Seabed sediments of Søre Sunnmøre, Norway

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ABSTRACT
An increasing number of activities compete for space in the Norwegian coastal zone, making access to detailed seabed information particularly valuable. We present a suite of thematic marine base maps of the near-shore areas of five municipalities in west Norway (567 km²; at 62°N5°E). This set of full-coverage seabed maps includes sediment grain size, seabed terrain (shaded relief), slope, sediment accumulation basins, anchoring conditions, and duggability (trenching properties). The sediment grain size map is a geological interpretation of multibeam echosounder data supported by video observations and physical samples of seabed sediments. The other maps in the suite are derived from this sediment map, and/or directly from the bathymetry data. All maps are at a scale of 1:20,000 and are freely accessible for download or online viewing. Marine base maps are intended for all end-users with a need for knowledge of seabed conditions and may be especially valuable for marine spatial planning.

1. Introduction
Norway is a coastal and maritime nation with a legacy of economically important activities taking place along one of the world’s longest shorelines. Fisheries, aquaculture, tourism, industry, infrastructure and recreation all have specific, and often conflicting, needs for area use in the coastal zone (Hersoug & Johnsen, 2012; Jentoft & Buanes, 2005). The main responsibility for marine spatial planning in coastal waters lies with the municipalities (Plan- og bygningsloven, 2008). Relevant background knowledge about physical seabed characteristics such as terrain or sediment type may, however, be scarce. The Norwegian Hydrographic Service (NHS) routinely conducts high-resolution multibeam echosounder (MBES) surveys in order to update navigational charts. In many nearshore areas MBES coverage is however still sparse, and since Norway’s Defence legislature restricts the use of high-resolution bathymetry data in coastal waters (within 12 nautical miles from the coast) these data are rarely available to the public. Planning authorities and stakeholders alike typically have to make do with the sparse seabed information included in navigational charts, and might not even be aware that more detailed marine data exist.

Over the last 15 years, the Geological Survey of Norway (NGU) has developed marine base maps, a series of map products intended to make detailed seabed information accessible to all users of Norwegian coastal areas without violating Defence policies. Drawing on experience from Norway’s ongoing offshore mapping programme MAREANO (Bellec et al., 2009, 2017; Buhl-Mortensen, Buhl-Mortensen, Dolan, & Holte, 2015; www.mareano.no), marine base maps are based on MBES data and field observations in the form of video data and physical samples. Through expert interpretation and spatial analysis, the high-resolution survey data are converted into full-coverage thematic maps of seabed properties. Presented at scales 1:10,000–1:50,000, interpreted vector maps (e.g. sediment grain size) of nearshore areas can be published freely, and high-resolution raster maps of for example seabed terrain may be published alongside the vector maps where permitted by Norwegian Defence Authorities.

The fundamental element in a suite of marine base maps is a vector map of interpreted seabed sediment types. The spatial distribution of sediment is linked to physical conditions such as water depth, wave action, current strength, and past and present sediment input. Different grain sizes represent different living conditions for benthic organisms, and grain size is a key factor in benthic habitat modelling (Brown, Smith, Lawton, & Anderson, 2011; Buhl-Mortensen et al., 2015; Ryan et al., 2007). Knowledge of sediment type distribution is also valuable when planning human activities in the coastal zone, as stability and other geotechnical properties of seabed sediments vary with grain size and sediment homogeneity. The level of detail included in a comprehensive map of seabed types could however be an obstacle to a non-geologist’s use of this information. To counter this, a suite of marine base maps can include other thematic maps derived directly from the sediment types through expert
understanding of their various properties. These more applied maps are intended to give users with various backgrounds easy access to the marine spatial information most relevant to them, such as locations of soft sediment accumulation basins, variability in anchoring conditions, and diggability of different seabed types. Examples of current users include municipal spatial planners, professional and recreational fishers, local aquaculture entrepreneurs, and marine habitat mappers.

Marine base maps are distributed free of charge in a variety of formats. These include WMS, downloadable files for use in GIS applications, online map viewers (www.ngu.no, www.mareano.no), and files compatible with navigational software onboard vessels. To date areas with marine base maps total c. 10,000 km², c. 11% of Norwegian coastal waters. In some of the covered areas, sediment type maps and MBES data form the basis of further mapping and modelling efforts, for example of oceanographic variables (Slagstad & Knudsen, 2012) or benthic habitats (Dolan et al., 2012; Plassen, Van Son, Lepland, & Longva, 2015). Sediment maps are also shared via the EMODnet portal for European seabed habitats (www.emodnet/eu).

This paper presents a suite of scale 1:20,000 marine base maps in a 567 km² study area on the Norwegian west coast (around 62°N/5°E, Figure 1 (Main Map)) – marine base maps for online viewing can also be found at geo.ngu.no/kart/marin_mobil under ‘Thematic maps’). The area is topographically diverse, with both sheltered and open fjords, shallow exposed bank areas, and numerous islands ranging from skerry-sized to c. 170 km². While water depth in most of the study area is 0–100 m, the deepest fjords well exceed 600 m in depth. Geomorphological processes both Quaternary and modern influence the distribution of seabed sediment in the study area (Aarseth, 1997 Landvik & Hamborg, 1987; Mangerud, Larsen, Longva, & Sonstegaard, 1979; Ottesen, Boe, & Grøsfjeld, 1995). We describe the process of seabed sediment mapping based on MBES data and observations, and how other thematic marine base maps are derived from this initial sediment map and from the bathymetry data. Mapping was commissioned by five municipalities who collaborate in managing their shared marine areas, and the maps have been actively used in marine spatial planning since their 2016 completion. High-resolution bathymetry data in the study area have been declassified by the Norwegian Defence Authorities and are thereby available to all end-users.

2. Methods

The production of large-scale, full-coverage marine base maps depends on access to high-resolution multibeam echosounder (MBES) data. Modern-day nautical charts are often based on MBES data, but the fine details of seabed topography and sediment types are generally not reflected in these (Figure 2). Seabed reflectivity (backscatter) data are frequently recorded along with MBES depth soundings and may give valuable insight in the spatial variation of seabed sediment types as reflectivity is often correlated to grain size (see Lamarche & Lurton, 2018, and references therein). Backscatter values are however relative, and so ground-truthing in the form of seabed observation (e.g. video or physical samples) is needed to reliably interpret seabed types based on MBES data. The mapping project presented here included field work with NGU’s 17 m R/V Seisma in August 2014 and August 2015. During these cruises we recorded seabed video transects and obtained physical sediment samples, and we also acquired additional MBES data.

2.1. Multibeam echosounder (MBES) data acquisition and processing

This project was limited to mapping 576 km², c. 70% of the nearshore marine areas of the five municipalities Hareid, Ulstein, Herøy, Sande and Vanylven (Figure 1). MBES data from 38 surveys in the study area were provided by NHS. These surveys were conducted over the years 2006–2012 using four different MBES systems and covering a depth range of 0.2–636 m. We also had access to 6 km² of older MBES data from an earlier NGU research project in the area, gridded to 5 × 5 m (Longva, Blikra, Olsen, & Stalsberg, 2001). During the 2014 fieldwork we acquired incidental data with a WASSP MBES, and this amounted to 175 km² of extra MBES data (bathymetry and backscatter), mainly overlapping areas already surveyed. Figure 3 shows the area covered by each MBES survey included in this study, while Table 1 lists the specifics of the systems used in acquisition.

NHS supplied raw data for all 38 MBES surveys as well as hydrographically accepted XYZ bathymetry data for 29 surveys. At NGU, data from all surveys were gridded to a horizontal resolution of 1×1 m using QPS Dmagic software.

Multibeam backscatter was processed from raw data at NGU using QPS FMGT and Atlantic Geoscience Center Grass 5 software (supplied by the Geological Survey of Canada). The majority of data were processed using default settings in each software. Minor adjustments were made as required to overcome the effects of bad soundings and/or changes in acquisition settings. The data were gridded to 1 × 1 or 2 × 2 m horizontal resolution, depending on sounding density and data quality. In two NHS survey areas, no backscatter data had been recorded during MBES acquisition, and from the older NGU project only bathymetry data were available (Figure 3). Seabed sediment interpretation in these three areas is therefore based on full-coverage bathymetry data supplemented by

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discontinuous backscatter data acquired during fieldwork (Elvenes, Dolan, Buhl-Mortensen, & Bellec, 2013).

Bathymetry and backscatter data were converted to ESRI raster grid format and exported to ESRI ArcMap (v. 10).

2.2. Video transects and grab samples

Interpretation of sediment types in the study area is based on seabed video recorded by a towed camera, combined with physical sediment samples obtained by grab. A total of 219 video transects were recorded during the two field seasons, while 92 sediment samples were collected for on-board grain-size assessment. The locations of all samples and video transects are shown in Figure 1. These were planned with the aim to best cover seabed variability in the study area, as inferred from bathymetry and backscatter data. Table 2 lists the distribution of all observation points (video and samples) across different depth intervals. Video positioning was based on a transponder mounted on the towed camera frame, and is horizontally accurate to a decimetre-scale. The ship’s position was used for grab samples, and we estimate accuracy to tens of metres.

R/V Seisma was equipped for video recording at 0–200 m depth, with direct image transfer from camera to ship. We manually logged seabed types in real time using custom-built logging software (CampodLogger, developed by the Norwegian Institute of Marine Research) with a 15-category classification system and options for commenting. Seabed types were logged as geo-referenced point observations, normally registering a new point every 10 s at the camera’s position, and the logs were converted to ESRI ArcGIS shapefile format. All videos were later reviewed to ensure registration of any seabed types not included in the software’s 15 categories. The recorded videos have a duration of 2–28 min (average 10 min 57 s, median...
Figure 2. Comparison of details in nautical chart (left), shaded relief image from bathymetry data (centre), and backscatter intensity (right) from a part of the study area. Backscatter intensity is often correlated to sediment grain size (Lamarche & Lurton, 2018). MBES data acquired in 2007 by NHS, nautical chart by NHS accessed July 2018 at www.norgeskart.no.

Figure 3. NHS survey areas in Søre Sunnmøre, classified by MBES system and acquisition year. Specifics of each survey are given in Table 1.
10 min 15 s), and transects cover 50–960 m of seabed (average 277 m, median 233 m). For video transects we targeted sharp boundaries between seabed types, where possible. During transects the vessel would be drifting or motoring at very low speed.

Homogeneous, fine-grained seabed types were targeted for physical sampling using a custom-made, unsealed grab with a footprint of c. 40 × 40 cm, typically penetrating 5–30 cm. Samples were used to validate interpretations of soft seabed types in video images and to provide ground-truthing in areas not covered by video transects, including in water depths >200 m. All samples were photographed on deck, and grain size distribution assessed visually.

### 2.3. Supplementary data

Through the Norwegian Mapping Authority, we had access to an archived point dataset compiled from seabed samples taken during manual soundings for navigational charting. In the study area, c. 3000 sounding points were available, with highest densities in coastal and sheltered areas. These legacy data predate modern echosounder and positioning systems and have limited reliability due to this, the sampling method (a greased sounding-line), and the sediment description not being standardised. Nevertheless, they were helpful in indicating seabed type in areas where fieldwork ground-truthing data were sparse.

The Norwegian Mapping Authority also provides orthorectified aerial imagery for online viewing (www.norgeskart.no) and as a web map service (WMS). In nearshore areas, these terrestrial images are a great aid to identifying the types of sediment that occur both above and below sea level, such as beach or talus deposits. In this project we also made use of the imagery to distinguish cobble/boulder-dominated seabed types from bedrock outcrops along the numerous steep sea cliffs in the study area.

### 2.4. Interpretation

The seabed sediment grain size map that forms the basis of many other products in the marine base map suite was manually digitised on screen at a scale of 1:10,000 for viewing at 1:20,000. Manual digitising of sediment type boundaries, although a relatively time-consuming and subjective strategy, allows for expert judgement in the geological mapping process. Recent years have seen great progress in the development of automated seabed classification methods (Diesing et al., 2014; Diesing & Thorsnes, 2018; Ierodiaconou et al., 2018; Innangi et al., 2018). However, at the time of mapping (2014–2016) we found no automated method sufficiently developed for large-scale mapping of a complex, nearshore environment influenced by a multitude of geological and oceanographic processes, and where MBES data originate from multiple surveys and echosounders.

In total, 20 seabed sediment classes were observed and mapped in the study area (Table 3). The classification follows the NGU standard for seabed sediment mapping (Boe et al., 2010), which is modified from Folk (1954). We base our interpretation mainly on MBES bathymetry and backscatter data. Backscatter, although affected by multiple factors unrelated to sediment grain size, is widely used as a proxy for seabed sediment type (Lurton & Lamarche, 2015). While some sediments are closely associated with landforms that can be detected and delineated in shaded relief bathymetry images (e.g. bedrock outcrops, sand waves, or the coarse material of morainic ridges or talus deposits), others may be more reliably identified in backscatter data. Figure 4 gives examples of sediment type boundaries discernible in different datasets and of how the digitised map product relates to the MBES data.

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**Table 1.** MBES survey data delivered by NHS and used in the study (see also Figure 3).

| MBES system | Frequency | Recommended maximum operating depth | Acquisition depths in study area | Year of data acquisition | Number of surveys | Total area covered | Backscatter available |
|-------------|-----------|-------------------------------------|----------------------------------|--------------------------|-------------------|-------------------|---------------------|
| EM 710      | 40–100 kHz| 2800 m                              | 7–636 m                         | 2012                     | 4                 | 241 km²           | Yes                 |
| EM 1002     | 95 kHz    | 1000 m                              | 13–307 m                        | 2007                     | 2                 | 71 km²            | Yes                 |
| EM 3000     | 300 kHz   | 200 m                               | 0.8–63 m                        | 2006                     | 1                 | 2 km²             | No                  |
| EM 3002D    | 300 kHz   | 200 m                               | 0.8–221 m                       | 2007                     | 9                 | 143 km²           | Yes                 |
| EM 3002D    | 300 kHz   | 200 m                               | 0.2–207 m                       | 2008                     | 11                | 172 km²           | For 10 surveys (129 km²) |
| EM 3002D    | 300 kHz   | 200 m                               | 0.8–76 m                        | 2009                     | 2                 | 1 km²             | Yes                 |
| EM 3002D    | 300 kHz   | 200 m                               | 0.9–310 m                       | 2012                     | 9                 | 206 km²           | Yes                 |

* Konsgberg Maritime’s recommended operating depths for current and discontinued products are available via links for each product at https://kmdoc.kongsberg.com/ks/web/nokbg0240.nsf/WebProductSupportListingAZ?ReadForm#E

**Table 2.** Video observations and sediment samples at various depth intervals. Spatial distribution is shown in Figure 1.

| Depth interval (m) | Percentage of logged video observation points | Number of sediment samples obtained |
|--------------------|---------------------------------------------|-------------------------------------|
| 0–20               | 6.6                                         | 2                                   |
| 21–40              | 23.4                                        | 12                                  |
| 41–60              | 20.6                                        | 8                                   |
| 61–80              | 14.6                                        | 17                                  |
| 81–100             | 10.7                                        | 12                                  |
| 101–120            | 8.1                                         | 10                                  |
| 121–140            | 6.3                                         | 7                                   |
| 141–160            | 5.3                                         | 4                                   |
| 161–180            | 3.4                                         | 1                                   |
| 181–200            | 1.0                                         | 2                                   |
| 201–300            | -                                           | 7                                   |
| 301–400            | -                                           | 4                                   |
| 401–500            | -                                           | 6                                   |
In the study area, we experienced that the highest backscatter values correspond to gravel- or cobble-dominated seabed types, while muddy and sandy seabed types give low values. The reflected signal from exposed bedrock is generally low or mixed. This makes backscatter data a poor choice for delineating bedrock outcrops; however, these features are often conspicuous in shaded relief images (Figure 4) and can in such cases be delineated from the bathymetry data.

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Table 3. Seabed sediment (grain size) types in the study area and translation used for the derived maps sediment accumulation basins, anchoring conditions, and diggability.

| Seabed sediment (grain size)     | Sediment accumulation basins                                      | Anchoring conditions | Diggability          |
|---------------------------------|------------------------------------------------------------------|----------------------|----------------------|
| Mud-dominated                    | Likely accumulation of soft sediment                             | Very good            | Diggable, stable trench |
| Sandy mud                       | Likely accumulation of soft sediment                             | Very good            | Diggable, stable trench |
| Gravelly sandy mud              | Little accumulation                                              | Good                 | Diggable, stable trench |
| Mud/sand with cobbles/boulders  | Little accumulation                                              | Difficult            | Hardly diggable       |
| Sandy gravel                    | Likely accumulation of soft sediment                             | Very good            | Diggable, stable trench |
| Gravel                          | Little accumulation                                              | Good                 | Diggable, unstable trench |
| Gravelly muddy sand             | Little accumulation                                              | Good                 | Diggable, unstable trench |
| Muddy sand                      | Likely accumulation of soft sediment                             | Good                 | Diggable, unstable trench |
| Gravel and cobbles              | Likely accumulation                                              | Difficult            | Hardly diggable       |
| Gravel, cobbles and boulders    | Little accumulation                                              | Difficult            | Hardly diggable       |
| Cobbles and boulders            | Little accumulation                                              | Difficult            | Hardly diggable       |
| Sand, gravel and cobbles        | Little accumulation                                              | Difficult            | Hardly diggable       |
| Sand, gravel, cobbles and boulders | Likely accumulation of soft sediment         | Difficult            | Hardly diggable       |
| Bedrock                         | Thin or discontinuous sediment cover on bedrock                  | Poor                 | Not diggable          |
| Exposed bedrock                 | Little accumulation                                              | Poor                 | Not diggable          |

2.5. Deriving other thematic maps from MBES data and interpreted sediment map

Presenting seabed information in the form of thematic maps accessible to end-users outside the geological community is a key objective in the production of any suite of marine base maps. NGU bases the selection of thematic maps on stakeholder requests first identified in a 2005 forerunner project (Andresen, Longva, Lepland, & Thorsnes, 2005).

Raster maps in the marine base map suite include seabed terrain (shaded relief) and slope, and raster analyses were conducted in ESRI ArcGIS with Spatial Analyst. Hillshading for seabed terrain maps used azimuth = 315°, altitude = 45°, and Z factor = 10 (Hillshade tool). When used in WMS, terrain is displayed at 2, 10 or 50 m resolution depending on viewing scale. Slope was calculated from a 10 m bathymetry grid using default settings of the Slope tool, and is displayed in the map suite both as a 5-class raster layer and as a polygon layer outlining areas of slope >30°.

Thematic feature maps were translated from the attributes in the map of interpreted seabed sediment grain size classes by assigning new values to all polygons according to a geological interpretation of sediment properties. Table 3 shows the relationship between original grain size classes and the reclassified thematic layer categories.

3. Map products

3.1. Seabed sediments (grain size)

There is clear regional variability in sedimentary conditions in the morphologically diverse study area, and this is reflected in the seabed sediment map that forms the basis of the marine base map suite (Main Map). Varying levels of exposure, bottom current velocities and sediment input all influence the spatial distribution of sediment types, and we identify four main sedimentary regions (1–4) and a transition zone in the study area (Figure 5). Table 4 summarises the distribution of sediment types in each region.

(1) Exposed bank areas in the north-west typically have water depths of 0–70 m, alternating with 100–150 m deep troughs. These areas are open to exposure from oceanic wind and wave action from the west and the north and are affected by the strong north-easterly Norwegian Coastal Current (Børresen, 1987; Ersdal, 2001). On the shallow banks we find sand and coarser sediment types (gravel, cobbles, boulders) which are often well-sorted. Deposits of sand and gravelly sand will generally be confined in drifts with sharp boundaries to coarser sediment types. Some sedimentation of finer material occurs in troughs, where we find sandy mud or muddy sand in addition to coarser, heterogeneous sediment types. Outcropping bedrock is common in the bank areas, where it may be fully exposed or covered with a thin and/or discontinuous layer of sand or other coarse material.

(2) Sheltered archipelagic areas between the large islands Hareidlandet, Gurskøya and Leinøya are characterised by a complex morphology both above and below sea level. Numerous small submarine basins (50–100 m deep) are separated by sills of bedrock and morainic material, and vertical water mixing in the area is limited (Chapman & Hareide, 2009). To the east, south and west, islands give shelter from wind and wave action, however the area is relatively open to the north. The spatial distribution of seabed sediment closely follows the bathymetry in this area. In basins, sediments are predominantly muddy with occasional buried or half-buried coarse material. Frequent bedrock...
outcrops also occur here, and these tend to be partly covered in sandy or muddy sediment. On ridges and in troughs connecting muddy basins, the seabed is generally coarse and heterogeneous. Video observations show that muddy sediments are present even in areas dominated by very coarse material (cobbles and boulders), in some cases covering the coarser sediments. Boundaries between sediment types are often gradual, due to accumulation of soft sediment.

Table 4. Spatial distribution of mapped seabed sediment types in each sedimentary region (see also Figure 5).

| Sediment type* | Exposed banks | Sheltered archipelago | Open-ended fjord | True fjord | Transition zone |
|----------------|---------------|-----------------------|------------------|------------|----------------|
| Thin/discontinuous sediment cover on bedrock | 13.9 | 25.9 | 13.1 | 11.5 | 18.3 |
| Exposed bedrock | 23.4 | <0.5 | 0.6 | 1.6 | 9.2 |
| Mud | <0.5 | 5.6 | 3.1 | 16.4 | 1.3 |
| Sandy mud | 0.7 | 14.8 | 33.8 | 16.4 | 10.5 |
| Muddy sand | 3.6 | 7.4 | 8.8 | 6.6 | 11.8 |
| Sand | 11.7 | <0.5 | <0.5 | <0.5 | 6.5 |
| Gravelly sandy mud | <0.5 | <0.5 | 4.4 | 1.6 | 1.3 |
| Gravelly muddy sand | <0.5 | 1.9 | 5.6 | 4.9 | 5.2 |
| Gravelly sand | 5.1 | 1.9 | 1.3 | 1.6 | 6.5 |
| Sandy gravel | 0.7 | <0.5 | <0.5 | <0.5 | <0.5 |
| Sand, gravel and cobbles | 7.3 | 20.4 | 7.5 | 9.8 | 15.7 |
| Sand, gravel, cobbles and boulders | 2.2 | 20.4 | 13.1 | 18.0 | 7.2 |
| Gravel and cobbles | 13.9 | <0.5 | 1.3 | <0.5 | 2.0 |
| Gravel, cobbles and boulders | 13.1 | <0.5 | 0.6 | <0.5 | 2.6 |
| Cobbles and boulders | 4.4 | <0.5 | <0.5 | 1.6 | <0.5 |
| Mud/sand with cobbles/boulders | <0.5 | <0.5 | <0.5 | 1.6 | <0.5 |
| Mud/sand with gravel/cobbles/boulders | <0.5 | 1.9 | 6.3 | 4.9 | 2.0 |
| Cobbles/boulders covered by mud/sand | <0.5 | <0.5 | 0.6 | 3.3 | <0.5 |

*Sediment types ‘Muddy sandy gravel’ and ‘Gravel’ cover areas <1 km² and are not included.
3. Open-ended fjords: The islands Hareidlandet and Gurskøya are bounded on the landward side and towards the north by up to 600 m deep, interconnected, open-ended fjords, one of which extends far offshore towards the northwest. These fjords have no sills at their seaward edge, and are conduits for tidal currents as they lead into very large fjord systems in the east and southeast. Fjord sides are steep, while fjord beds are mostly flat due to sediment infill (Boe et al., 2004). The many bedrock outcrops in the fjord sides are generally covered by a thin and/or discontinuous layer of heterogeneous, sandy sediment. In this region, muddy sediment types are rarely found shallower than 200 m below sea level. Talus is frequent on slopes at all depths, and the coarse material may be covered by muddy sediments in deeper parts. Fjord beds are predominantly muddy, although sandy and gravelly sediments occur even at depths of 400–500 m, indicated by higher backscatter values and confirmed by grab samples.

4. True fjords of the southern part of the study area are morphologically more diverse than the open-ended fjords. While deep and steep-sided in some parts and with much talus and outcropping bedrock, fjords may also display densely-spaced recessional moraines of very coarse material alternating with muddy, sandy or gravelly bedded types in shallower areas (Figure 4). In the outer part of Syvdsfjorden, a large terminal moraine creates a shallow sill with coarse sediment cover. Circulation in this region is limited, and we find more soft-sediment accumulation here than in open-ended fjords. Near river mouths common sediment types are muddy sand and gravelly muddy sand, while deeper parts of fjords are mud-dominated with occasional occurrences of heterogeneous, coarser sediment types.

There are no sharp boundaries between the four identified sedimentary regions, but rather a transition zone where characteristics of two or more regions may be combined. Within this zone the seabed in troughs and sheltered areas is predominantly muddy, while exposed banks are dominated by sand and coarser sediment. Outcropping bedrock occurs throughout, either fully exposed or with thin/discontinuous sediment cover. Transitions between seabed types may be sharp (exposed areas where erosion occurs) or gradual (sheltered areas with ongoing deposition).

3.2. Other marine base maps

The present suite of marine base maps from Søre Sunnmøre includes seabed terrain (shaded relief) and slope maps derived from MBES bathymetry raster data as well as three thematic feature maps derived from the seabed sediment (grain size) map. Seabed terrain is displayed as a shaded relief raster illuminated from the northwest, and is available at horizontal resolutions of 2, 10 and 50 m. When used in WMS, the three resolutions appear at different viewing scales.

Slope is based on a 10 m resolution bathymetry grid. The 5-class slope raster has class breaks at 10°, 30°, 50° and 70°, and areas of slope >30° can be accessed separately as a polygon layer.

Sediment accumulation basins include the mud-rich seabed types where deposition of soft sediment is likely to be an ongoing process. Some muddy seabed types contain coarse material at the surface, indicating little recent sedimentation, and these are not considered accumulation areas. Sediment-covered bedrock is not included in this category, as the data density does not allow discrimination between different types of sediment cover.

Anchoring conditions vary with sediment grain size, and anchoring methods for both vessels and fixed installations can be optimised to a known seabed type. The best anchoring conditions are found in muddy, homogeneous seabed types, and good conditions are found in sandy or gravelly seabed types. Where the span of grain sizes in the sediment is large, or where the dominating grain size is cobbles or boulders, anchoring may be difficult. Bedrock typically offers poor anchoring conditions, but could provide stable foundation for permanently bolted anchoring. In consideration of this, we assign a separate class to bedrock shallower than 30 m depth (i.e. within diving reach).

Diggability or trenching properties describes how easily a seabed type can be dug. Muddy, sandy or gravelly homogeneous sediment are all diggable, but trench stability is likely to be higher in muddy seabed types. Very coarse and heterogeneous seabed types are not easily diggable, while bedrock is not at all diggable.

End-users of the thematic maps should acknowledge that the mapping scale of 1:20,000 causes some loss of the finer-scale seabed variation. For example, areas mapped as ‘sand, gravel and cobbles’ and classified as having difficult anchoring conditions may well include patches where conditions are good. Also, sediment composition on the seabed surface may not always reflect what is buried beneath, as where a sand drift has accumulated on top of coarser sediment.

4. Conclusions

This paper presents a suite of marine base maps in scale 1:20,000 from a nearshore study area on the Norwegian west coast. Based on MBES bathymetry and backscatter, video observation and seabed samples, we interpret the spatial distribution of 20 seabed types in the study area. This interpretation is translated into thematic
maps of sediment accumulation basins, anchoring conditions, and diggability, while shaded relief and slope maps are derived from the MBES data.

Changing sedimentary conditions during and after the last Ice Age have contributed to a highly diverse seabed across the study area, with coarse sediment such as in moraines or talus deposits alternating with accumulations of finer material. There is however clear regional variability. Exposed bank areas are dominated by sand and coarser sediment, while sheltered archipelagic areas and fjords are muddier environments. In deep, open-ended fjords more affected by tidal currents, little mud is accumulating even at depths exceeding 200 m. Bedrock outcrops are common in all regions. In all but the most exposed areas there will generally be a thin or discontinuous sediment layer covering outcrops.

Knowledge of seabed properties is valuable for anyone with interests in the coastal zone. This is supported by results from coastal mapping in other countries (e.g. Inter-Departmental Marine Coordination Group, 2012; Johnson et al., 2017). By mapping seabed sediment distribution in detail, and converting this information to thematic maps, we provide the basis for better spatial planning of areas subject to pressure from multiple user groups. In the study area, maps are already being actively used in municipal spatial planning and by entrepreneurs in low-trophic aquaculture (e.g. kelp production), and they are available onboard vessels in commercial and recreational fisheries. A pilot project of mapping marine nature types according to the standardised Nature in Norway system (NiN; Halvorsen et al., 2016) also builds upon the marine base maps from Søre Sunnmøre, which are combined with biological and oceanographic data to describe and classify ecological variation in the marine environment.

Following publication of the maps presented here, NGU used newly acquired green laser LiDAR data from uncharted shallow water in the study area to extend sediment mapping into the intertidal zone where possible (Dolan, Bellec, Elvenes, & Lepland, 2018). Future work in the region includes observing how local management and other stakeholders make use of the marine base maps, and improving the delivered map products to best fit users’ needs while reflecting seabed conditions accurately. Development of accessible indices of map confidence is also a priority. NGU is currently working towards this in and other seabed mapping projects.

Software
Basic bathymetry data processing at NGU was done using QPS Dmagic software. Backscatter data were processed using QPS FMGT and Atlantic Geoscience Center Grass 5 software (supplied by the Geological Survey of Canada). All gridded MBES data were exported to ESRI ArcMap (v.10), where seabed sediment (grain size) was interpreted and digitised on-screen using ArcGIS Editor. Derived thematic maps were created in ArcGIS using Data Management, Conversion, and Spatial Analyst tools. Map layout was created in ArcGIS v. 10.5.1.

Data
Marine base maps from the study area and from other areas mapped by NGU are available for online viewing, as WMS layers or for download at www.ngu.no

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Disclosure statement
No potential conflict of interest was reported by the authors.

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