Revealing the secrets of Norway’s seafloor – geological mapping within the MAREANO programme and in coastal areas

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Abstract: Results from geological mapping within the MAREANO (Marine Areal Database for Norwegian Coasts and Sea Areas) programme and mapping projects in the coastal zone reveal a rich and diverse seafloor in Norwegian territories. The geomorphology and sediment distribution patterns reflect a complex geological history, as well as various modern-day hydrodynamic processes. By early 2019, MAREANO has mapped more than 200 000 km² (c. 10%) of Norwegian offshore areas, spanning environmental gradients from shallow water to more than 3000 m depth, with ocean currents in places exceeding 1 m s⁻¹ and water temperatures below −1°C. Inshore, along the 100 000 km-long Norwegian coastline, the Geological Survey of Norway (NGU) has conducted a series of seabed mapping projects in collaboration with local communities, industry and other stakeholders, resulting in detailed seabed and thematic maps of seabed properties covering c. 10 000 km² (11% of the areas). Bathymetric and geological maps produced by MAREANO and coastal mapping projects provide the foundation for benthic habitat mapping when combined with biological and oceanographic data. Results from the mapping conducted over the past decade have significantly increased our understanding of Norway’s seafloor and contributed to the knowledge base for sustainable management. Here we summarize the main results of these mapping efforts.

The multidisciplinary Norwegian seabed mapping programme MAREANO (Thorsnes et al. 2008; MAREANO 2019) is a collaboration between the Geological Survey of Norway (NGU), the Institute of Marine Research (IMR) and the Norwegian Mapping Authority (Norwegian Hydrographic Service (NHS)). The programme is financed by the Ministry of Trade, Industry and Fisheries, and the Ministry of Climate and Environment. These ministries, along with the ministries of Petroleum and Energy, Local Government and Modernisation, and Transport and Communications, form the MAREANO Steering Board.

Between 2006 and early 2019, more than 200 000 km² of seabed have been mapped (Fig. 1), corresponding to around 10% of the Norwegian offshore area. The areas mapped span broad environmental gradients with water depths extending to more than 3000 m, ocean currents exceeding 1 m s⁻¹ and seawater temperatures below −1°C. Dramatic landscapes (Fig. 2) have been observed, with canyons up to 1 km deep formed by fluid-flow processes and sliding, and locally almost subvertical margins. Continental slopes vary in width from 30 km to more than 100 km, with gradients locally reaching 60°. Shelf plains and banks (30–300 m water depth) and cross-shelf troughs (200–500 m water depth) occur over wide areas, and a rich faunal diversity has been observed (e.g. Bellec et al. 2008, 2009, 2010, 2016, 2017a, b; 2019; Chand et al. 2008, 2009, 2012; Thorsnes et al. 2008, 2009, 2016a, b, 2017; Bøe et al. 2009, 2012, 2015, 2016; Buhl-Mortensen et al. 2009a, b, 2012, 2015; Dolan et al. 2009, 2012b; Elvenes et al. 2012, 2013, 2016; Rise et al. 2013, 2015, 2016a, b; Elvenes 2014; King et al. 2014; Bjarnadóttir et al. 2016, 2017; Diesing and Thorsnes 2018).

Results from MAREANO (MAREANO 2019) have contributed significantly to the revision of Norway’s management plan for the Barents Sea–Lofoten areas, as well as the management plan for the Norwegian Sea (Fig. 2). These plans are used by Norwegian authorities in their management of the northern seas, particularly in relation to fisheries and petroleum activities.

Spatial management of the Norwegian nearshore areas is the responsibility of coastal municipalities. Municipal jurisdiction extends to 1 nautical mile off-shore of a baseline joining the outermost islets and skerries. Coastal marine areas cover c. 90 000 km², comprising a wide range of environments from rocky, exposed shallows to fjords up to 1300 m...
Fig. 1. Areal coverage of seabed sediments (grain size) maps at scale 1:1,000,000–1:4,000,000 by April 2019. Areas mapped in higher detail in Norwegian areas are shown with black (MAREANO and previous projects in the North Sea) and red outlines (coastal mapping projects). L, Lofoten.
deep. Through a series of mapping projects in cooperation with local authorities and other stakeholders, NGU has published geology-focused seabed maps and derived thematic maps ('marine base maps': Elvenes et al. 2019; NGU 2019a) covering c. 10,000 km² of the coastal areas (Fig. 1; see below). These offer invaluable knowledge to marine spatial planners and the many users of the Norwegian coastal zone.

In this paper, we describe the mapping process and the geological maps produced by NGU. The geological maps (e.g. Fig. 3), along with bathymetry, biological data and oceanographic modelling results, form the basis for further mapping and modelling of benthic habitats (including biotopes, nature types, vulnerable habitats, etc.) both offshore and in the coastal zone (e.g. Buhl-Mortensen et al. 2009a, b, 2012, 2015; Dolan et al. 2009, 2012a; Bekkby et al. 2012; Elvenes et al. 2013; Gonzalez-Mirelis and Buhl-Mortensen 2015). Mapping of the environmental chemistry of the seabed sediments (e.g. Pb and PAH) is included in the MAREANO programme and in multiple coastal mapping projects (e.g. Elvenes et al. 2018; Jensen et al. 2018; Knies and Elvenes 2018).

All maps from MAREANO and NGU’s coastal mapping projects are published online and are freely available for viewing, downloading and WMS use (MAREANO 2019; NGU 2019a). Additionally, a series of composite, printable PDF MAREANO maps is published online (e.g. Bjarnadóttir et al. 2017; NGU 2019a).

Fig. 2. Example of nearshore–offshore seabed morphology mapped by MAREANO, Lofoten–Vesterålen, north Norway. V, Vesterålsgrunnen. See Figure 1 for the location of Lofoten.

Methods

MAREANO

Mapping of a new area commences with multibeam echo-sounder surveys by NHS or external contractors according to defined standards (NHS 2018). Other bathymetry data may be available from the petroleum industry, research institutions or the Olex database (mainly single-beam echo-sounder data) (e.g. Elvenes et al. 2012).

Multibeam echo sounders are used for detailed mapping of the bathymetry. Furthermore, co-registered backscatter data provide additional information on the composition and structure of the seafloor through the amplitude of the returned signal from the seafloor (e.g. Lurton and Lamarche 2015). Bathymetry data are processed by NHS and subcontractors (data correction and cleaning), and, after quality control, NHS produces terrain models at horizontal resolutions appropriate to the sounding density (in the range 2–50 m). Backscatter datasets are processed from raw data by NGU using industry-standard software to produce mosaics with a pixel resolution of 1–50 m, depending on the data density and quality. Since 2010, water column data have also been acquired as part of the MAREANO multibeam echo-sounder surveys. Subcontractors acquire sub-bottom profiler data (only a few surveys prior to 2018), yielding additional information about the structure and composition of the uppermost c. 100 m of the seafloor.
IMR and NGU plan and arrange common sampling cruises. Given MAREANO’s wide mapping focus, the station planning must take broad-scale environmental variability into consideration, including both geological and biological diversity, as well as identifying suitable locations for retrieving samples for chemical analysis. High-resolution bathymetry and backscatter data, supplemented with available oceanographic model data, are fundamental to this station planning process.

While early MAREANO station planning was essentially expert driven (but guided by a simple unsupervised classification of the physical environment), MAREANO has now phased in more objective and automated methods (Thorsnes et al. 2015). The sampling effort is matched as far as possible to the scale of the map product(s) and available budgets. Approximately 10 stations per 1000 km² have been visited for the collection of video data, allowing visual observation of seabed sediments and megafauna. A proportion of these stations (generally two per 1000 km²) are so-called full stations where a range of sampling gear (see below) is used in support of multidisciplinary mapping (geology, biology, chemistry). These general averages in terms of station density have been adapted from area to area in recent years, depending on the complexity of the seabed and/or the length of the video lines. In 2018, the sampling density for video and geological grab samples was increased to 20 stations per 1000 km², in connection with a reduction in the length of video lines from 700 to 200 m. This change allows more locations to be documented which generally increases the environmental space observed within a similar timeframe.

MAREANO employs the towed video platforms Campod and Chimaera for seabed video surveying deployed from relatively large, stable research vessels with dynamic positioning (e.g. R/V G.O. Sars). These platforms are equipped with a low-light charge-coupled device (CCD) (forward-looking) and high-definition (HD) video cameras, in addition to

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**Fig. 3.** Landscapes and landforms in an area mapped by the MAREANO programme outside north Norway. The map is made for viewing at a scale of 1:100 000. S, Sveinsgrunnen; M, Malangsdjupet. See Figure 2 for the location of Andøya.
lights, scale indicator and a geopositioning transponder accurate to c. 2% of the water depth. The HD camera has a manual zoom and focus, and is mounted on a pan-and-tilt device. The video platforms are used both temporarily parked on the seabed for detailed studies and in a transect mode towed by the ship along a predefined survey line. The height above the seabed is maintained by a winch operator using visual observations from the forward-looking camera.

A variety of other physical sampling gear is used by MAREANO at full stations including grab, box corer, multicorer and gravity corer, all providing material and information from the seafloor and uppermost metres of the seafloor for geological and ecological (infauna and epifauna) studies. The multicorer is used for environmental sampling of undistorted core material. Epibenthic sledge and beam trawl are employed to sample fauna on and above the seabed. Oceanographic properties are measured with CTD, ADCP and rosette sampler.

During MAREANO sampling cruises, sub-bottom profiler data (e.g. TOPAS topographical parametric sonar) are acquired during transit between all stations and along selected transects covering features of special interest (e.g. sand waves or pockmarks observed in multibeam bathymetry). Sub-bottom penetration depends on grain size and compaction of the seabed, and may be up to 100 m with a vertical resolution of 0.5–1 m in fine-grained sediments. These data support the geological interpretation and are particularly useful for the production of NGU’s sediment genesis map (see below). Sub-bottom profiler data are now also regularly acquired during the MAREANO multibeam mapping cruises.

Coastal mapping

Coastal mapping projects have so far been limited to areas with existing multibeam data available from NHS or other sources (e.g. the Norwegian Defence Research Establishment (FFI)). Additional multibeam data are occasionally acquired during NGU cruises. Pre-cruise station planning for video surveying and physical sampling in the coastal zone is expert-driven, based on multibeam bathymetry and backscatter, and the number and distribution of stations vary depending on seabed complexity and the availability of existing observations. Commonly, 100–200 stations are visited per 1000 km². Automated methods for station planning, like those now adopted by MAREANO, need to be improved before they integrate the complexities of the coastal environment and the geologist’s need for ground truthing, particularly when multibeam backscatter datasets from multiple sources are applied, as these can be challenging to harmonize.

In the coastal zone, where surveys are generally conducted from NGU’s 17 m-long research vessel R/V Seisma, video data are recorded by means of a towed platform equipped with one low-light CCD camera and one HD camera, as well as lights, scale indicator and geopositioning transponder. Camera settings are locked during operation, and the platform is kept at 0.5–1 m above the seabed while the ship is moving at low speed. Video lines are generally 50–300 m long. Their final lengths are adapted en route depending on the heterogeneity of the observed seabed. The main sampling gears consist of grab and multicorer or Niemistö-corer.

Sub-bottom profiler (TOPAS) data are also acquired on coastal mapping cruises on R/V Seisma during transits between stations, as well as along selected transects, and data are used to support the geological interpretations.

Results

In MAREANO, geological seabed maps based on high-quality multibeam echo-sounder data (5 m grids) and seabed ground-truth data include seabed sediments (grain size), seabed sediments (genesis), sedimentary environment, and landscapes and landforms. These are all mapped for use at the scale 1:100 000 (digitizing scale c. 1:50 000) (Table 1) and coarser. Marine base maps for the coastal zone are generally made for use at the scale 1:20 000 (digitizing scale c. 1:10 000). In both cases, map scales may vary depending on the purpose, multibeam data quality and available ground-truth data.

Landslapes and landforms

The marine landscape mapping performed by MAREANO delimits broad-scale morphological elements (Thorsnes et al. 2009). Landscape classification is based on the national nature description and typification system NiN (Nature types in Norway: Artsdatabanken 2019). NiN defines landscapes as large geographical areas with a visually homogeneous character. Through a semi-automated GIS method (Elvenes 2014), bathymetry data and derived terrain attributes (e.g. slope, curvature, relative relief, relative vertical position) are used to categorize all areas of the seabed as one of the following classes: strandflat; smooth continental slope; marine canyon; marine valley; shallow-marine valley; fjord; deep sea plain; continental slope plain; continental shelf plain; and hilly/mountainous marine landscape (Fig. 3). Strandflat is the crystalline platform which characterizes large parts of the Norwegian coast and in many areas contrasts sharply with the sedimentary rocks of the continental shelf. Fjords and marine valleys are the results of concentrated glacial erosion...
during repeated glaciations, with fjords incising the mainland. Continental shelf plain is the residual low-relief landscape between marine valleys on the continental shelf.

For areas with multibeam data coverage, MAREANO’s marine landscape maps are based on bathymetry data with a horizontal resolution of 50 m and are at a scale of 1:100 000. In other areas, maps are based on best available resolution data such as Olex or IBCAO bathymetry, which are generally of lower quality (larger uncertainty) than multibeam data. Landscape delineation in areas without multibeam data coverage is, therefore, conducted at coarser map scales – typically 1:500 000–1:1 000 000. Marine landscape maps do not form part of the coastal marine base maps, although some mapped areas are covered by the MAREANO classification.

Marine landforms (Figs 3 & 4) are mapped in MAREANO based on detailed bathymetry and sub-bottom profiler data, supported by video observations of the seabed. Landforms are interpreted and digitized manually in GIS as polygons or lines, depending on the type of landform and size. Examples of landforms mapped are drumlin, moraine, esker, meltwater channel, crevasse-fill ridge, glacial lineation, glaciotectonic hole, glaciotectonic hill, sediment wave field, channel, canyon, slide scarp, slide front, slide fan, submarine slide and pockmark area. A collaboration has been developed between MAREANO, the British MAREMAP programme and the Irish INFOMAR programme to develop a common framework for morphological and geomorphological mapping (Dove et al. 2016).

Thousands of cold-water coral reefs occur on the Norwegian continental shelf and in the coastal zone (e.g. Mortensen et al. 2001; Bøe et al. 2016; Thorsnes et al. 2016a, 2017; Jarna et al. 2017). From 2018, offshore coral carbonate mounds are mapped by a methodology that combines image segmentation and spatial prediction based on multibeam bathymetry. The results of Diesing and Thorsnes (2018) show that, for a limited study area, the image-object mean planar curvature is the most important predictor, and their approach allows the presence and absence of carbonate mounds to be mapped.

| Map products: | MAREANO | Coastal mapping projects |
|---------------|----------|-------------------------|
| Seabed sediments (grain size) | Included: | Included: |
| Map scale/raster resolution: | 1:100 000–1:3 000 000 | 1:10 000–1:50 000 |
| Seabed sediments (genesis) | Yes | No |
| Sedimentary environment | Yes | No |
| Accumulation areas | No | Yes |
| Anchoring conditions | No | Yes |
| Digability | No | Yes |
| Slope >30° | No | Yes |
| Slope (raster) | No | Where |
| Seabed terrain (raster) | Yes | Where permitted |
| Backscatter (raster) | Yes | Where permitted |
| Landforms | Yes | Where permitted |
| Marine landscapes | Yes | Where permitted |
| Mapping strategy | Large and coordinated mapping efforts, long-term planning | Smaller projects in cooperation with local authorities and stakeholders |
| Video transects | Length | Standardized: 700 m pre-2018, 200 m from 2018 | Adjusted to local conditions, often 200–300 m |
| Number | Standardized but varying from area to area, typically 5–20 transects per 1000 km² | Adjusted to local conditions, often c. 100 transects per 1000 km² |
| Video platform Samples | Towed and stationary on seabed Sediment grab and other sampling equipment, standardized number of samples | Towed Mainly sediment grab; number of samples adjusted to local conditions |

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Fig. 4. Landscapes and landforms mapped by MAREANO. (a) Continental shelf and slope with canyons and slides outside Vesterålen, north Norway. In this area, water depths increase from around 50 m on the Sveinsgrunnen Bank to 200 m in the Malangsdjupet Trough and to more than 2000 m in the Lofoten Basin. See Figure 3 for the location of Sveinsgrunnen and Malangsdjupet. (b) Sand waves (up to 5 m high) and coral reefs (up to 17 m high) in the Hola Trough outside Vesterålen, north Norway. Water depths are 70–90 m on the Vesterålsgrunnen Bank and 200–270 m in the Hola Trough. See Figure 2 for the locations of Hola and Vesterålsgrunnen. (c) Iceberg plough marks and pockmarks in the Barents Sea. In this area, with water depths of around 270 m, pockmarks are 20–50 m across and 2–5 m deep, while plough marks are 60–70 m wide and 6–7 m deep. See Figure 1 for the location.
with high accuracy. This method is currently being scaled up for application to wider areas. Prior to the development of Diesing and Thorsnes’ (2018) method in 2018, coral reefs and associated sediments were manually digitized and classified as ‘bioclastic sediments’ (Bellec et al. 2014). In the seabed sediments (grain size) map (see the following subsection), coral carbonate mounds are indicated as ‘mud, sand and gravel of biological origin’, while, in the seabed sediments (genesis) map, they are classified as ‘bioclastic sediment’.

Seabed sediments (grain size)

The seabed sediments (grain size) map (Fig. 5) reflects the sediment or bottom type in the uppermost c. 10 cm of the seabed, categorized as one of 35 defined classes (NGU 2019b). Most of the classes comprise a mixture of grain sizes (e.g. ‘gravelly sand’ or ‘mud and sand with gravel, cobbles and boulders’), which is a signature of predominantly glacially influenced environments.

For expert-driven interpretation and compilation of the grain-size map, all available data (i.e. multi-beam bathymetry and backscatter, videos, seabed samples taken with grab, box corer, and multicorer, as well as sub-bottom profiler data) are used by the geologist, and published literature is consulted where available. The classification of sediment type is determined by the final scale of the map and the degree of detail in the data used for interpretation and map compilation.

Seabed sediments (genesis)

The seabed sediments (genesis)/Quaternary geology map reveals processes on the seafloor during and after the last ice age. The map describes deposits and bottom types in the upper 1–2 m of the seafloor (i.e. not only the surface deposits influenced by the most recent processes).

For mapping of seabed sediments (genesis), the geologist chooses from amongst 32 sediment/bottom type classes (NGU 2019c). Examples include

![Fig. 5. Seabed sediments (grain size) in an area mapped by the MAREANO programme outside north Norway. The map is made for viewing at a scale of 1:100 000.](image-url)
suspension deposit, glaciomarine deposit, bedload (traction) deposit, contourite, glaciofluvial deposit, till, mass-movement deposit, debris-flow deposit and exposed bedrock. Vast areas, especially on the continental shelf, are dominated by sediments deposited in glacial environments.

The map is based on the seabed sediments (grain size), as well as the landscapes and landforms maps, in addition to further interpretation of multibeam bathymetry, and sub-bottom profiler and seismic data. The classification of sediment type is determined by the final scale of the map and the degree of detail in the data used for interpretation and map compilation. So far, seabed sediments (genesis) maps have only been compiled within MAREANO for the offshore areas.

**Sedimentary environment**

The sedimentary environment map is based on the seabed sediments (grain size) map and the datasets used for producing that map. A predefined number of classes is used for compilation (NGU 2019d). The main purpose of the map is to visualize areas of erosion and deposition of sediments, and how bottom currents influence the seabed.

Deposition of fine-grained sediments (mud and sandy mud) primarily occurs in deep or sheltered waters. Erosion may remove fines and deposit sand where bottom currents become weaker or where sand is transported back and forth by tidal currents. The shallowest areas are often dominated by erosion, although fine-grained sediments may accumulate in local, topographical depressions. A lag deposit of sandy gravel, cobbles and boulders is often formed where bottom currents (wave, tidal or oceanographic currents) are strong. Grain size generally indicates the strength of the bottom currents; mud suggests weak bottom currents, while coarser sediments or erosion suggest stronger currents.

**Marine base maps in the coastal zone**

The marine base maps published by NGU since 2003 (Sandberg et al. 2005; Longva et al. 2008; Thorsnes et al. 2013; Elvenes et al. 2019) present geological information relevant to end users outside the geological community in a format that is comprehensible to geologists and non-geologists alike. As described above, sediment type mapping in Norwegian nearshore areas is based on pre-existing multibeam echo-sounder data ground-
truthed by video observation and physical samples. Figure 6 shows an example of shaded bathymetry, backscatter and interpreted sediment types from a Norwegian fjord.

Since grain size can be difficult for the non-specialist to interpret with respect to everyday applications, the detailed, full-coverage maps of seafloor sediment types (grain size) are supplemented with thematic maps based on expert knowledge of sediment properties and on high-resolution multibeam data. A full stack of marine base maps will contain shaded relief bathymetry and slope data of the highest permitted resolution (given military restrictions), seafloor sediments (grain size), anchoring conditions, digability and accumulation basins (examples shown in Fig. 7). Most marine base maps published since 2015 have a scale of 1:20 000. This suite of applied marine base maps conveys useful information on the coastal marine environment to managers, industry, fishermen, recreational users, marine scientists, etc., even in areas where access to high-resolution multibeam bathymetry is restricted by the Norwegian defence authorities.

Harmonized maps for EMODnet Geology

The EMODnet (European Marine Observation and Data Network) Geology portal (EMODnet Geology 2019) aims to provide harmonized information on marine geology in Europe. NGU has delivered harmonized datasets at different scales (both MAREANO and coastal data) on landscapes and landforms, seafloor substrates (seafloor sediments (grain size)), the Quaternary (seafloor sediments (genesis)), the pre-Quaternary, mineral occurrences, sediment accumulation rates, geological events and probabilities, and coastal behaviour.

Summary

Results from MAREANO and coastal mapping projects show that Norway has a rich and diverse seafloor. The geomorphology and sediment-distribution patterns reflect a long geological history and complex modern-day hydrodynamic processes. By 2019, approximately 10% of the Norwegian seafloor had been mapped: c. 200 000 km$^2$.

Fig. 7. Marine base maps. Example of use of the seafloor sediments (grain size) map (in addition to detailed bathymetry) for compilation of the derived thematic maps for anchoring conditions, digability and accumulation basins. See Figures 5 and 6 for the legends to the seafloor sediments (grain size) map. In the thematic maps, the most favourable conditions for anchoring are shown in green; for digging, in light grey; and for soft-sediment accumulation, in blue.
offshore and 10,000 km² in the coastal zone. Geological maps by MAREANO include seabed sediments (grain size), seabed sediments (genesis), sedimentary environment, and landscapes and landforms. These are made for use at a scale of c. 1:100 000. Marine base maps for the coastal zone include seabed sediments (grain size) and the derived maps – anchoring conditions, digability and accumulation basins – made for use at a scale of c. 1:20 000. Bathymetric and geological maps produced by MAREANO and coastal mapping projects, along with biological and oceanographic data, have been found to form an invaluable basis for further mapping and modelling of benthic habitats, with grain-size and landscape maps often serving as important predictor variables. In addition, mapping of seabed chemistry (including pollution) is included in the working programmes of both MAREANO and the coastal mapping projects.

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Data availability statement The datasets generated and/or analysed during the current study are available in the NGU repository, www.mareano.no and www.ngu.no.

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