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Original Article

An evaluation of compiled single-beam bathymetry data as a basis for regional sediment and biotope mapping

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Maps of surficial sediment distribution and benthic habitats or biotopes provide invaluable information for ocean management and are at the core of many seabed mapping initiatives, including Norway's national offshore mapping programme MAREANO (www.mareano.no). Access to high-quality multibeam echosounder data (bathymetry and backscatter) has been central to many of MAREANO's mapping activities, but in order to maximize the cost-effectiveness of future mapping and ensure timely delivery of scientific information, seabed mappers worldwide may increasingly need to look to existing bathymetry data as a basis for thematic maps. This study examines the potential of compiled single-beam bathymetry data for sediment and biotope mapping. We simulate a mapping scenario where full coverage multibeam data are not available, but where existing bathymetry datasets are supplemented by limited multibeam data to provide the basis for thematic map interpretation and modelling. Encouraging results of sediment interpretation from the compiled bathymetry dataset suggest that production of sediment grain size distribution maps is feasible at a 1:250 000 scale or coarser, depending on the quality of available data. Biotope modelling made use of full-coverage predictor variables based on (i) multibeam data, and (ii) compiled single-beam data supplemented by limited multibeam data. Using the same response variable (biotope point observations obtained from video data), the performance of the respective models could be assessed. Biotope distribution maps based on the two datasets are visually similar, and performance statistics also indicate there is little difference between the models, providing a comparable level of information for regional management purposes. However, whilst our results suggest that using compiled bathymetry data with limited multibeam is viable as a basis for regional sediment and biotope mapping, it is not a substitute. Backscatter data and the better feature resolution provided by multibeam data remain of great value for these and other purposes.

Keywords: benthic biotopes, habitat mapping, MAREANO, Maxent, multibeam bathymetry, sediment grain size, single-beam bathymetry, spatial modelling, terrain variables.

Introduction

Multibeam echosounder data (bathymetry and backscatter) reveal the seabed in unprecedented detail and provide an excellent basis for geological interpretations and the identification of seabed terrain of ecological relevance. Full coverage multibeam data allow scientists, using expert interpretation and modelling, to bridge the gap between scattered video and sampling observations and make a full coverage map so often required by management. A recent review by Brown *et al*. (2011) highlights how widely used multibeam echosounder data have become in benthic habitat mapping. An earlier review (Brown and Blondel, 2009) shows the advances in processing and interpretation of backscatter data that have accompanied this rise in the use of multibeam echosounders, increasing the utility of multibeam data for habitat mapping and related studies. It appears that multibeam technology is largely fulfilling the potential suggested by earlier studies that pioneered the technology for habitat mapping, surficial geology, and to provide information for ocean management (Todd *et al.*, 1999; Kostylev *et al.*, 2001; Gardner *et al.*, 2003; Pickrill and Todd, 2003).

During its first six years of operation (2006–2011), Norway's national seabed mapping programme MAREANO (www.mareano.no) relied heavily on full-coverage multibeam data. New multibeam data were acquired across 76 000 km^2 of seabed, and a further 15 000 km^2 of existing multibeam data were made available to the programme. Besides the direct output of multibeam mapping in the form of bathymetry and backscatter data, MAREANO delivers information on seabed geology, habitats, biodiversity and environmental status (pollution) in the form of thematic maps, which serve as a scientific basis for ocean management. All these applied map products rely on additional data from video and physical samples acquired during biological and geological sampling cruises, but the availability of multibeam data has been central in the production of the maps to date, since a backdrop of full coverage data is essential for linking the local sampling information and providing a baseline for interpretation and modelling.

There is little doubt of the value of multibeam data; yet such data require significant investment, both in acquisition and in data-processing and management resources. Norway is fortunate to have a well-funded seabed-mapping programme with annual funding rising from around 3 million Euros (23.6 million Norwegian kroner) in 2006 to 12 million Euros (92.4 million Norwegian kroner) in 2011. However, while the early years of MAREANO enjoyed mapping in areas where existing multibeam data were available, by 2011 multibeam data acquisition alone accounted for around 40% of the total annual budget (i.e. around 4.8 million Euros). The expense of multibeam data acquisition, however worthwhile and justifiable the data prove to be, can become a hurdle for even well funded projects. Although the data may have a significant return on investment, the initial financial outlay involved makes multibeam data inaccessible to many seabed-mapping programmes worldwide with more limited funding than MAREANO. The use of existing, often compiled, bathymetry data with little or no multibeam coverage is often the only viable solution where such data are required, despite the likelihood of inherent uncertainty (e.g. Calder, 2006). Even though they lack backscatter data, non-multibeam bathymetry datasets can offer a reasonable view of geomorphology for regional interpretation. Such bathymetry data have provided the basis for a number of geological and biological habitat mapping initiatives that have successfully delivered information for ocean management, e.g. the BALANCE project (Kotilainen and Kaskela, 2011) and UKSeaMap (McBreen *et al*., 2011).

In the second phase of MAREANO (2011–2015) the programme will continue seabed mapping, mostly in areas where the volume of existing multibeam data is low. To acquire full data coverage in all these areas would require significant investment and potentially an even greater share of the annual budget. Moreover, MAREANO faces a demand for timely delivery of the scientific information. With ever increasing pressure for information from ocean managers, the scenario of waiting for multibeam coverage to be built up over vast areas of Norway's offshore sea area before starting to map geology and habitats seems to be an unsustainable approach. A feasibility study (Elvenes *et al*., 2012) evaluating the potential use of alternative full-coverage data sources for regional sediment and biotope mapping was therefore conducted as part of an assessment of cost-effectiveness for future seabed mapping activities within the MAREANO programme.

This paper is based on the more extensive report by Elvenes *et al.* (2012), and focuses on evaluating the use of alternative bathymetry data sources for geological and habitat mapping. It specifically examines the potential for making surficial sediment maps and biotope maps from compiled single-beam data supplemented by limited multibeam data. The results of this mapping are compared with sediment and biotope maps developed using full coverage multibeam data that have already been published by MAREANO, where biotopes are regarded as the habitat for a specific biological community (Buhl-Mortensen *et al*., 2009b) rather than being determined by physical attributes. The study uses single-beam bathymetry data compiled by the commercial vessel navigation system provider Olex AS (www.olex.no) and acquired by Olex users (typically fishermen and other working vessels) as they go about their daily operations at sea. Olex is one of the most widely used systems in Norway and therefore offers the best available data coverage, however similar products are available from other software vendors and may have better coverage in other parts of the world. The Norwegian Olex data were compiled to a 50 m grid by the Norwegian Hydrographic Service for use by MAREANO.

Several previous studies (e.g. Parnum *et al*., 2009; Schimel *et al*., 2010a; Serpetti *et al*., 2011; Haris *et al*., 2012) have compared the performance of single-beam and multibeam echosounder data for benthic habitat mapping, often through the use of automated or semi-automated methods for acoustic ground discrimination and habitat interpretation, with an emphasis on physical habitats. These and other studies have helped identify the relative merits of each technology, and several studies have also included assessment of related seabed mapping technologies such as side-scan sonar (e.g. Schimel *et al*., 2010b). This type of comparison is beyond the scope of this study, as we are interested in finding out whether compiled single-beam bathymetry data are fit for purpose as a source of full coverage information upon which to interpret surficial geology and model biotope distribution from video observations, not in assessing the relative ability of multibeam and single-beam acoustics to discriminate sediment type or provide a proxy to benthic habitat.

The objective of this study is to compare sediment and biotope maps based on two different topographic inputs (bathymetry data):

(i) full multibeam coverage (bathymetry and backscatter), and

(ii) multibeam coverage (bathymetry and backscatter) limited to four areas on the continental shelf, with compiled single-beam bathymetry (no backscatter) in the intervening areas.

It is only natural that most studies reported in the literature use the best available data for applied map product generation, and MAREANO is no exception. However, the extensive multibeam and Olex bathymetry datasets available within the study area provide a rare opportunity to take a step back and test the scenario whereby the data input to these map products was less detailed. As well as directly comparing the map products resulting from use of each bathymetry data input, this simulated exercise can help to assess to what extent multibeam data are essential for seabed mapping and what information could be delivered using existing data at a fraction of the cost. As countries around the world are increasingly obliged to produce geological and habitat maps in order to comply with legislative acts such as Europe's Marine Strategy Framework Directive (Council of the European Communities, 2008), there is an increasing demand to deliver such maps in a cost-effective and timely manner. Studies such as this highlight the added value of multibeam data, but also illustrate how much can be achieved with coarser data. We hope our results can contribute to a scientific basis for prioritizing where multibeam data are really essential in light of mapping and management objectives, and where alternative data may be fit for purpose.

Methods

Study area and data

The study was carried out in an area already mapped by MAREANO, comprising the Nordland VII and Troms II areas off Lofoten–Vesterålen–Troms, Northern Norway (management area names according to Norwegian Petroleum Directorate). Within the study area, both multibeam and compiled single-beam data of reasonable quality and coverage are available (Figure 1). The single-beam bathymetry data were compiled by the commercial vessel navigation system provider Olex AS (www.olex.no). Fishing vessels, fish farmers, research institutions, and tourist companies are among those using the Olex system during daily operations at sea, and all users are encouraged to contribute their echosounder data to a central database administered by Olex AS. Data coverage is built up line-by-line in the database with internal, proprietary routines for quality control. The resulting compiled dataset reflects the density of contributing vessels operating in any given area in terms of coverage and quality. Many of the working vessels contributing to the Olex bathymetry dataset are fishing boats, and hence data coverage is very good in the area where fisheries occur, including the study area used here. Below the upper parts of the continental slope, however, sparse data are available as few working vessels operate here (Figure 1b).

Olex bathymetry data were made available to MAREANO and compiled to a 50 m grid by the Norwegian Hydrographic Service for use by MAREANO partners. This was the best practical resolution of the data with respect to coverage, density and quality, and 50 m is also the best resolution allowed by the Norwegian

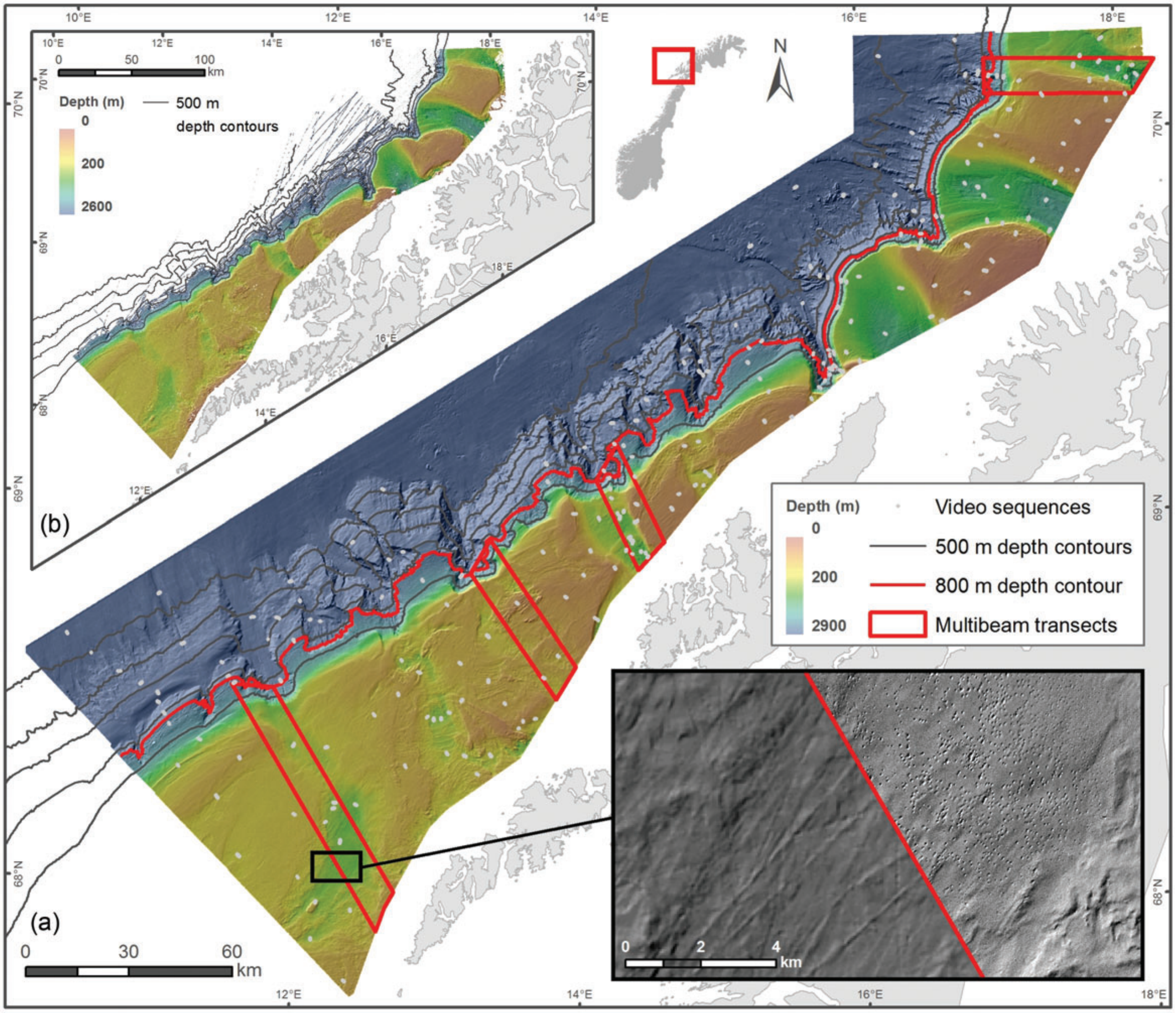

Figure 1. (**a**) Colour shaded relief image of the composite multibeam and Olex bathymetry dataset (Olex–MB). The dataset comprises Olex data across all shelf areas except within the multibeam transects indicated. Data below 800 m depth are multibeam data only, as Olex data coverage is very poor. The position of MAREANO video lines (each ca. 700 m long) is also indicated. Inset map shows one example of the difference in resolution/quality between shaded relief bathymetry generated from Olex data at 50 m (left) and multibeam data at 5 m (right) resolution. (**b**) Colour shaded relief image of Olex bathymetry data only, illustrating the extent and density of coverage. Note that the colour range of the bathymetry in (a) and (b) has been adjusted to emphasize features on the continental shelf.

Defence Authorities within a boundary of 12 nautical miles from shore. As no formal measure of horizontal or vertical accuracy is available, the data are difficult to use for hydrographic purposes. However, they can still give valuable information for geological interpretation and benthic habitats.

The study area in Nordland VII/Troms II (hereafter referred to as NVII/TII) is located at the continental margin between 68°N and 70°N, and displays a wide range of broad-scale geomorphic features and diverse sediment types within a depth range of 2500 m. Further details on the geomorphology, geology and oceanography are given by Bellec *et al.* (2009), Buhl-Mortensen *et al.* (2009a), Thorsnes *et al.* (2009), Buhl-Mortensen *et al.* (2010), Elvenes *et al.* (2012) and references therein. Detailed observations of biology and sediment distribution are available from 222 video lines (Figure 1a) recorded by MAREANO using the towed video platform CAMPOD from Norway's Institute of Marine Research. The positioning of these video lines was planned using full multibeam bathymetry and backscatter data, allowing optimum placement with respect to topographic and sediment variation (for which backscatter data serve as a proxy at the cruise planning stage).

In this study we make a comparison of sediment and biotope maps based on two different sets of bathymetry data: *Full multibeam coverage (bathymetry and backscatter)* and *Olex bathymetry supplemented by limited multibeam data*. The full MAREANO multibeam data holding is the best available data in the area, with data including surveys conducted over a number of years using various multibeam echosounders (Elvenes *et al.*, 2012). These data comprise both bathymetry and backscatter datasets and are typically suitable for gridding at 5 m resolution on the shelf and 25 m in deeper waters. The composite Olex and multibeam dataset (hereafter referred to as the Olex–MB dataset) simulates a potential future mapping scenario where only limited multibeam data are acquired. Four 10 km wide transects of multibeam data (cut from the best available dataset) were used to supplement the Olex data, where the positioning of these transects was selected to give representative coverage of geomorphic variation and expected sediment types. Most of the study area is therefore covered only by Olex bathymetry data (no backscatter) at 50 m resolution, while within the four transects Olex data is replaced with multibeam data at 5 m grid resolution (bathymetry and backscatter). Below 800 m, the coverage of Olex data is low. In order to be able to conduct habitat modelling based on the Olex–MB dataset in a manner directly comparable to modelling based on all available data, MAREANO multibeam data from deeper areas were included in the Olex–MB dataset. At the time of the study, however, the quality of available backscatter in these deep areas was very low, and the data were not of much aid in sediment interpretation (the data have since been reprocessed using more advanced methods and the published sediment map updated accordingly).

The Olex–MB dataset is shown in Figure 1a, with locations of the four multibeam transects indicated. The inset map shows an example of the difference in data resolution and quality between 50 m Olex data and 5 m MAREANO multibeam data. Further examples of the differences in data resolution/quality, and hence in the ability to resolve seabed features, are shown in Figure 2. It is clear from these figures that the multibeam data give more complete information, and would be required for detailed studies; however the objective of this simulated study is to see to what extent a lower resolution/quality will affect interpretation and modelling with a view to sediment and biotope mapping on a regional scale (1:100 000 to 1:250 000).

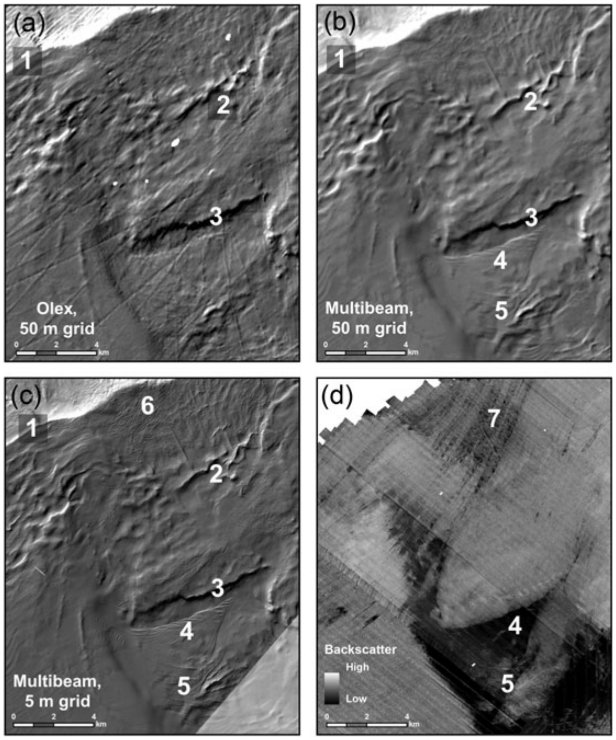

Figure 2. Detailed view of the MAREANO and Olex datasets illustrating some typical seabed features recognizable in each dataset. (**a**) Shaded relief image of Olex data, 50 m resolution. (**b**) Shaded relief image of MAREANO multibeam data, 50 m resolution. (**c**) Shaded relief image of MAREANO multibeam data, 5 m resolution. (**d**) Multibeam backscatter, 5 m resolution. 1 = shelf edge, 2 = larger moraines, 3 = escarpment, 4 = sandwave field, 5 = smaller moraines, 6 = iceberg ploughmarks (5 m bathymetry only), 7 = current lineations (backscatter only).

Data analysis

Several steps are involved in data analysis for the production of sediment and biotope maps based on each bathymetry dataset and video observations. The sections below provide salient information on the various parts of the analysis while further details are given by Elvenes *et al.* (2012). In addition we present a workflow diagram (Figure 3) which shows how the various parts of the data analysis come together in the production of biotope maps using the different input (predictor variable) data from the multibeam and Olex–MB datasets.

Geological interpretation

Two independent interpretations of surficial sediment distribution are compared in this study. The first interpretation, based on multibeam data, follows methods described by Bellec *et al.* (2009) and uses full resolution multibeam bathymetry and backscatter data. Video and other supporting data were used to classify backscatter decibel values in backscatter mosaics and to identify geological processes leading to the interpreted map. The second interpretation of sediment distribution is based on the composite Olex–MB dataset, and made by an independent geologist (SE) without reference to previously published maps or discussion with the geologist responsible for the multibeam-based maps (VKB). Within multibeam transects and below 800 m, interpretation was based on highest available resolution multibeam bathymetry and backscatter

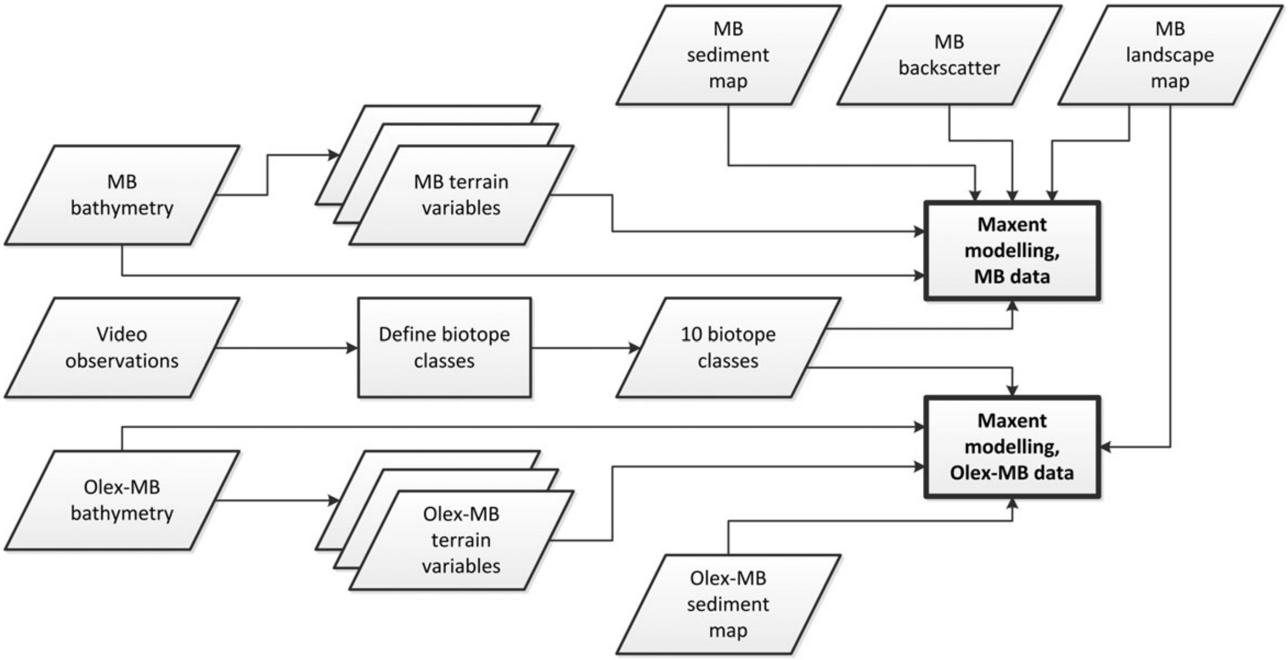

Figure 3. Summary workflow for the production of biotope maps based on different data inputs. MB = multibeam.

(the quality of the latter however being very low in areas below 800 m at the time of the analysis), as well as all available video data, whereas in the remaining area Olex 50 m bathymetry and a random selection of video lines were used. Some of the available video lines were omitted in an attempt to partially simulate a situation where sampling cruises are planned using a dataset with only limited backscatter information, so that video/sample stations may not be optimally placed. For both datasets, the interpretation process draws on the geologist's knowledge of seabed geomorphology and sediment processes to determine the most likely distribution of surficial sediments (grain size) across the entire study area using all available data. Sediment classes are according to the MAREANO standards outlined by Bøe *et al.* (2010), which are based on a modified version of Folk's classification (Folk, 1954).

Among the products published by MAREANO are maps of sedimentary environment (erosion and deposition areas). These are interpreted from multibeam datasets, and the sedimentary environment map from the study area was used as a further predictor variable in biotope modelling. As reported by Elvenes *et al.* (2012), it is not possible to interpret this information adequately from Olex data since interpretation relies heavily on knowledge of fine scale variations in multibeam backscatter in relation to geomorphology.

MAREANO also publishes maps of submarine landscapes, offering a broad-scale classification of geomorphic features based on a semi-automated method for delineation (Elvenes, in press). An initial assessment prior to the work of Elvenes *et al.* (2012) revealed that there is negligible difference between landscapes classified using Olex data and multibeam data. The landscape input to biotope modelling in this study is therefore identical for the two models, and based on the published classification from multibeam data.

Terrain analysis

Bathymetry-derived terrain variables (summarized by Wilson *et al.*, 2007; Dolan *et al.*, 2012) may serve as proxies to more direct effects that influence the distribution of benthic fauna. These influences operate across many spatial scales, and it can therefore be valuable to derive proxy terrain variables at different scales in order to promote the chance of finding the most relevant variables for use in biotope distribution modelling. Whilst several studies have attempted to find the most appropriate spatial scales for various fauna or habitats they are modelling (e.g. Monk *et al.*, 2011; Rengstorf *et al.*, 2012), there remains no consensus among the scientific community as to which are the most suitable scales. Beyond a general agreement that both fine- and broad-scale influences are important, it is doubtful that one answer to the question of the most appropriate scale exists. Most likely it will remain advisable for any modelling study to conduct their own assessment of which predictor variables are most important, including an assessment of spatial scales. The best solution will probably vary depending on available data and the entity to be modelled.

For biotope modelling within the study area, the variables summarized in Table 1 were computed both from the original multibeam and the composite Olex–MB datasets. Both datasets were at this time gridded to 50 m resolution, which offers a practical trade-off between topographic detail and computational resources for regional modelling. The majority of variables were calculated using Landserf software (Wood, 2009), which facilitates the computation of terrain variables at multiple scales. Selected analysis window sizes ranged from 3 × 3 pixels ($n = 3$) to 49 × 49 pixels ($n = 49$) representing length scales from 150 m to ca. 2.5 km. ArcGIS Spatial Analyst was used to compute BPI using the equation given in Wilson *et al.* (2007), with a rectangular neighbourhood at the same neighbourhood sizes as the Landserf analysis, and Jenness' DEM Surface Tools extension for ArcGIS (Jenness, 2011) was used for rugosity calculations ($n = 3$ only). Means and standard deviations for each of these terrain variables were calculated using a 200 × 200 m moving window, in order to match the spatial scale of biotope predictor variables (i.e. terrain variables) with that of

Table 1. Summary of terrain variables computed from the 50 m grid of bathymetry data for the Nordland VII/Troms II study area.

Terrain variable type	Terrain variable	Analysis window size ($n \times n$ raster cells)	Notes	Geological relevance	Ecological relevance
Slope	Slope	$n = 3, 9, 21, 49$	Computes the slope angle in the direction of steepest slope.	Stability of sediments (grain size). Local acceleration of currents (erosion, movement of sediments, creation of bedforms).	Stability of sediments (ability to live in/on sediments). Local acceleration of currents (food supply, exposure, etc.).
Aspect (orientation)	Eastness	$n = 3, 9, 21, 49$	Computes the orientation of the seabed, i.e. which direction it is facing.	Relation to direction of dominant geomorphic processes.	Exposure to dominant and/or local currents from a particular direction (food supply, larval dispersion, etc.).
	Northness	$n = 3, 9, 21, 49$			
Relative position	Bathymetric position index (BPI)	$n = 3, 9, 21, 49$	These indices provide an indication of whether any particular pixel forms part of a positive or negative topographic feature with respect to the surrounding terrain. Plan and profile curvature measure this effect perpendicular and parallel to the slope.	Flow, channelling of sediments/currents, hydrological and glacial processes. Useful in the classification of landforms.	Index of exposure/shelter, e.g. on a peak or in a hollow (food supply, predators, etc.).
	Curvature (mean, planar and profile)	$n = 3, 9, 21, 49$			
Terrain variability	Rugosity	$n = 3$	These indices provide a measure of how much the seabed terrain varies, or how rugged it is.	Terrain variability and structures present reflect dominant geomorphic processes.	Index of degree of habitat structure, shelter from exposure/predators (link to life stages). Structural diversity linked to biodiversity.
	Fractal dimension	$n = 9, 21, 49$			

the video data representing the biotopes (see *Biotope data*). For modelling purposes, observations from a towed camera are pooled and mapped to a central sample point every 200 m along the video line, representing the biotope 100 m to either side of that point.

Biotope data

The biological data input to modelling consisted of 947 sample points representing ca. 200 m segments of seabed observed by the towed video platform CAMPOD. Each sample point was assigned a biotope class based on species composition, determined through a hierarchical succession of detrended correspondence analyses (DCA; Hill, 1973) using the software PC-Ord (McCune and Mefford, 2006). DCA is an indirect gradient analysis that identifies groups of samples with similar species composition first, then assesses the correlation of the environmental variables in relation to these groups along the various axes in multidimensional space. The input to the DCA was a species matrix derived from detailed analysis of all video data with quantitative registration of all observed taxa (Buhl-Mortensen *et al.*, 2009b). DCA results were plotted in 3D space using the three DCA axes, allowing identification of point clusters (classes). Distinct classes were identified and removed prior to re-analysis of the remaining point data, facilitating the classification of points that would appear very closely spaced in a 3D-plot of the full dataset. The process was repeated until all points were classified to a visually satisfactory division and number of classes, which were also checked in geographic space.

Modelling biotopes

Modelling in this study was conducted using the software program Maxent (Phillips *et al.*, 2004, version 3.3.3e), which implements the maximum entropy principle to predict biotope distribution based on presence-only point data and full-coverage environmental predictor variables (see also Elith *et al.*, 2011, for an explanation). The Maxent method is one that performs well in comparison with other modelling approaches (Elith *et al.*, 2006; Huang *et al.*, 2011) and which has gained widespread use in terrestrial and increasingly in marine habitat modelling applications (e.g. Tittensor *et al.*, 2009; Howell *et al.*, 2011; Huang *et al.*, 2011; Pittman and Brown, 2011; Monk *et al.*, 2012; Yesson *et al.*, 2012). It was beyond the scope of this study to cross-check the performance of different modelling methods, our focus here being the results obtained using the same modelling method but different input data derived from the multibeam and Olex–MB datasets.

The selection of the best available predictor variables is an important consideration and one that is particularly interesting to examine here in comparison with the predictor variables from the full multibeam dataset. Potential environmental predictor variables derived from available data and maps included the following:

(i) continuous variables (200 × 200 m means and standard deviations of bathymetry, backscatter, multiple scale terrain variables (Table 1) and latitude), and

(ii) categorical variables (sediment grain size, sedimentary environment and landscape).

For the multibeam dataset this gave rise to a total of 73 variables, while the number was slightly lower for the Olex–MB composite dataset where some data were not available or were difficult to compute. Latitude was included in the models to allow biogeographic influence to be tested.

The same modelling approach was conducted for both the multibeam and the Olex–MB datasets. As the biotope point data used for each model were identical, our models test only the differences in the input bathymetry (and backscatter) data, and this facilitates comparison of results based on the multibeam and the Olex–MB datasets and derived terrain variables. In order to prevent issues of overfitting and the use of inter-correlated variables we first applied forward selection with Monte Carlo permutation using CANOCO for Windows 4.52 (ter Braak and Šmilauer, 2002) to select the most suitable (continuous) predictor variables from all those available. Categorical variables were also included in the model, and during modelling Maxent performs its own assessment of the importance of continuous and categorical variables alike.

The maximum entropy modelling method implemented in Maxent allows the distribution of each biotope class to be modelled individually, and provides measures of model performance. These individual models were then combined to a single full-coverage map indicating the most likely overall distribution of biotopes, based on the habitat suitability scores from each model. The composite map was cross-checked with the original observation points to acquire a measure of model performance. An error matrix was used to assess performance across classes, including computation of the user's and the producer's accuracy and the Kappa statistic, which are standard measures of classification performance that are seeing growing application in marine habitat classification (e.g. Lucieer *et al*., 2013).

Results and discussion

Sediment maps

The two independently made interpretations of sediment distribution in the study area are shown in Figure 4, with Figure 4a representing the MAREANO-standard published sediment maps (e.g. Bellec *et al*., 2009) and Figure 4b the result of interpreting sediment grain size based on the composite Olex–MB dataset. Resolution and data quality of the latter is lower across much of the area, and high-quality backscatter information is only available within the four transects. This is a challenge for the Olex–MB-based sediment interpretation, and leads to it being, of necessity, far more influenced by morphology than the multibeam-based interpretation. In the Olex–MB dataset, there exists no direct proxy with acoustic backscatter to link with video observations across most of the study area.

Sediment grain size maps based on Olex–MB data are significantly less detailed than those currently produced by MAREANO using high-resolution multibeam and supporting data. This is not surprising, since for the majority of the area we are basing interpretations on lower resolution (50 m) bathymetry data, for the most part without backscatter information. With regard to the level of detail and information content of the input, and the information that can be linked to this information from video ground-truth data, we consider the Olex–MB maps to be at a mapping scale of 1:250 000 or coarser, and feature digitizing was undertaken following topology rules suited to this cartographic scale. Contrastingly, the sediment interpretation published by MAREANO was produced at a 1:100 000 scale, which is a cartographic scale suited to both the data and user demands. It is important to note that the multibeam dataset also gives the potential for finer scale mapping, e.g. 1:25 000, in areas of special interest. We have seen in Figure 2 how the resolution affects the terrain features that can be recognized within the Olex-only areas of the Olex–MB dataset, and Elvenes *et al*. (2012) show further examples of the impact of resolution and data quality on the identification of coral reefs and sandwaves, which are significant in sediment interpretation and for other MAREANO products. Without the availability of full coverage backscatter data, detecting terrain features such as sandwave fields (e.g. Bøe *et al*., 2009), moraine ridges, pockmarks, etc. becomes particularly important; the bathymetric signature of each allows expert interpretation based on prior knowledge of the most likely sediments occurring on such features. It is important to remember also that the sediment distribution does not always correspond to changes in topography—an example of this is shown in Figure 2 where certain sedimentary structures (current lineations) are only discernible from the backscatter data. The multibeam transects included in the Olex–MB dataset greatly assisted sediment interpretation, since they meant backscatter information were available for at least part of major landscape types in the study area (i.e. covering both banks and troughs).

Despite the lack of detail in one dataset and some differences in interpretations, both the maps from the Olex–MB dataset and the published maps show the same general trends in the distribution of offshore sediments. It should be noted that it is quite possible that the Olex–MB-based sediment maps turned out better in the simulated study than they might have done in a real situation. Interpretation was based on sediment information from video lines, and even though an effort was made to reduce the number of lines used in the simulation, the location of video lines in a study area is planned in order to give optimal coverage of bottom types. Without the aid of full-coverage backscatter data in the planning process, line placement could be less optimal, resulting in information not being available to the sediment interpreter. A real study where backscatter data were not available, however, could perhaps make use of external data such as sediment information from navigational charts to compensate at least partially for the lack of backscatter information. In an actual situation, data from other sources (e.g. modelled bottom currents) could also have helped to better translate a sediment distribution map into a map of sedimentary environment. Models of bottom current would also greatly assist sediment interpretation and biotope mapping even when full multibeam data are available.

Classification of biotopes

Classification of biotopes was achieved on the basis of video data alone. Following multivariate analysis (DCA) of the species matrix derived from video observations, ten classes with distinct species composition were identified across the whole of NVII/TII. The spatial distribution of classes is indicated in Figure 5a, with Figure 5b showing a 2D representation of the initial DCA 3D plot. Plotting the DCA results in 3D space allowed us to identify clusters of points with similar species composition, and to assign a class to each point based on this. The size and diversity of the sample point dataset necessitated that we conduct a succession of DCA analyses, where the most distinct groups identified in a 3D plot were classified and removed prior to re-analysing the remaining point data. A list of typical taxa for each of the ten biotope classes, together with physical characteristics, is given later in the result section (*Biotope modelling*). Note that physical characteristics (terrain variables etc.) were related to the biotope classes after classification, and thus did not influence the classification process (*Biotope data*).

Biotope modelling

As stated in *Modelling biotopes*, available environmental predictor variables included bathymetry, backscatter (multibeam dataset

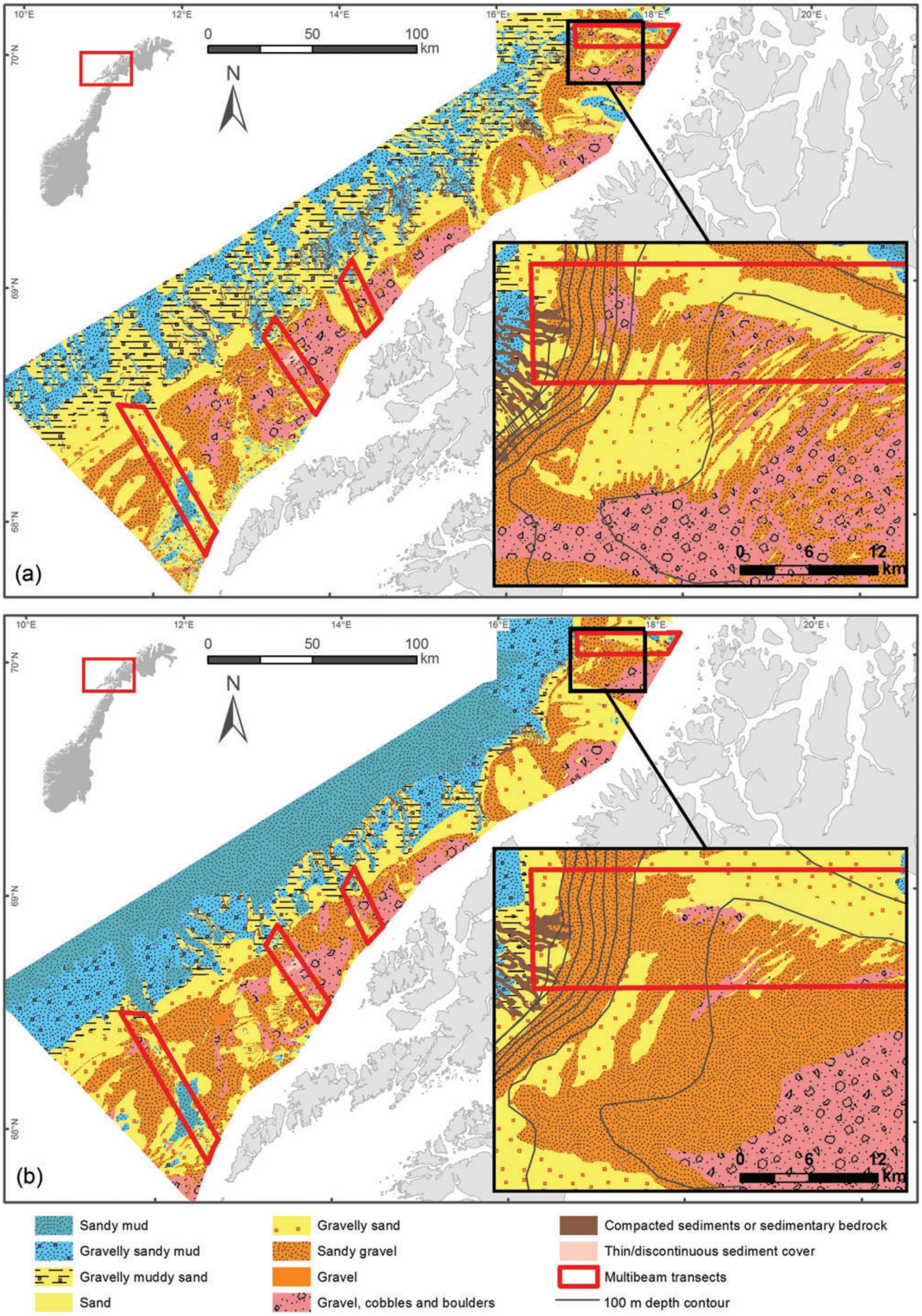

Figure 4. Interpreted maps of surficial sediment grain size with classes following Bøe *et al.* (2010) based on a modified version of Folk (1954). (**a**) MAREANO published map based on full coverage multibeam (bathymetry and backscatter) data. Note that the map version used for this study was published in 2010 and has since been updated following more advanced processing of backscatter data (see www.mareano.no). (**b**) Grain size map interpreted from the Olex – MB dataset: Olex bathymetry data supplemented with MAREANO multibeam and backscatter data in transects (red) and in the area below 800 m.

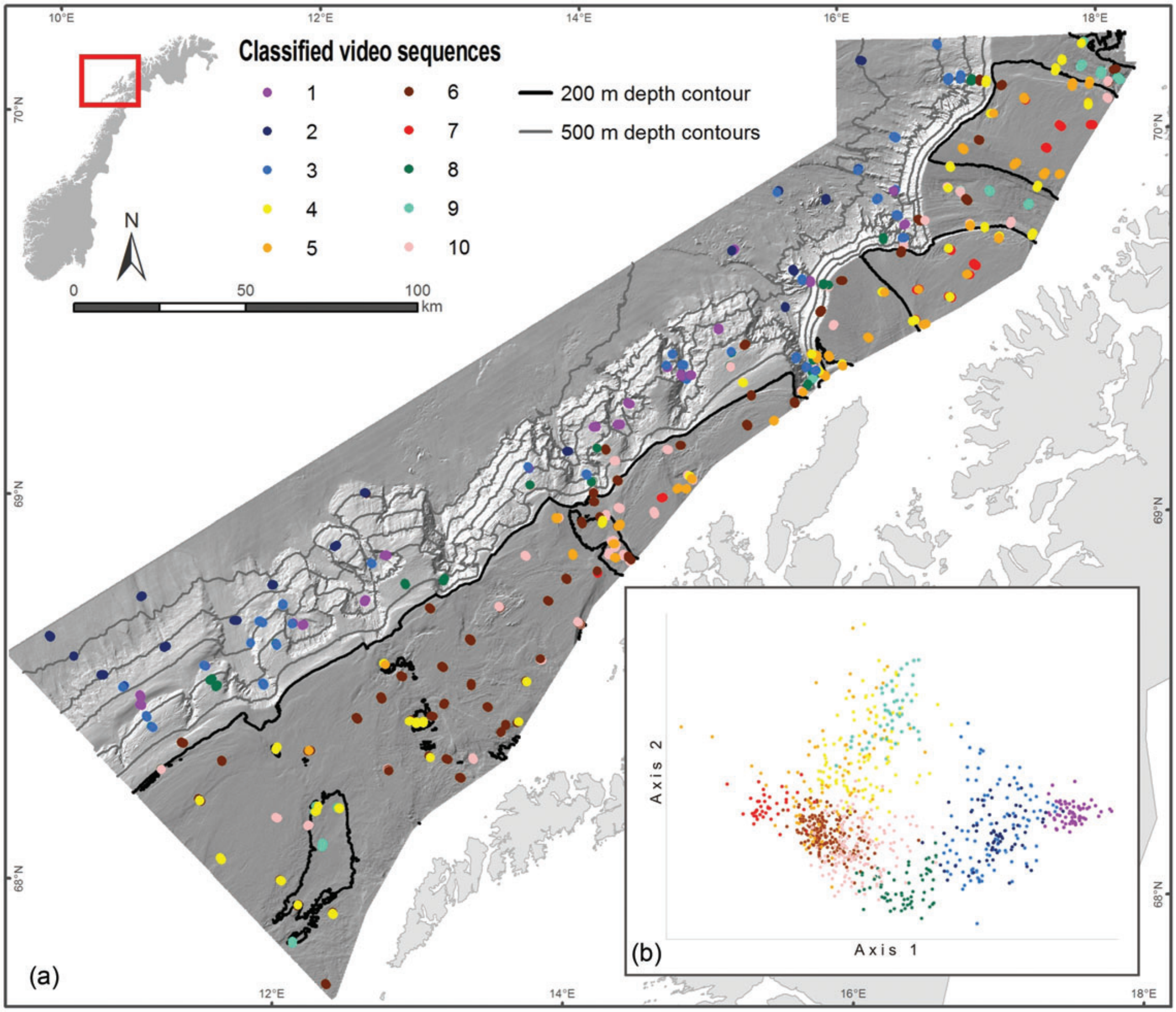

Figure 5. (**a**) Spatial distribution of classified video sequences. Note that points from the same video line may be obscuring each other at this overview map scale. (**b**) 2D representation of a detrended correspondence analysis 3D plot showing clustering of the 947 video sample points used in this study. Colours in both (a) and (b) correspond to the ten final classes used in modelling.

only), latitude, 200 m means and standard deviations of the multiple-scale terrain variables listed in Table 1, as well as the categorical variables sediment grain size, sedimentary environment and landscape. Biotope point data for each class (*Biotope data*) served as the response variable in our models.

A summary of the selected environmental variables from the multibeam (73 variables available) and Olex–MB datasets (64 variables available) is given in Table 2. The selection process for identifying the best environmental predictor variables was performed independently for the multibeam and the Olex–MB datasets, following the methods described in *Modelling biotopes* and by Elvenes *et al*. (2012). We see that some predictor variables are common to both—depth, landscape, sediment grain size, latitude, mean broad-scale slope ($n = 49$) and mean broad-scale northness ($n = 49$). These are among those variables which show the least variation between the multibeam and Olex–MB datasets: landscape is identical, mean depth is virtually the same, and broad-scale measures of slope and orientation (northness) that serve as proxies to exposure to dominant currents/food supply and to the stability of sediments are also very similar. Artefacts in the Olex–MB dataset, which could otherwise be expected to influence modelling, are largely smoothed out by the broad analysis scale and the 200 m averaging. Sediment grain size remains important, despite the disparity in the interpretations based on the different datasets.

Of the remaining variables there are two significant ones that are not used in the Olex–MB dataset—backscatter data and sedimentary environment (categorical). Since Maxent requires all environmental predictor variables to have full coverage, backscatter data is something that we must live without when working with combined data such as the Olex–MB dataset. However, the sediment grain size map offers an interpreted regional view of the nature of the sediments for which backscatter data are only an acoustic proxy. In the rest of the variables there is no clear pattern. Each set of variables includes measures of slope, orientation, relative position and terrain variability at various scales, though the multibeam variables include a few more fine-scale variables ($n = 3$), perhaps indicating that fine-scale variation is ecologically significant, whereas at this scale the corresponding calculations on the Olex–MB dataset

Table 2. Environmental predictor variables used in biotope modelling.

Variable	Window size (raster cells at 50 m resolution)	MB	Olex–MB
Mean depth		×	×
Mean backscatter		×	
Landscape type (categorical)		×	×
Sediment grain size (categorical)		×	×
Sedimentary environment (categorical)		×	
Mean UTM latitude		×	×
Mean slope	21 × 21	×	
	49 × 49	×	×
Standard deviation of slope	49 × 49		×
Mean of northness	9 × 9		×
	49 × 49	×	×
Mean of eastness	3 × 3		×
	9 × 9		×
Mean bathymetric position index (BPI) value	49 × 49	×	
Standard deviation of BPI values	3 × 3	×	
	21 × 21		×
Mean of mean curvature	49 × 49	×	
Standard deviation of mean curvature	3 × 3	×	
	49 × 49		×
Standard deviation of plan curvature	49 × 49		×
Mean of rugosity	3 × 3	×	
Standard deviation of rugosity	3 × 3		×
Mean of fractal dimension	49 × 49	×	
Total number of variables used in Maxent modelling		**15**	**14**

Means and standard deviations were calculated over a 200 × 200 m analysis window. Bold print indicates variables that were used in modelling of both datasets.

Table 3. Summary of model performances using different combinations of environmental predictor variables.

	MAREANO multibeam (area shallower than 800 m)	Olex–MB (area shallower than 800 m)
Terrain variables, sediment maps, landscape, backscatter	**71.5%**	*(no backscatter)*
Terrain variables, landscape, backscatter	71.8%	*(no backscatter)*
Terrain variables, backscatter	69.0%	*(no backscatter)*
Terrain variables, sediment maps, landscape	70.1%	**67.0%**
Terrain variables, landscape	68.1%	64.1%
Terrain variables only	66.5%	63.5%

Numbers indicate percentage of points correctly classified in the composite biotope map with respect to observed biotope points.

are largely highlighting artefacts or noise in the data. It is likely that some variables selected for the Olex–MB modelling are addressing environmental influences not captured by the "missing" variables—sedimentary environment and backscatter. In particular we note that both components of the orientation variables (northness and eastness) are important in the Olex–MB dataset, which lacks the bottom energy proxy information from sedimentary environment data. These orientation components may therefore be stand-in variables for current exposure.

Modelling was conducted with different combinations of the selected variables to evaluate the importance of each variable type and compare this between the multibeam and Olex–MB datasets. Table 3 summarizes model performance for different scenarios, given as the percentage of input points that are predicted correctly with respect to all available classified biotope points by the model. As an additional check on the performance of the models we calculated confusion matrices for each model (Tables 4 and 5), where the user's and the producer's accuracy provide a summary of performance across biotope classes. The producer's accuracy refers to the probability that a certain biotope observed on the seabed is classified as such by the model, while the user's accuracy refers to the probability that a pixel with a certain biotope class value in the modelled biotope map really is this class. The Kappa statistic (K), calculated using these accuracy values, provides a measure of overall performance assessing the degree to which the biotope map and point data agree over and above that which could be expected by chance alone. According to the interpretation scale of Altman *et al.* (1991), which was adopted by Lucieer *et al.* (2013) for benthic habitat mapping, the values of the Kappa statistic can be interpreted as: $K < 0.2$ poor, $0.2 < K \leq 0.4$ fair, $0.4 < K \leq 0.6$ moderate, $0.6 < K \leq 0.8$ good, $0.8 < K \leq 1.0$ very good. This puts both our multibeam and Olex–MB based models at the lower end of the "good" category, suggesting minimal difference in performance, although the multibeam model is slightly better. Even if the values vary and are generally slightly lower for the Olex–MB model, we see similar trends in the producer's accuracy between classes for both models. Trends in the user's accuracy show a little more variation, most likely due to differences in the respective predictor variables used. For example in the case of Class 7 we note that the coarse sediments associated with this biotope are less extensive in the Olex–MB sediment interpretation (Figure 4). This variation in sediment class extent could be a source of variation

Table 4. Summary of biotope model performance above 800 m for multibeam-based biotope model.

Class	4	5	6	7	8	9	10	Total	User's accuracy
4	81	9	6	1	1	0	7	105	0.77
5	11	58	11	7	0	1	8	96	0.60
6	5	19	134	3	6	3	23	193	0.69
7	0	12	2	26	0	0	4	44	0.59
8	0	0	4	1	37	0	5	47	0.79
9	5	0	0	0	0	40	3	48	0.83
10	2	7	9	2	7	8	110	145	0.76
Total	104	105	166	40	51	52	160	**678**	
Producer's accuracy	0.78	0.55	0.81	0.65	0.73	0.77	0.69		

***K* = 0.66**

The user's and the producer's accuracy are given for each class, showing how the model performance varies across classes, and performance is summarized by the Kappa statistic (*K*).

Table 5. Summary of biotope model performance above 800 m for Olex–MB-based biotope model.

Class	4	5	6	7	8	9	10	Total	User's accuracy
4	70	11	7	2	3	3	8	104	0.67
5	8	54	8	4	0	2	8	84	0.64
6	12	11	133	6	4	0	26	192	0.69
7	1	9	1	30	0	1	0	42	0.71
8	0	0	5	0	39	1	3	48	0.81
9	7	0	0	1	2	36	2	48	0.75
10	4	11	20	3	11	6	84	139	0.60
Total	102	96	174	46	59	49	131	**657**	
Producer's accuracy	0.69	0.56	0.76	0.65	0.66	0.73	0.64		

***K* = 0.61**

The user's and the producer's accuracy are given for each class, showing how the model performance varies across classes, and performance is summarized by the Kappa statistic (*K*).

between the models based on multibeam and Olex–MB data, since the respective sediment classification is an important predictor variable in each.

The final maps of predicted biotope distribution using full multibeam and combined Olex–MB data are shown in Figure 6, with Table 6 listing physical properties and typical fauna for each of the ten biotope classes. As Olex data were only used in areas shallower than 800 m, model results from deeper areas have been discarded from the final Olex–MB biotope map presented in Figure 6b. Classes 1–3 are thus barely represented in this map and were not included in the calculation of Kappa statistics (Tables 4 and 5).

A visual comparison shows that the general trends are similar across both maps. There are some differences in the predicted extents of the dominance of biotopes, and since the biological input to each map is identical any differences must be due to the influences of the differing predictor variables used. The Olex–MB-based map appears somewhat more fragmented, and includes certain visible artefacts. Examining the performance statistics for the area above 800 m for biotope maps based on each dataset we see that the multibeam-based map performs slightly better, but only by a few percent (e.g. 70.1% for multibeam vs. 67.0% for Olex–MB with a set of predictor variables including terrain variables, sediment maps and landscape). Using standard ArcGIS analysis tools, Elvenes *et al.* (2012) added a 50 m buffer to each biotope sample point and reassessed the performance. This additional test indicated that both the multibeam and Olex–MB-based maps above 800 m scored over 80% when cross-checked against the buffered point data, the good scores suggesting that both map products are adequate for use in regional-scale offshore management. This slight difference in model performance is confirmed by the Kappa statistics for each model (Tables 4 and 5), which confirm that the multibeam model performs marginally better, but that both datasets yield reliable models which can be considered to have good performance (Altman, 1991).

We suggest two major reasons why the results are so similar in the study area, despite the differences in the quality and number of variables available as input data from the multibeam and Olex–MB datasets. Firstly, the resolution of the model and input terrain variables was the same (50 m) in both biotope models. Secondly, the study area is dominated by a very diverse broad-scale geomorphology (banks, valleys, canyons, etc.) and the biotope distribution exhibits quite a strong link to this, as we can see in Figure 5a and as examined by Buhl-Mortensen *et al.* (2009a). As long as depth, landscape features, sediment distribution and broader-scale terrain attributes are among the important predictor variables, the role of smaller-scale features becomes less significant, as does the presence of artefacts or noise in the bathymetry data. Based on this study we cannot be certain how successful the same type of modelling might be in an area dominated by more local variations in environmental conditions. The inclusion of additional data besides terrain-derived proxies for environmental influences on faunal distribution (e.g. bottom currents, temperature, light availability etc.) is also likely to improve the models regardless of bathymetry data input, but may in addition help to reduce differences between the bathymetric input and variables derived from these data.

Following the promising results of this study, MAREANO has begun mapping on the mid-Norwegian shelf using a combination of multibeam, Olex and other alternative bathymetry data together with video data and samples acquired in 2012. In this real-life situation, rather than the situation reported here, the combined Olex and

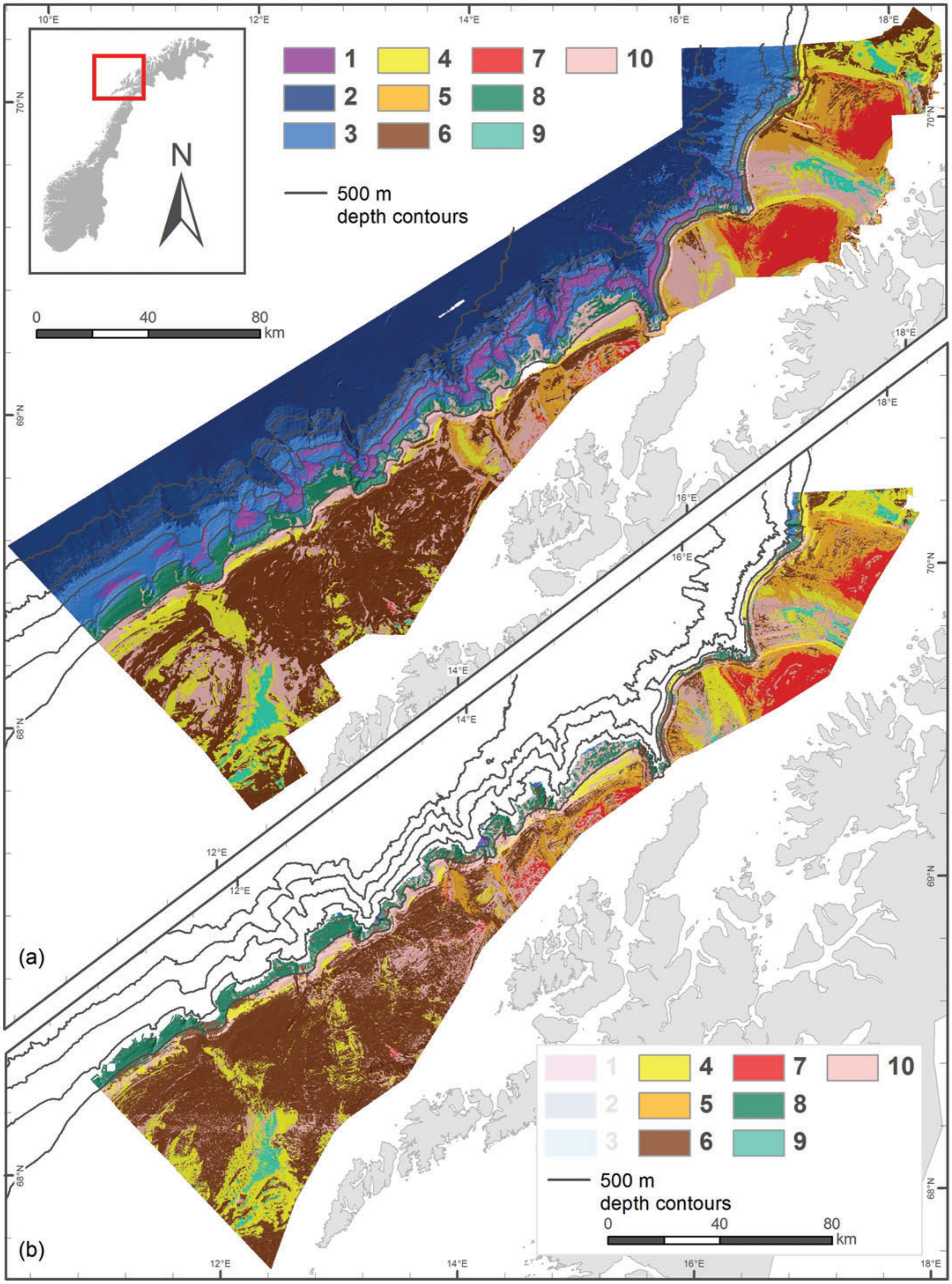

Figure 6. Modelled distribution of biotopes in the study area. (**a**) Model results from the MAREANO dataset. (**b**) Model results from the Olex–MB composite dataset (area below 800 m is disregarded due to lack of Olex coverage). See Table 6 for biotope description.

multibeam data were the only available basis for the planning of sampling cruises. Existing bathymetry data were also made full use of in identifying areas of interest for multibeam surveys. Results from sediment interpretation and biotope modelling on the mid-Norwegian shelf will provide further grounds for assessing how successful this type of mapping can be based on combined data sources.

Table 6. Summary of the physical and biological characteristics of each biotope class represented in the final composite biotope map (Figure 6).

Biotope class	Depth range	Landscape type (Halvorsen *et al.*, 2009)	Sediments and terrain	Typical taxa (from video observation)	Other characteristics
1	1200–1500 m	Continental slope/canyon	Variable sediment composition (mud to gravelly sand), regional/local topography uneven	Nemertini pink, Actiniaria small pink, Hexactinellida bush, *Lycodes* sp, *Bythocaris*	
2	>1500 m	Deep sea plain/ continental slope (lower)	Gravelly, sandy mud	*Rhizocrinus*/*Bathycrinus*, *Elpidia*, *Hymenaster*, *Kolga*, *Caulophacus*	
3	1000–1700 m	Continental slope (middle)	Variable sediment composition (mud to gravelly sand), regional topography uneven	*Chondrocladia*, *Lucernaria*, Pycnogonida, *Umbellula*, *Ophiopleura*	
4	150–300 m	Continental shelf plains/marine valleys	Sand/gravelly sand, flat areas	*Asteronyx*, *Funiculina*, *Ditrupa*, *Flabellum*, *Pteraster*	
5	70–180 m	Continental shelf plains/marine valleys	Variable sediment composition (sand to coarser), flat areas	*Pteraster*, *Ceramaster*, *Hippasteria*, *Sebastes* spp., *Spatangus*	Mainly north of 69°N
6	<300 m	Continental shelf plains/marine valleys	Variable sediment composition (gravelly sand to coarser), flat areas	*Phakellia*, *Craniella*, *Geodia* spp., *Stryphnus*, *Mycale*	
7	50–80 m	Continental shelf plains	Gravel, cobbles and boulders, flat areas	Gorgonacea, *Filograna*, Tunicata white, *Lithothamnion*, Serpulidae	North of 69°N, erosional environment
8	500–850 m	Continental slope (upper)	Gravelly and/or muddy sand, steep areas of uneven topography	*Gorgonocephalus*, *Crossaster*, *Paragorgia*, *Gersemia*, *Drifa*	
9	200–350 m	Marine/shallow marine valleys	Sandy/muddy sediments, flat areas	*Kophobelemnon*, *Parastichopus*, Pandalidae, *Virgularia*, *Steletta*	
10	100–500 m	Continental shelf plains/marine valleys/ continental slope (upper)	Variable sediment composition, variable topography	*Lophelia*, *Acesta*, *Axinella*, *Primnoa*, *Protanthea*	

Conclusions

This simulated study provided a rare opportunity to evaluate the potential contribution of alternative bathymetric data sources, such as the Olex bathymetry dataset, in the context of seabed map production on a regional basis through direct comparison with maps based on multibeam data. Only sediment distribution and biotopes were considered in this study, but the Olex data could also contribute by providing background full-coverage data for other map products relevant to MAREANO and similar initiatives worldwide, such as species distribution models for vulnerable species (e.g. corals, sponges), biodiversity assessment or landscape mapping.

From the work undertaken in this study we see that a combination of alternative full-coverage bathymetry data supplemented by limited multibeam data can be used for the production of regional sediment maps and for modelling biotope distribution. There are, however, important differences in the level of mapping detail attainable. The use of lower resolution/quality data also has further consequences in the wider context of seabed mapping, including the inability to detect important topographic features such as coral reefs, and less complete data for optimal planning of sampling cruises. All of these influences should be considered when evaluating the cost-effectiveness and choice of mapping technology in the future, but we have shown that significant progress in sediment mapping and biotope modelling can be made with limited multibeam data availability, provided that adequate alternative bathymetry data and direct observations of the seabed are available.

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