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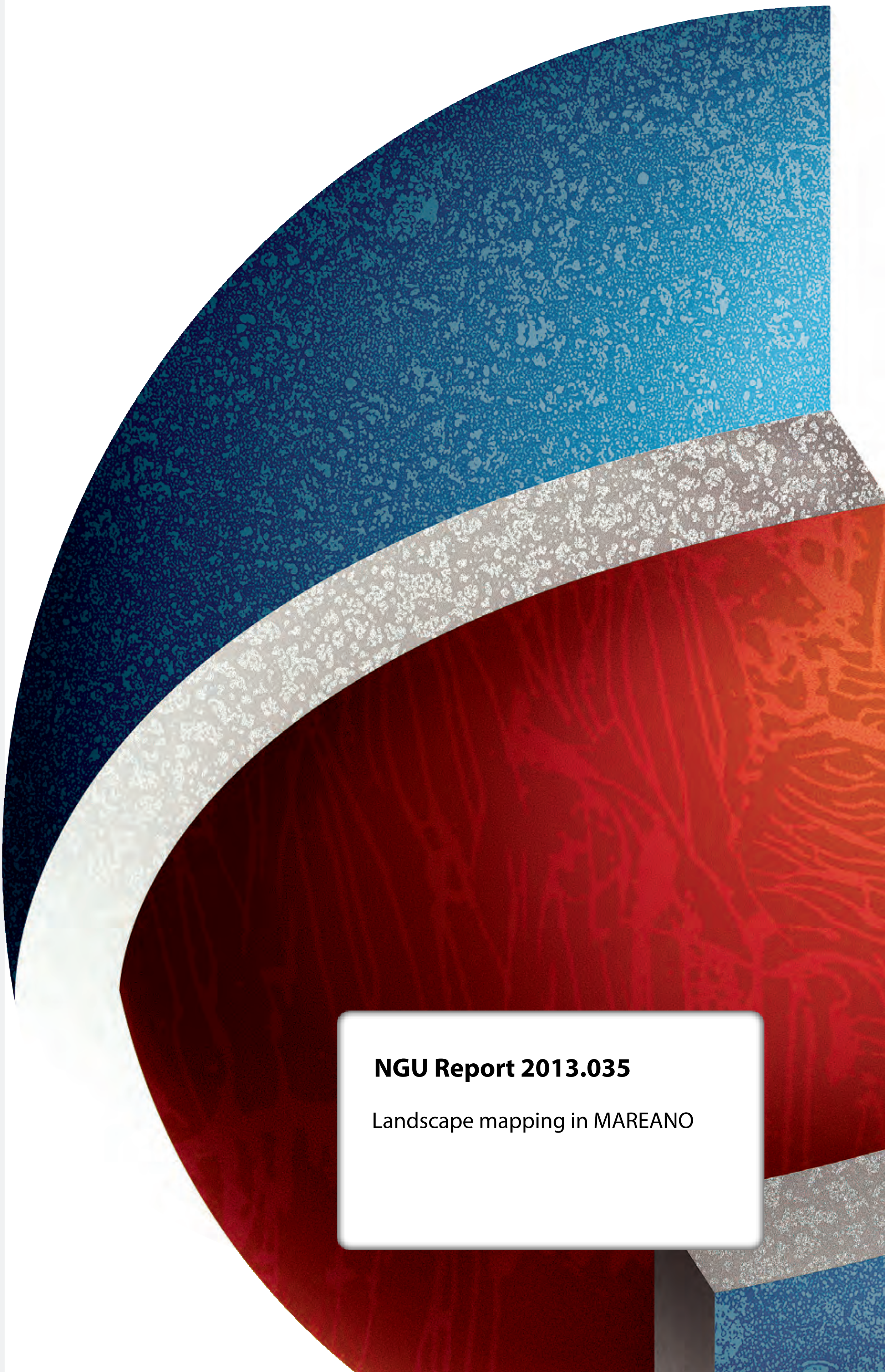

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Landscape mapping in MAREANO

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REPORT

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Landscape mapping in MAREANO

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Summary:

Norway's ongoing seabed mapping programme MAREANO (Marine AREA database for NOrwegian waters) includes delineation of the sea floor into large geomorphic units, which are referred to as marine landscapes. These landscape units are mapped in accordance with Version 1.0 of the nature-type classification system Nature types in Norway (Naturtyper i Norge, NiN), and the classification operates at the 'landscape' level of NiN. Similar to their terrestrial counterparts, marine landscapes are defined in NiN and MAREANO as broad-scale, non-overlapping, full-coverage areas with a uniform surficial appearance. The following eight marine landscape types and subtypes have been identified and mapped in the MAREANO areas so far (2013): *Strandflat*, *smooth continental slope*, *marine canyons*, *fjords*, *marine valleys*, *shallow marine valleys*, *deep sea plain*, and *continental shelf plains*.

To help overcome subjectivity in the classification of marine landscapes, a semi-automated method of systematic GIS analyses has been developed. Four quantitative terrain descriptors are used to distinguish the different landscape types: *Slope*, *relative relief* (the range of depth values in a 1 km^2 neighbourhood), *bathymetric position index* (BPI, the relative vertical position of a point in a specified neighbourhood), and *curvature*.

Landscape maps are an important output from the MAREANO programme. The broad-scale overview presented by these maps provides a useful basis for environmental management, and the maps can also be used to support further scientific research and product development. For example, MAREANO's modelling of benthic habitats has been shown to benefit from the inclusion of classified landscapes as a predictor variable.

This report details the methods developed and applied to create all MAREANO landscape maps published from 2010 to 2013, and includes a step-by-step outline of the procedure used. As a result of this work, landscape classifications are now available for a total of 265.600 km^2 of seafloor from 62°N to 73°N. Landscape maps can be accessed at www.mareano.no, together with other maps and results from the MAREANO programme.

Keywords: Marine geology	Landscape classification	MAREANO
Naturtyper i Norge (NiN)	GIS	Quantitative terrain descriptors
Methods	Morphology	Mapping

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NORWEGIAN SUMMARY/NORSK SAMMENDRAG

Det tverrfaglige MAREANO-programmet (Marin AREAldatabase for NOrske havområder) kartlegger havbunnen og produserer en lang rekke temakart som publiseres fortløpende på www.mareano.no. Ett av kartproduktene er *Marine landskap*, som viser og beskriver de store trekkene i havbunnstopografien. Kartleggingen av marine landskapstyper bygger på første versjon av klassifikasjonssystemet *Naturtyper i Norge* (NiN, www.artsdatabanken.no). NiN og MAREANO definerer landskap som "større geografiske områder med enhetlig visuelt preg", og landskapsinndelingen skal være flatedekkende og ikke-overlappende. I tillegg til å gi oversikt over terrenget på havbunnen er landskapskartene viktige grunnlagsdata for andre MAREANO-aktiviteter, for eksempel biotopmodellering.

MAREANOs landskapskartlegging begynte i 2010, og i 2013 dekker publiserte kart over marine landskap i norske havområder 265.600 km^2 mellom 62°N og 73°N. Følgende åtte landskapstyper er funnet i det kartlagte området: *Strandflate*, *jevn kontinentalskråning*, *marine gjel*, *fjorder*, *marine daler*, *grunne marine daler*, *dyphavsslette* og *kontinentalsokkelslette*.

Store variasjoner i topografi og datakvalitet i områder som skal kartlegges stiller krav til at metodikken som benyttes gir tolkningsuavhengige og reproduserbare resultater. For å sikre en mest mulig objektiv landskapskartlegging har MAREANO utviklet en GIS-basert metode som identifiserer de ulike marine landskapstypene basert på fire enkle parametre som kan hentes ut direkte fra lavoppløselige dybdedatasett (50 m eller grovere). De fire parametrene er *skråning*, *relativt relieff*, *batymetrisk posisjonsindeks* (BPI, et mål for relativ vertikal posisjon) og *krumning*, og denne rapporten viser steg for steg hvordan vi gjennom systematiske GIS-analyser kan skille ut hver enkelt landskapstype med et minimum av tolkning.

Metodikken som presenteres her har vært brukt i framstillinga av alle marine landskapskart fra norske farvann som er blitt publisert mellom 2010 og 2013, men er åpen for revisjon. MAREANO-programmet utvider sin kartlegging til stadig nye områder, og det er sannsynlig at vi må ta hensyn til nye landskapstyper i framtida. Så lenge en oppdatert kartleggingsmetode gir resultater som tilsvarer de som tidligere er publisert vil det imidlertid ikke være nødvendig å bytte ut eksisterende landskapskart.

1. INTRODUCTION

The multidisciplinary MAREANO programme (www.mareano.no) aims to comprehensively map the seabed in Norwegian offshore waters. Products generated by MAREANO include maps of bathymetry, landscapes and landforms, sediment grain size and genesis, sedimentary environment, biomass, benthic biotopes, and environmental status/pollution. Landscape maps were incorporated in MAREANO's set of standard map products in 2010, following the publication of a nature typification system for ecological variation in Norway (www.artsdatabanken.no; Halvorsen et al., 2009) which was developed through a project initiative from the Norwegian Biodiversity Information Centre (www.biodiversity.no). Prior to 2009, no major landscape mapping ventures had been undertaken in Norway's marine areas (Thorsnes et al., 2009). MAREANO's maps of marine landscapes are thus the first published from the focus areas on the Norwegian continental shelf, continental slope and deep sea (Figure 1). Marine landscape maps are a valuable asset to environmental management, and form basis for further scientific research and map product development. For example, within the MAREANO programme it has been shown that models of benthic habitat distribution benefit from the inclusion of landscapes as a predictor variable (Elvenes et al., 2012).

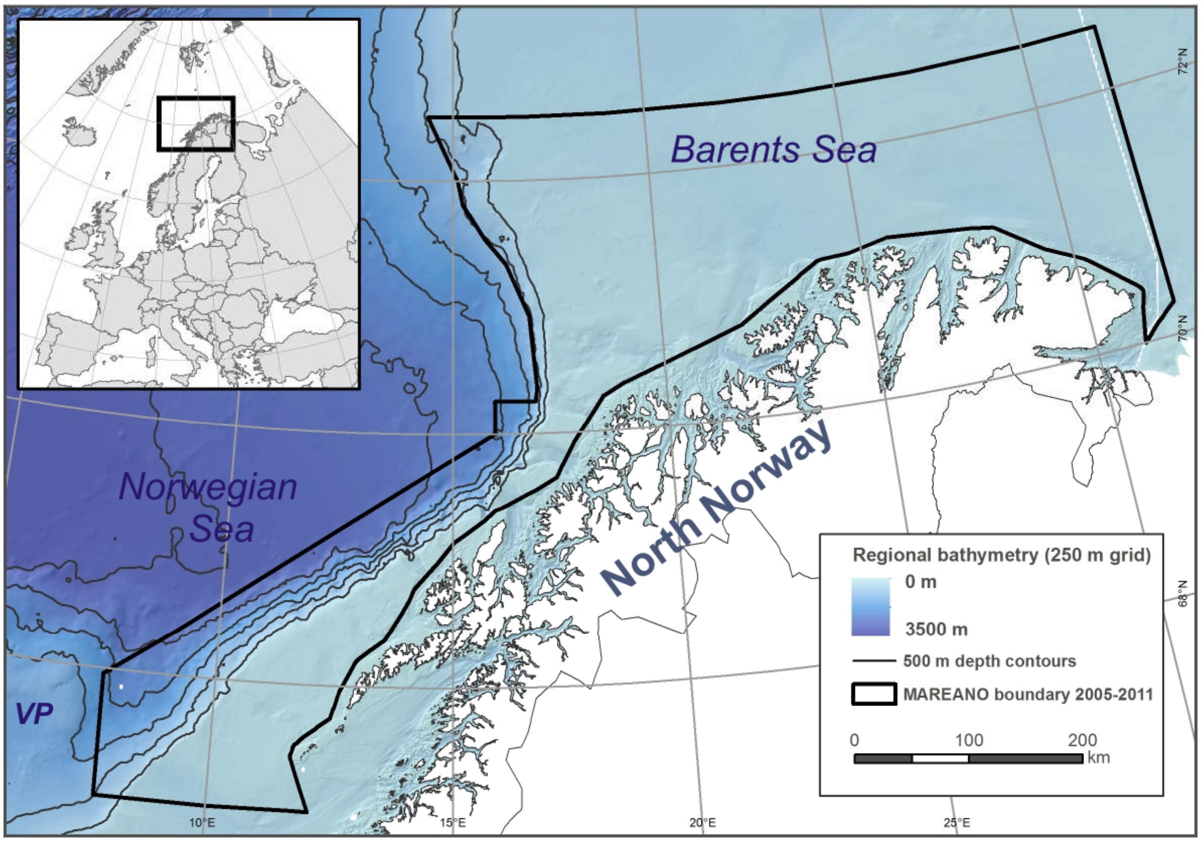


Figure 1. Focus areas for mapping during the first stage of MAREANO (2005-2011). VP - Vøring Plateau.

A substantial volume of high-quality multibeam echosounder data has been collected and made available through the MAREANO programme. These data have been of great value in developing a method for mapping marine landscapes at a level of detail comparable to terrestrial mapping efforts. However, the focus of MAREANO mapping is now moving to areas without full multibeam coverage. In such areas it becomes increasingly prudent to make use of existing bathymetry data of lower or uneven quality. Since MAREANO landscape mapping aims to produce regional rather than local geomorphic classifications, this lack of 100% multibeam data should not be limiting. The method for landscape classification developed here accounts for this, and has been designed such that it does not place too much reliance on access to high-quality data.

1.1 Nature types in Norway

Nature types in Norway (Naturtyper i Norge, NiN) is a framework for describing Norwegian nature at all levels and in both terrestrial and marine areas (Halvorsen et al., 2009). NiN Version 1.0 was published in 2009 (Halvorsen et al., 2009) and became foundation for the marine landscape classification method developed within MAREANO[1]. NiN v. 1.0 (Figure 2) incorporates nature typification at 5 levels, each of which offers increasing ecological detail. Landscapes in NiN v. 1.0 are primarily classified on the basis of physical properties of the terrain, and are defined as broad-scale, non-overlapping, full-coverage areas with a uniform surficial appearance, characterised among other things by a typical distribution of landforms. For an area to qualify as a landscape unit in NiN v.1.0, it should cover a minimum of 1 km^2 and be mappable at a scale of 1:500 000 (Halvorsen et al., 2009). NiN v.1.0 identifies five main landscape types represented in Norway, each with a characteristic geomorphometric[2] signature (Table 1).

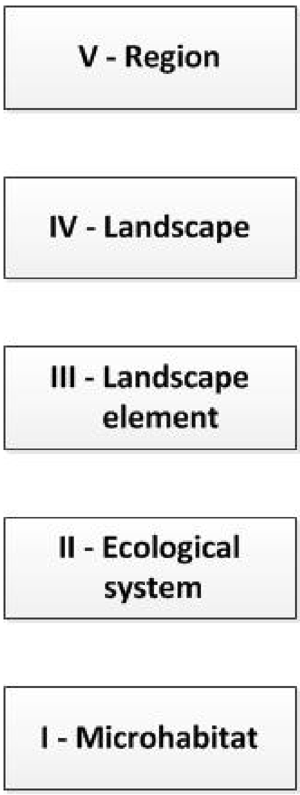


Figure 2. The 5 main levels of Nature types in Norway*'s hierarchical system (NiN v. 1.0), basis for a framework designed to accommodate all variation in Norwegian nature (modified from Halvorsen et al., 2009).*

[1] NiN is currently undergoing a revision process, and at the time of writing it is planned that version 2.0 will be published late in 2014.
[2] Geomorphometric analyses address the quantitative properties of terrain surfaces (Pike et al., 2009).

Table 1: Landscape types in the NiN system (v. 1.0), modified from Halvorsen et al. (2009). See Section 3.1 for a detailed description.

Landscape type	Geomorphometric signature	Subdivisions relevant to marine areas
1. Strandflat	Coastal platform eroded in crystalline bedrock, uneven surface	(no subdivisions)
2. Continental slope	Transition zone between continental shelf and deep sea plain	2.1 Smooth continental slope 2.2 Marine canyon
3. Fjord and valley landscapes	Distinct, elongated basins of minimum 10 km length, 1 km width and 200 m depth	3.1 Marine valley 3.2 Open fjord landscape 3.3 Narrow fjord landscape
4. Plains	Areas of relative relief lower than 50 m/km^2	4.1 Deep sea plain 4.2 Continental slope plain 4.3 Continental shelf plain
5. Hilly and mountainous landscapes	Areas of relative relief higher than 50 m/km^2, not fulfilling requirements for other landscape types	5.1 Hilly/mountainous marine landscape 5.2 Coastal archipelago

1.2 Overcoming subjectivity in landscape mapping

Broad-scale landscape types such as valleys and plains are often conspicuous features well-suited to being digitised manually for many mapping purposes. This approach, however, raises issues of interpretation and subjectivity. For a long-term programme such as MAREANO, where mapping will be carried out over several years by different interpreters working with different-quality data from different areas, these issues are particularly relevant. To ensure that MAREANO landscape maps are directly comparable in spite of these sources of variation, we have developed a standardised, semi-automated classification method based on systematic, statistical GIS analyses of bathymetry data. This report details the MAREANO approach to landscape classification, and includes a step-by-step outline of the procedure used for marine landscape mapping in accordance with NiN v. 1.0 (Section 4.2).

Semi-automated classification has been applied in the production of all MAREANO landscape maps published to date (2013). The present report therefore provides a timely documentation of the methodological development and of the maps produced from 2010 to 2013. However, as the MAREANO programme progresses to new areas, new landscape types may come into consideration for mapping. Future modifications and follow-up reporting are envisaged, both in order to adapt the methodology to data available for MAREANO mapping and in order to incorporate any changes to the NiN typification system that may arise following the revision process to NiN v. 2.

2. STUDY AREA AND DATA

2.1 Study area

The initial years of MAREANO mapping focussed on the continental margin off North Norway (Figure 1). This is an area that displays great geomorphological diversity, particularly at 68°N -70°N where the continental shelf is narrow and the continental slope steep (Figure 3). The shelf is cross-cut by steep-sided troughs, numerous deep canyons incise the continental slope, and a sharply defined crystalline bedrock platform is present along much of the coastline (Thorsnes et al., 2009).

By 2009, high-quality multibeam bathymetry data had been collected from a total of 100 000 km^2 offshore North Norway. Much new knowledge of seabed topography in these waters was therefore available to NiN during the initial identification and definition of Norwegian marine landscapes, ensuring that landscape variation here is well-represented in the NiN system. A first attempt to apply NiN landscape definitions to MAREANO seabed data was published by Thorsnes et al. (2009). The authors interpreted landscapes visually based on multibeam bathymetry data, and based on expert judgement suggested that eight different landscape types are present in the study area, which spans 40 000 km^2 of complex terrain. The first landscape maps published by MAREANO in 2010 included the area studied by Thorsnes et al., mapped anew in accordance with the semi-automated methods described in this report. This allows direct comparison between the preliminary findings of Thorsnes et al. and the MAREANO-published maps.

Since the first publication of landscape maps, the MAREANO programme has expanded to other parts of Norway's marine areas, including the Barents Sea and the continental shelf off Mid-Norway. This has provided opportunity to check the validity of the semi-automated method for landscape mapping in new areas, and to make adjustments to the technique as necessary.

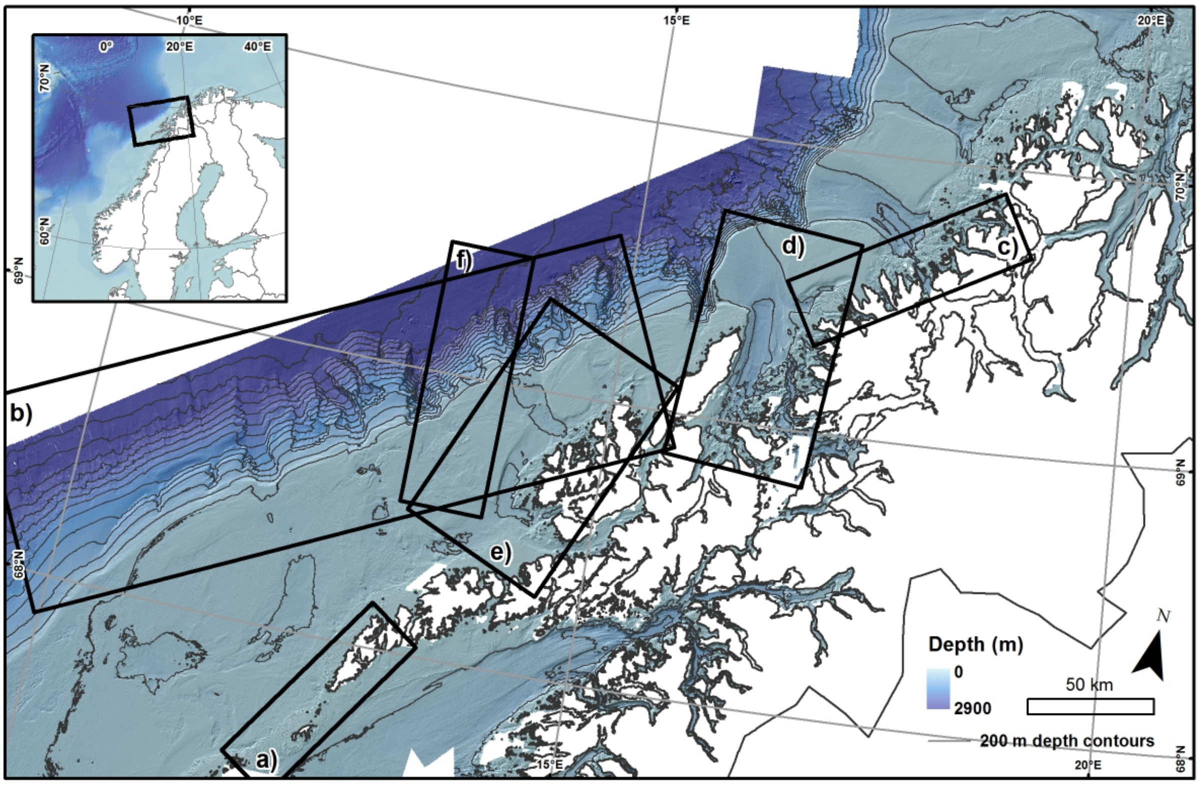


Figure 3. The continental margin off North Norway displays considerable variation in landscape types. Frames indicate the extents of the following figures of landscape type examples: a) Figure 4 – Strandflat, b) Figure 5 – Continental slope, c) Figure 6 – Fjords, d) Figure 7a – Marine valley, e) Figure 7b – Shallow marine valleys, f) Figure 8 – Plains.

2.2 Bathymetry data

During the first phase of MAREANO mapping (2005-2011), full-coverage multibeam echosounder data were acquired across 76 000 km^2 of the seabed off North Norway. In addition to this, the programme made use of existing data from earlier multibeam surveys, bringing the total area of full-coverage multibeam bathymetry available to MAREANO to >90 000 km^2 in 2011. These data are generally of high quality, and are typically gridded at 5-25 m horizontal resolution depending on the water depth and multibeam system used. The multibeam datasets also include full-coverage backscatter data, a measure of seabed acoustic reflectivity often used as a proxy to sediment properties (Lurton, 2002).

In the second phase of MAREANO (2011-), new multibeam surveys are chiefly conducted in areas of high priority, for cost-efficiency purposes. Where multibeam coverage is low, alternative sources of bathymetry data are being sought out and evaluated for use by MAREANO. A recent study (Elvenes et al., 2012) explored the potential for producing sediment and biotope maps using compiled single-beam bathymetry data at 50 m horizontal resolution, and concluded that this can be possible at a regional scale, provided at least some representative multibeam data exist within the area to be mapped. Other bathymetry sources in current MAREANO focus areas include discontinuous 3D seismic data of varying resolution, and compiled full-coverage low-resolution bathymetry datasets (an example of the latter is shown in Figure 1).

High-quality multibeam and backscatter data offer an excellent basis for analysis and interpretation of seabed morphology and sediment cover. However, a key focus in the development of an automated landscape mapping procedure for MAREANO has been to ensure that the method is equally applicable to datasets of low or variable quality, as will often be encountered in large mapping initiatives. Landscape mapping in MAREANO is based on bathymetry resampled to a 50 x 50 m horizontal resolution. Multibeam backscatter data are of more relevance to other map products (such as sediment grain size maps), and are not employed in landscape classification. Resampling bathymetry data to a 50 m grid size facilitates GIS computation while maintaining a sufficiently high resolution to accurately delineate the >1 km^2 landscape units defined by NiN v. 1.0. The use of a 50 m grid for landscape mapping also bypasses issues of military restrictions on data resolution – 50 m is the highest publicly available resolution of bathymetry data inside the Norwegian territorial boundary of 12 nautical miles from the coast.

3. METHODS

3.1 Landscapes and their signatures

The NiN landscape definition (Version 1.0) states that landscapes are broad-scale, non-overlapping, full-coverage areas with a uniform surficial appearance, and that any landscape unit should cover a minimum of 1 km^2 and be mappable at a scale of 1:500 000 (Halvorsen et al., 2009). Variation in surficial appearance across an area of sea floor, as expressed by variation of values in a bathymetry dataset, can be detected by geomorphometric analysis using GIS tools. In order to automatically distinguish different landscape types, we need to establish which surficial characteristics will help to identify each landscape type, and which GIS tools perform better in recognising and delineating these. Listed below are the landscape types that should be expected to be present in the study area, with the characteristics most relevant for automated classification. Locations of Figures 4 to 8 are marked in Figure 3.

3.1.1 <u>Strandflat</u>

Strandflat is the term for the eroded crystalline bedrock platform that is a distinguishing trait of much of the Norwegian coastline (Holtedahl, 1998). The platform is generally bounded both land- and seawards by abrupt changes in slope, which in the marine parts are often linked to the transition from crystalline bedrock to sedimentary rocks and glacial deposits on the continental shelf. The fractured and uneven topography of crystalline bedrock can thus be considered characteristic of this landscape type, in combination with proximity to coastline and in many areas a steep bounding slope towards other landscape types. Figure 4 shows a typical example of strandflat in the MAREANO area.

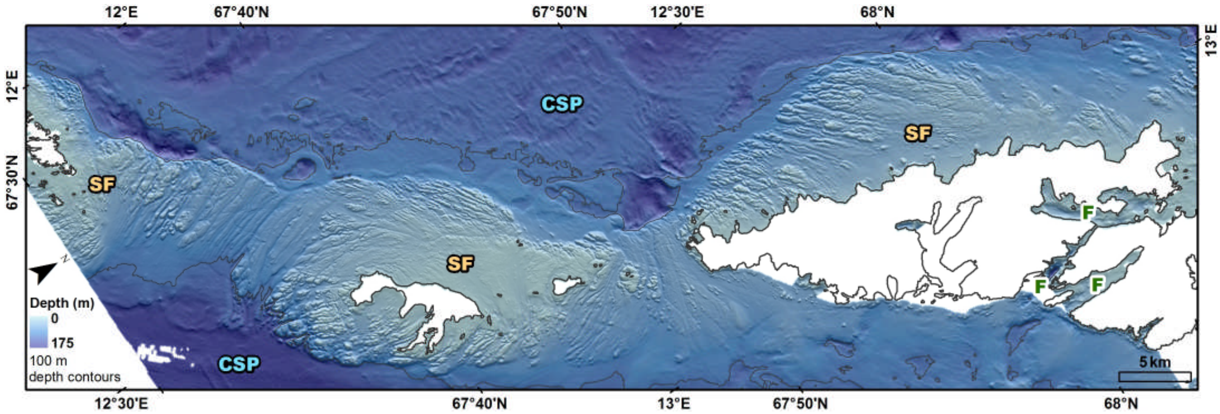


Figure 4. The eroded crystalline bedrock platform called strandflat *(SF) is characterised by an uneven topography, and a steep slope often forms the boundary with the less rugged* continental shelf plain *(CSP). F – Fjord.*

In literature, the seawards boundary of the strandflat has often been set arbitrarily at 20-50 m b.s.l. (e.g. Holtedahl, 1998, and references therein). Given that available bathymetry data now provide a much clearer image of the submerged part of the strandflat, MAREANO landscape mapping does not use a <50 m b.s.l. boundary, instead basing the classification on known topography. In a number of areas, however, the characteristic surface structure of crystalline bedrock is found at depths far greater than what would commonly be considered “strandflat” (see e.g. the >200 m b.s.l. example circled in Figure 7a). To accommodate such cases, it has been deemed necessary to set a new arbitrary boundary for this landscape type at c. 200 m b.s.l., classifying deeper areas as parts of other landscape types (e.g. fjords or marine valleys).

3.1.2 <u>Continental slope</u>

The continental slope constitutes the transition zone between continental shelf and deep sea, bounded landwards by the continental shelf edge and seawards by the upper part of the continental rise (Figure 5). With outer shelf depths in Norwegian waters averaging 200-400 m and the continental rise occurring at about 2000-2500 m, this landscape type is distinguished by its slope gradient, which varies from <1° to >10° when calculated on a 50 m bathymetry grid (analysis window = 3 x 3 grid cells) using ArcGIS Spatial Analyst and excluding canyon areas.

Following NiN definitions, the continental slope landscape type is divided into two subtypes: *Marine canyons* and *smooth continental slope*. Canyons are large incising features cross-cutting the continental slope and in some cases extending onto the continental shelf with the upper limit of the canyon constituting the shelf edge. On the Norwegian continental margin, this landscape type is found only between 68°N and 70°N, where 15 canyons of varying morphology have been described (Rise et al., 2013). The canyons are generally steep-sided and their area clearly demarcated by sharp boundaries of abrupt changes in slope gradient.

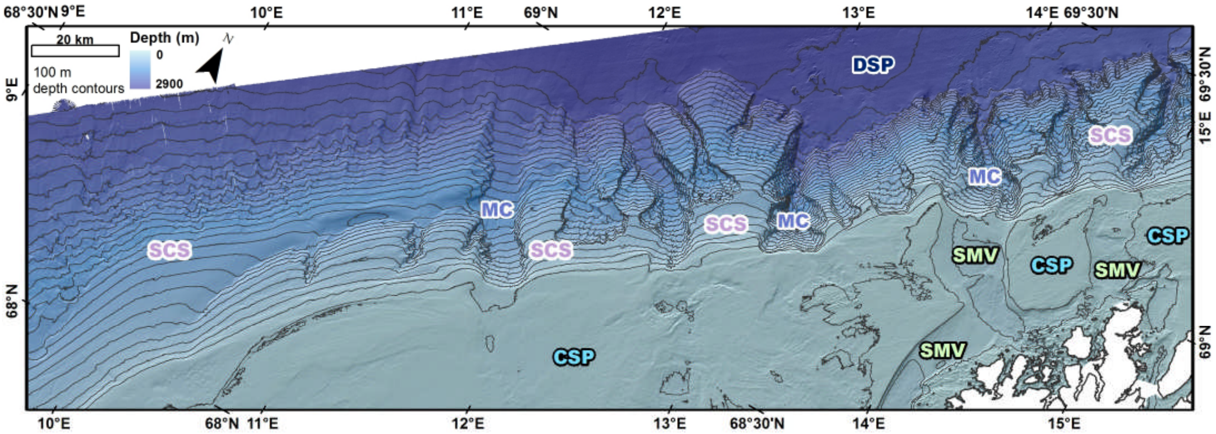


Figure 5. The continental slope forms the transition between continental shelf and deep sea, and the steepness of the slope may vary greatly. On the North Norwegian continental margin, a smooth continental slope *(SCS) is cross-cut by several* marine canyons *(MC). Both landscape types are bounded seawards by the* deep sea plain *(DSP) and landwards by the* continental shelf edge. *CSP – Continental shelf plain, SMV – Shallow marine valley.*

Between marine canyons, and outside the area where they occur, the continental slope is not divided into further subtypes. Rather, all area between continental shelf edge and foot of slope is categorised as smooth continental slope regardless of morphological variation such as slide scarps, slide deposits and gullies, except where the slope is intercepted by a non-sloping area such as the Vøring Plateau (Figure 1). In the NiN system, this plateau would be classified as belonging to the “plain” landscape type (subtype *continental slope plain*).

3.1.3 Fjord and valley landscapes

NiN lists five landscape subtypes belonging to the “fjord and valley” category: *Marine valleys*, *open fjord landscapes*, *narrow fjord landscapes*, and *open* and *narrow* (terrestrial) *valley landscapes*. In marine mapping, the latter two are safely disregarded. Additionally, discrimination between the two fjord landscape types is based on total vertical relief and will therefore require a dataset combining marine and terrestrial topography. As the focus of MAREANO mapping is in offshore areas, no attempt has yet been made to link MAREANO bathymetry datasets to terrestrial data. Consequently, NiN’s two fjord landscape subtypes are grouped into one (*fjord*) in MAREANO landscape mapping.

Both fjords and marine valleys are defined as elongated basins that exceed 10 km in length and 1 km in width, and that may have clear boundaries to surrounding landscape types (Figure 6, Figure 7a). Fjords intersect the coastline and will typically be over-deepened with a sill at the outer end, whereas marine valleys are found on the continental shelf, often but not exclusively in the continuation of fjords. NiN sets a minimum depth for marine valleys at 200 m in cross-profile, defining shallower features as local variation within the surrounding landscape type (e.g. *continental shelf plain*). However, the Norwegian continental shelf

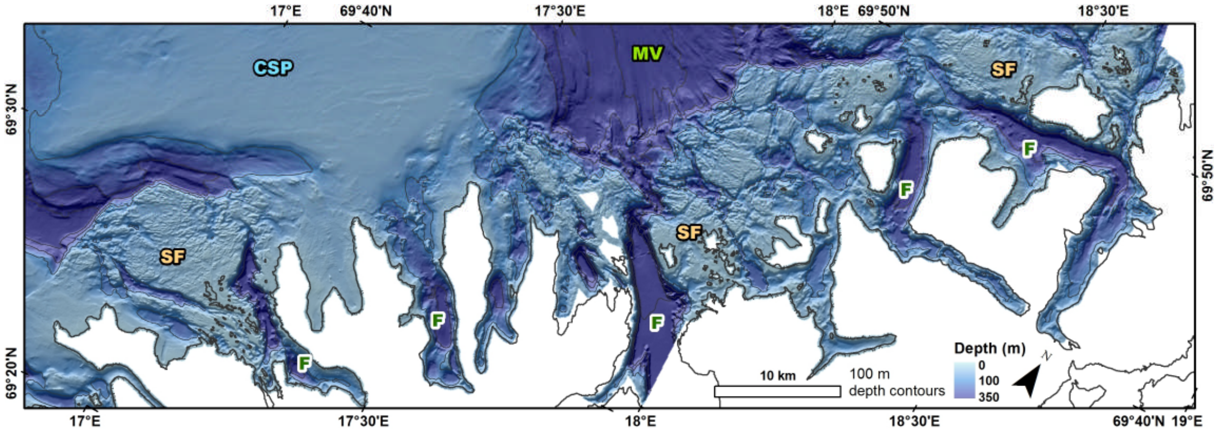


Figure 6. Fjords *(F) are over-deepened, glacially eroded basins that intersect the coastline. Along the Norwegian coast, fjords often lead into larger* marine valleys *(MV) on the continental shelf. SF – Strandflat, CSP – Continental shelf plain.*

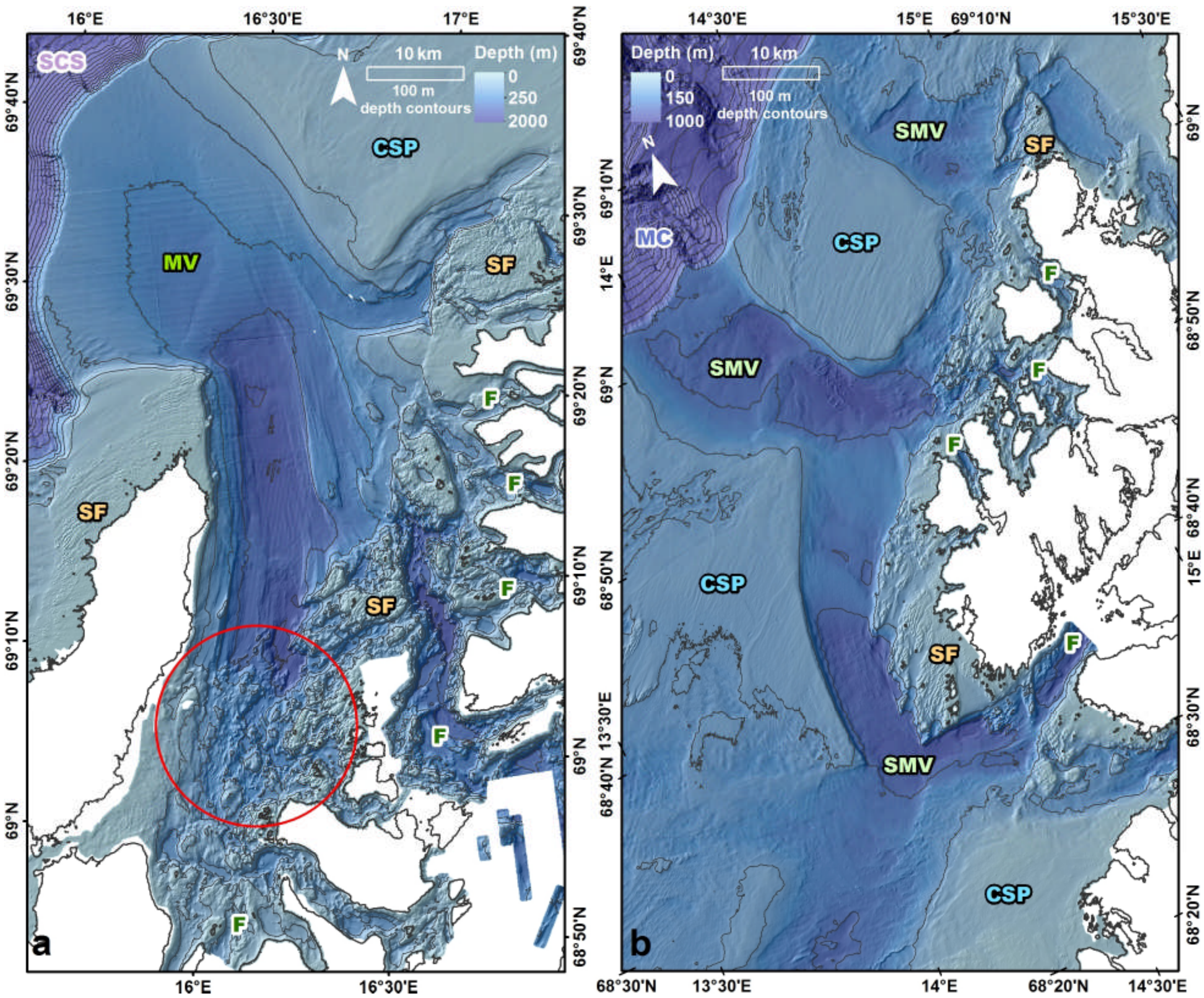


Figure 7. Marine valleys *(MV) on the continental shelf should have a minimum cross-profile depth of 200 m (a). Conspicuous valley features with depths of 100-200 m (b) are classified as* shallow marine valleys *(SMV). SF – Strandflat, CSP – Continental shelf plain, F – Fjord, SCS – Smooth continental slope, MC – Marine canyon. The circle in (a) indicates an area of uneven terrain below c. 200 m b.s.l.*

contains a number of conspicuous valley forms that do not quite fulfil NiN's depth requirements despite being morphologically similar to the "true" marine valleys (Figure 7b). In order to have these elements included in the landscape mapping, a new subtype is introduced for MAREANO mapping purposes – the *shallow marine valley* with a cross-profile relief of 100-200 m. Mapping shallow marine valleys separately from valleys that meet NiN constraints allows for later flexibility regarding whether to group the former with the marine valleys, to consider them variation in a continental shelf plain landscape, or to keep them as a separate landscape type.

3.1.4 Plains

The geomorphometric term *relative relief* is well-established in landscape categorisation (e.g. Rudberg, 1968; Halvorsen et al., 2009; Pike et al., 2009; Erikstad et al., 2013), and denotes vertical range within a predefined moving neighbourhood (e.g. 1 km^2). In NiN, any larger area with relative relief lower than 50 m/km^2 is called a "plain". There are three subtypes relevant to marine areas: The *deep sea plain* comprises all low-relief area seawards of the continental slope, whereas *continental slope plain* refers to areas where the continental slope flattens out to form plateaus (e.g. the Vøring Plateau, see Figure 1), and *continental shelf plain* to the low-relief areas on the continental shelf that are not attributed to other landscape types such as marine valleys or strandflat. Figure 8 shows an example of deep sea plain and continental shelf plain separated by a steep continental slope. At the time of writing (2013), MAREANO mapping has not extended to areas where continental slope plains are found.

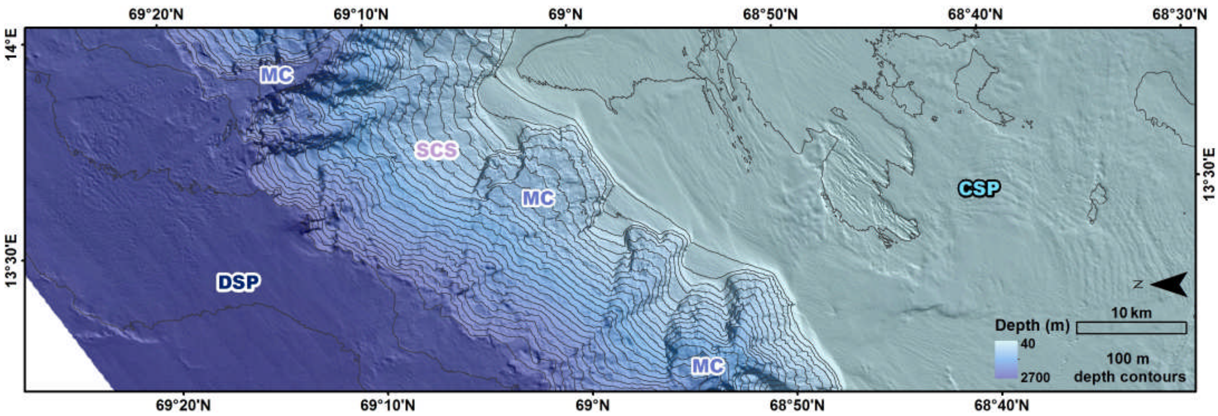


Figure 8. Deep sea plain *(DSP) and* continental shelf plain *(CSP) are the two types of "plain" landscapes found in MAREANO areas to date (2013). Plains are characterised by having a relative relief (range of depth) of <50 m in a 1 km^2 neighbourhood. SCS – Smooth continental slope, MC – Marine canyon.*

3.1.5 Hilly and mountainous landscapes

If the relative relief of an area exceeds 50 m in a 1 km^2 neighbourhood, and the area does not make up part of any other landscape type (e.g. forming the side of a valley), it falls under the NiN category *hilly and mountainous landscape*. This landscape type is widespread in terrestrial Norway, with NiN differentiating between subtypes in lowlands and high mountains and with relative relief greater or smaller than 200 m/km^2. In marine areas, NiN lists two hilly and mountainous landscape subtypes: *Hilly/mountainous marine landscape* including all submarine areas with a relative relief above 50 m/km^2, and *coastal archipelago* which covers partially submerged medium- to high-relief areas that are not part of the strandflat.

MAREANO landscape maps have not as yet (2013) included either of NiNs two hilly/mountainous landscape categories for marine areas. In the 40 000 km^2 area initially mapped, there are a few occurrences of terrain that would fit the criteria of hilly/mountainous marine landscape, as pointed out by Thorsnes et al. (2009). In accordance with decisions made in the initial stages of MAREANO mapping, however, minor areas with a relative relief somewhat greater than 50 m/km^2 surrounded by continental shelf plain or deep sea plain are routinely treated as local variation of the predominant landscape type in the published landscape maps. A different question arises regarding areas of crystalline bedrock that lie too deep to be considered strandflat (i.e. deeper than c. 200 m b.s.l., see example in Figure 7a). While these areas can be spatially extensive, they are often geomorphologically linked to glacially eroded features such as fjords or marine valleys, in many cases constituting a boundary zone between fjord and valley. In MAREANO landscape mapping, we therefore opt to include deep high-relief areas in *fjord* or *marine valley* landscape subtypes wherever this can be justified from a geomorphological point of view.

MAREANO datasets do not yet include areas where the “coastal archipelago” subtype of hilly and mountainous landscapes can be expected to occur, and consequently developing a method to automatically distinguish this subtype from the strandflat has not been prioritised to date.

3.2 Software and tools used

Landscape mapping in MAREANO is structured as a series of GIS analyses performed on bathymetry data from the area to be mapped. All data processing, analyses and calculations in this study have been conducted using the ESRI ArcGIS software package (versions 9.3 and 10.0) including the Spatial Analyst extension. As the landscape mapping method is based on relatively simple GIS computation, however, it should be straightforward to adapt the procedure to other GIS software.

NiN v. 1.0 makes distinctions between different landscape types based on surficial appearance, expressed as geomorphometric parameters such as slope and relief. On the

Norwegian continental margin, marine landscapes may be identified through the application of four different quantitative terrain descriptors calculated on a bathymetry dataset: *Slope*, *relative relief*, *bathymetric position index* (*BPI*) and *curvature*. Table 2 lists the methods applied for calculating each in ArcGIS, while Section 4.1, Section 4.2, and Appendix 1 detail the procedure of landscape identification.

Table 2: Quantitative terrain descriptors used in identifying marine landscapes in the MAREANO programme from 2010 to 2013.

Terrain descriptor	**Explanation**	**ArcGIS Spatial Analyst tool (v. 10.0)**	**Analysis window size in 50 m grid (raster cells), as employed in MAREANO mapping**
Slope	Maximum rate of change in elevation from a cell to its neighbours (ArcGIS uses algorithm from Horn (1981))	Surface - Slope	3 x 3
Relative relief	Range of elevation values in 1 x 1 km moving window (Rudberg, 1968; Halvorsen et al., 2009)	Neighbourhood Statistics - Focal Statistics (Statistics type = Range)	20 x 20
Bathymetric position index (BPI), large neighbourhood	Relative vertical position of a cell in its neighbourhood (Weiss, 2001; Lundblad et al., 2006)	1)Neighbourhood Statistics - Focal Statistics (Statistics type = Mean) 2) Subtract mean values from original bathymetry (Math - Minus)	300 x 300
Curvature	Second derivative value of the input surface on a cell-by-cell basis, quantifying surface concavity/ convexity (ArcGIS uses algorithm from Zevenbergen and Thorne (1987))	Surface - Curvature	3 x 3

The choice of geomorphometric parameters is to a degree based on NiN's landscape type definitions (v. 1.0). *Slope* and *curvature* (Figure 9, Figure 10 a/b) are both basic quantitative terrain descriptors used in numerous surface classification studies (see e.g. Dolan et al., 2012, for a recent review), and numerous calculation algorithms exist for both. Simple, user-friendly tools for slope and curvature calculations are included in many GIS toolsets, but attention should be paid to the fact that different algorithms may yield very different results (Dolan, 2012), making consistency of method an important concern. For MAREANO landscape mapping purposes, the slope and surface tools included in the ArcGIS Spatial Analyst Toolbox have so far (2013) been used exclusively. Both these tools have a fixed analysis window of 3 x 3 raster cells. Curvature is here used as a measure of surface roughness in small neighbourhoods, a parameter which other calculations may represent equally well. The selection of curvature is due to the near-normal distribution of output values (see Section 4.1) and to the fact that it is a basic ArcGIS tool which is widely used for terrain analysis (e.g. Evans, 2012, and references therein).

Relative relief (Figure 11) is NiN's main criterion in differentiating between "flat" and "rugged" landscapes (v. 1.0), where the former is defined as having a range in elevation of less than 50 m in a square moving neighbourhood of 1 x 1 km, and the latter as having a larger elevation range in a same-sized neighbourhood (Halvorsen et al., 2009). In a bathymetry raster where pixel size is 50 x 50 m, this corresponds to a 20 x 20 cell neighbourhood for analysis.

Bathymetric position index (BPI, Figure 12) is a parameter indicating the vertical positioning of each cell in a raster dataset relative to its neighbourhood. Originally developed for terrestrial surface analysis (*topographic position index* (TPI); Weiss, 2001; Jenness, 2013), the procedure is easily adaptable to bathymetry data (Lundblad et al., 2006). Dedicated BPI tools are available for ArcGIS (e.g. Wright et al., 2012), but have not been employed in MAREANO landscape mapping. Instead we conduct a two-step analysis using basic Spatial Analyst tools (Neighbourhood Statistics, Minus), which returns satisfactory results and which, unlike most dedicated tools, will allow the user to select a rectangular neighbourhood for analysis.

BPI is sensitive to neighbourhood size, in that a larger neighbourhood will highlight larger terrain features and vice versa. A 300-cell rectangular neighbourhood, corresponding to sea floor distances of 15 x 15 km when applied to a 50 m grid, has been the preferred analysis size in MAREANO mapping to date (2013). This gives a broad-scale estimate of relative position. A 15 x 15 km neighbourhood is sufficiently large to pick up targeted terrain features in landscape mapping (e.g. marine valleys and canyons) while still keeping computation times reasonably short.

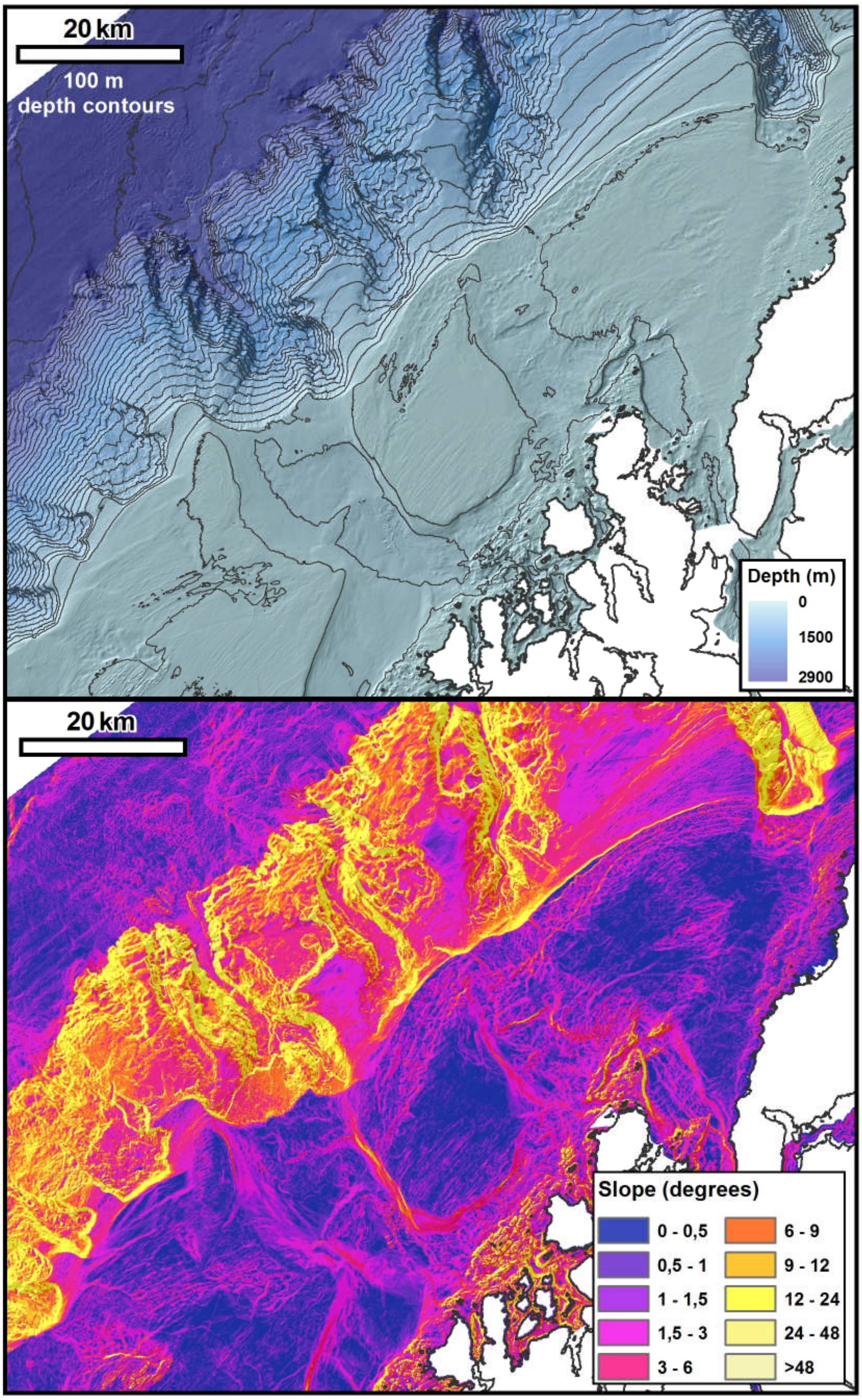


Figure 9. Visual representation of the terrain descriptor slope, *example from the North Norwegian continental margin. In MAREANO landscape mapping, the slope parameter is of importance when locating edge features. Slope is calculated on a 50 m bathymetry grid using ArcGIS Spatial Analyst (analysis window = 3 x 3 grid cells).*

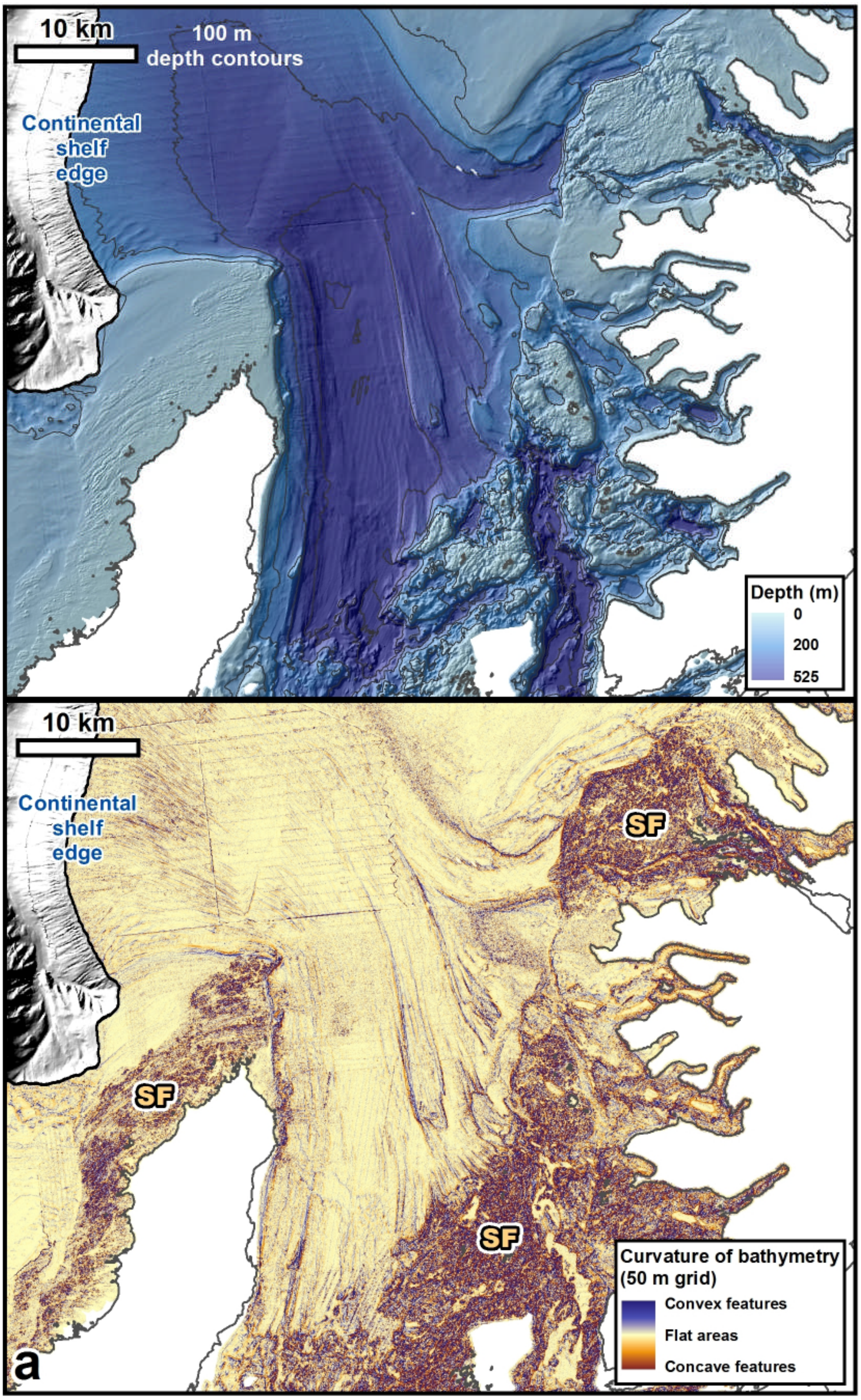


Figure 10a. Visual representation of the terrain descriptor curvature, *example from the North Norwegian continental shelf. As a parameter in MAREANO landscape mapping, curvature serves as a measure of surface roughness when identifying strandflat (SF) areas, and as an indicator of the boundary between deep sea plain and continental slope (see Figure 10b). Curvature in Figure 10a is calculated using ArcGIS Spatial Analyst (analysis window = 3 x 3 grid cells), on the basis of a 50 m bathymetry grid.*

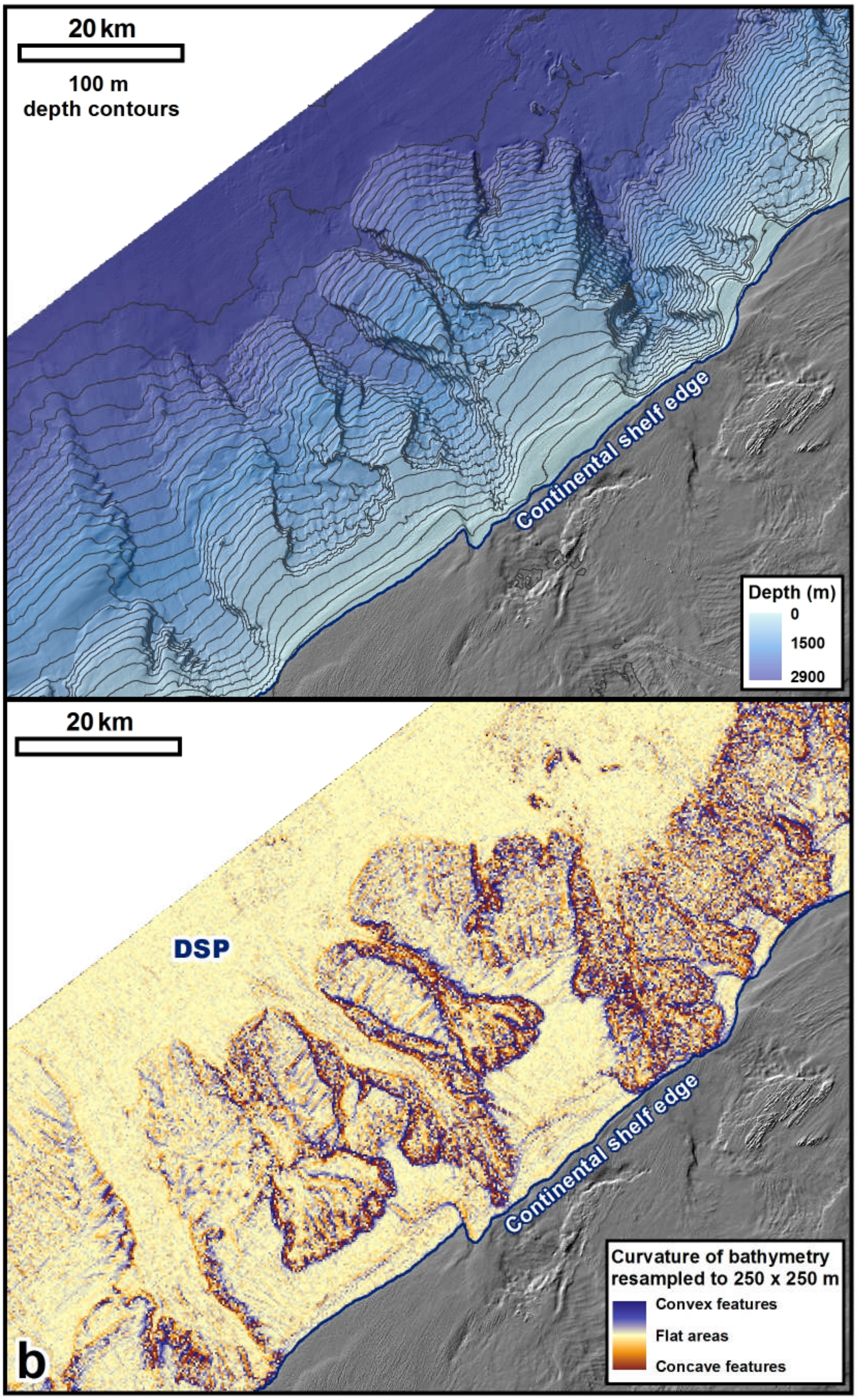


Figure 10b. Visual representation of the terrain descriptor curvature, *example from the North Norwegian continental slope/deep sea. As a parameter in MAREANO landscape mapping, curvature serves as a measure of surface roughness when identifying strandflat areas (see Figure 10a), and as an indicator of the boundary between deep sea plain (DSP) and continental slope. Curvature in Figure 10b is calculated using ArcGIS Spatial Analyst (analysis window = 3 x 3 grid cells), on the basis of a 50 m grid resampled to 250 m prior to curvature calculation.*

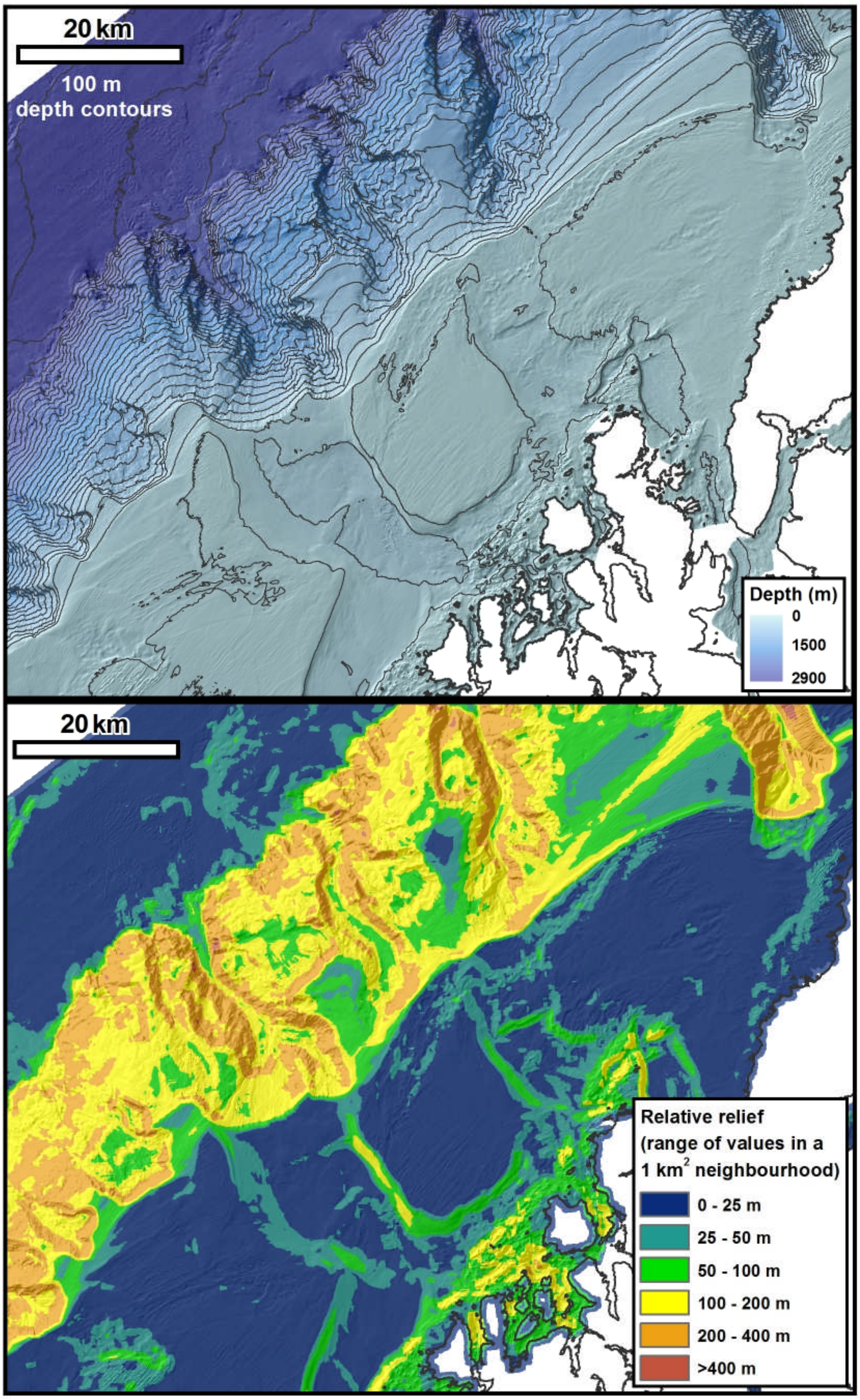


Figure 11. Visual representation of the terrain descriptor relative relief, *example from the North Norwegian continental margin. Relative relief is a measure of the range of depth values in a specified neighbourhood, defined as 1 km^2 for NiN and MAREANO purposes, and functions as the main identifier for "flat" landscape types (i.e. plains, which should have a relative relief of <50 m/km^2). In MAREANO landscape mapping, relative relief is also a key parameter when locating edge features. Relative relief is calculated on a 50 m bathymetry grid using ArcGIS Spatial Analyst (analysis window = 20 x 20 grid cells).*

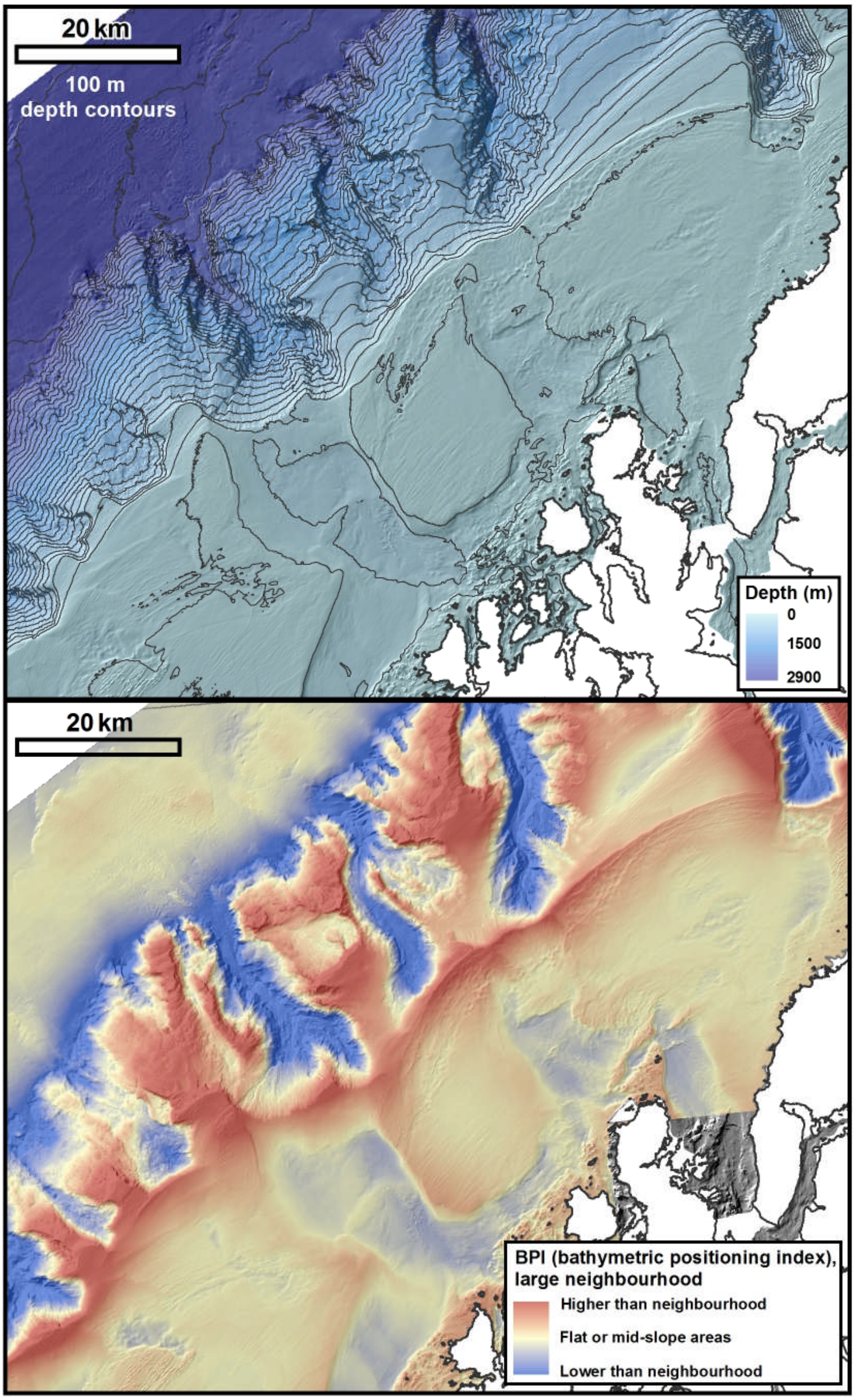


Figure 12. Visual representation of the terrain descriptor BPI *(*bathymetric position index*), example from the North Norwegian continental margin. BPI indicates the vertical position of a raster cell relative to its neighbourhood, and will highlight smaller or larger terrain features depending on the selected analysis window size. In MAREANO landscape mapping, a broad-scale (i.e. large-neighbourhood) BPI is valuable in locating edge features, which will generate a positive BPI signal, and depressions, which will yield negative BPI values. BPI is calculated on a 50 m bathymetry grid using ArcGIS Spatial Analyst (analysis window = 300 x 300 grid cells).*

4. SEMI-AUTOMATED MAPPING OF MARINE LANDSCAPES

4.1 Selecting cut-off values based on the statistical properties of quantitative terrain descriptors

Diverse topography and a great range in depth values present several challenges to automated identification of landscape types. An essential element in the development of a robust landscape classification for MAREANO has been the definition of appropriate cut-off values for the various quantitative terrain descriptors that are used to delineate different landscape units. For example, the strandflat is an element characterised by having large variations in curvature values. Where should we draw the line between "large" and "not so large" variations?

For certain landscape types and quantitative terrain descriptors, the NiN classification has pre-determined absolute cut-off values (the "low" relative relief of plains is defined as <50 m/km^2, fjords and marine valleys have fixed size requirements) based on experience (Halvorsen et al., 2009). However, if an automated classification method is to be applicable over larger regions, reliance upon absolute values may lead to mis-identification of landscape types. If, for example, an absolute slope angle value is to be defined in order to delineate the continental slope, the area classified by automated analysis would be either too large or too small. This is demonstrated in Figure 13, and is due to the fact that slope angle values within one continental slope landscape unit may vary by an order of magnitude dependent on area or calculation method. A better approach is to identify universal properties of the bounding areas of the continental slope (i.e. continental shelf edge and foot of slope), and aim for automated delineation of these. Any area falling between the shelf edge and the foot of slope will then belong to one of the three landscape types *smooth continental slope*, *marine canyon,* or *continental slope plain,* and further statistical analyses needed to separate the three can be run on a dataset limited to the continental slope.

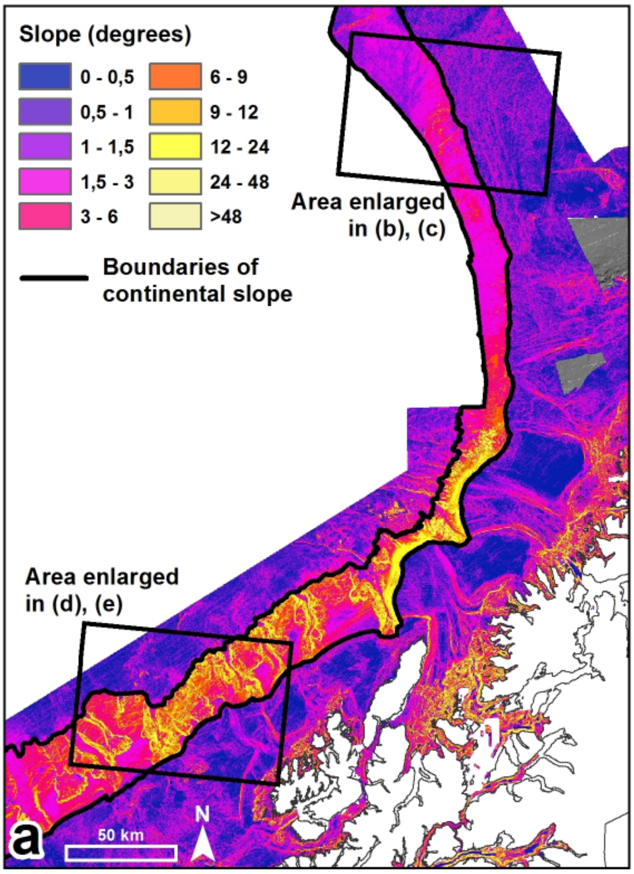
Figure 14 shows an example of applying our technique to find the continental shelf edge based on a combination of three limited *areas of interest* (AOIs). In spatial analysis, an AOI is the part of a datasets that satisfies certain limitations, e.g. lies within a defined depth interval or contains a defined assembly of landforms. The assumptions in the analysis illustrated in Figure 14 are that the boundary between continental shelf and continental slope needs to display low slope values (contrary to the continental slope), high values of relative relief (contrary to much of the continental shelf), and high BPI values (contrary to basins or to the foot of slope). Three AOIs, each representing the part of the original dataset that displays the required values of one of the three parameters, are combined in one AOI that shows where all three requirements are met, and consequently where the shelf edge should be located.

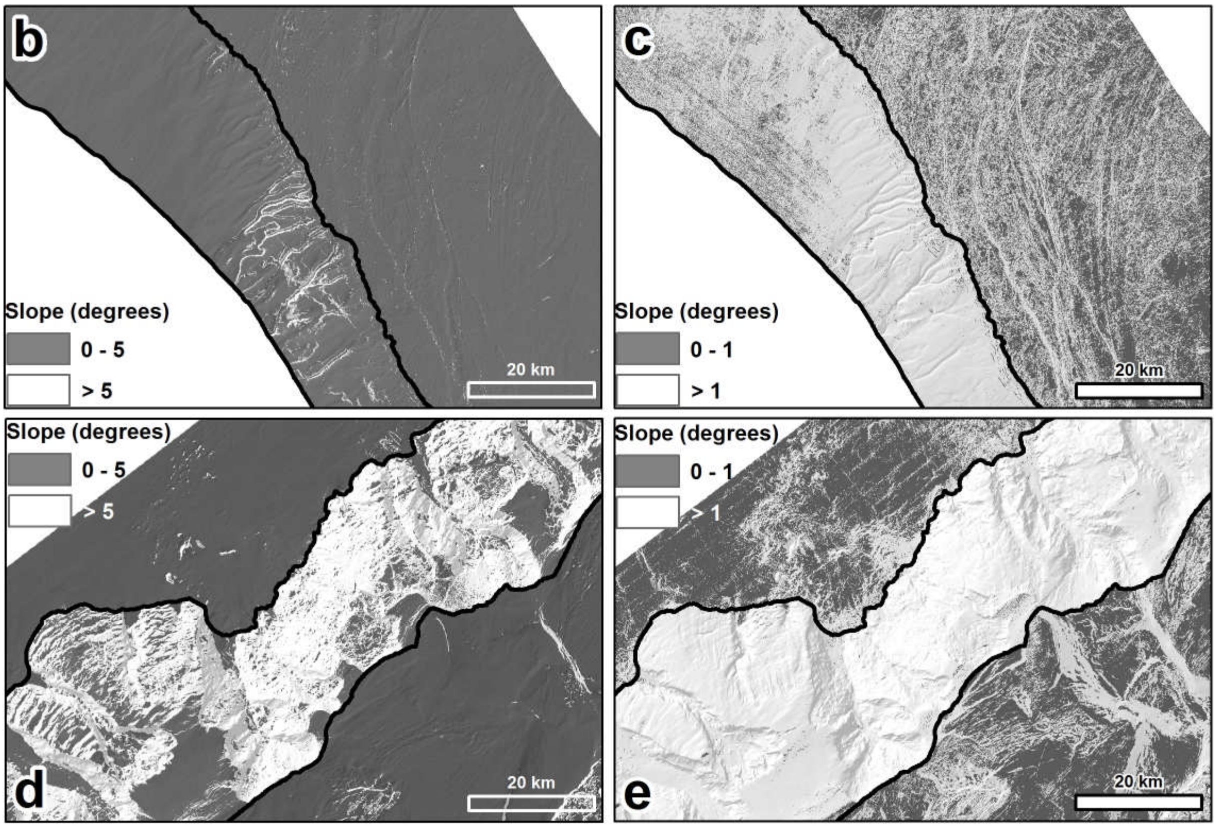
After finding the continental shelf edge, the feature can be used to split the original dataset in two parts: Any deep sea plain or landscape types found on the continental slope will lie seawards of the shelf edge, while all landscape types on the continental shelf or in coastal areas will lie landwards of the shelf edge. This allows for re-analysing the slope/deep sea plain area separately from the shelf/coast area, thereby obtaining relevant statistical values – a strong curvature signal from the strandflat will for example no longer be obscured by an even stronger curvature signal from marine canyons.

In order to avoid applying absolute cut-off values, statistics from various relevant AOIs can be brought into play. In Figure 14, where areas are classified as "low slope" or "high relative relief", cut-off values equal the average of slope and relative relief values, respectively, from *low-relief areas*. Low-relief areas are defined by NiN (v. 1.0) as having a relative relief <50 m/km^2, and can be easily identified and isolated from the full initial bathymetry dataset. The assumption is that average values drawn from a complete, full-coverage dataset will vary unacceptably between datasets, whereas average values from areas defined as "flat" should be comparable regardless of the total variation in the area to be mapped. Similarly, cut-off values for curvature as an indicator of rough surfaces associated with the strandflat are based on statistics for the area landwards of the continental shelf edge only. This increases the likelihood that a strong curvature signal will be generated by the uneven topography of strandflat surfaces, as most other landscape types represented landwards of the shelf edge tend to have less rough surficial appearances (with the exception of areas of exposed crystalline bedrock that occur too deep to be considered part of the strandflat – see comment on "hilly and mountainous landscapes" in Section 3.1). Output values from the curvature tool have a near-normal distribution, and empirical testing in several areas has shown that cut-off values related to standard deviation (σ) work well in picking out strandflat areas among landscape types characterised by more even surfaces. The proportion of strandflat to other landscape types in an area will affect the distribution of curvature values, as will the resolution and quality of the bathymetry data, but a fixed cut-off value of +/- 1 σ has been found to work well for MAREANO datasets so far.

Figure 15 demonstrates classification of broad-scale (large-neighbourhood) BPI values according to standard deviations calculated across different AOIs. In Figure 15a, classified BPI values from the complete dataset highlight prominent features such as the continental shelf edge (high positive BPI) and marine canyons (low negative BPI), while features on the continental shelf yield closer-to-average values. Figure 15b, on the other hand, shows BPI values calculated using the same neighbourhood size (15 x 15 km) and classified in the same way as in a, but calculated on a dataset where all strandflat/fjord areas and all areas seawards of the continental shelf break have been removed. The remaining AOI consists of the continental shelf only, where the dominating landscape types will normally be continental shelf plain and marine/shallow marine valleys. Positive terrain features on the shelf will often be related to the upper parts of valley sides, and with the new BPI analyses highlighting these features, boundaries between continental shelf plain and marine/shallow marine valley can be identified in a manner similar to finding the continental shelf edge in the full dataset (Figure 14). By using cut-off values for low slope, high relative relief and high BPI based on statistics from the relevant AOI only, relevant features are more readily identified (Figure 15c).

Figure 13. An illustrated example of applying absolute cut-off values to slope data. In an attempt to trace the boundaries of the continental slope based on steepness of slope, a calculation of slope values yields the result shown in (a). However, as values vary greatly within the continental slope area, a cut-off value tuned to separating continental slope from neighbouring plains in one area may not be applicable in another. In this example, setting the cut-off value to 5° (b, c), to correspond with the average value of the entire dataset, will work well in the steep southern area while the more gently-sloping northern area is not distinguished from the plain above it. Conversely, the cut-off value of 1° (d, e), required to return results from the northern area, will also pick up much of the small slope variations in neighbouring landscape types, making automated classification difficult in both areas. A better approach is to not define the continental slope by absolute steepness, but rather aim for delineating its upper and lower boundaries based on universal properties (see Figure 14).





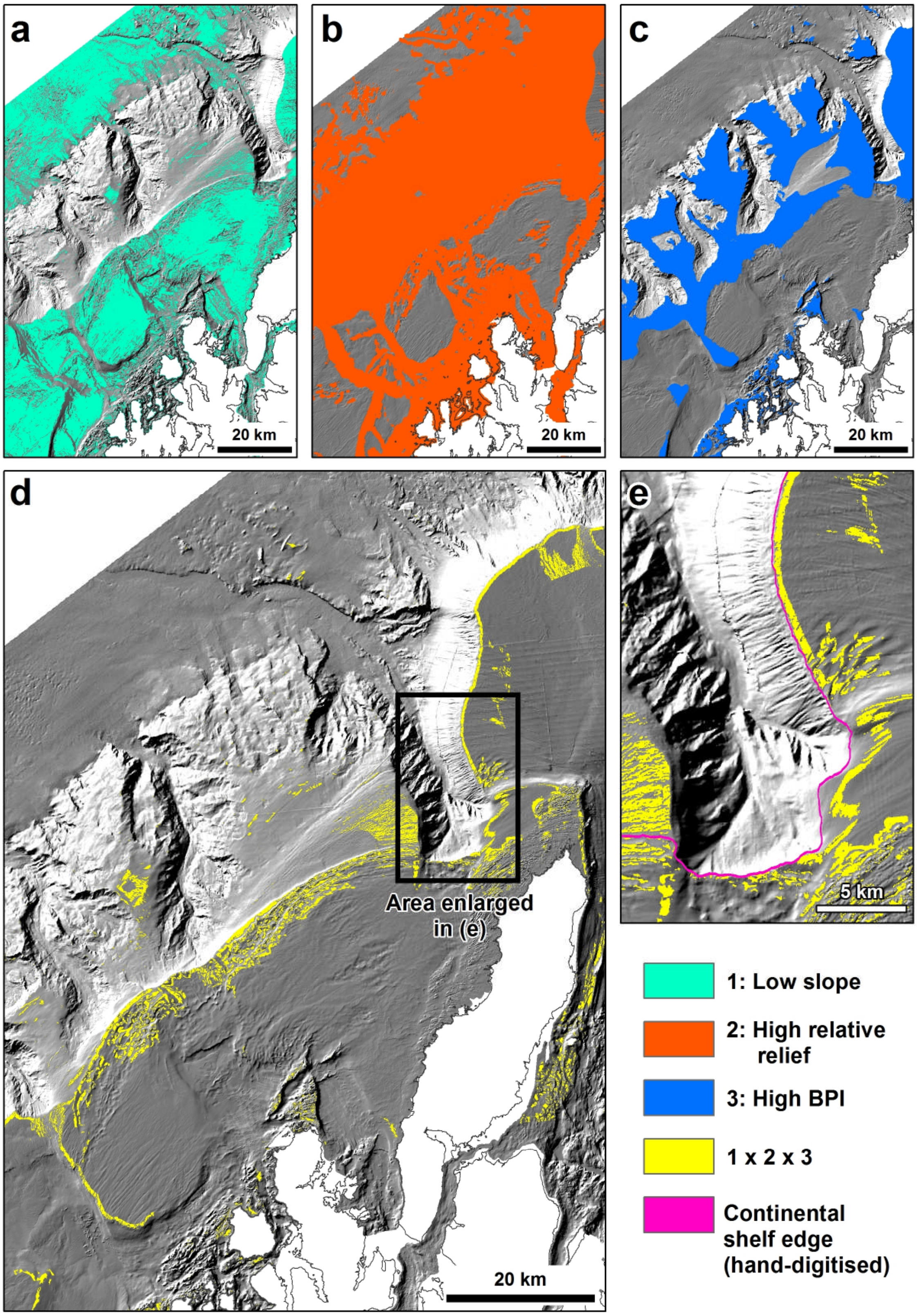
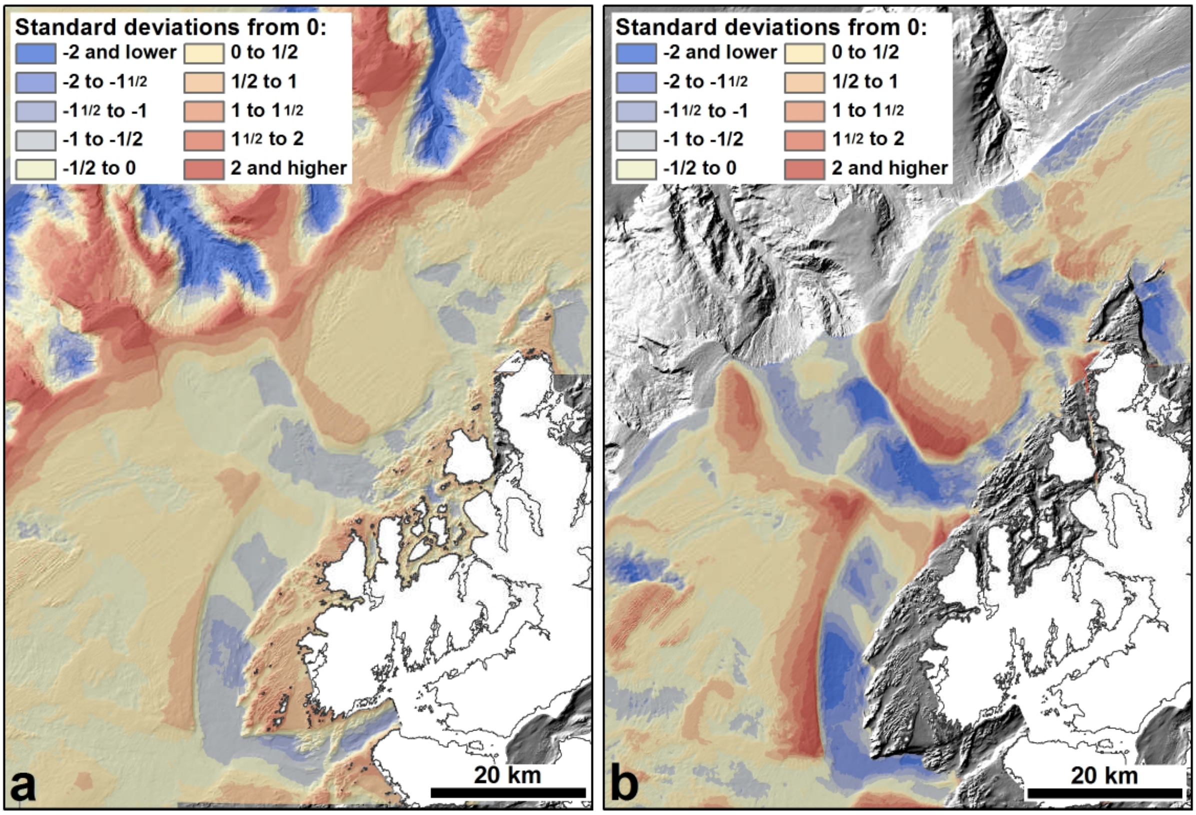


Figure 14. Locating the continental shelf edge by combining three terrain parameters. The boundary between continental shelf and continental slope is assumed to be found where slope values are low (a), but where relative relief (b) and BPI (c) are high (see Section 4.1 for a discussion on cut-off-values). Spatial analysis returns areas that meet all three requirements (d, e), and this is where the shelf edge should be located. In MAREANO, the continental shelf edge is hand-digitised at this stage (e), in order to make the final landscape maps suitable for publishing at a scale of 1:100 000.



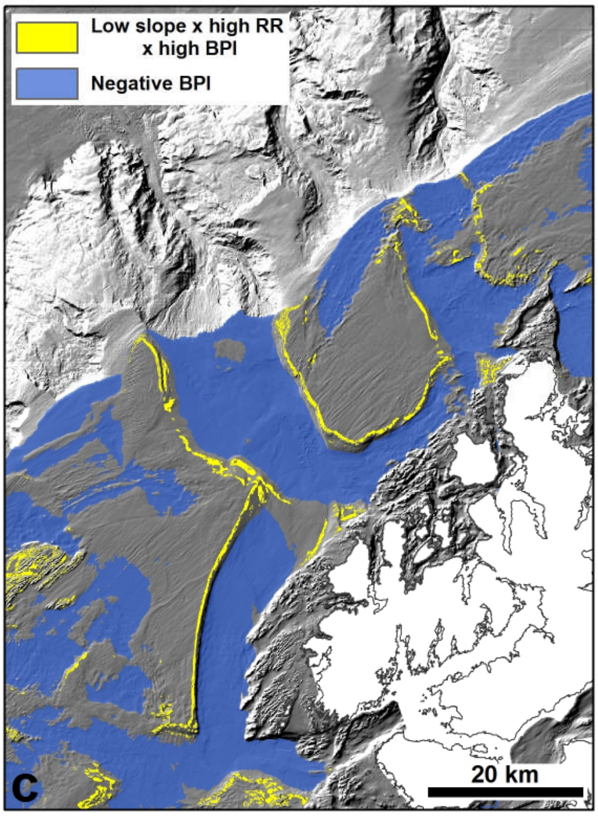


Figure 15. Classifying BPI by standard deviation. BPI is a terrain parameter with a near-normal distribution of values, and the distribution is affected by the character of an analysed area. In (a), the very diverse topography of the continental slope (upper left) is highlighted in a broad-scale BPI analysis (300 x 300 cells on a 50 m bathymetry grid). In (b), the same analysis window applied exclusively on the continental shelf highlights topographic features that do not stand out in (a). Actual BPI values of (a) and (b) are similar, but setting a cut-off value based on standard deviation (e.g. defining "high" BPI as >1/2 standard deviation from 0) returns different results. High BPI is used to locate edge features, and (c) shows how the boundaries between (shallow) marine valleys and continental shelf plains are found through an analysis similar to the one shown in Figure 14, but run on data from the continental shelf only. Negative BPI serves to identify basins that may qualify as marine or shallow marine valleys.

4.2 Step-by-step landscape mapping procedure

The following section outlines the overall strategy for identifying and mapping marine landscapes in MAREANO. Details of analysis window sizes, tools, and cut-off values in current use are listed in Appendix 1, but may be subject to adjustment as the MAREANO mapping programme progresses to new areas. The procedure described here has been arrived at through detailed and extensive practical experimentation, and has worked well for mapping all MAREANO areas to date (2013).

In accordance with MAREANO practice, landscape maps are digitised for publication at a map scale of 1:100 000. To ensure full coverage and no overlapping of landscape types, and to achieve a visually satisfactory end result, all landscape units are digitised by hand following appropriate cartographic principles for digitisation at this map scale. Included in the number of manually digitised features is the continental shelf edge, which is found early in the landscape classification process and which constitutes a boundary for several different landscape types in the final map product. The inclusion of manual digitising as necessary steps in an otherwise computerised landscape classification method may appear contrary to the ambition of developing an automated, objective approach to marine landscape mapping. However, all hand-digitised boundaries are of the kind that will eventually need to be digitised before publishing, and consequently it has not yet been a priority to refine the method further to provide a fully automated procedure.

Step 1. Initial analyses of the entire bathymetry dataset (50 m bathymetry grid).

a) Slope
b) Relative relief
c) Broad-scale BPI

Step 2. Locating continental shelf edge (Figure 14). Area should have i) lower slope values and ii) higher relative relief values than the average of flat areas in the dataset, and iii) high broad-scale BPI.

a) Reclassify slope, relative relief and BPI to show only relevant areas of interest (AOIs)
b) Combine AOIs to find areas that meet all three requirements
c) Manually digitise continental shelf edge based on result from b)

Step 3. Locating foot of slope. Area should have i) negative broad-scale BPI, and ii) deviations in curvature values at transition zone between flat seafloor (deep sea plain) and sloping terrain (continental slope).

a) Perform curvature analysis of area seawards of continental shelf edge
b) Reclassify curvature and BPI to show only relevant AOI

c) Combine AOIs to find areas that meet both requirements
d) Manually digitise foot of slope based on result from c)

Step 4. Separating marine canyons from smooth continental slope. Marine canyons have several identifying characteristics that can be found through GIS analysis. Examples include negative broad-scale BPI along thalwegs, clear-cut boundaries with surrounding smooth continental slope that are highlighted by neighbourhood analyses at various scales, and abrupt changes in slope direction. Canyons in the MAREANO area, however, had been manually digitised by other NGU geologists prior to the onset of semi-automated landscape mapping. These visually interpreted results were simply incorporated in the MAREANO landscape maps after inspection and small boundary adjustments. Further attempts to develop a more automated mapping protocol for marine canyons have not yet been made, as no new occurrences of this landscape type have been encountered during MAREANO mapping. Consequently, visual interpretation remains the *de facto* standard for mapping marine canyons, but with regard to future mapping MAREANO is not restricted to one single method for canyon mapping as best practice.

Step 5. Isolating strandflat/fjord areas from other landscapes on the continental shelf. Areas should have large deviations in curvature signal (due to surface roughness).

a) Perform curvature analysis of area landwards of continental shelf edge
b) Reclassify curvature to show only relevant AOI
c) Manually digitise boundaries of areas with high surface roughness based on result from b)

Step 6. Locating marine valleys/shallow marine valleys (Figure 15). Breaks in valley sides should display properties similar to those encountered at the edge of the continental shelf (Step 2), i.e. i) lower slope values and ii) higher relative relief values than the average of the continental shelf (note different cut-off values than for locating continental shelf edge), and iii) high broad-scale BPI. Bottoms of valleys should have negative broad-scale BPI. Marine valleys and shallow marine valleys must meet size requirements set by NiN and MAREANO.

a) Perform analyses for slope, relative relief and BPI of continental shelf only (excluding strandflat/fjord areas identified in Step 4)
b) Reclassify slope, relative relief and BPI to show only relevant AOIs
c) Combine AOIs to find areas that meet all three requirements for breaks in valley sides
d) Visually inspect results with a focus on proximity to negative-BPI areas, ignore areas that are not basin-like features
e) Inspect located basins to determine whether they meet size requirements for marine valley/shallow marine valley landscape types
f) Manually digitise boundaries of marine valleys and shallow marine valleys

Step 7. Separating strandflat from fjord areas. Fjords are elongated basins with defined size requirements. Bottoms of fjords should have negative broad-scale BPI. Sides of fjords may have a conspicuous slope signal. Areas below c. 200 m b.s.l. should not be classified as strandflat.

a) Reclassify BPI to highlight areas with negative values
b) Visually inspect areas of high slope values with a focus on proximity to negative-BPI areas, ignore negative BPI values that are not fjord-related
c) Manually digitise boundaries between strandflat and fjord areas based on BPI, slope, and bathymetry values

Mapping fjords has not been a priority in MAREANO to date (2013), as most fjord areas occur landwards of MAREANO designated mapping areas. The procedure for fjord mapping is therefore likely to be developed further in the future, and would be much improved by the addition of terrestrial topography datasets.

Step 8. Inspecting digitised landscape units. Through Steps 1-7, the following landscape types have been identified and digitised: *Deep sea plain*, *smooth continental slope* and *marine canyons*, *marine valleys* and *shallow marine valleys*, *continental shelf plains*, *strandflat*, and *fjords*. By inspecting the resulting landscape map with a view to areas that do not meet the criteria of NiN landscape definitions, it becomes clear whether further analysis is needed. Examples of findings not fully meeting NiN criteria may include high-relief areas occurring on a continental shelf plain, strandflat-like features in deep water, or plateaus of un-sloping terrain within the boundaries of the continental slope. When such cases are encountered, the interpreter must judge by size and appearance of the uncharacteristic area whether to classify it as a new landscape type (e.g. *hilly/mountainous marine landscape* or *continental slope plain*) or to dismiss it as merely an element of variation within the surrounding landscape type.

5. RESULTS

From 2010 to 2013, full-coverage landscape maps of 265 600 km^2 of Norwegian marine areas have been made publicly available at www.mareano.no and through related map services. The mapped area extends from 62°N to 73°N, and includes c. 200 individual landscape units ranging in size from 1 km^2 to >40 000 km^2. Of the 11 marine landscape types and subtypes defined by NiN, 7 have been found in areas mapped by MAREANO (Table 3). Certain adjustments to the NiN definitions have been made for the purposes of MAREANO landscape mapping, notably the joint registration of open and narrow fjords in one category (*fjords*), the addition of a subtype of marine valleys that are not as deep as required by NiN (*shallow marine valleys*), and the inclusion of some features >1 km^2 in the surrounding landscape type where this is found to be reasonable.

Figure 16 shows the end result of MAREANO landscape mapping, as published on www.mareano.no. All landscape units have been manually digitised for publication at a map scale of 1:100 000, following statistical analyses in accordance with the procedure for semi-automated landscape mapping presented here. When compared to the initial findings of Thorsnes et al. (2009), as demonstrated in Figure 17, it is clear that marine landscapes classified semi-automatically through a systematic procedure turn out quite similar to the result of an expert's visual interpretation of seabed topography. Although the 2009 landscape map is of a much lower resolution than published MAREANO maps, both maps show approximately the same spatial distribution of landscape units.

Comparing results this way is a valuable cross-check on the practical performance of the semi-automated methods described here. A semi-automated classification procedure should be able to produce an interpretation which is in keeping with expert judgement, but which yet retains an additional element of objectivity and quantifiability not always attainable in expert interpretation.

Table 3. A summary of landscape types found in MAREANO areas, 2010 to 2013.

Landscape type		Number of units identified	Average size of units (km^2)	Total area (km^2)
1. Strandflat		84	90	7 700
2. Continental slope	Smooth continental slope	10	5 280	52 800
	Marine canyons	22*	150	3 400
3. Fjord and valley landscapes	Fjords	40	130	5 100
	Marine valleys	14	3 920	54 900
	Shallow marine valleys	15	1 510	22 700
4. Plains	Deep sea plain	1	7 000	7 000
	Continental slope plains	0	-	-
	Continental shelf plains	27	4 150	112 000
5. Hilly and mountainous landscapes	Hilly/mountainous marine landscape	0	-	-
	Coastal archipelago	0	-	-
	Sum:	**213**	**Sum:**	**265 600 km^2**

*including smaller features not discussed by Rise et al. (2013)

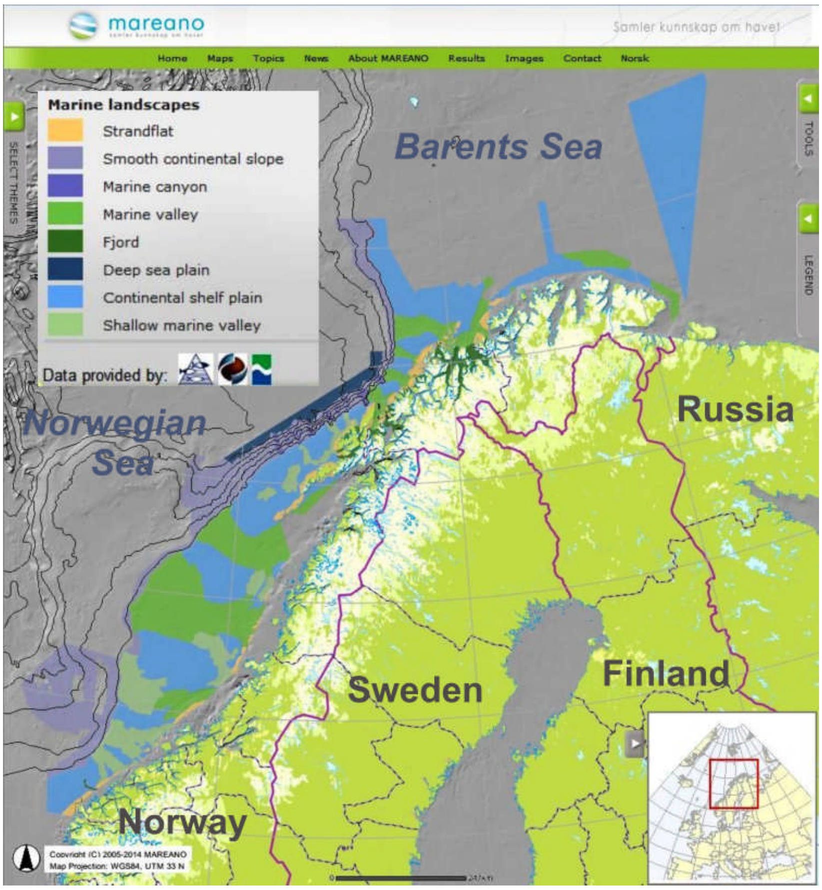


Figure 16. MAREANO landscape maps published on www.mareano.no, December 2013. The total area mapped amounts to 265 600 km^2, with seven of NiN's landscape types (v. 1.0) represented. Landscape maps are publicly available, e.g. through NGU's WMS service.

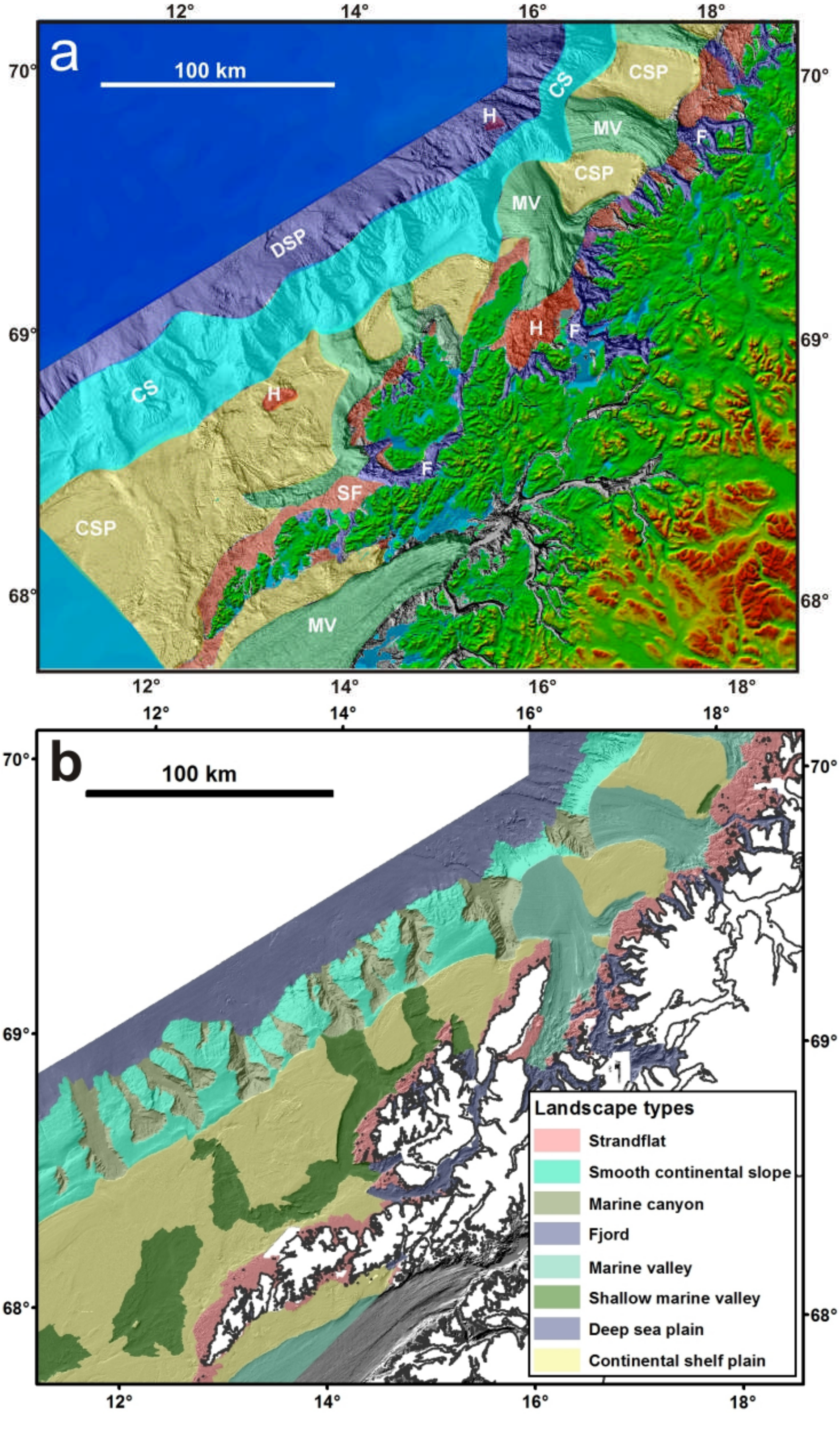


Figure 17. A comparison of the first published map of marine landscapes classified according to NiN definitions (a; modified from Thorsnes et al., 2009) and the MAREANO landscape maps arrived at through the semi-automated classification procedure described in this report (b). To improve comparability, the colour scheme of (a) is approximated in (b). Despite differences due to the better spatial resolution of (b) and the addition of a new landscape type (shallow marine valleys), the overall impression is one of similarity, implying that the semi-automated method is able to distinguish features that are visible to an expert interpreter.

6. DISCUSSION AND CONCLUSIONS

The MAREANO method for classification and mapping of marine landscapes, presented here, has shown wide applicability across several datasets and marine areas. The method is under continuous development in order to match the requirements for mapping additional landscape types and work with different data sources. Future adjustments to all components of the procedure are envisaged as the programme progresses. Factors such as varying bathymetry data quality and resolution in new areas, more effort directed towards discriminating between landscape types that have thus far not been well-represented within MAREANO boundaries, or even alterations made to NiN's landscape definitions in the ongoing revision may all make considerable modification of the procedure outlined here unavoidable in the future.

From the step-by-step approach outlined in Section 4.2, it is clear that the current landscape mapping procedure is better tuned to identifying and delineating certain landscape types than others. Examples of features that are easily distinguished include continental shelf plains, marine valleys, and the upper and lower boundaries of the continental slope, whereas further development of the procedure would be beneficial to diminish the interpreter's role in mapping e.g. fjords and marine canyons. Additionally, some of the landscape types defined by NiN are not yet covered in MAREANO's mapping procedure. In the case of fjords, most fall outside (i.e. inshore of) the original MAREANO boundary (Figure 1), while access to pre-digitised boundaries of all marine canyons hitherto found in the MAREANO area has downplayed the need for developing a method of precisely delineating canyons. Since indisputable occurrences of NiN landscape types *continental slope plain*, *hilly/mountainous marine landscape*, or *coastal archipelago* have so far not been encountered during MAREANO mapping, little effort has been made to tune the semi-automated mapping method to identifying these. Until other project initiatives can support development of the landscape classification procedure outside MAREANO areas these aspects of method development have relatively low priority, with the focus remaining on implementation and refinement of landscape mapping within MAREANO areas.

When mapping “marine” landscapes, it becomes evident that several landscape types are easily traced across the shoreline and into the terrestrial realm. Notable examples from the MAREANO area include strandflat and fjord units, both landscape categories where using the present-day shoreline as a bounding feature makes little sense from a geomorphological or geomorphometric perspective. However, terrain datasets that incorporate both marine and terrestrial areas are rare. Technical challenges associated with mapping shallow waters render the simple combination of terrestrial and marine datasets difficult, as both datasets will lack sufficient coverage of the coastal zone. Inclusion of NiN’s two separate fjord categories (*open* and *narrow*, based on total vertical relief) into MAREANO’s semi-automated landscape mapping method is therefore not envisaged in the near future.

Most quantitative terrain descriptors and cut-off values employed in MAREANO landscape mapping have been arrived at through a process of empirical testing. Preference has been given to the use of analysis tools returning results that allow for an objective selection of cut-off values (e.g. by having a normal distribution), and computation methods have been restricted to those that rely on basic tools, or that are easily implementable in many GIS software packages. During development of the semi-automated method, access to high-quality full-coverage multibeam bathymetry data has been of great value. However, landscape maps published since 2012 have increasingly been based on other types of bathymetry data (e.g. compiled single-beam echosounder data, data from seismic surveys, or low-resolution regional bathymetry), as MAREANO multibeam mapping has been focused on high-priority areas. Using data from multiple sources in automated mapping has turned out to be challenging. The required preparation of a full dataset on which to perform analyses is time-consuming, and differences in data quality and resolution across the combined dataset may generate false or unreliable terrain analysis output. Examples include smooth surfaces (e.g. continental shelf plains) yielding high slope or curvature values along the edges of original datasets, as well as rough surfaces (e.g. strandflat) returning a very variable curvature signal due to variable resolution of input data. In both cases, cut-off values based on the statistic properties of quantitative terrain descriptors must necessarily be applied with care, as artefacts in the data or false readings will obscure the true signal of the terrain.

Another consequence of including lower-resolution, non-multibeam bathymetry data in MAREANO landscape map production is that gridding the data to 50 m prior to analysis may not be optimal in all areas to be mapped in the future. This needs to be taken into account in the further development of the semi-automated mapping method. A 50 m grid size is however a great deal finer than what would technically be required for mapping units at a scale of 1:500 000 (Tobler, 1988), and as the use of a 100 x 100 m grid is standard in terrestrial landscape mapping conducted in accordance with NiN v. 1.0 (Halvorsen et al., 2009), a somewhat lower resolution of input bathymetry data should not compromise the quality of final map products.

As the MAREANO programme advances, more of Norway’s marine areas will become subject to landscape mapping through application of systematic, statistical GIS analyses. The details of the method may vary, even to the degree of replacing tools or quantitative terrain descriptors, but the core of delineating marine landscapes remains distinguishing units of uniform surficial appearance by way of statistical analysis of bathymetry data. This said, it is envisaged that future changes of the mapping protocol need not imply revision of already published landscape maps. Comparability with earlier work can be maintained by ensuring that results arrived at through a new method will match those previously published.

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Appendix 1: Stepwise procedure for mapping marine landscapes in MAREANO areas, 2010-2013

		Definitions of cut-off values used in MAREANO mapping	Examples of cut-off values used in MAREANO mapping to date (2013, using 50 m bathymetry grid unless otherwise noted)	ArcGIS Spatial Analyst tools (v. 10.0)
1) Initial analyses	a) Slope			Surface → Slope
	b) Relative relief			Neighbourhood Statistics → Focal Statistics (Statistics type = Range)
	c) Broad-scale BPI			1)Neighbourhood Statistics → Focal Statistics (Statistics type = Mean) 2) Subtract mean values from original bathymetry (Math → Minus)
2) Locate continental shelf edge	a) Find relevant areas of interest (AOIs): low slope, high relative relief, high BPI	i) Cut-off value for "low slope" = average slope value of flat areas (defined as having relative relief >50)	0. 98° 1.03° 1.21° 1.23°	Reclass → Reclassify
		ii) Cut-off value for "high relative relief" = average relative relief value of flat areas (defined as having relative relief >50)	13.4 m/km^2 15.0 m/km^2 18.2 m/km^2 18.7 m/km^2	Reclass → Reclassify
		iii) Cut-off value for "high BPI" = 0 + 1/2 standard deviation (from full dataset)	12.5 14.4 29.6 44.5	Reclass → Reclassify
	b) Combine AOIs			Map Algebra → Raster Calculator (multiply the reclassified AOIs)
	c) Digitise continental shelf edge			
3) Locate foot of slope	a) Curvature analysis of area seawards of shelf edge			Surface → Curvature
	b) Find relevant AOIs: Negative BPI, large curvature deviation	i) Cut-off value for negative BPI = 0	0	Reclass → Reclassify
		ii) Cut-off values for high/low curvature = 0 +/- 1/2 standard deviation	0.022/-0.022 (from bathymetry gridded to 250 m)[1]	Reclass → Reclassify
	c) Combine AOIs			Map Algebra → Raster Calculator (multiply the reclassified AOIs)
	d) Digitise foot of slope			
4) Separate marine canyons from smooth continental slope[2]	Possible identifying features of marine canyons: - Negative BPI along thalweg - Clear-cut boundaries detectable through neighbourhood analyses			

5) Isolate strandflat/fjord	a) Curvature analysis of area landwards of shelf edge			Surface → Curvature
	b) Find AOI: Large curvature deviation	Cut-off values for high/low curvature = 0 +/- 1 standard deviation	0.14/-0.14 0.16/-0.16 0.18/-0.18 0.21/-0.21	Reclass → Reclassify
	c) Digitise strandflat/fjord			
6) Locate marine/ shallow marine valleys	a) Re-analyse areas landwards of shelf edge (excluding strandflat/fjords) for slope, relative relief and BPI (as in Step 1)			
	b) Find relevant AOIs for breaks in valley sides: low slope, high relative relief, high BPI (as in Step 2)	i) Cut-off value for "low slope" = average slope value of continental shelf (excluding strandflat/fjords)	0.97° 0.99° 1.07° 1.54 °	Reclass → Reclassify
		ii) Cut-off value for "high relative relief" = average slope value of continental shelf (excluding strandflat/fjords)	13.9 m/km^2 14.1 m/km^2 15.9 m/km^2 23.2 m/km^2	Reclass → Reclassify
		iii) Cut-off value for "high BPI" = 0 + 1/2 standard deviation (from continental shelf, excluding strandflat/fjords)	16.46 20.25 28.11 30.63	Reclass → Reclassify
	c) Combine AOIs			Map Algebra → Raster Calculator (multiply the reclassified AOIs)
	d) Inspect results to find basins (basins have negative BPI)			
	e) Inspect basins to determine if size requirements are met			
	f) Digitise valley boundaries			
7) Separate strandflat from fjords[2]	Identifying features of fjords: - Defined size requirements - Negative BPI - Fjord sides may have conspicuous slope signal Areas below c. 200 m b.s.l. should not be classified as strandflat			
8) Inspect digitised landscape units	Parts of a landscape unit not fully meeting the relevant criteria may require further digitising and re-classification to a different landscape type			

[1] Only one foot-of-slope area has been mapped by MAREANO so far (2013)

[2] A best practise for mapping marine canyons and fjords has not yet been established

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