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Geomorphometry in the deep Norwegian Sea

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Abstract— **The deep Norwegian Sea spans depths reaching to nearly 6000 m and an area of around 1 000 000 km^2 extending both sides of the rugged mid-Atlantic Ridge. Armed with coarse regional bathymetric and oceanographic datasets the Norwegian national offshore mapping programme, MAREANO, was tasked with mapping 'representative areas' of this vast seabed terrain. Here we introduce the planning process, guided by semi-automatic methods, and present examples from newly acquired ship-borne multibeam bathymetric mapping in this varied deep-sea terrain with a focus on the use of these bathymetry data for onward substrate, geomorphological, and habitat mapping. We discuss the challenges of using these data with existing, lower quality, bathymetry data, as well as highlighting some typical data artefacts which can limit the calculation of meaningful terrain attributes and thereby their use in geological and habitat mapping.**

I. INTRODUCTION

During 2019 new multibeam bathymetry data were acquired in the deep Norwegian Sea by Norway's national offshore mapping programme MAREANO. The survey design was produced to meet management information needs across this vast seabed terrain within budgetary constraints, which precluded full coverage mapping, and comprised a series of boxes, mostly around 35 km x 35 km (Figure 1). These new data provide insights into previously unseen seabed topography and can be set against a backdrop of existing, lower quality multibeam data as well as compiled data from multiple sources (e.g EMODnet bathymetry [1] GEBCO [2]). Connection lines were acquired between all survey boxes to provide an achievable level of continuity in the survey, which will be invaluable for onward use of the data in geological and habitat mapping.

Whilst the multibeam surveys concurrently acquire bathymetry, backscatter and water column data, alongside sediment echosounder data to aid geological interpretation, our focus here is on the bathymetric data. By presenting examples from contrasting types of terrain we examine how these data can be used for far more than just hydrographic purposes and focus on the use of bathymetric data in the development of geological and habitat maps. We discuss the opportunities and challenges associated with fusing these new data with existing, lower resolution data, as well as previewing plans to ground-truth these data in order to provide the additional layers of information MAREANO requires for geological and habitat mapping.

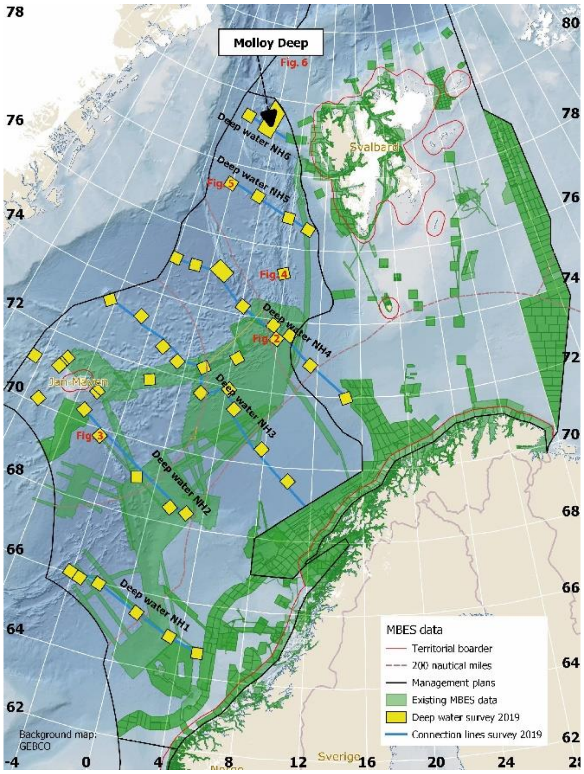

Figure 1. The study area spanning around 1 000 000 km^2 in the in the deep Norwegian Sea. The 2019 deep water multibeam (MBES) survey areas are indicated in yellow with connection lines coloured blue. Existing multibeam data are shown in green. Image: NHS/MAREANO. For details of bathymetric data available for download see https://www.mareano.no/en/maps-and-data/marine-geospatial-data

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Acoustic mapping of the seabed from surface vessels in the open ocean can present many challenges, not least from the effects of bad weather which often limits survey operations and impacts data quality. These challenges, together with geometric and sensor-related effects linked to the multibeam systems, can generally be overcome to provide processed data and digital terrain models, hereinafter referred to as Digital Bathymetric Models (DBMs), that fall within relatively forgiving deep-water hydrographic standards, but which lead to uncertainty in onward analysis and applied map development for other purposes like geological and habitat mapping. We discuss some methods highlighting these issues including how this uncertainty might best be conveyed to end users alongside the DBM.

II. METHODS

A. Survey planning

Full coverage mapping of the seabed in waters deeper than 200 m is the ambition of Seabed 2030 [3], an initiative to populate global DBMs such as GEBCO with real sounding data. Innovative acquisition methods [e.g. using autonomous vehicles, crowd sourcing from industry and the private sector] are among many approaches to achieving this ambitious goal by 2030, with national mapping programmes such as MAREANO playing an important role towards this global effort. At the national level, however, mapping agencies face the very real task of juggling available funds and management demands for information within shorter timeframes when planning their bathymetric and related surveys. Even in a well-funded programme like MAREANO this can present a challenge. Full coverage multibeam mapping of the deep Norwegian Sea has recently been estimated to require thousands of ship days, at a cost of around 100 million Euro, with significant further costs associated with additional data collection for geological and habitat mapping. Meanwhile government and management agencies require information on this part of the Norwegian seabed within relatively short time scales. When tasked with providing ‘representative information’ on the seabed of the deep Norwegian Sea MAREANO therefore opted for a compromise solution mapping as many different seabed environments as possible within a suitable timescale (2-3 years).

At a broad scale we can see from regional bathymetry data that the study area comprises continental slope, abyssal plain, marine hills and mountains, concentrated along mid-Atlantic Ridge, as well as the continental shelf near the island of Jan Mayen. Overlying this terrain is a complex pattern of ocean circulation giving rise to different water masses and dynamics occuring in different parts of the area. In order to map representative parts of the seabed we need as complete a picture of the total environment as possible at the survey planning stage. The different environments identified can then be assessed and survey effort balanced against logistical and budgetary contraints. We conducted an unsupervised classification using principal component analysis and k-means clustering of the seabed for the entire deep Norwegian Sea based on the best available bathymetric data (EMODnet bathymetry 2018) and derived terrain attributes plus near-bottom oceanographic attributes (temperature, salinity, current speed). This classification provided an intitial means by which to identify areas of the seabed with similar environmental characteristics. When combined with further knowledge on the geological history and oceanographic characteristics of the area, plus information from previous surveys we were able to prioritise areas to be surveyed.

Based on previous experience in the Barents Sea, MAREANO has found the box-transect to be better matched to management information demands than simple line-transects which provide a very blinkered view of geology and habitats. This box-transect approach was adopted in the deep Norwegian Sea and provides a convenient means by which to map different environments. The size of box was chosen to suit geological and habitat mapping at scales in the range 1:100 000 to 1:250 000, although the achievable map resolution will also be dependent on data quality and available ground-truthing (video and physical samples) from follow-up surveys. We estimate that, even with potential data loss from employing multiple scale terrain analysis methods [4] as required, an area of at least 1000 km^2 will be mapable within each box. This is a reasonable size to get a ‘feel’ for the geological, habitats and environmental status of the area, as required by MAREANO and is supported by information from connection lines (generally one multibeam swath width [≈ 5.5 x water depth [5]] wide).

B. Data acquisition, processing and analysis

Data were acquired using a Kongsberg Maritime EM304 deep water multibeam echosounder on MV Geograph by DOF Subsea AS under contract to MAREANO through the Norwegian Hydrographic Service (NHS), in partnership with the Geological Survey of Norway (NGU). Multibeam data require cleaning following standard procedures [6] to remove outliers and correct for geometric and motion effects. This work was done by the contractor using industry-standard software with quality control of the bathymetry data undertaken by NHS. Final DBMs were produced by NHS at resolutions from 10-25 m depending on water depth for onward use by MAREANO partners. Supporting information on vertical and horizontal uncertainty were provided by the contractor.

For interpretation and onward analysis, the data were imported to ArcGIS desktop software. Here the data were combined with existing bathymetry data from other sources providing further regional context to the data. We examine methods for data fusion with available existing DBMs such as Petrasova et al. [7] as well as exploring derivation of terrain attributes both on the regional and high-resolution DBMs [6]. The potential use of the DBMs for geological and habitat mapping including the impact of common data artefacts [8] will be discussed in the context of these methods. We also discuss the use of the data in planning ground-truth surveys, essential to the development of these applied map products. This potentially includes follow-up very high-resolution bathymetric surveys from remotely operated and/or autonomous underwater vehicles [9].

III. RESULTS AND CONCLUSIONS

Selected results will be presented to highlight the invaluable insights into deep-sea topography gained by these data, in additional to discussing the technical challenges associates with their ‘jigsaw-puzzle’ configuration and varying quality.

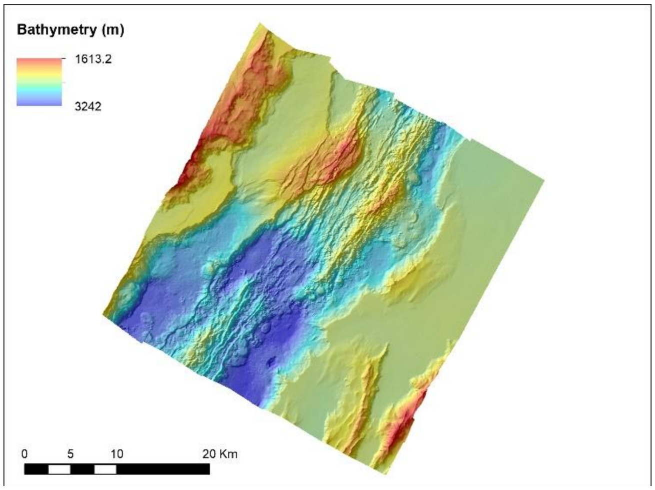

Figure 2 Example colour shaded relief image of topography at the Mid-Atlantic Ridge – see Figure 1 for location

Figure 2 shows an example of the varied topography present at the Mid Atlantic Ridge along transect NH04. We note the contrasting textures of this terrain, likely to have different substrate types and habitats associated with it. This dramatic topography contrasts with the relatively flat abyssal plain that covers large parts of the survey area, yet the new DBMs reveal that in many places, even this flatter part of the seabed is far from devoid of topographic features. An example is shown in Figure 3.

Through MAREANO partnership in EMODnet these new bathymetry data will be incorporated into and help to improve the next revision of EMODnet bathymetry using standardized methods. Nevertheless, within shorter timescales MAREANO scientists require methods to integrate the new DBMs with existing data on a more local scale.

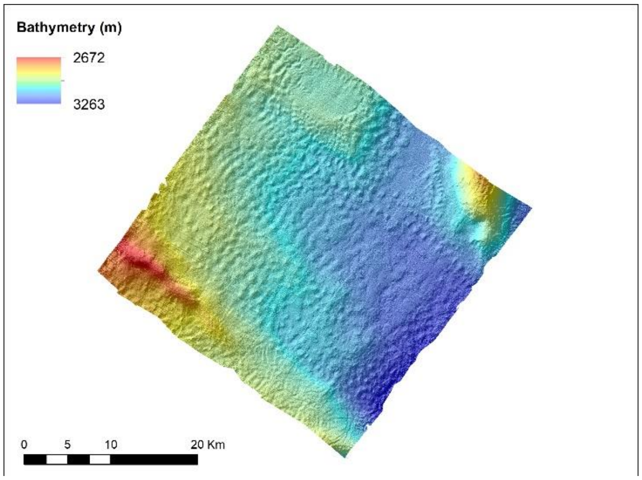

Figure 3 Example colour shaded relief image showing topography on the abyssal plain away from the mid-Atlantic Ridge – see Figure 1 for location

Together with MAREANO partners NHS, NGU are examining methods for data fusion that give the best results for onward use of the data, particularly for the generation of terrain attributes. In Figure 4 we show an example of the new multibeam bathymetry data against a backdrop of existing EMODnet bathymetry data with visible artefacts from multi-source data, most of which is at far lower resolution.

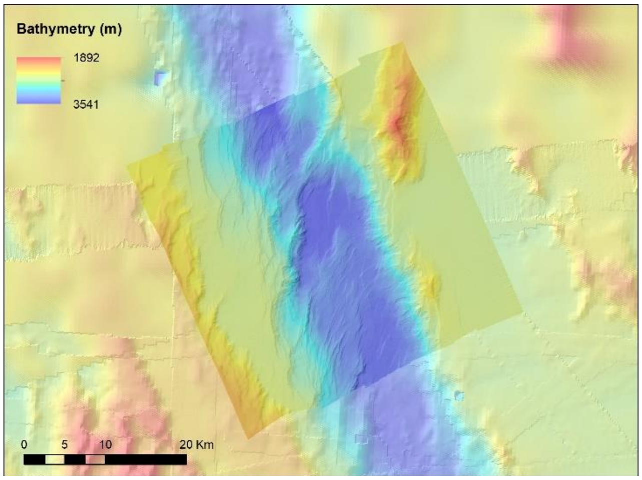

Figure 4 Colour shaded relief image of new multibeam data overlain on existing EMODnet data, compiled from multiple sources. The same colour scale is used for both datasets – see Figure 1 for location.

Despite the invaluable insights into deep sea topography offered by the new DBMs we note that several of the survey areas are plagued by visible artefacts in the data, mostly due to challenging sea conditions. The data are also subject to more systematic vertical and horizontal uncertainty, influenced by echosounder geometry. An example area affected by such problems is shown in Figure 5 where we highlight the effect of the issue and its consequences for terrain attributes such as slope. Whilst the most rugged terrain in this area is clearly delineated, we also see smaller sized along- and across-track artefacts in the data. These low-level, yet persistent, artefacts can present problems when using the data in onward substrate interpretation and habitat mapping, particularly when terrain attributes such as slope and rugosity are used as predictor variables. Methods to overcome these artefacts include filtering and use of larger neighbourhoods for the generation of terrain attributes, however, the success of these approaches can be limited by the relatively small area covered by the survey blocks.

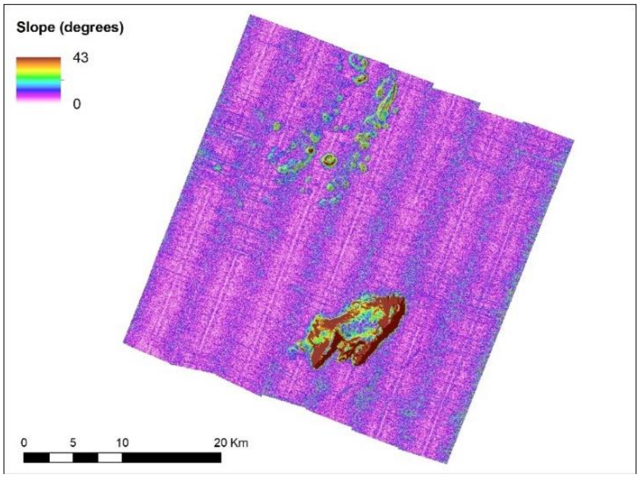

Figure 5 Example of data artefacts visible in many datasets. Here the motion-related artefacts resulting from surveys in poor weather conditions are visible in a slope map derived from the bathymetry data. Slope calculated in ArcGIS using Horn’s algorithm [10] using a 3 x 3 pixel neighbourhood on a 25 m DBM i.e. over a distance of 75 m x 75 m.

Finally, we acknowledge that this survey of the deep sea has often documented far more dramatic terrain than is present on land. Depths in the vicinity of the Molloy Deep span more than 4000 m. In the visualization shown in Figure 5 we see how the topography of the Molloy Deep dwarfs the height of Stetind, a notorious anvil-shaped mountain on the Norwegian mainland, which rises to a height of 1392 m. Although such visualisations and vertical exaggeration can help us gain an impression of this dramatic relief in various GIS software we note a general challenge of effectively visualizing negative relief.

Despite any limitations they may have, these new bathymetry data offer an essential baseline for planning follow-up surveys that will provide more information on the geology and habitats present which will be reported by MAREANO in due course. Whilst their extent is relatively small on a global scale these data will help improve regional bathymetric datasets and advance methods for marine geomorphometry in deep sea environments.

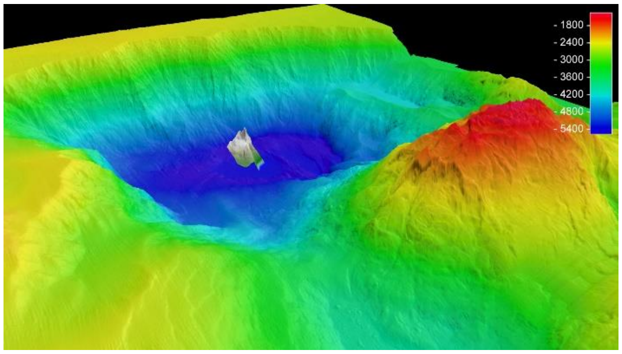

Figure 5. 3D colour shaded relief image of Molloy Deep (5 569 m deep) viewed from the northeast. A terrain model of the mountain Stetind (1 395 m high) has been placed on the bottom of Molloy Deep to illustrate the relative size. DBM resolution 25 m. The colour-scale bar indicates the depths in the Molloy Deep DBM. Image: Kartverket/MAREANO

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