figure 3 displays a 120 kHz echogram transect over the Leksa Reef, covering a distance of two nautical miles acquired during cruising for approximately 17 minutes. The panels to the right depict the results of BEI-processing of the echosounder data (relative frequency response, r(f)), and clearly shows that the off-reef r(f) differ from the on-reef r(f). This is related to the different backscatter of energy at the different frequencies from the on- and off-reef areas (for further explanation see Korneliussen and Ona 2002; Svellingen et al. 2002).

Figure 4 shows the processed parameters vs. distance for the same transect as in Figure 3. The first profile (Fig. 4A) is the Nautical area backscattering (Nab) coefficient for 38 kHz, and the second profile (Fig. 4B) is the r(f) for 18 and 120 kHz, both calculated using BEI. Both parameters change when passing over an area comprising coral structures, most clearly for the Nab (a) and the r(120) kHz (b).

Figure 4C shows the roughness (E1) and hardness (E2) parameters processed by RoxAnn. RoxAnn also recognises a clear difference in character when entering the zone with living corals; E1 rises sharply and E2 drops to a minimum.

Equally important is that the area between the two western summits and the eastern, having no corals, is recognized, most clearly by the RoxAnn E1 parameter.

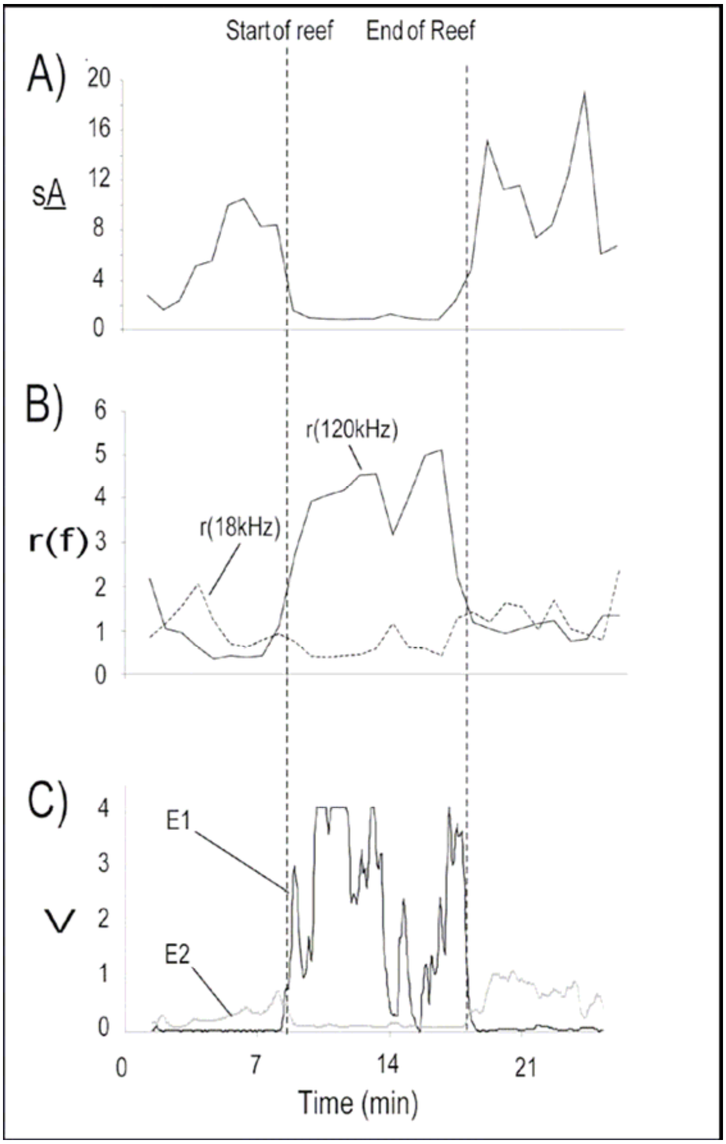

Fig. 4 *Acoustic classification of the Leksa Reef west of Trondheimsfjorden.* **A** *Nautical Area Backscattering Coefficient, s_A, for the first bottom echo at 38 kHz.* **B** *r(18kHz) and r(120kHz) as functions of sailed distance.* **C** *Roughness, E1, and hardness, E2, from the RoxAnn system as a function*

of time. The data in **A** *and* **B** *are averaged over 0.1 nautical miles, which in this case is about 50 pings, while the RoxAnn system averages over five seconds or approximately five pings. From Svellingen et al. (2002)*

The Røst Reef – case study

The RoxAnn system was used when the large Røst Reef-complex was discovered in May 2002. The presence of corals was verified by ground-truthing using tethered camera platform (Fosså and Alvsvåg 2003). Figure 5 shows the cruise tracks where the E1 and E2 combination indicative of corals is shown in green. The reef-complex is 35-40 km long, up to 3 km wide and lies mainly between 300 and 400 m depth in a steep and rugged part of the continental shelf break.

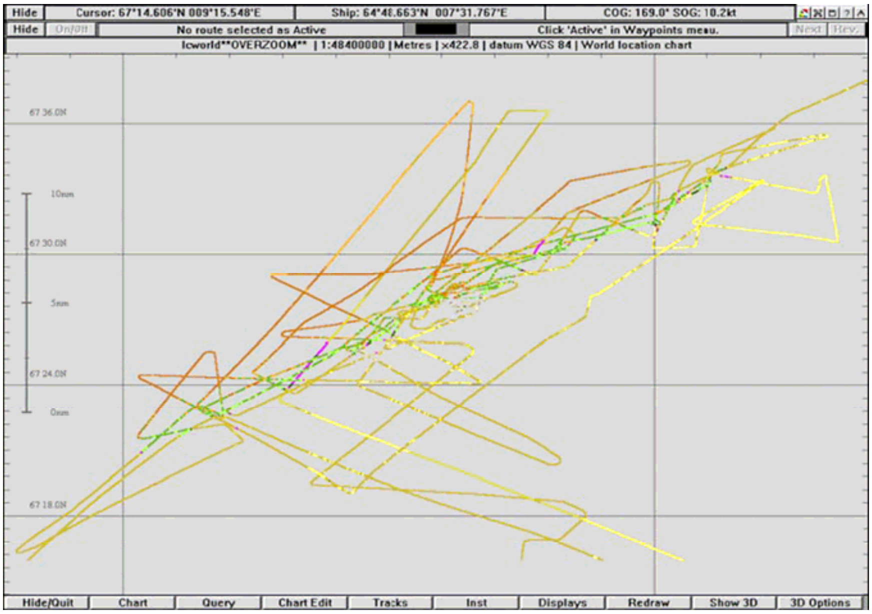

Fig. 5 *Monitor screen dump showing the path of RV "Johan Hjort" over the Røst Reef in May 2002. Coral reef echoes are recognized and coloured green by the RoxAnn bottom classification system. The green area is about 35 km long*

The reef complex was mapped in detail in October 2002 and May 2003 using an EM 1002 multibeam echosounder and was ground-truthed with an ROV. Multibeam data showed that the corals grow along the back wall of a giant submarine slide which took place 4 000 years ago (Laberg and Vorren 2000). The geological setting of this reef complex is spectacular consisting of steep, dissected ridges, which are several tens of metres high occurring within a zone up to 2 km wide seaward from the shelf break. Inspection with the ROV showed that the highest concentrations of *Lophelia* colonies were found on the ridges in the uppermost part of the back wall zone between 300 and 380 m depth. Coral mounds also occurred on the shelf close to the slide area.

Conclusion

It is possible to identify coral reefs using standard hydro-acoustic instrumentation. The Simrad EK500 multi-frequency echo sounder used in combination with the BEI and the RoxAnn bottom classification system provides fairly accurate identification of *Lophelia* reefs. The RoxAnn system uses a single frequency, while the BEI uses multiple frequencies to recognize the reefs. The identification of the r(f) signature for *Lophelia* reefs used by BEI is based on empirical data from only two sites, and therefore needs further validation. There is also a need for a conceptual model to explain why the backscatter from the reefs differs from that of the surrounding seabed. It is currently not possible to decide which of these systems perform best. Furthermore, we have experienced that topographical heights and a steep hilly seafloor may give false indications of coral reefs. In practical use, however, we can confirm the expediancy of this system to support detection of coral reefs.

Seismic

Seismic acquisition is used for investigating the seafloor and sub-seafloor by remote sensing. A source, generating an acoustic signal which can vary from MHz to 10 Hz, and receivers (hydrophones) recording the reflected sound, constitute the basic setup. The configuration can vary greatly, depending on the source signal, distance from source to receivers, and amount of receivers as some of the main parameters that can be adjusted. The settings vary according to the target of the investigation; deeper investigations require lower frequencies and generally give lower resolution.

Industry seismic

Seismic performed by the oil industry in Norway is acquired with the main areas of interest deep below the seafloor. This requires low frequency equipment, and dominating frequencies are usually 10-100 Hz. Processing is performed to optimise the deeper features, thus neglecting surficial features such as the cold-water reefs.

High resolution seismic

One example of a configuration for shallow investigations/high resolution acquisition is two 40 cubic inch sleeve-guns generating a signal with typical frequencies between 80 and 200 Hz, and a single channel digital streamer with 20 hydrophones receiving the signal, resulting in a vertical resolution of ~3 m.

Sub bottom profiler

Collection of sub-bottom profiler (SBP) data ('pinger', penetration echosounder, TOPAS etc.) is often done simultaneously with heavier equipment (airguns, 'boomer', 'sparker' etc.). SBP gives better resolution than seismic data, but poorer penetration. SBP typically consists of a number of transceivers mounted in the keel or hull of the vessel, and typically operates at frequencies from 2-12 kHz, obtaining vertical resolution of less than one metre.

Shooting rate and vessel-speed are two parameters that influence the horizontal resolution (and file-size) of the data, along with the non-adjustable water depth. A shooting rate of 10 seconds and vessel speed of 5 knots results in trace distance of 25.7 m, whereas a shooting rate of 5 seconds and a vessel speed of 3 knots gives a trace distance of 7.7 m.

For modern seismic acquisition systems, signals are recorded digitally, and the signal to noise ratio (S/N) can be improved by post-processing using methods such as bandpass filtering, trace mixing and automatic gain control (AGC), among others.

The Fugløy reefs – case study

The ability to identify cold-water coral reefs using seismic data depends on the acquisition parameters (resolution) of the seismic system, and the size of the reefs. Identifiable reefs typically appear as acoustically semi-transparent cone-shapes, often located on, or forming their own topographic highs (Fig. 6). The reef structure causes high spreading and absorption of acoustic energy, resulting in a weakened, or even absent sub-reef seafloor, also noted on conventional echosounder (Strømgren 1971). The frequency content of high resolution seismic data such as the example in Figure 6A usually allows penetration of the reef structure, so that the sub-reef seafloor is imaged, which is of importance for estimating the size of the coral reefs. SBP sometimes yields internal reflections within and around the reef structure (Fig. 6B), which allows for a tentative, but by no means definitive, classification of the various reef-zones, related to the state of the reefs (open coral structures, sediment-clogging, rubble zone etc.).

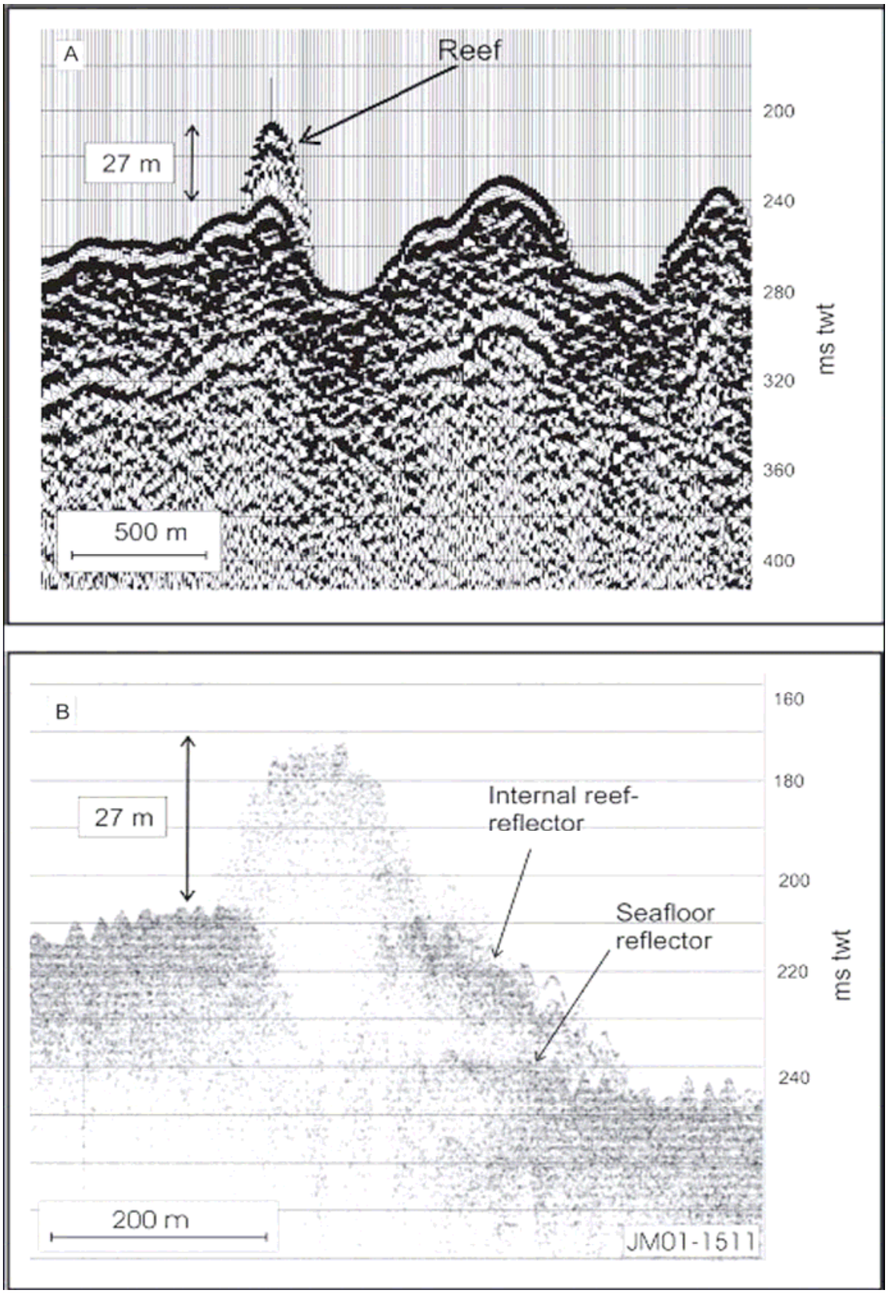

Fig. 6 A *Sleeve-gun profile across a reef, showing the acoustically transparent cone-shape characteristic of a reef. The frequency and penetration of this equipment allows us to measure the height of the reef, which in this case is 30 m.* **B**

Sub-bottom profiler over the same reef (but on a different course) showing the low amplitudes that result from the scattering of energy. Internal reflectors are sometimes visible on sub-bottom profiler, but reefs that exceed 20 m in height are seldom penetrated fully to reveal the sub-reef seafloor. From Lindberg et al. in press

As reefs often have an acoustic signature that can be interpreted and discarded as noise, they need to be of a certain size in order to be correctly identified on seismic data. Reefs larger than ~2 times the vertical resolution of the seismic systems are distinguishable on individual traces, but in order for the reefs to be identifiable, they must be of sufficient horizontal extent compared to the spacing of seismic traces to allow for identification of their characteristic acoustic signature. This is further dependant on the water depth and vessel speed, and can thus vary from survey to survey.

The sub-bottom profiler data are usually acquired with higher data density than lower frequency seismic, and is as such a better tool for identifying deep-water coral reefs, but lower frequency seismic (sleeve-gun data) constitute an important supplement for a complete image of the reefs and their surroundings. Full penetration of the reefs in order to image their true vertical extent, is only achieved by this type of profiling.

Conclusions

Identification of reefs using seismic profiling is possible, but it is not an optimal tool without additional information. Seismic data and sub bottom profiling provides detailed two-dimensional information about the reefs and their surroundings which is not accessible through other sensing systems. It does not, however, provide definite confirmation of reef existence or detailed information on their horizontal extent. On-going research on the use of high-resolution 3D seismic will greatly contribute to the understanding of the reefs in space and time, and will be an important supplement to other mapping techniques. Increased awareness on the characteristic appearance of reefs on seismic records is desirable as there are undoubtedly many reefs profiled on oil drill-site surveys etc. that have not been properly identified.

Side-scan sonar

Method

Side-scan sonar (SSS) is a common tool for mapping features on the seafloor. The system consists of a torpedo-shaped towfish that is towed behind the vessel (although hull-mounted versions exist) and contains transducers transmitting sound waves sideways and receiving the reflected signals. The signals are conveyed to the vessel and recorded digitally and/or printed on paper to produce an image comparable to an aerial photograph of the seafloor (Fig. 7). The SSS exist in a wide range of frequencies, usually ranging from 100 to 500 kHz for high-resolution mapping, but systems down to 30 kHz (TOBI) and 6.5 kHz (GLORIA) exist for larger scale mapping purposes. Higher frequencies result in better resolution, but a reduced coverage area per unit time. Depending on the frequencies used, some penetration can be achieved so that the sonograms do not exclusively represent the seafloor, but also characteristics of the uppermost deposits on the seafloor. This allows for imaging of features that are not identifiable by multibeam bathymetry, as the latter only represents seafloor topography. The swath-widths of SSS-systems vary greatly according to the height above the seafloor the towfish is towed, the applied frequency and beam-width.

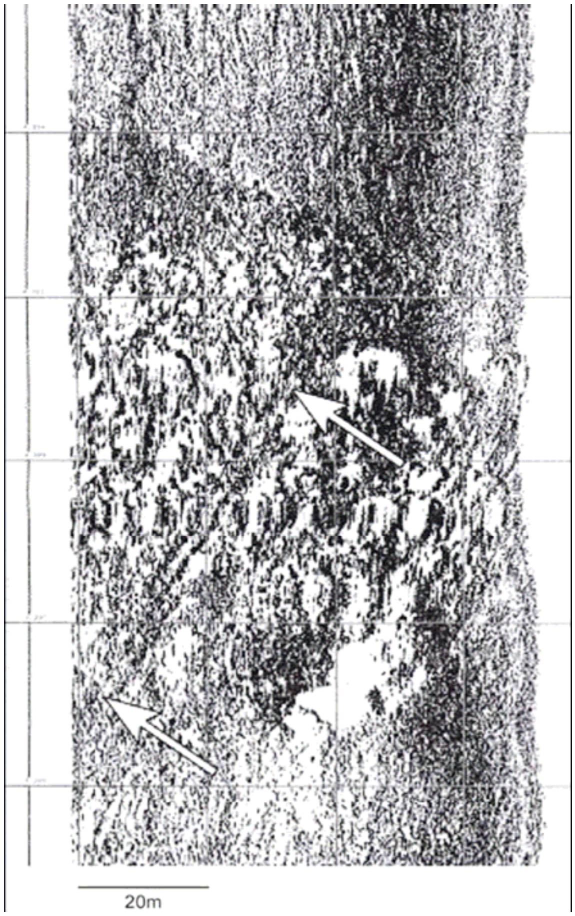

Fig. 7 *Side-scan sonar echogram. Lophelia colonies and a trawl track (between the arrows) through the coral area as seen by an SSS. The coral mounds are elongated in shape due to the speed of the printer. The area was ground-truthed with ROV. From Fosså et al. (2002).*

Signature of reefs on SSS

Given that the frequency and resolution are sufficient, reefs can be distinguished from the adjacent seafloor using SSS (Fig. 7; Freiwald et al. 2002; Lindberg et al. in press). This is due to a number of factors: the difference in incidence angle caused by the reefs steep sides, the rough surface that the coral colonies form, and finally the comparatively flat and often homogeneous sediments found next to the reefs.

Generally, the coral reefs appear as areas of highly varying backscatter ('rough Texture') and sometimes exhibit a 'cauliflower' signature on the sonargraphs (Fosså et al. 1997; Freiwald et al. 2002;

Masson et al. 2003; Lindberg et al. submitted). This is caused by the individual colonies which have a hemispheroidal shape and therefore cause widely different backscatter over short distances, resulting in a mottled, or cauliflower texture.

Depending on the height above the seafloor at which the towfish is towed, the reefs often cast an acoustic shadow on their far side, which can also be used to estimate their height (Fosså et al. 1997).

Conclusions

Side-scan sonar provides relatively fast mapping of large areas and can detect features not visible by other instruments, e.g., multibeam bathymetry or seismic. Advanced image and texture analyses significantly increase the data quality and if acquired close enough to the seafloor, sonograms can be of high resolution. Drawbacks are that the systems are often difficult to operate in areas of high relief, which is often the case with reefs, and that the system is susceptible to rough seas.

Multibeam echosounder

Modern multibeam swath systems use frequencies spanning from a few kHz to several hundred kHz and typically comprise more than hundred beams. The beams are transmitted at different angles from the same transducer unit, creating a fan perpendicular to the vessel direction. The angle of the fan is termed swath angle, which along with the water depth determines the width of the corridor mapped.

A wider swath angle and deeper water increases the corridor mapped but reduces the resolution as the distance between the individual beams increases; the so-called footprint (the area covered by a single beam) increases. For the mapping of large coral reefs, such as observed on the continental shelf at Røst, a large swath angle is sufficient (Fig. 8A). The individual mounds are clear and relatively easy to interpret. With a narrow swath angle and thereby increased resolution (Fig. 8B), it does not resolve any new features but makes it possible to study the morphology of individual mounds in larger detail. This is useful when studying individual coral mounds, but not for regional mapping.

Only the depth information is used to produce topographic maps of the seafloor. Echo strength, or backscatter strength, can be extracted from the multibeam data and presented as seabed backscatter maps (Kenny et al. 2000). Echo strength depends on hardness, roughness and the homogeneity of the seabed sediments. Some sediment types can be identified from the backscatter. The analysis of backscatter strength is, however, complicated as this factor is not given only by the seabed properties (Lurton 2002). One of the main problems is the variation due to the incident angle across an individual swath. This causes a characteristic stripe effect through the backscatter mosaic (Fig. 9). A normalization of the backscatter across the swath is therefore an essential part of the backscatter processing, but has been largely unsuccessful until recently (Novarini and Caruther 1998).

At present there is much effort dedicated to improve the processing of backscatter data. Robert Courtney (Geological Survey of Canada, Atlantic) has recently developed a new technique to normalize backscatter. This technique has been used on data from the Røst Reef. The results show high backscatter intensity associated with mounds identified as coral reefs (Fig. 10). To understand backscatter response and enable interpretation of the data, it is necessary to ground-truth an area as shown in Figure 10 and to compare the results with the backscatter. A coral reef is a mosaic of surface morphologies with different reflectivity. There can be living colonies only on parts of a mound, e.g., on the top or on one side, or small colonies. This variation in surface morphology and proportion between live versus dead corals complicates the interpretation.

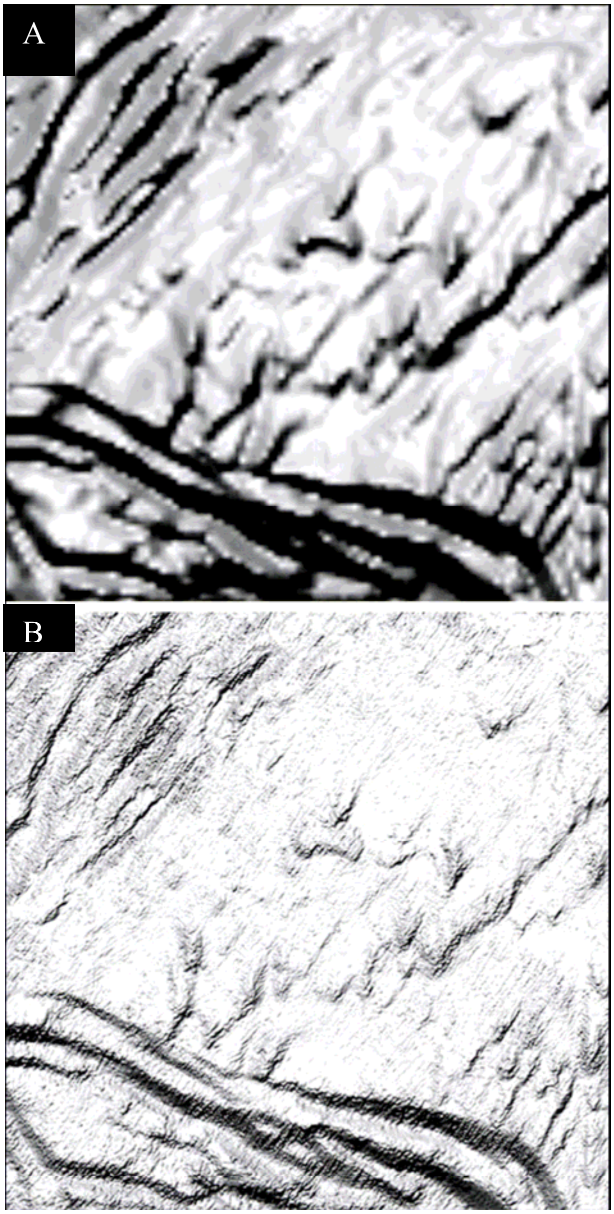

Fig. 8 *Bathymetry data acquired with a Simrad EM1002 multibeam swath system, which has 111 beams and adjustable swath angle.* **A** *A 1.07 km2 wide area from the Røst Reef mapped using a swath width of 68 degrees. At 300 m depth, the distance between the beams is 10 m.* **B** *The swath angle reduced to obtain a distance of 2 m between the beams. Similar processing methods were used for both data sets and the XYZ files where gridded using a cell size of approximately one-third of the acquisition cell size. Noise seems to be more*

dominating at the high-resolution data set, but also provide a tool for investigating the morphology of individual mounds, which can be used to differentiate between sediment mounds and coral reefs

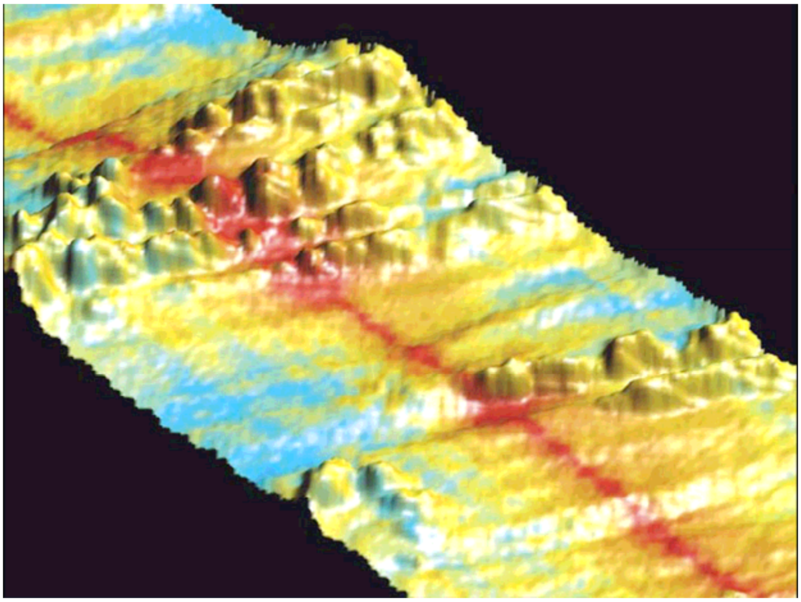

Fig. 9 *A 300 m wide transect of multibeam backscatter intensity draped over multibeam bathymetry data over the Sula Reef. The backscatter intensity drops with the distance from the center beam, easily observed with the very high backscatter intensity indicated in red*

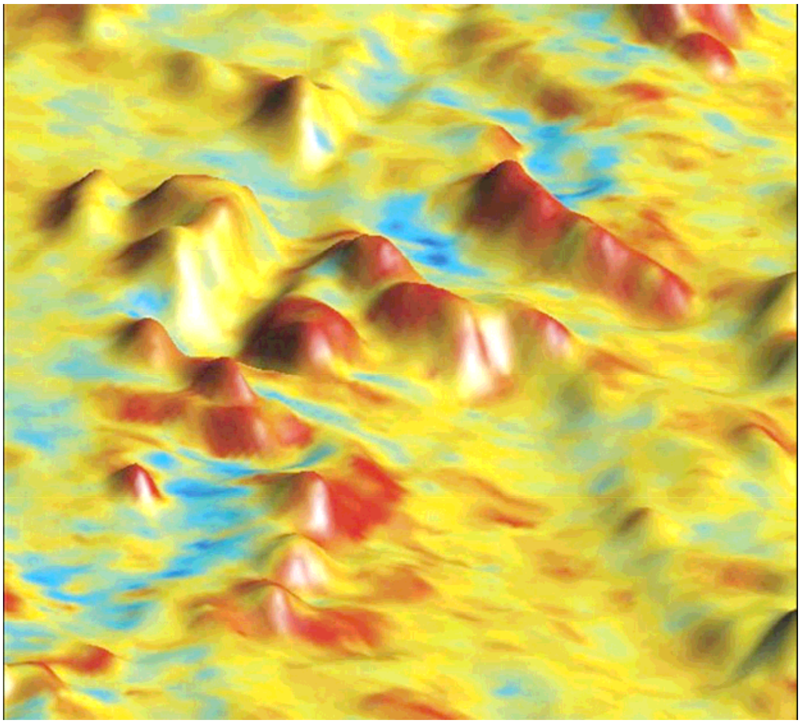

Fig. 10 *Multibeam backscatter intensity draped over multibeam bathymetry from a 250 m wide part of the continental shelf at the Røst Reef. The majority of the mounds defined as possible coral reefs are associated with very high backscatter intensity, however a few located in the top left corner area have low backscatter intensity. This can be artificially due to backscatter processing, but so far no evidence is found for this. Speculation regarding this phenomenon has been link to the condition of the reefs*

Automatic reef recognition using backscatter

The ideal mapping tool would be automatic recognition of coral reefs from backscatter data, similar to the use of RoxAnn, but with the advantage of covering larger areas. Automatic interpretation and coral recognition has previously failed due to the above-mentioned striping effect. Hopefully, it will be improved with novel normalizing methods.

A first trial of automatic reef classification was performed by transforming backscatter data into a raster format and creating a scatter diagram. A supervised automatic classification over the central part of the Røst Reef was tested for mapping areas with corals. High backscatter strength is believed to represent corals due to the roughness and hardness of the coral mounds (Fig. 11). In the figure the two centerlines of a swath that covers the central area of the figure were processed using the new normalizing technique. The red areas represent high backscatter, which are being classified as coral reefs according to the backscatter strength. The classification seems to be correct in interpreting the coral mounds on the continental shelf and the corals located on the detached sediment ridges, but also parts of the seabed where we believe there are no corals were classified as such.

Automatic recognition of coral reefs involves automatic processing of backscatter and unsupervised classification. Figure 11 shows the first step, but many problems must be solved before the processing and classification is automatic. Depth dependency of backscatter data is just one of the problems, and the EM1002 multibeam echosounder uses three different pulse lengths according to depth and the pulse duration is also affecting the backscatter strength (Bunchuk and Zhitkovskii 1980). The results are promising, but exact ground-truthing is necessary for further adjustments of the classification parameters.

Olex and multibeam bathymetry

To handle the large amounts of data obtained during multibeam mapping and to clean the data and produce maps requires an operator dedicated to that work. It can take many hours to obtain the maps. At sea it is, however, a great advantage to be able to display the acquired data in real time for immediate identification of potential coral reefs. An example of software that can be connected directly to a multibeam echosounder and display data continuously is Olex, a mapping and navigational software which also allows for plotting of ROVs or benthic landers during operation given sufficient positioning equipment is used.

Our experience is that Olex, in combination with multibeam echosounders, provides an efficient tool for coral mapping. The most important characteristic to use for detecting Lophelia reefs from multibeam data is the characteristic growth forms of the reefs. They form dome-shaped, often elongated structures, which rise significantly over the surrounding seabed. Further indications can be spotted from the surrounding seabed since the reefs are often associated with irregularities in the seafloor topography, such as iceberg plough-marks, slide ridges or other features that contribute to locally increased current velocities.

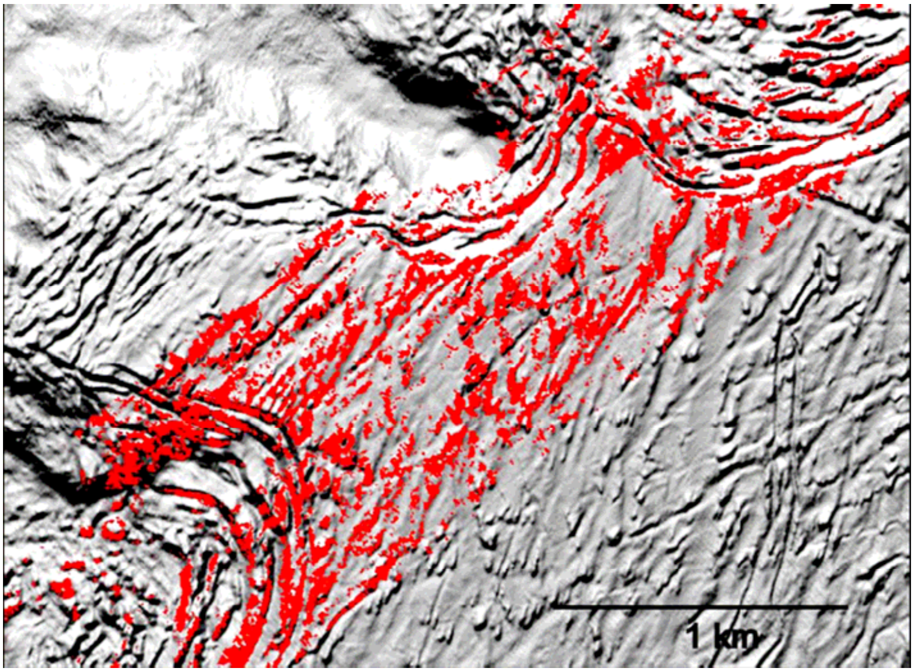

Fig. 11 *Automatic reef recognition using backscatter data. Bathymetry from central Røst Reef, draped by the supervised classification of the newly processed backscatter data. Only the two centre lines (corresponding to the red belt) were processed using the new technique, which covers the central area of the figure. The red areas being classified as coral reefs according to the backscatter strength. It is clear that the classification is correct in interpreting all coral mounds on the continental shelf and the corals located on the detached sediment ridges. Further adjustment of the classification parameters is needed, as the interpreted areas seem to extend beyond the known occurrence of corals*

Although the procedure described above is effective for large-scale mapping of coral occurrences, representative validation and ground-truthing are essential. However, our experience is that benthic structures of non-coral origin seldom exhibit similar topography to Lophelia reefs.

The Træna reefs – case study

In Træna a 23 x 13 km area was mapped in 2003 (Fig. 12). During the last glaciation the ice sheet shaped large ridges parallel to the ice flow direction on this part of the continental shelf (Rokoengen et al. 1995; Ottesen et al. 2002). These lineations are all orientated in a WNW-ESE direction, clearly imaged by the multibeam bathymetry (Fig. 12). The processes that shaped the large circular deep in the mid-eastern part of the mapped area are not known. New data indicate different glacial movement directions or possibly that the structure was generated during several glacial periods (Dag Ottesen, NGU pers. comm.).

Ground-truthing with ROV on five locations confirmed the presence of *Lophelia* on the inspected mounds. Interpretation of the multibeam bathymetry indicates that there are nearly fifteen hundred coral reefs in the mapped area. These were similar in size (approximately 150 m long, 40 m wide) and locally orientated in the same direction. There is no obvious geological explanation to the orientation of the reefs. The most obvious explanation is that the local current regime directs the growth of the corals.

Side-scan sonar versus multibeam bathymetry

A site survey with SSS and some ground-truthing with ROV was performed by Fugro Geoteam on behalf of Statoil in 1992 in a part of the Træna area (Figs. 12A, 13). The results indicated numerous coral reefs in the area (Hovland and Mortensen 1999).

Multibeam data were not acquired during this survey so the presence of coral reefs was interpreted using SSS data only (Hovland and Mortensen 1999). The site is therefore suitable for a comparison between two of the methods used for coral mapping.

Figure 13 shows the interpretation of multibeam bathymetry (B) and SSS-data (C) from the same sub-area in Træna. The major topographical features of the area can be found with both methods, such as the large iceberg plough-marks and the larger mounds. However, the interpretation of what is coral mounds and what is not differs in the two studies. The interpretation of the SSS gives much more coral mounds than the multibeam, and occasionally two close, but individual reefs, was merged into one.

Why these differences? Apart from the subjectivity of the interpretation, there are some explanations related to the specifics of the instruments. The grazing angle and the acoustic shadows caused by the topography makes it difficult to obtain an overview of the mounds and their morphology with SSS. The morphology is one of the most important characteristics used to distinguish between coral mounds and sediment mounds using multibeam bathymetry. Even with the difficulties associated with SSS-interpretation, the results have many similarities with the multibeam interpretation, both regarding identifying the coral reefs and determining the shape.

The detailed positioning is another problematic issue associated with the SSS. In deep water cable length causes a large layback. Large beacons must be attached on the cable or the side-scan fish for an accurate acoustic positioning, which often cause instability of the towfish and add noise to the data. By only using the layback as used by the Geoteam survey there will be significant error in positioning the towfish due to strong currents often observed in coral reef areas.

Conclusions

Mapping coral reefs using multibeam bathymetry is greatly assisted by visualization tools, such as sun-shaded relief maps where the sun illumination can be altered. Using sun-shaded bathymetry, the pattern of mounds and the general topography are visible, and it often becomes possible to differentiate between coral mounds and sediment mounds, when combining typical reef shapes. High-resolution multibeam bathymetry can resolve morphology of individual mounds and is very useful in differentiating coral reefs from sediment mounds in complex areas. Newly developed processing methods for multibeam backscatter data will be crucial to obtain more confidence regarding mapping of coral reefs. With further development and the use of multibeam echosounders close to the bottom, for example in an Autonomous Underwater Vehicle (AUV), this may also allow for interpretation of the proportion between living and dead coral on a reef.

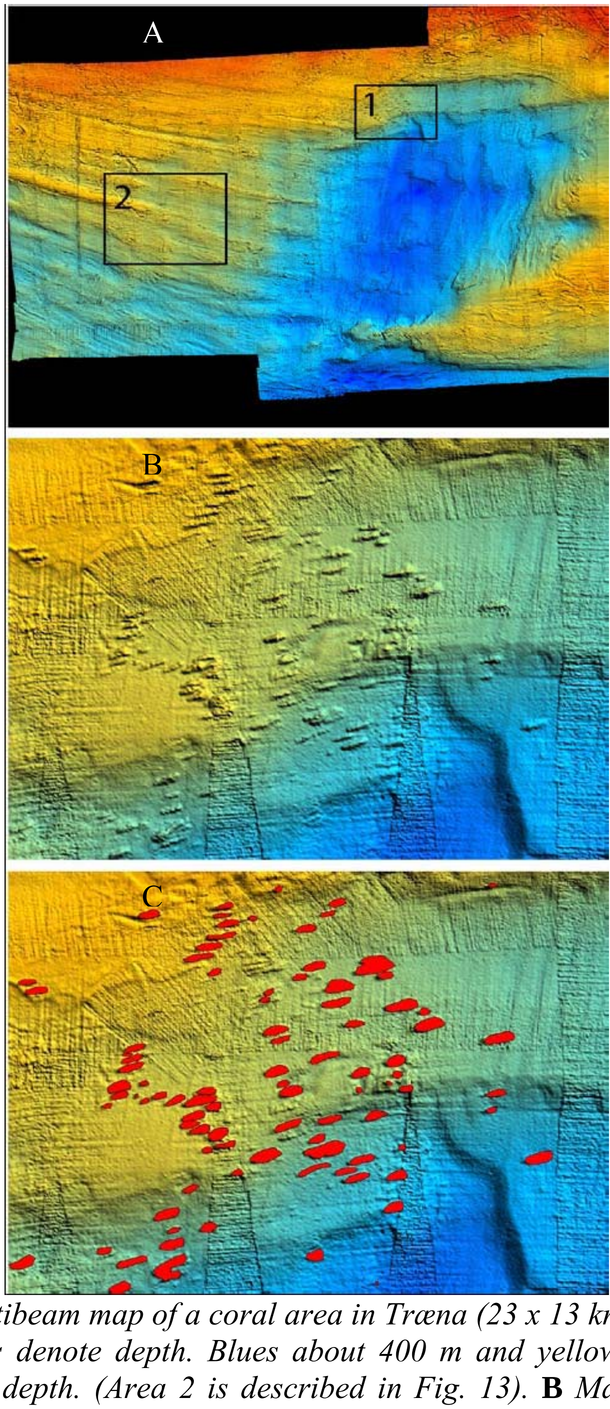

Fig. 12 A *Multibeam map of a coral area in Trœna (23 x 13 km). The colours denote depth. Blues about 400 m and yellow about 300 m depth. (Area 2 is described in Fig. 13).* **B** *Magnified picture of framed area 1 (2 x 3 km).* Lophelia *build characteristic mounds on the sea bottom that are easily recognised on the multibeam map. However, mounds of stones and till can be misinterpreted as coral mounds, so*

ground-truthing is necessary. **C** *Interpretation of B. Red areas is interpreted as being coral mounds*

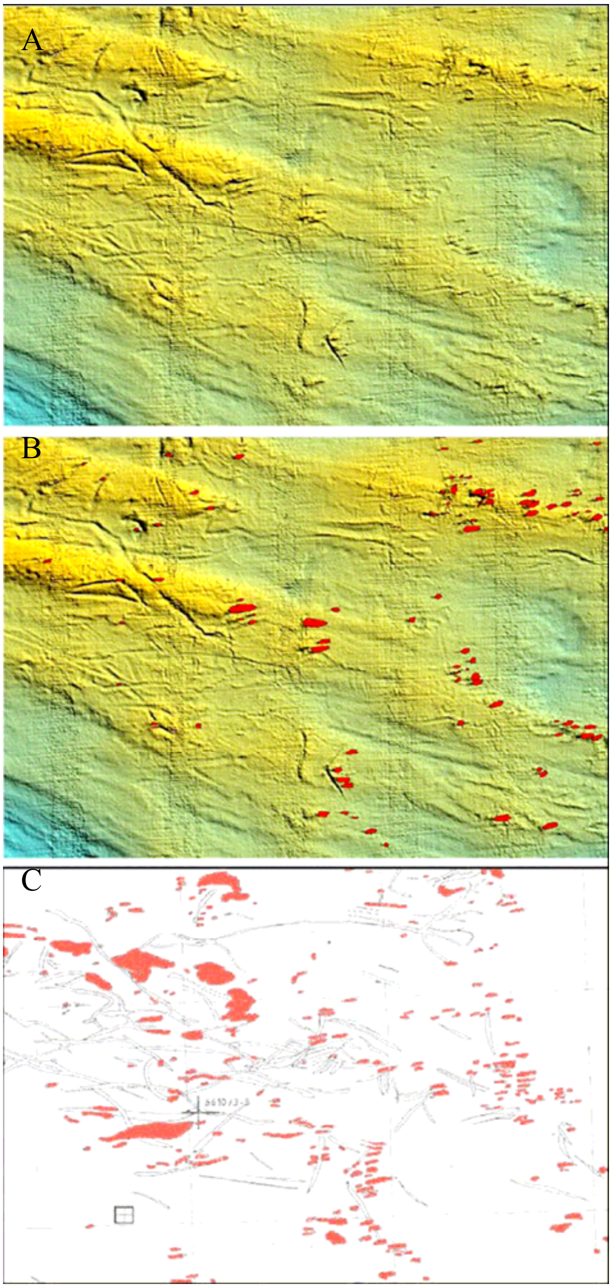

Fig. 13 *Interpretation of the seafloor using multibeam bathymetry and Side-Scan Sonar (SSS).* **A** *Framed area 2 (3.5 x 4.5 km) from Figure 12a without any interpretation.* **B** *Possible coral mounds (red). Interpretation based on multibeam map.* **C** *Interpretation of seabed features in the same area based on SSS*

Ground-truthing, detailed mapping and assessment

Sampling the reef fauna

The most extensive studies of the fauna on *Lophelia* reefs have been performed by Dons (1944), Burdon Jones and Tambs Lyche (1960), Jensen and Frederiksen (1992) and Fosså and Mortensen (1998), based entirely or partially on sampling with triangular dredge. Mortensen et al. (1995) studied the megafauna (>5 cm) using ROV and video.

Fosså and Mortensen (1998) compared the number species from their own study with four earlier studies in the northeast Atlantic and found that only 15 species of a total of 744 were in common for all studies. This reflects that the studies were undertaken in regions with fauna differences. However, it also indicates that the number of species associated with the reefs is much higher than recorded so far. The number of studies of the fauna is too low, which partly reflects the inherent difficulties with sampling this habitat.

Fosså and Mortensen (1998) compared the sampling characteristics of van Veen grab, triangular dredge, ROV and gravity corer in the study of reef biodiversity and concluded that grab and dredge are the two most effective gears with respect to number of species. Suction sampling using ROV (e.g., Buhl-Mortensen and Mortensen 2004) samples a part of the fauna that is very poorly collected with other gear.

Grab

Fosså and Mortensen (1998) recommend using a grab for description of the macrofauna because it effectively samples both coral and associated fauna and damages less corals than dredge sampling. It is also recommended to equip the grab with a video camera to improve sampling precision. Mortensen et al. (2000) describe a video-assisted grab which was used to locate and sample Lophelia. They conclude that a video-assisted grab can replace the use of traditional, more destructive dredging and trawling techniques. In Canada, Schwinghamer et al. (1996) developed a hydraulicallyactuated video-grab. It was designed to minimize disturbance to the sampling area and to provide the scientific operator with the ability to visually select the precise sampling area on the seabed, close and open the grab remotely, and verify that it closed properly prior to recovery. This grab has also been used to sample corals and associated fauna (Buhl-Mortensen and Mortensen 2005).

Because a *Lophelia* reef represents a habitat with several sub habitats (Fosså and Mortensen 1998; Freiwald et al. 2002), many samples are needed to provide a representative picture of the associated fauna, qualitatively as well as quantitatively. The only way to know exactly which part of a reef that has been sampled is to simultaneously use video recording of the bottom, e.g., video-assisted grab or ROV-sampling.

Dredge

A triangular dredge provides large samples with a corresponding large area being impacted. Dredges are not suitable for sampling mobile fauna, e.g., crustaceans, because they are easily washed out of the sample on the way to the surface and it is not known from which part of a reef, or perhaps the surrounding seabed, they were caught. Grab sampling actually catch small mobile animals better then a dredge, but the larger and scattered animals will usually not be represented (Fosså and Mortensen 1998). During the 1990's it became clear that any form of trawling or dredging has a devastating effect on the *Lophelia* colonies and should be avoided (Fosså et al. 2002).

Gravity and vibro corers

Vertical sampling of reefs and the surrounding seabed is important in order to understand the recent geological history of the area. As most of the reefs along the Norwegian continental shelf are still growing, and the areas experience continuous sedimentation, one must sample coral skeleton below the seafloor in order to unravel the development of the reefs through time. Information about the sediment, paleo-oceanography, age-determination ($_{14}$C and U/Th), geochemistry (stable isotopes, gas-content), and bio-erosion are some examples of useful application of gravity and vibro cores (Hovland et al. 1997; Lindberg and Mienert 2005; Dorschel et al. in press; Rüggeberg et al. in press).

Coring is not suitable for investigation of macrofauna, but can give a good description of the temporal changes of a specific location rather than allowing for mapping of the seafloor in the area. Both gravity and vibro corer may cause physical damage to the reefs if used among living colonies. The vibro corer is probably the most damaging.

Tethered video platform

IMR has used a very simple camera system developed in-house for ground-truthing. The system is connected to the vessel with a cable supplying camera and lights with electrical power and transmitting video signal to a monitor in real time. The inspection of the seabed is performed as the vessel drifts with the current and the wind. Lowering and lifting the camera control the distance to the seabed. The video platform is cheap, lightweight, and easy to operate and repair at sea. A dive takes very little time and it can be operated from relatively small vessels. It has been used extensively in the coral mapping project in Norway, especially when ROV-systems were not available.

The drawback of the system is that it is drifting with the vessel, meaning that one cannot stop or turn. Coral mounds may consist of only small patches of living corals that are easily missed during a drift leading to wrong conclusions about the status of a reef. However, in major coral areas this equipment is very useful for ground-truthing giving presence-absence information.

Remotely Operated Vehicle (ROV)

When detailed observations, high quality imagery or selective samples are required, ROVs often offer the best solution. While considerably more costly, technically complicated and demanding for the basic organisation of an investigation than the techniques described above, ROVs are very useful tools for the characterisation of habitats, targeted sampling and operational tasks such as installation of in situ experiments. Videos and photographs obtained during ROV-surveys provide the best documentation of both biological values and current threats to a broader public. Very precise and well-controlled ground-truthing and mapping operations can also be performed with ROVs.

The success of ROV-operations is largely dependent on the support systems available, such as for precise navigation. A good procedure is to obtain high-resolution multibeam maps prior to ROV-operations, and then use this information for ROV-navigation.

Operations of this type were successfully performed on board the R/V "G.O. Sars" in 2003. Advanced software (e.g., Olex) and hardware (positioning equipment) allowed the ROV to be directed to specific sites for close inspection and targeted sampling (Fig. 14).

Conclusions

Description of the biological diversity of Lophelia-reefs requires many samples because of the highly variable habitat architecture. A summary of advantages and disadvantages of different sampling gear is given in Table 1.

The triangular dredge is an effective gear to sample both dead and live corals and to study epifauna. However, it is destructive and should under all circumstances be avoided in areas with living corals. A dredge is still useful in the coral rubble zone if one can assure that living corals will not be impacted. However, also here one should be careful this zone has a rich fauna and is part of the complete coral habitat. The grab is a more precise and a more considerate gear. The most effective is a video-assisted grab where one sees the seabed and can release the grab precisely. This method is also well fitted to sample live corals with a minimum of damage. The gravity corer is not adequate for studying the living *Lophelia* community. The only way to know exactly which part of a reef that has been sampled is the simultaneous use of video, e.g., video-assisted grab or ROV-sampling. The combination of these methods provides the best picture on both fine and broad scales.

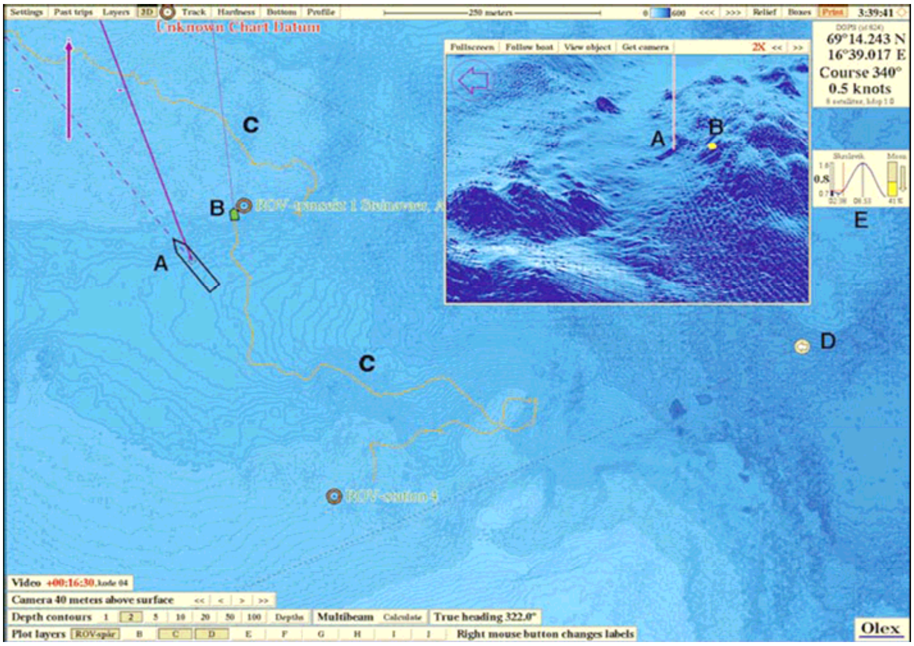

Fig. 14 *Monitor screen dump from the Olex navigational software during work with an ROV survey in the Steinavær area, Andfjord, Northern Norway from the R/V "G.O. Sars", July 2003. The bathymetry of the area was surveyed immediately prior to the ROV work, and is illustrated by shaded depth contours (2 m isobaths) and a 3D view (2x vertical exaggeration).* **A** *Position of the research vessel.* **B** *Position of the ROV.* **C** *Recorded ROV tracks (individual parts of the tracks are time-coded, permitting synchronisation with recorded video).* **D** *Origin of 3D view.* **E** *Position in the tidal cycle at the closest recording station*

Mapping procedure by the oil industry

Oil companies operating in Norway are obliged to map corals in connection with laying of pipelines and drilling operations. A typical mapping procedure has four phases as described by the Norwegian Directorate of Fisheries (2004):

1. A corridor 150-300 m wide is mapped with multibeam echosounder, side-scan sonar and ultra high resolution 2D seismic (250-1500 Hz) in order to obtain a rapid and inexpensive overview of the regional seabed conditions and the possibility for coral reefs to occur in the area.

2. Processing and interpretation to identify potential reefs and other obstacles. Planned pipeline transects and drill-sites are then adjusted accordingly.
3. In the third phase, ROV with video camera and optional side-scan sonar (1000 Hz) are used for ground-truthing.
4. The final pipeline track or drill site is decided upon based on all the information.

	Pros	**Cons**
Triangular dredge	Covers large area Large samples Inexpensive	Destructive Poor spatial resolution Not quantitative
Grab	Approximately quantitative Good spatial resolution Small impacted area Inexpensive Video-assisted grab increases spatial information	Somewhat destructive Often difficult to obtain successful samples
ROV	Covers large areas Documents damage to corals and other fauna from human activity Maps megabenthos Documents fish behaviour Describes macro-structure of *Lophelia* colonies and reef Precise sampling with manipulator	Expensive to very expensive Complicated
Gravity corer	Samples the sediment stratification Sample micro- and meiofauna	Covers small area Not suitable for studies of living macrofaunal community

Table 1 *Pros and cons of different gear used for sampling the Lophelia coral habitat (modified from Fosså and Mortensen (1998))*

Monitoring

Monitoring is an increasingly urgent issue as more reefs and deep-water coral habitats are discovered in areas with human activities. In Norwegian waters and elsewhere, deep-water reefs have become protected against trawling and some have received status as Marine Protected Areas (Fosså and Alvsvåg 2003; Freiwald et al. 2004). Programmes should be initiated to monitor important biological factors and the implementation of regulations. At present there is no coral monitoring in Norway, nor is there any experience. The issue, however, is very important and therefore we present some of the methods and possibilities regarding monitoring of reefs at great depths.

Due to the complexity of *Lophelia* reefs, traditional methods such as grab and dredge for sampling the seabed are probably not suitable for monitoring temporal changes of reef fauna. Video and photographic sampling of fixed areas will probably give better indications on changes in the megafauna and the condition of the reefs. To obtain high-resolution data from deep-water benthic habitats platforms equipped with electronic sensors and electro/hydraulic engines are needed. For monitoring there are two different types of platforms: (i) mobile, e.g., ROVs, AUVs and towed gear, and (ii) stationary, e.g., landers and cabled systems. Below we deal in short with the possibilities of landers and cabled systems for monitoring.

Landers

Benthic landers are instrumented platforms that are left on the seafloor for measuring physical and biological variables over a period of time. The employment of landers in deep-water coral habitats has a recent history and few results have been published (Duineveld et al. 2004; Roberts et al. 2005). Landers have proven very useful for process studies and detailed description of the near seafloor environment (Parker et al. 2003; Duineveld et al. 2004; Roberts et al. 2005). Roberts et al. (2005) used a so-called photolander with still cameras and a set of optical instruments at two reef sites (the Sula Reef off mid-Norway and the Galway carbonate mound in the Porcupine Seabight). The cameras provided time-lapse photographs from the seabed, while other instruments recorded particles in the water close to the seafloor.

A drawback of landers is the limited power supply. They are not connected to power lines from land and therefore rely on battery power.

Cabled systems

Cabled seafloor observatories have many attributes in common with benthic landers, but an important difference is that they are supplied with electric power from land. Several cabled ocean observatories are being planned around the world (Momma 2000; Heath 2003) such as The Monterey Accelerated Research System (MARS) and The European Sea Floor Observatory Network

(ESONET). A few successful attempts have previously been made to observe isolated deep-sea phenomena using out-of-service analogue cables (Petitt et al. 2002).

Cabled seafloor observatories enable long time-series of data from benthic environments, but because they rely on expensive fibre optic cable networks this technology is dependent on major economical support, e.g., large institutions and industry.

By linking visual monitoring with environmental recording, we can begin to understand the effect of long-term environmental dynamics on deep-water reef communities. Approaches like this have tremendous potential to help us understand not just the natural history of this ecosystem, but also offers a unique opportunity to evaluate and calibrate climatic proxies that potentially can be extracted from deep-water coral skeletons.

Conclusions and recommendations

In order to fully understand the reef habitat, its structure and ecological function, it is necessary to have a good understanding of the biology, geology, hydrography and geochemistry of coral ecosystems achieved by systematic research. Mapping, sampling and monitoring of deep-water coral reefs in Norwegian waters and elsewhere are essential tasks for which we have presented methods and strategies summarised in Tables 2 and 3. Not surprisingly, the best methods are often linked to the highest cost, but there are also viable low-cost alternatives that can be performed from small vessels. Below we describe a procedure for mapping of deep-water coral reefs that we have found useful. It can be accomplished during one single cruise or following several successive ones. Site selection is based on existing information (e.g., from fishermen) or by studying the general seabed topography. The first search in a new area is performed following a grid of survey lines and with the RoxAnn activated. Usually in an area with well developed reefs, RoxAnn will give positive signals. Having received strong indications that corals are present, we perform a multibeam mapping of the area. The multibeam data are then interpreted and potential structures for ground-truthing are chosen.

Purpose	**Types of sample**	**Horizontal resolution**	**Vertical resolution**	**Resolution and time span**	**Size of vessel**	**Costs**	**Comments**
Large scale mapping							
Identification Mapping	Single track acoustic data	Effort dependent	cm		All sizes	Low / High	Efficient and low cost
Identification (Mapping)	Single track acoustic data	N/A	N/A		Large / Medium		Useful supplement for geological understanding
Identification Mapping	Area coverage, and reflection strength of bottom	Down to dm	N/A		All sizes		
Identification Mapping	Area coverage, bathymetry and backscatter	Down to 2X2 m	cm		Medium /lagre	Very high	Highly recommended

Types of sample	**Horizontal resolution**	**Vertical resolution**	**Resolution and time span**	**Size of vessel**	**Costs**	**Comments**	**Method**
Ground-truthing & detailed mapping							
Epi(coral)fauna and corals	Depends on distance travelled on bottom	N/A	Poor	Small	Low	Destructive to reefs Not recommended	**Single (Split-beam)**
Fauna and corals, sediment	Equals grab size	N/A	Poor	Small	Low	Recommended with video	**Seismic**
Coral skeleton, sediment	Equals corer size	mm	Potentially thousands of years	Medium	Low	Useful for pales studies	
Video footage, photo	Down to dm	N/A		Small	Low		**Side Scaon sonar**
Mutiple	Down to cm	N/A		Small / medium	High	Highly recommended	**Multibeam**
Mutiple	Down to cm	N/A		Large	Very high	Highly recommended	

Method	Purpose
Dredge	Biodiversity (Mapping)
Grab	Ground truthing, biodiversity,
Corer	Sub bottom investigation
Tethered camera platform	Ground truthing
ROV	Ground truthing, fauna, deployment and retrieval of instruments *in situ*
Manned submersible	

Table 2 *Overview of mapping tools for Lophelia reefs*

Platform	Mobility	Tasks	Range	Temporal resolution	Comments
ROV	Moving (Stationary)	Visual inspections	Small to medium instrumentation e.g, video, acoustics	Short-term	Highly recommended
AUV	Moving	Acoustic (Visual)	Large; miles	Short term	Recommended
Lander	Stationary	Visual	Local to medium	Short- and long term. Non permanent	Highly recommended
Cabled system	Stationary	Visual, Multiple sensors	Short to long. Depends on instrumentation and cable network	Long term, almost permanent	Authors have no experience, but the method has a great potential

Table 3 *Monitoring of deep-water coral reefs*

Mapping procedure

Prior to the cruise

1. Background information about coral fields from fishermen, oil companies etc.
2. Selection of study area

During cruise

3. Initial survey using RoxAnn as a coral detection method
4. Confining the area subject to multibeam mapping using indications from RoxAnn and coarse topographical clues
5. Multibeam mapping
7. Ground-truthing using ROV or tethered video platform. ROV can be navigated on topographical maps obtained in 5
8. Optional biological sampling of the coral ecosystem and environmental factors

Post cruise

9. Analyses of multibeam backscatter and production of maps.

Acknowledgements

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5.4 Article 4

Sediment classification using multibeam backscatter amplitude versus grazing angle.
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Geoacoustic parameter of seabed sediments from the first order perturbation model and Multibeam backscatter data.

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Abstract

Cross plotting multibeam backscatter strength acquired at the Nadir and the critical angle, has shown a noticeable good correlation with seabed sediment properties. Reduced quality of the backscatter data near nadir is common, emphasising the use of the backscatter data at low grazing angles for sediment determination is likely to increase the confidence of the results. Locating the grazing angle of the cusp (local maximum), which is also the position of the critical angle, makes it possible to calculate the compressional speed of the seabed sediments. Matching the acquired backscatter data to a model response for the lower grazing angles has shown good correlation when the shear wave component is incorporated. This provides an estimate of the density, shear wave speed, compressional and shear wave attenuation of the seabed sediments.

Keywords: *Multibeam backscatter, angular response, Seabed determination*

1. Introduction

Modern multibeam systems are normally manufactured and calibrated to acquire high-resolution bathymetry. The use of multibeam backscatter data for mapping sediment boundaries and sediment classification has been explored in a less extent. The overall backscatter signal comprises surface and volume scattering. Surface scattering is caused by the seafloor roughness, which is a function of seabed sediments and seabed morphology causing part of the incident signal to be scattered as incoherent energy. In the presence of roughness this energy will be scattered in all directions with a part scattered towards the transmitter. This part is termed surface backscatter.

At larger grazing angles (the angle between the beam axis and the seabed) a part of the incident energy may penetrate the seabed. This depends on the impedance contrast between the seawater and the seabed sediment. Higher frequency and harder seabed sediment reduce the amount of penetrating energy. Scatterers that are at the interface or are buried inside the sediments generate additional scattering, which is termed volume scattering. Volume scattering can be significant in areas of softer sediments that contain scatterers of geological or biological origin.

Surface backscatter is the only component scattered towards the transmitter at grazing angles lower than the critical. For flat seabed this angle is defined where no energy penetrates the seabed, but a single angle does not define this when roughness is present. In practice backscattering strength is observed to increase rapidly at smaller grazing angles, which is within the pure surface scattering domain (Jackson and Briggs, 1992). A slower increase from the critical angle to the centre domain (near normal incidence) is observed, where both volume and surface scattering contribute to the backscatter strength. High backscatter strength is observed within the centre domain, which is from around 70° to normal incidence (the normal incidence angle is here termed nadir). The received intensity in this domain consists mainly of specular reflection and volume scattering.

Seafloor segmentation using normalised backscatter data have been successfully performed and utilised for habitat mapping (Todd et al., 2000). Sediment characteristics have been determined using various types of ground truthing, and were extrapolated to other areas of similar backscatter characteristics. The backscatter strength provides a primary indication of sediment type. Cross plotting the backscatter strength at nadir and critical angle (Fig. 1.), has shown a noticeable correlation with sediment type (Christensen et al., in press). The sediment properties from this analysis was obtained by grab sampling, free fall penetrometer data and video inspection of the seabed, in an area that consists of four fjords surrounding three islands, a coastal setting in the Møre area, western Norway. The focus of this paper will be modelling the backscatter strength from the critical cups, while the nadir region is ignored. Backscatter acquisition near nadir, is known to be associated with numerous problems, such as amplitude detection, effect of sidelobe interference and subbottom reflections (Hughes Clarke et al., 1997). The smallest variation is often located near nadir, while large variations have been noted at certain sediment types at smaller grazing angles. A previous test revealed the extreme difficulty in differentiating between till and coral reefs near nadir, while there was a clear difference in the recorded backscatter strength at a grazing angle of 45˚ (Fosså et al*.,* 2005).

The purpose in this work is to investigate the possibility of extracting physical parameters of fine-grained sediments using AVA (Amplitude Vs. grazing Angle) curves from multibeam backscatter data. Partly by analysing the AVA curves and partly by comparing these curves with theoretical modelling. Extracting the exact sediment composition or physical parameters from a sample is associated with some uncertainty, as the sediment structure might be altered and fine-grained material is likely to be suspended during the sampling process.

2. Methodology

3.1 Multibeam system

Experimental data that used to compare the theoretical data to the model response was acquired using an EM1002 multibeam echo sounder. This system utilises 111 beams with a ping rate of more than 10 Hz and has an angular coverage of up to 150º when equal distance setting option of the beams was chosen. The EM1002 multibeam operates with a frequency of 95 kHz; in fact it is 98 kHz for the inner part of the swath (beam angles less than 50º) and 93 kHz for the outer part of the swath (beam angles higher than 50º) (Mosher et al., 2002).

3.2 Data acquisition and processing

Multibeam data were acquired and processed using Simrad software, which extracts both the correct slant range and backscatter values from the ensonified area at the seabed. This area is bounded by the transmitter beam pattern at nadir and by beam geometry and the transmitting pulse length at other angles. The backscatter data is post processed and a backscattering coefficient, BS, given in decibel per unit area is obtained, which can be compared with other published values. The system has been calibrated to obtain an inherent uncertainty in the values due to variation in transducer sensitivities and may be estimated to be typically ±1 dB for the used system. Data analysed in this paper have been selected from areas where the seabed is almost flat, to minimise the slope effect. Nevertheless the incident angle has been corrected for seabed slope, before converting to grazing angle.

3.3. Theoretical modelling

The theoretical backscatter strength is calculated as a function of grazing angle using a first order perturbation model of the Rayleigh-Rice theory. This is largely based on the work by Essen (1994). The model assumes a horizontal interface, with perturbation as surface heights given by a two-dimensional function roughness spectrum. The first and the second order terms represent coherent and incoherent energy. Expanding the acoustic fields within the water and in the seabed sediments as power series of the height variation will provide a formula that is used in the perturbation model (Hovem, 2005).

The Rayleigh-Rice model approximates the acoustic field locally as a plane wave, which is only considered a problem in very shallow waters. The model is also only valid in case the roughness amplitude is small compared to acoustic wavelength (Essen, 1994). Even at high frequency used by multibeam systems the roughness approximation is not always fulfilled at areas of coarse-grained sediments.

3.3.2 Rayleigh-Rice model

The boundary conditions require the continuity of pressure and the normal particle velocity component, which must be satisfied separately by the first order perturbation model. The zero terms are the only terms that exist when the surface is completely flat and the acoustic field is a sum of an incident wave and reflected wave in the specular direction. In a rough surface the diffuse fields must be considered and it is taken into account in the first order perturbation model. The additional diffuse fields will therefore not be incorporated in the energy balance. The lack of energy balance is typical for all perturbation theories (Hovem, 2005). In this paper energy is balanced by the incident intensity versus the reflected and transmitted intensity and does not include the diffused incoherent field, i.e. does not conserve the energy. Furthermore the model does not account for larger scale roughness, which may modulate the grazing angle dependence or cause shadowing. This approach reproduces the backscattering coefficient as a function of incident angle, without accounting for multiple scattering (Essen, 1994).

The roughness spectrum is considered isotropic, which means the roughness has no preferred directions (Hovem, 2005), a property that eliminates any effect of the survey direction in areas where the seabed is flat. More details concerning the seabed roughness obtained from multibeam data is very rarely available. Earlier attempts to describe the features of observed backscatter using a Gaussian-shaped roughness spectrum have been inappropriate (Essen, 1994). It is more common to assume that the spectrum follows a scaling constant and exponent value. The exponent values reported in the literature are within a large range. At low operating frequency a frequency dependency have been observed, but this dependency seems to be absent for small roughness (fine-grained sediments) and at high frequencies (*e.g.* Ulrich, 1996). A frequency of nearly 100 kHz is used here, and the calculation of the scattering strength has been chosen to make the model response frequency independent.

The model response is the backscattering strength as a function of the grazing angle
(Fig. 2). The model shows how the backscatter strength decreases sharply as the grazing angle increases past the critical angle, which is associated with a cusp (a local maximum). This decrease indicates that the boundary becomes relatively transparent at angles where penetration is possible (Jackson et al., 1986). The rise in the backscatter strength at the critical angle can occur due to the following combined effects: the transmission coefficient is rising along with the reflection coefficient just before the critical angle is reached. If the surface is smooth and if there is no attenuation in the sediments, there will be a sudden drop in the transmission coefficient to zero and the reflection coefficient becomes unity. If, on the other hand, there is attenuation, total reflection does not occur. Now the

increased transmission into the sediments extends over a larger angular band around and, despite the losses that occur in the sediments, this increased transmission can produce increased scattering from the sediments (Novarini and Caruthers, 1998).

3.3.3 The shear wave component

Multi channel seismic data have shown that the acoustic field within the seafloor consists of both pressure and shear waves. Shear waves do not occur in fluids and must therefore be generated by pressure to shear conversion (P-S) at the seabed. This energy penetrates the seabed and reduces the energy scattered or reflected in the seawater. The maximum P-S conversion occurs on either side of the critical angle, but no conversion occurs at the critical angle. Models that comprise P-S conversion make the cusp relatively higher.

Incorporating the shear wave component into this model also shows relative larger cups (Fig. 3), compared to the cusp where the shear wave component was not incorporated (Fig. 2).

The geoacoustic input parameters in relation to the properties of the water, which are used as an estimate for the seabed sediment when the model response matches the experimental data. The attenuation of seawater was estimated to 35 dB/km for the used frequency (Medwin and Clay, 1998). This value was used to obtain specific attenuation value of the seabed sediment. A change of the different input parameters affects the model response differently. A change in compressional speed will affect the backscatter strength at all grazing angles. A higher attenuation of the compressional wave smoothens the cusp at the critical angle, but with very small effect at other grazing angles. A change in the model density has a large effect on the backscattering strength for all the grazing angles, with exception at the critical angle. Changing the input shear wave speed changes the response of the backscatter strength at lower grazing angles and high grazing angle, but have no or very little effect on the backscatter response at the critical angle. The higher the shear speed input is, the lower the backscatter strength is. The shear wave attenuation has a minimal effect at the critical angle, while the compressional attenuation has a large effect at the critical angle and less affect at other angles. The drop in the modelled backscatter strength on the low grazing angle side of the critical angle seems to be more abrupt with high shear wave attenuation.

4. **Results and discussion**

4.1 Experimental results:

Marine geophysical methods are not individually capable of discriminating all types of seabed sediments from the scattered acoustic signals. This is due to many factors, some of them related to noise. AVA as a processing technique for seabed sediment classification will inevitably suffer the same handicaps. Nevertheless, results indicate the possibility of differentiating between fine-grained sediments, sandy sediments and coarse-grained sediments (Fig. 4). These profiles show distinct difference in backscatter intensity according to the sediment type. The thicker black curves show the mean for each of the three sediments, which are used for further modelling (Fig. 4). The variance in backscatter strength within each of the three sediment classes makes it difficult to increase the number of sediment classes without a significant overlap. The largest variation in the backscatter strength is found in sand, while the variances for till and clay are much smaller ((Fig. 4 and Table 1). A rough classification, with a few classes such as fine-, medium- and coarse-grained sediments is probably the most reasonable result from a classification based purely on the use of mean backscatter strength.

A local maximum, cusp, is observed at the 40˚(140˚) grazing angle on the profiles (Fig. 4 and Fig 5). A second and minor local maximum is observed in areas of clay at lower grazing angle (Fig. 4 and Fig. 5). This cusp is believed to be associated with the critical angle (Fig. 5). This cusp is smeared and therefore unclear for sand and till. This is not explained in the used model, but can be explained by the increased roughness. The increased roughness smears the critical angle over a larger angle interval, as well as the critical-angle effect of the transmission coefficient (Novarini and Caruthers, 1998).

The first step in fitting the model response to measured backscatter data is to calculate the compressional speed of the seabed sediments using Snell's law. Accurate measurements of the acoustic speed of the water are obtained by SVP (Sound Velocity Profiler) during the multibeam survey. The critical angle is determined by the position of the cusp. This together with the acoustic speed of water makes it possible to calculate the compressional speed. In this case the acoustic speed of water was found to be 1482 m/s. Using this and the interpreted critical angle (Fig. 4) the compressional speed of the seabed sediments was calculated to be between 1701 m/s and 1751 m/s (Table 2).

The calculated speed (Table 2) agrees with the published speed results. For coarse-grained till a velocity of 1640 to 1740 m s^{-1} was reported (Hunter and Pullan 1980), while the speed in coarse sand is similar to values estimated by Hovem (2005) and Hamilton (1980). On the other hand the calculated compressional speed of clay is higher than most published values for clay. In fact it is closer to published values in very fine sand (Hamilton 1976; Hamilton, 1980; Hamilton and Bachman 1982).

4.2 Results and discussion testing the AVA method in three sediment types

Fig. 6 shows the mean backscatter from each of the three sediment types and the best-fitted model of each of these curves, which is a result of many iterations with various parameters. The input parameters that were used to create this fit are listed in table 2.

There is an overall good match between the model response and the multibeam backscatter data at lower grazing angle. Comparing the model with the measured data using the χ^2 test shows that the match is within the 95% confidence interval for all three sediment types around the critical angle. The correlation in the 95% confidence interval is maintained up to 59˚ for clay and 56˚ for till. The model response differs from the measured backscatter at around 40° in sand, and the hypothesis is rejected according to the 95% confidence at a grazing angle of 43.5˚. The low backscatter strength measured in sand at grazing angle between 40˚ and 55˚ was not possible to mimic in the modelling, while maintaining the correlation at lower grazing angles.

The less accuracy of determining the compressional speed in the coarse grained sediments reduces the confidence of the modelled parameters of sand and till. Even so the modelled density of these sediment types are similar to other published densities (Hamilton and Bachman, 1982), when considering the presence of carbonate (shell fragments) in coarse sand. The clay density in the literature is estimated to be 1.4 times the density of water (Hamilton 1976;

Hamilton, 1980; Hamilton and Bachman 1982), which correlates to the measured values in cores (Lepland and Bøe, 2003). This seems very high compared to the AVA estimated density. The AVA, or any other remote sensing measurements are believed to be more accurate, especially in fine-grained sediments. Sampling sediments can alter their structure and water will be drained from the samples during recovery and analysis. Measurements conducted in laboratories will therefore yield an over-estimated density value. Video recording of grabbing has also shown how the finest parts of the seabed are suspended and removed during sampling operation. Results from analysing samples will therefore be associated with uncertainty compared with results from remote sensing. The uncertainty is largest for fine-grained sediments, as the turbulence generated by grabbing is most likely not strong enough to suspend coarser particles. It is therefore believed that the AVA will provide a more accurate estimate of some of the geoacoustical parameters.

Published shear speed are for different sediment types often given in a large interval, for example in Hovem (2005). The AVA modelled compressional shear speed of sand is in the higher part of the sand interval, while the compressional shear speed is in the low end of the till interval given by Hovem (2005). The compressional shear speed of clay from the AVA is higher than the published values by Hovem (2005) and Hamilton (1980).

The sensitivity of the compressional speed of the AVA model and the poor definition of the cusp at the critical cusp reduces the confidence of the AVA results in sand and till. The problem is not only related to the smearing of the cusp, but also the model limitation according to the roughness and the isotropic assumption. The Rayleigh-Rice theory assumes that the roughness amplitude is less than the acoustic wavelength, this might not be fulfilled in the coarser sediments. It has been suggested that the perturbation theory can still yield reasonable results even if the small roughness requirement is not strictly fulfilled (Essen, 1994). Glacial deposits (till) and tidal currents deposit (coarse sand within the test area) are not likely to be isotropic. The clay within the test area is however likely to be isotropic. The results for clay seem promising and an additional site was chosen to evaluate the model.

4.3 Results and discussion of a second AVA test in clay

Extracting AVA profiles were performed to test the results of clay. This was performed less than a kilometre south of the clay location used in the first site, where the area covered by the port channel is confirmed homogenous clay by ground truthing, using both free fall penetrometer and video assisted grab. The port channel is presented by grazing angles 0° to 90°, while the starboard channel comprises grazing angles 90° to 180° and was converted as negative grazing angle plus 180°. In this test over forty AVA curves were extracted (Fig. 7). These results were similar to the previous test (Fig. 4.)

The cusp believed to be associated with the critical angle has been individually interpreted from each of the AVA profiles (Fig. 7 and Fig. 8). The results of this interpretation are summarised in table 3.

The observed grazing angles for both channels and from the first test are very similar, resulting in near equal calculated compressional speed. This indicates the high accuracy of this method, where a small variance is noticed in each site. The mean of the two compressional speeds in table 3 was used, when fitting a model response to the mean backscatter curve between grazing angle 20° and 90° (Fig. 7). The best match between experimental data and model response (Fig. 9) was achieved using the parameters in table 4.

The model response seems to correlate very well up to about a grazing angle of nearly 70°. A correlation between the model and data within the 95% confidence interval is confirmed between 23º and 67º grazing angle. The deviation between the model and the data increased drastically at higher grazing angles.

The parameters found in test 2 are all similar to the parameters found for clay in the first test, with exception of the shear wave speed. The shear speed estimated from the first site is lower than the published values, while the estimates of the second site lies within the range of the published values (Hovem 2005). The shear speed values published by Hamilton (1980) are in-between the values obtained from the two test areas.

The modelled attenuation values are associated with some uncertainties in test 1, where the shear wave attenuation is very small in the soft sediment as compared to harder sediments, table 1. An opposite trend was expected. The increased shear wave attenuation of clay in test 2 is closer to the expected values in comparison with sand and till attenuation values in test 1.

The input parameters for clay sediment from the two test areas provide nearly the same model response. A low shear wave speed reduced the backscattering strength, which in test area 1 was compensated for, by the low shear wave attenuation.

The few AVA curves obtained in test area 1, do not allow excluding possible outliers. The large number of AVA profiles and the knowledge from test 1 permit the exclusion of potential outliers.

5. Conclusion

The purpose of this paper was to verify the AVA classification introduced in an earlier paper. It can be confirmed that the backscatter at the critical angle can be used to separate seabed sediments. Three different sediments; clay, coarse sand and till, were classified using this technique. This classification is also possible using other grazing angles or the overall backscatter strength. Determining the critical angle opens the possibility for extracting the compressional speed of seabed sediments. This was however only possible with high confidence in areas comprising fine-grained sediments (clay), as the cusp is smeared and unclear in coarser sediments, which reduced the confidence of the compressional speed determined using this method.

Four additional geoacoustic seabed parameters can be estimated by fitting the modelled AVA curves to the measured AVA response. A good match between model response and multibeam data was achieved in the three tested sediment types. The models sensitivity to the compressional speed reduces the confidence of the AVA model in coarse-grained sediments where the critical angle is difficult to determine. The AVA method is best used in fine-grained sediments, where estimates of density as well as compressional and shear speed are obtained with good confidence. Estimates of compressional and shear attenuation are found, but the confidence of these estimates are reduced, as they are significantly different from published data.

The entire theoretical model was based on the assumption of frequency independent scattering, this is probably correct for frequency higher than 100 kHz. This might not be appropriate for the used frequencies, as a change of backscatter strength observed at a grazing angle of 40° corresponds to a frequency change. This model shall however be implemented to EM3002 data, which utilises a frequency of 300kHz across the entire swath, and the assumption of frequency independence scattering is likely to be more accurate in this case. The shallow water multibeam, EM3002, has a large opening angle, and is therefore more likely to resolve the critical angle.

A high statistical correlation between the model and the experiential data does not necessarily mean that the parameters used in the model are all correct. In this work a good correlation was obtained in test area1, but the shear parameter values of clay do not conform to the other sediments in the area. A deviation was also noted according to published shear wave parameters.

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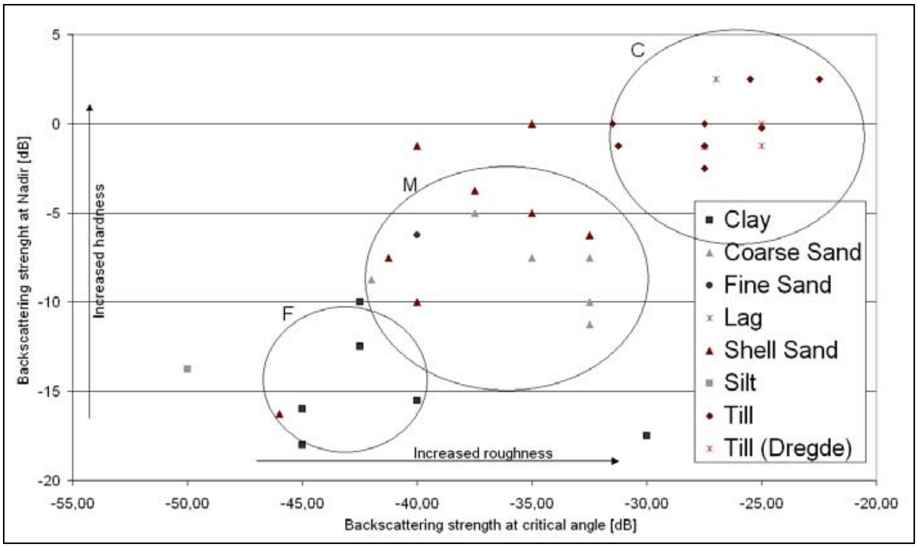

Fig. 1. Cross plot of multibeam backscatter strength at nadir and critical angle, from fifty locations where sediment types were confirmed by ground truthing. Circle codes: F – fine grained sediment, such as clay and silt; M – sandy sediments; C – till and lag deposits, from (Christensen et al., in press).

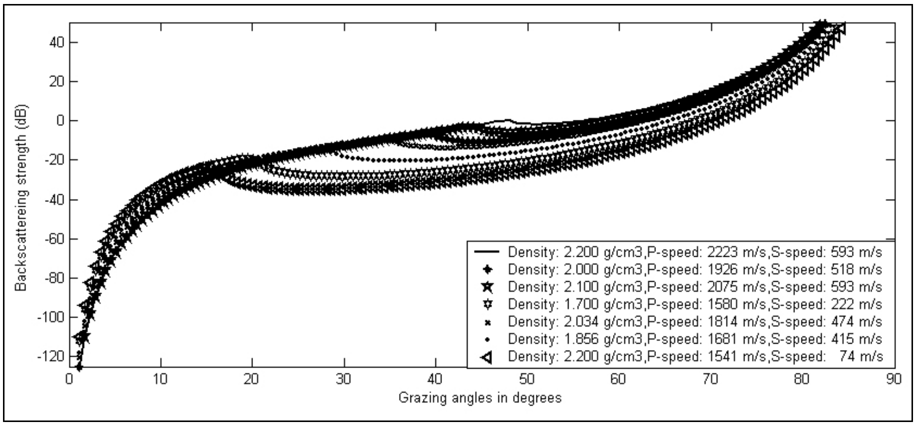

Fig. 2. Modelled backscatter response from the Rayleigh-Rice model using different geoacoustic parameters, where the critical angle is characterised by cusp (local maximum).

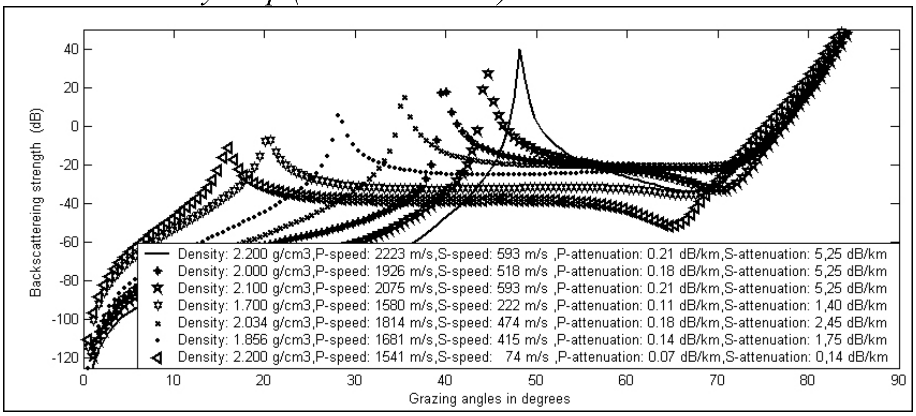

Fig. 3. Modelled backscatter response from the Rayleigh-Rice model using the same geoacoustic parameters as in Fig. 2, but incorporating the shear wave component.

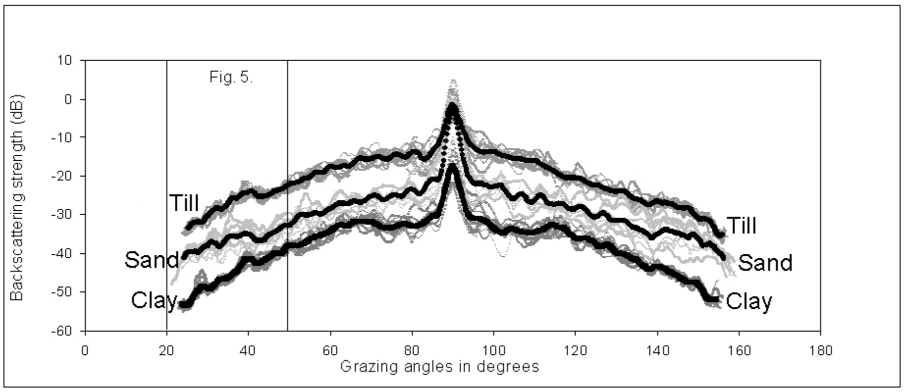

Fig. 4. AVA profiles with backscatter strength (dB) along y-axis and grazing angle at the x-axis (port 0˚-90˚, starboard grazing between

90˚ and 180˚ converted as (-grazing angle + 180˚)). Thirty AVA profiles, ten from three different areas comprising clay, coarse sand and till.

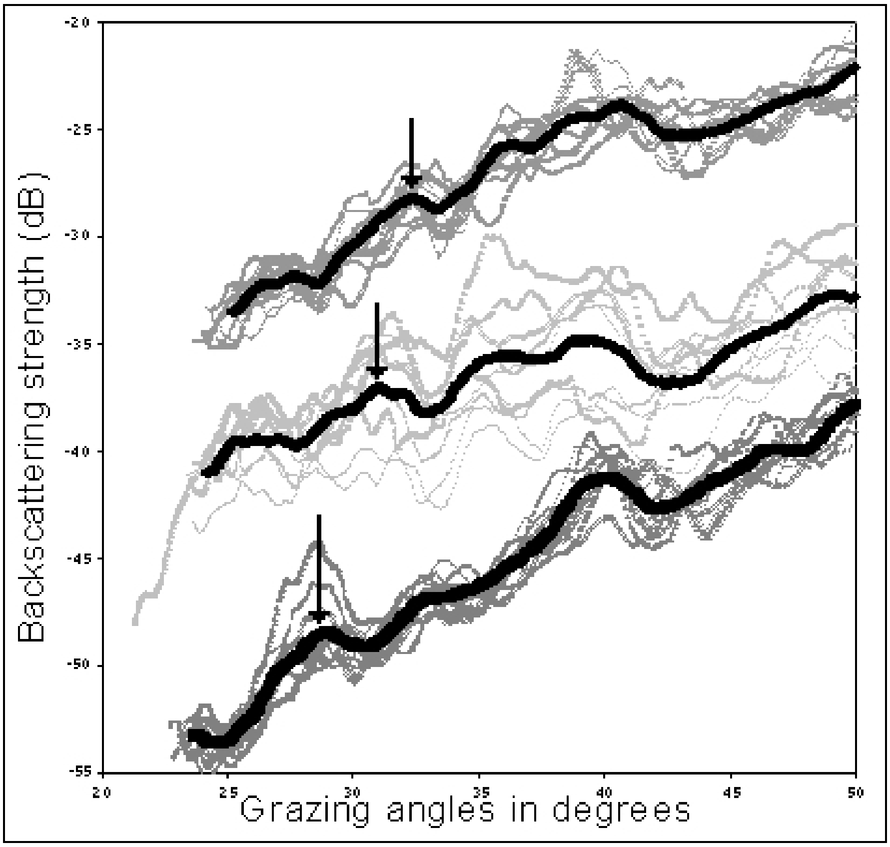

Fig. 5. Details of the backscatter strength at the low grazing angle shown in Fig. 4. Arrow shows the interpreted critical angle, the shift in backscatter strength at 40º degree grazing angle is believed to be associated with the frequency change.

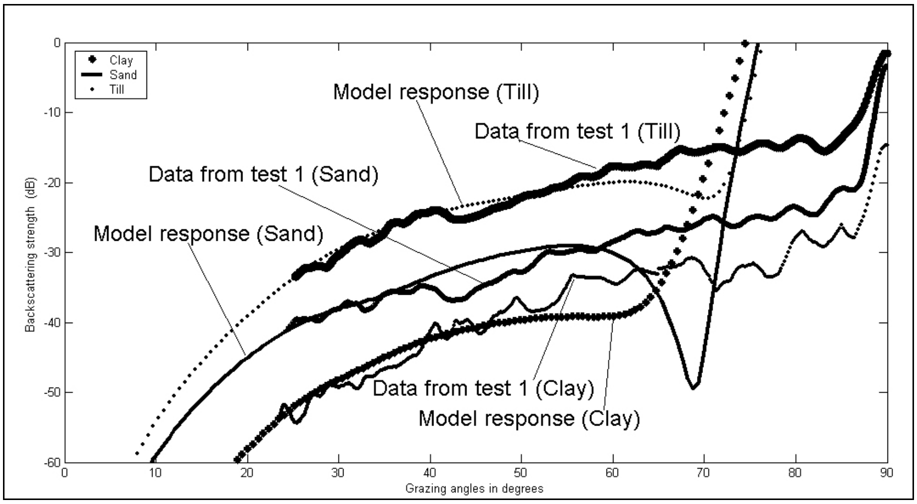

Fig. 6. Best obtained match between the model response and the mean for each of the three sediment types. The geoacoustic input parameters for obtaining this match are listed in table 1.

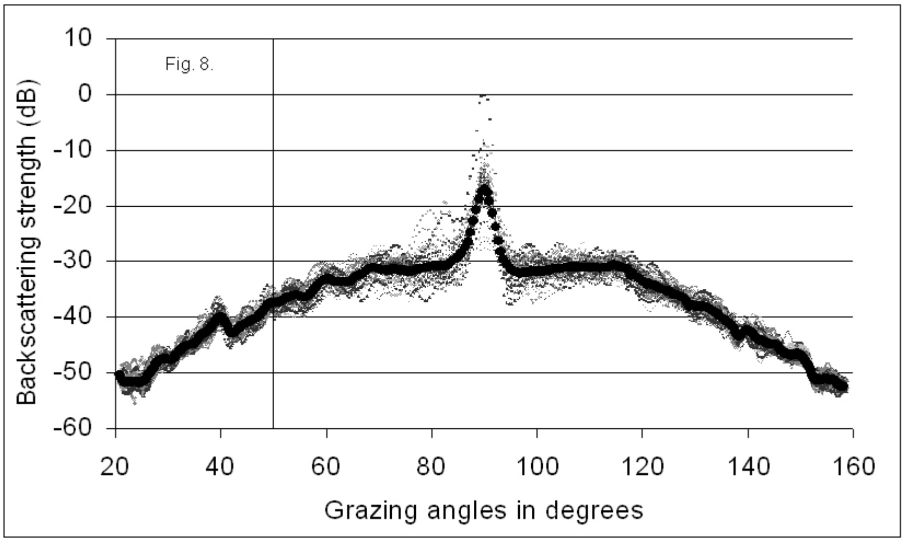

Fig. 7, Forty-two AVA profiles with backscattering strength (dB) along y-axis and grazing angle at the x-axis. The effect of frequency change is visible at the 40° and 140°, while the cusp believed to be associated with the critical angle is located at the grazing angles 29.78° (Fig. 8.) and 150.24°.

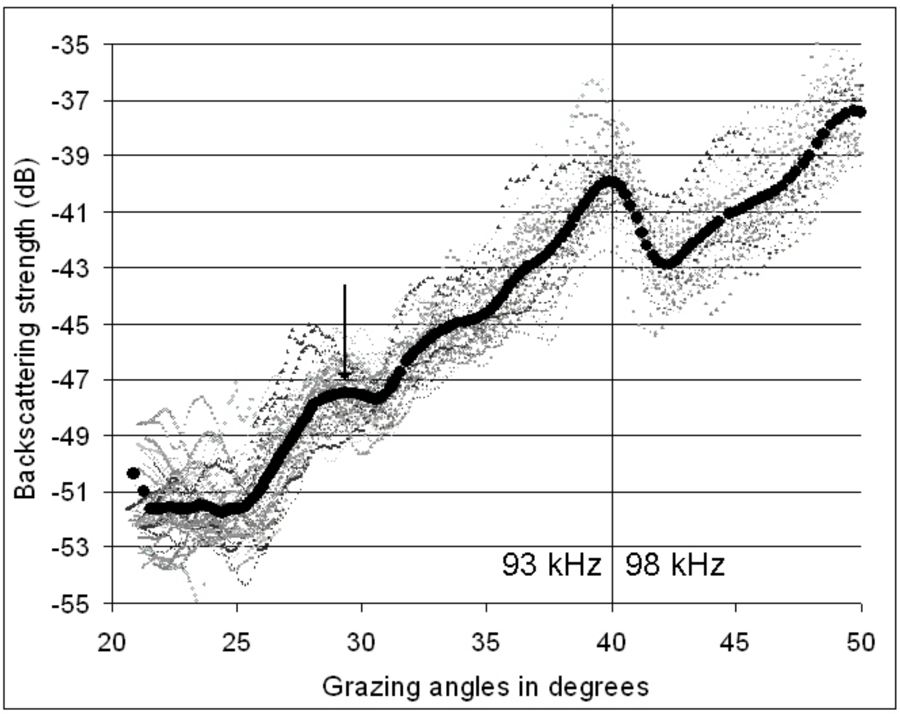

Fig. 8. Showing the details at the lower grazing angles of the Forty-two AVA profiles from Fig. 7. with the interpreted cusp marked by an arrow and the frequency change annotated.

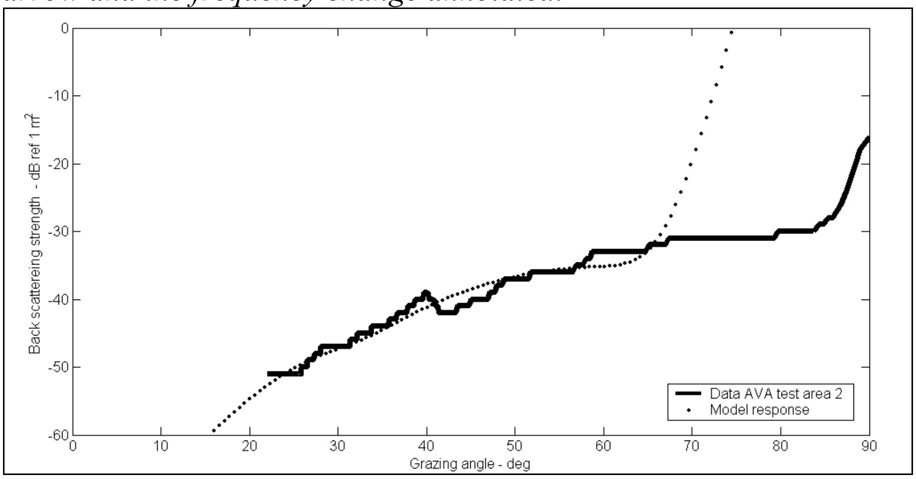

Fig. 9. Best-obtained match between the model response and the mean for AVA curves showed in Fig. 7. The compressional speed calculated using Snell's Law and the position cusp observed in Fig. 8.

	Clay	*Sand*	*Till*
Maximum difference from mean	*6.74 dB*	*8.27 dB*	*7.07 dB*
Mean of the maximum difference for each angle	*2.44 dB*	*4.22 dB*	*2.33 dB*
Standard deviation of the maximum difference for each angle	*0.105 dB*	*0.13 dB*	*0.038 dB*

Table 1, deviation from the mean for each of the three sediment types. The mean and standard deviation are calculated from the mean and the maximum difference for each angle.

Sediment type	*Clay*	*Coarse sand*	*Till*
Compressional speed, calculated using Snell's law	*1701 m s^{-1}/s*	*1726 m s^{-1}*	*1751 m s^{-1}*
Shear wave speed, deduced	*74.1 m s^{-1}*	*593 m s^{-1}*	*637 m s^{-1}*
Density, deduced	*1.10 g cm^{-3}*	*1.40 g cm^{-3}*	*1.62 g /cm^{-3}*
Compressional attenuation, deduced	*35 dB/km/kHz*	*49 dB/km/kHz*	*49 dB/km/kHz*
Shear wave attenuation, deduced	*126 dB/km/kHz*	*147 dB/km/kHz*	*171.5 dB/km/kHz*

Table 2. Calculated compressional speed from the AVA curves shown in Fig. 4 and 5. The four additional geoacoustical parameters were deduced from the matching the model to the experimental data, Fig. 6. To obtain realistic values each of the parameters were limited to vary within a narrow range, which was determined using various literature estimation (e.g., Hovem, 2005; Hamilton 1976; Hamilton, 1980; Hamilton and Bachman, 1982; Lepland and Bøe, 2003).

Parameter	Port cusp	Starboard cusp
Mean grazing angle	29.78˚	29.76˚ (150.24˚)
Minimum grazing angle	28.3	28.1˚ (151.9˚)
Maximum grazing angle	30.66˚	30.6˚ (149.3˚)
Standard deviation of angles	0.59˚degree or 10 m/s	0.71˚degree or 12 m/s
Calculated compression speed (Mean)	1707.5 m/s	1707.2 m/s

Table 3. Summarised interpretation of the cusp, numbers in brackets referring to the x-axis values in Fig. 7. The calculated compressional speed was performed using Snell's law and a 1482 m/s as the acoustic speed of water.

Parameter	*Clay*
Compressional speed, calculated using Snell's Law	*1707,35 m s^{-1}*
Shear wave speed, determined	*222.3 m s^{-1}*
Density, determined	*1.10 g cm^{-3}*
Compressional attenuation, determined	*49 dB/km/kHz*
Shear wave attenuation, determined	*161 dB/km/kHz*

Table 4. The input parameters used to fit the model to the EM3002 data, as shown in Fig. 9.

5.5 Article 5

Multibeam backscatter classification of seafloor properties – examples using response on e.g. deep-water coral reefs.
Printed in not peer-reviewed conference proceeding (1st International conference on underwater acoustic measurements: Technologies and results.

MULTIBEAM BACKSCATTER CLASSIFICATION OF SEAFLOOR PROPERTIES - EXAMPLES USING ANGULAR RESPONSE ON e.g. DEEP WATER CORAL REEFS

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Abstract: *Multibeam bathymetry is widely used in marine science, but backscatter has been analyzed only to a limited extent. Multibeam backscatter is the incoherent part of the energy return from the seafloor, and is related to e.g. roughness, hardness and the slope of the seafloor. The two first factors are to a large degree controlled by the properties of the substrate. Large habitat forming species such as corals also show a characteristic backscatter response and opens new potential for mapping biota. Backscatter strength measured from various grazing angles provides information on sediment properties and can thus reduce ground-truthing. Three categories could be* *defined: fine (clay-silt), medium (sand) and coarse (gravel–till) substrates.* Lophelia *deep-water coral reefs show a distinct acoustic response that can be used to identify and separate this biota from other substrates. Boundaries around areas with similar acoustic response can be defined manually with raw backscatter data, but boundaries can also to a certain degree be defined automatically based on processed backscatter.*

Keywords: Multibeam backscatter, angular response, substrate classification, coral reefs

1. INTRODUCTION

There is a need to develop an efficient survey method for large-scale seabed habitat mapping that can discriminate between substrates and special habitats such as coral reefs. Multibeam mapping and various interpretation techniques of the backscatter have shown very promising results [1]. These results have until now mainly been used for mapping substrate boundaries by drawing polygons around areas with homogeneous acoustic response. The response is assumed to correlate with a particular substrate type, which is determined by various ground truthing methods such as grab sampling and visual inspection.

The purpose of this paper is to present an acoustic method for substrate determination and automatic mapping of substrate boundaries that can reduce the need for ground truthing.

2. MATERIAL AND METHODS

The sampling of the different substrates were performed in a coastal environment in Møre and Romsdal on the west coast of Norway. The *Lophelia pertusa* corals were sampled offshore on the continental shelf on the Sula reef complex (65° 0' N, 9° 20' E).

A multibeam echo sounder transmits up to more than hundred beams (a swath) perpendicular to the vessel. This provides a wide coverage of the seafloor, with a resolution that depends on water depth, frequency of the signal, number of beams and the swath angle. Travel time is used to measure water depth, but most modern multibeam echo sounders also acquire the strength of the received signal, which is termed backscatter and is here used for mapping substrate boundaries and to obtain information on the substrate.

Backscatter strength represents the seafloor's ability to reflect acoustic energy, and depends on roughness, hardness and homogeneity of the substrates. Other physical factors such as the slope of the seafloor and water depth also influence the backscatter strength. Most of these disturbing effects can be eliminated or reduced with existing processing techniques. The EM1002 backscatter data are compensated for signal strength, source level, transmission loss and gain [2]. One problem, however is that the Simrad Kongsberg system change the pulse length at certain depths [3]. This influences the backscatter strength significantly [4]. The test area was located in a depth interval so the pulse length was kept on the shallowest setting, 0.2 ms (except for the coral reefs that were logged with 0.7 ms).

2.1 Interpretation of multibeam backscatter

In this paper we use a simple method for classification of the seafloor based on the backscatter strength where the effect of the grazing angle (the angle between a beam and the seafloor) [5] has been removed together with other effects not related to the substrate. Ground truthed locations were chosen to determine the backscatter strength intervals for the automatically defined classes. The medium class was defined as the class between the low and high backscatter classes. If the medium class was defined first, the results of automatic classification might have been altered. Ground truthing was performed with a video assisted grab [6].

3. RESULTS

3.1. Multibeam backscatter for mapping sediment boundaries

With automatic classification of normalised backscatter strength the seabed was divided into three substrate classes; low, medium and high backscatter strength (Fig. 1A). This classification is similar to the manual one; fine (clay to fine sand), medium (sandy sediments) and coarse (gravel, coarse grained glacial till and bedrock) (Fig. 1B). In the manual interpretation data from grab samples, video transects, sub-bottom profiler, multibeam bathymetry and backscatter were combined.

The comparison of the area of each class of the manual and the automatic classification shows a fairly good similarity (Fig. 2A), however, this is a very crude way of comparing the two methods and therefore we analysed each automatic class further in a manual way (the facit). This shows that the automatic classes low and high backscatter strength (LBS, HBS) seems to contain less than 15 % disagreement compared with the manual classification, respectively, while the medium class (MBS) contains 75 % disagreement (Fig. 2B). The significant larger spread observed in the MBS class is most likely caused by the order used for defining the boundaries in the automatic classification.

These results are crude and we therefore performed a more detailed analysis of the classification in Fig. 1. A relatively high similarity was observed in Nogvafjord, Haramsfjord and central part of the Longvafjord. There is however a mismatch between the two methods within the northern part of Longvafjord and in the south-eastern part of the survey area. The reason for this is due to reworking of the substrates by wave activity and the geological complexity of the substrates in the northern part of the Longvafjord. This makes the manual interpretation difficult. The backscatter signal is also influenced by the reworked substrates and in addition by the presence of a superficial layer of soft sediments.

Automatic classification of the south-eastern part of the survey area resulted in a significant higher proportion of medium-grained sediments compared with the manual interpretation. Bathymetry data show a pattern of moraine ridges covered with a varying thickness of fine-grained sediments. The backscatter strength indicated medium-grained substrates, while the manual interpretation suggested either coarse- or fine-grained sediments depending on the thickness of the overlying fine-grained sediments.

3.2. Seabed classification

Automatic substrate classification was performed with processed backscatter strength. The substrate types were related to intervals of the processed backscatter strength and utilized for classification of the seabed. The variation in raw backscatter strength is also effected by e.g. pulse length and grazing angle. The grazing angle variation causes the largest variation in most swaths. The variation is of such a character that it is practical to divide the swath into three different domains on each side of nadir [5]. Domain I is in the central part of the swath and is dominated by specular reflection. Domain II is located between domain I and the critical angle, where scattering from the surface (surface scattering) and from inhomogeneities within the seabed (volume scattering) contributes to the backscatter strength. Domain III is located at grazing angles lower than the critical angle, where only surface scattering contributes to the backscatter strength.

Cross-plotting backscatter strength from normal incident and critical angle has previously shown that it is possible to classify seabed sediments into three types; fine-grained (clay-silt), medium-grained (sand) and coarse-grained (gravel-till) sediments [7]. Three locations were sampled, one with substrate of clay, one coarse sand and one coarse grained glacial till. From each location the backscatter strength from ten swaths was extracted, and was then plotted as a function of grazing angle (Fig. 3). The resulting curves are termed AVA-curves (Amplitude Versus Angle). Within each substrate class there is a variance of about 5 dB, while the difference between the mean of the substrate classes is about 10 dB (Fig. 3). This means that the three substrate classes can be separated acoustically.

The backscatter strength at the critical angle is however associated with a local maximum. This local maximum can be used to determine the critical angle. This allows the calculation of the compressional speed of the substrate by Snell's law. Four other physical parameters (shear wave speed, compression and shear wave attenuation in the substrate, and substrate density) are possible to estimate through theoretical modelling software [8].

3.3. Coral reefs – case study

Lophelia pertusa build hemispherical colonies with a diameter up to about 2 m. Dead coral skeleton can accumulate and build reef structures with a height (vertical extension) of about 35 m [9]. In certain areas multibeam mapping has proved very effective to locate potential coral mounds by the interpretation of topographical features on sunshade relief maps. However, this method cannot be applied with the same success in areas where geological and coral structures resembles each other. In such areas the interpretation of backscatter strength can be a solution.

Processed backscatter data have previously made it possible to perform a supervised feature extraction of coral reefs, due to the very high backscatter strength from coral colonies [10]. The high backscatter is probably caused by the hard skeleton of the corals in combination with a high roughness. This is confirmed by the AVA-curves representing the corals in Fig. 4. The backscatter strength is higher than the other substrate types at almost all grazing angles except at nadir. At a grazing angle of 45˚ there is a local maximum (Fig. 4) that could be interpreted as caused by the critical angle that corresponds to a compressional speed close to 2100 m/s.

4. DISCUSSION

4.1. Backscatter mapping

Our results show a relatively high degree of similarities between manual interpretation of seabed substrates and automatic classification by means of multibeam backscatter strength. The manual interpretation is based upon the combination of several physical properties of the substrate while automatic classification is purely based on backscatter strength. Therefore it is expected that the manual interpretation will reflect the occurrence of the actual substrates better than the automatic classification. However, the automatic classification has the potential to cover large areas faster and more consistent than the manual interpretation and has therefore a great potential for efficient large scale mapping of bottom substrates.

4.2. Sediment classification

The AVA-method has some intrinsic problems. Firstly; half of the swath must be positioned inside an area with homogenous sediments, if not, the variation in the backscatter will reflect the variation in the substrates, secondly: a large open angle must be kept during acquisition, in-order to obtain data from the critical angle. This can be difficult at deep water because the distance between the beams increases with depth and one usually counteracts this effect by decreasing the open angle to keep a high resolution. Another problem is the noise level at the outer beams that can obscure the local maximum and hide the critical angle.

4.3. Coral reefs

The investigated coral reefs at Sula are located at approximately 300 m depth, which is significantly deeper than the substrate investigation in Møre and Romsdal at 150 m. The EM1002-system uses a longer pulse at 300 m compared to at 150 m depth. One has to take this into consideration when comparing data from different depths. At present it is difficult to tell what effect the difference may have on the backscatter strength. But it has been shown by [10] that backscatter response from coral reefs is higher compared to other substrates.

We found a compressional speed of corals on 2100 m/s. This value has to be verified by future measurements. There are however some uncertainties in determining the local maximum at the critical angle, especially for corals. This is probably so because the backscatter variation is larger than for other substrates (most likely due to the high roughness of corals and the likelihood of re-scattering in the open structures).

5. CONCLUSIONS

* It seems possible to map and distinguish between three broad substrate classes by automatic multibeam backscatter analysis, but before it can be used in large-scale mapping programs further testing of the reliability must be performed.

* AVA-curves indicate that it will be difficult to increase the number of substrate classes.

* *Lophelia* coral colonies have higher backscatter then the other investigated substrates, except at nadir where the backscatter strength corresponds to coarse grained glacial till.

6. ACKNOWLEDGEMENTS

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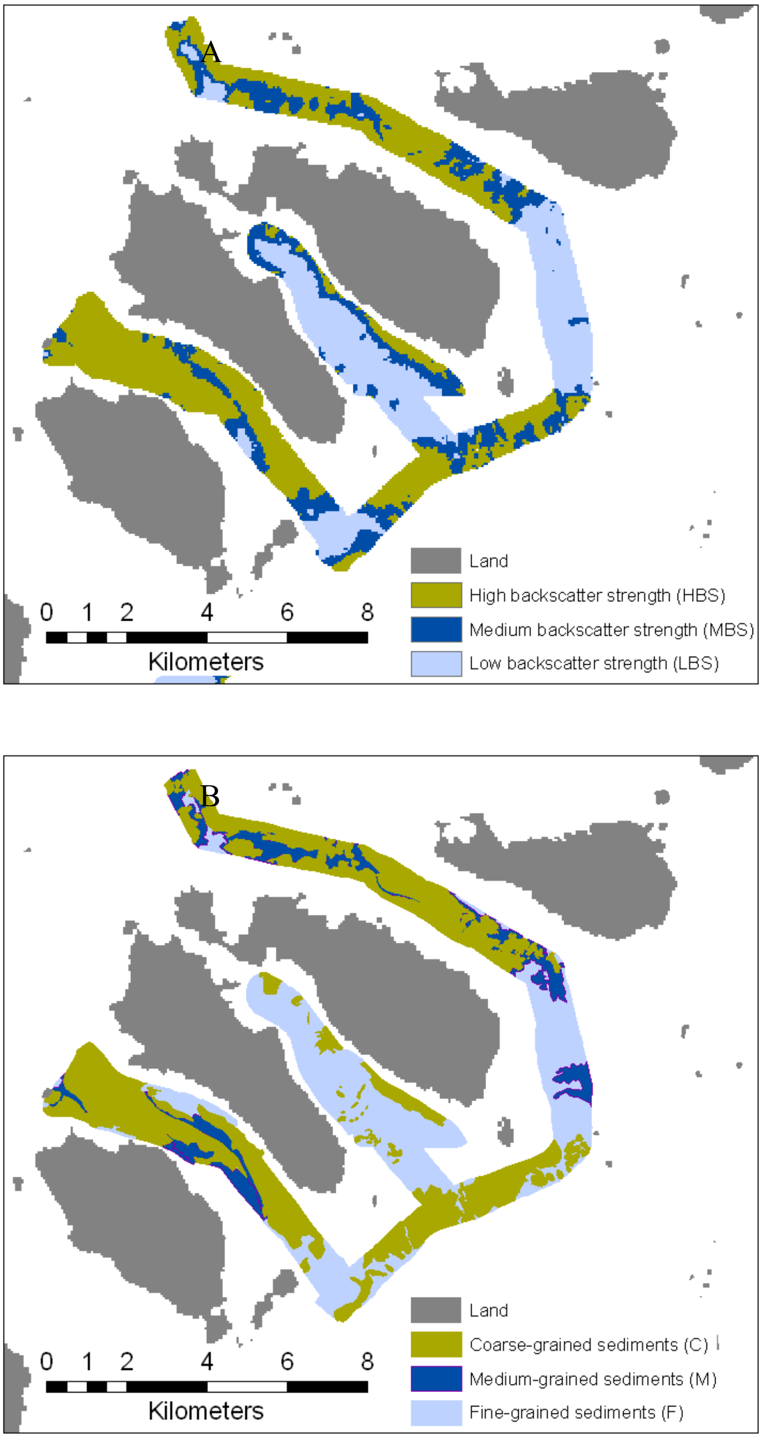

Fig. 1: **A**. Automatic classification based on processed backscatter strength. **B**. Manual classification based on all available data

(grab samples, video transects, sub-bottom profiler, multibeam bathymetry and backscatter).

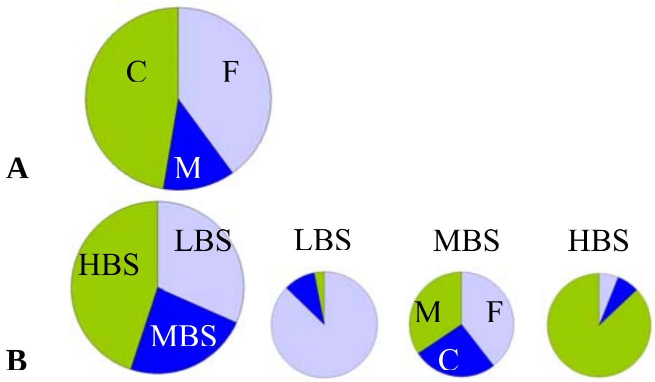

Fig.2: F, M, C = fine, medium and coarse-grained substrates, respectively and LBS, MBS, HBS = low, medium and high backscatter strength, respectively. **A**. Part of the studied area that is manually classified as one of the three substrate groups. **B**. Part of the studied area that is automatically classified as one of the three backscatter groups. The automatic classification was checked by analyzing each of the three acoustic classes with the manual method (small diagrams).

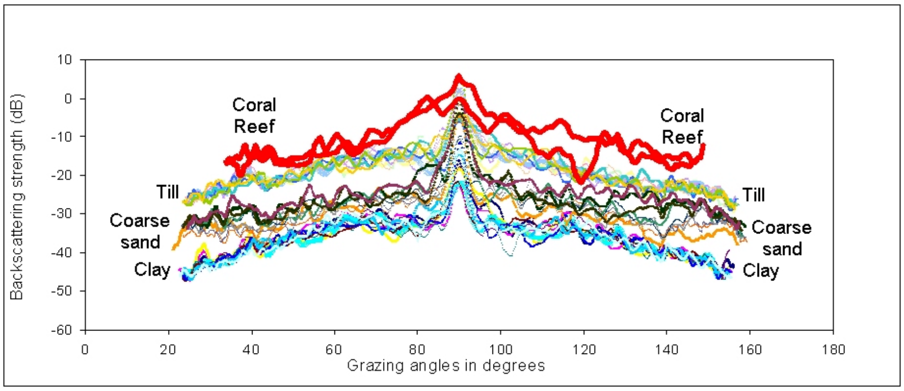

Fig. 3. Backscatter strength as a function of grazing angle = AVA-curves (port 0-90º, starboard 90-180º). Ten AVA-profiles

from each of the substrate types and two from coral reefs were analyzed.

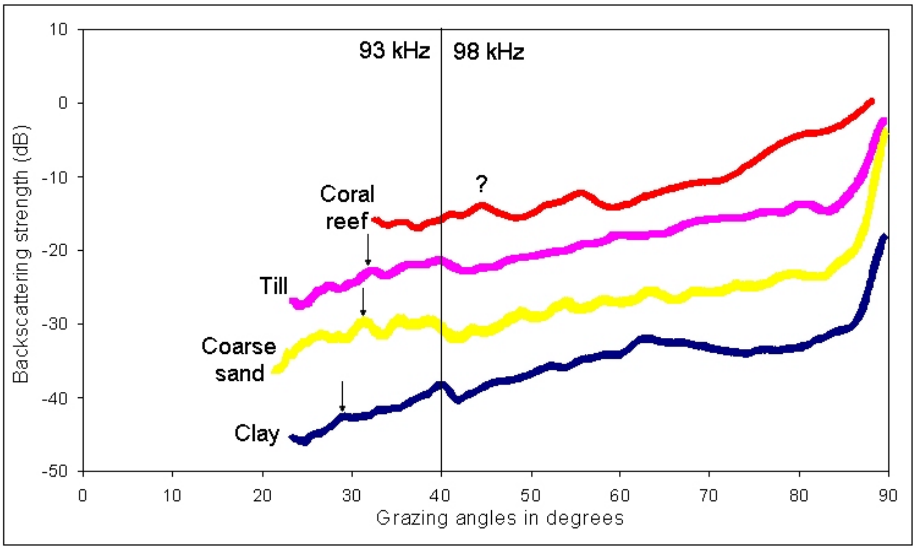

Fig. 4. Running mean for 100 points from the AVA-curves shown in Fig. 3.

6.0 Conclusion

The results of this work are concluded with the following nine statements. Just as important as these statements are the suggestions for further work listed in the next chapter.

- A two-cruise strategy was found to be most economically and scientifically beneficial. The first cruise focuses on acoustic acquisition and automatic interpretation, while the second cruise focuses on ground truthing. The period between the two cruises should be used for interpretation of the acoustic data and determination of the seabed properties from the acoustic data.
- A minor ground truthing program will benefit the interpretation performed between the two cruises. This ground truthing program is ideally based on automatic classification or raw multibeam backscatter data. An automatic classification can, however, be performed shortly after acquisition.
- Automatic classification based on post-processed backscatter data provides information of the substrates that closely reflects the seafloor geology, but with fewer details than a geological interpretation. The automatic classification is, however, a good start for a geological interpretation. Importing the automatic sediment boundaries into three-dimensional interpretation software would allow the boundaries to be modified and increase the number of mapped classes.
- Automatic classification based on mean backscatter strength comprises geologically broad classes, which might be difficult to narrow due to the stochastic nature of backscatter data.
- Multibeam and interferometric data enabled the classification of substrates and coral reefs. In most locations the bathymetrical character could be used, but in areas of complex morphology this was not possible. In these cases the multibeam backscatter was utilised and showed promising results.
- Feature extraction was fairly successful for coral reefs and outcropping bedrock. Several methods and data types were used. The accuracy of extracting these classes and the

possibility to extract further classes are likely to increase significantly by combining these methods.

- The habitat classification schemes developed by Greene *et al.* and Valentine *et al.* were both found to be very adaptable for medium scale habitat interpretation in Norwegian waters. The latter was chosen, as minor modifications would link the suggested data acquisition and interpretation procedure to the habitat classification.
- Interferometric data tend to have a higher standard deviation compared to multibeam data. Visual evaluation shows that interferometric systems are able to reproduce the same details as multibeam bathymetry systems.
- The AVA method for sediment determination and for interpretation is especially useful in softer sediments, where the volume scattering has a relatively large contribution, as the cusp is more prominent.

7.0 Further work

The Sushimap project has delivered a procedure for habitat mapping, but there are still a number of issues that have not been addressed properly, not only in conducting habitat mapping, but also in developing and improving the suggested methods. Some of the subjects related to this thesis, that will be further investigated in future are listed below.

- The comparison between EM3002 and the GeoSwath will continue either at the test site or at a new site. This comparison will not only address the bathymetry difference, but also the resolution of backscatter and GeoTexture data.
- Sediment classification using the AVA methods has been focused on using data at low grazing angles. Both modelling as well as securing the correctness of the measured backscatter at nadir should be addressed to improve the classification as well as add confidence to the results. The processing in the Simrad system is probably not absolutely correct, since pulse length change is causing a shift in the backscatter strength as reposted by Preston *et al.* (2001).
- Sediment determination using AVA technique has currently only been developed to forward modelling. The AVA technique shall be developed as an inversion tool.

- Ideally the AVA classification and post-processing of multibeam backscatter data should be linked. Robert C. Courtney has implemented a function that enables the export of correction values, which is the first step towards improving the method. These values are likely to show similar features to the AVA curves. Work has commenced using these values in ArcGis for sediment determination.
- Methods for importing interferometric data line by line into the three dimensional visualisation software have been successful. The methods, however, are inefficient and slow. Work to improve these has also commenced.
- Feature extraction combining bathymetrical response and backscatter strength are being developed, possibly also incorporating the seismic pulse.
- Incorporating backscatter and sonar images in bathymetrical processing for multibeam and interferometric data can help identify spikes and possibly increase the overall quality of the processing.
- Investigation of the minimum required distance between beams to resolve the cusp at the critical angle that will define the maximum water depth and resolution for individual multibeam echo sounder where it is still possible to use the AVA technique.
- Testing RoxAnn in the test area is being considered, as well as performing a larger analysis of all Topas data within this area. This should hopefully provide a strong indication of the possibilities and limitations of these methods.

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