First High-Resolution Benthic Habitat Map From the Greenland Shelf (Disko Bay Pilot Study)

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RESEARCH ARTICLE

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Key Points:

- Central Disko Bay pilot area was mapped in high-resolution with multibeam and ground-truth stations
- Five benthic habitats were identified focusing on bathymetry, seafloor topography, and sediments
- Two benthic communities (sessile fauna and shrimp/polychaetes) were associated with sediment types

Supporting Information:

Supporting Information may be found in the online version of this article.

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First High-Resolution Benthic Habitat Map From the Greenland Shelf (Disko Bay Pilot Study)

D. W. Krawczyk[1], K. B. Zinglersen[1], Z. Al-Hamdani[2], C. Yesson[3], M. E. Blicher[1], N. H. Arboe[1], J. B. Jensen[2], J. N. Wagnholt[1], F. Hansen[4], and L.-G. Rödel[2]

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Abstract A healthy ocean where marine habitats and ecosystems are mapped and protected is one of the UN's Sustainable Development Goals to sustainably use marine resources. Our study presents the first high-resolution benthic habitat map from Greenland integrating analyses of multibeam bathymetry and backscatter data, and ground-truth data including video sled, drop camera and day grab. The pilot area of 30 × 20 km is located on the continental shelf in central Disko Bay, West Greenland and all data were collected in a single, 10-day survey. Multibeam bathymetry data were gridded to a 10 × 10 m resolution, whereas backscatter mosaic was built from a 1 × 1 m grid cell to obtain higher resolution manifestation of seafloor properties. Ground-truth data consisted of 14 video transects, 17 drop camera deployments, and 17 sediment samples. Our results were verified with the published shallow seismic and vibrocore data from the Disko Bay region to link the geological background with the sedimentary environment. We distinguished five physical habitats in the area, based on the distribution of sediment types, water depth with general water masses and morphology. In addition, numerous gas seeps alongside pockmarks were observed in the area, as well as recent iceberg ploughmarks. The identified habitats were associated with two basic communities of benthic fauna, linked primarily to the distribution of sediments and representing hard bottom habitats (sessile fauna) and soft bottom habitats (shrimp/polychaetes). Our study is the first step toward mapping the entire seafloor of Disko Bay to provide a scientific context for the management of seafloor and marine resources.

Plain Language Summary Distribution of benthic habitats is an important element in understanding the function and services of the marine ecosystems. A well-founded knowledge of the marine bio environment is crucial for sustainable use of marine resources and Greenland economy is highly dependent on marine resources. Our pilot study presents a pioneer benthic habitat map from glaciated shelf of central West Greenland, Disko Bay. We chose a small area of 600 km^2 in a *c.* 30 × 20 km box which is characterized by a complex hydrography, geodiversity and rich marine biodiversity including rare observations of Vulnerable Marine Ecosystem indicator species. This area was mapped in high-resolution with multibeam echo sounder and ground-truth stations using underwater imagery and physical samples. Five benthic habitats were identified based on classifying data on water depth, seafloor topography, and sediment types. These habitats were represented by two biotopes, (1) attached fauna, such as sponges, soft corals, and sea lilies and (2) shrimp with tubeworms. Our first high-resolution benthic habitat model may have an important future application in seafloor management plans to sustainably use the oceans and marine resources in Greenland.

1. Introduction

The Greenland economy is by large dependent on marine resources, which is why a well-founded knowledge of the marine bio environment is crucial for decision-making and sustainable management. An important element in understanding the function and services of the marine ecosystem is the distribution of benthic habitats. Such knowledge with respective spatial datasets can be valuable to the management of the many elements of the Blue Economy, such as fisheries, offshore mining, marine constructions, and tourism.

Marine benthic habitats can be defined as geographically recognizable areas with particular seafloor environments that have distinct physical and abiotic characteristics and associated biological communities and assemblages (Lurton & Lamarche, 2015). Therefore benthic habitats can be defined by the environmental elements, such as seafloor depth (bathymetry), terrain features (morphology), sediment types, and water mass characteristics (hydrography), as well as the occurrence/distribution of benthic flora and fauna. Information about benthic habitats in Greenland are very sparse and based on an inconsistent collection of geological, hydrographical, and biological data. The first overview paper describing broad-scale benthic habitats along the West Greenland shelf was published by Gougeon et al. (2017). Their study documented several different surface substrate categories from soft bottom to hard rock and developed a classification model in order to make habitat predictions. However, the resolution and quality of environmental proxies limited the predictions to a single habitat class within a 3.5 × 3.5 km grid cell (Gougeon et al., 2017). Utilizing the knowledge from previous broad-scale study by Gougeon et al. (2017) we launched a pilot study in a small area in Disko Bay as the first study in Greenland to map benthic habitats in high resolution using the new multibeam system combined with digital and physical ground-truthing. Inspiration for this project and in particular the methodology, were long-term habitat mapping programs developed successfully in Canada (Kostylev et al., 2001; Todd & Kostylev, 2011) and Europe, that is, Norwegian program Mareano (Bellec et al., 2017; Buhl-Mortensen et al., 2012), MESH (2004), BALANCE (2005), and EMODnet/EUSeaMap (2009-now). The European projects aimed at producing high-resolution, broad-scale seabed habitat maps contributing to the fulfillment of the Marine Strategy Framework Directive (MSFD) aim of "good environmental status" of the European seawaters by 2020. Greenland, however, as a large country has a rather limited research capacity and is at the developing stage in terms of technology, infrastructure and management plan for sustainable use of seabed and marine resources. The first step to recognize "the potential of using remote-sensing data as proxy of biophysical indicators" in the Arctic environment was to create the "best practice" protocol for high-resolution benthic habitat mapping (Krawczyk, Zinglersen, et al., 2019).

The marine environment surrounding Greenland poses several challenges for planning and conducting field campaigns, such as seasonal sea ice cover, icebergs, highly complex topography (e.g., hundred meter steep slopes), and strong winds. Such a demanding environment requires extra efforts before and during data acquisition. The developed "best practice" protocol is a cost-effective and time-efficient mapping guide for the strategically important areas of the Greenland shelf. The advantage of this protocol is the effective sampling program combining acoustic survey with on-board processing and ad hoc data interpretation in order to select the optimal ground-truth sampling within one survey, instead of a separate acoustic survey followed by ground-truth sampling a year after (Krawczyk, Jensen, et al., 2019). The priority of this protocol is "mapping for discovery," that is, a single survey usually carried out for the first time in order to explore the seafloor and collect data on geological features, facies distribution and species habitats (Lurton & Lamarche, 2015).

We selected the Disko Bay region (central West Greenland shelf) for the pilot study not only due to dynamic benthic ecosystem comprising a significant part of Arctic marine biodiversity and biological richness, but also geological and hydrographical complexity and geodiversity, as well as logistical accessibility (i.e., research and naval ships). The relatively small pilot area has been selected as a pioneer high-resolution habitat mapping area in Greenland based on the existing knowledge on complex bathymetry, hydrography and rich marine biodiversity including rare observations of Vulnerable Marine Ecosystem indicator species. The current paper presents a detailed study of benthic habitats in central Disko Bay including a description of sedimentary environment and benthic communities on a high-resolution (meter) scale using combined multibeam and ground-truth data as seafloor descriptors. The multibeam-derived data, that is, bathymetry and backscatter provided information on water depth, seafloor topography, and rugosity, and allowed differentiating seafloor "types" and sediment grain size. The ground-truthing (in situ sampling) was needed to calibrate and validate the interpretation of multibeam data and we used image data from video sled and drop camera together with seabed samples using a day grab to characterize substrate types and the main benthic communities. In addition, the area was investigated in terms of existing geological data from the larger region to place our pilot area in a broader setting.

This paper provides new information on distribution of physical benthic habitats and associated faunal communities necessary to ensure representative environmental assessments and marine resources management of the Greenland seafloor, thus contributing to fundamental knowledge in natural and environmental management in Greenland eventually forming the basis for overall Marine Spatial Planning.

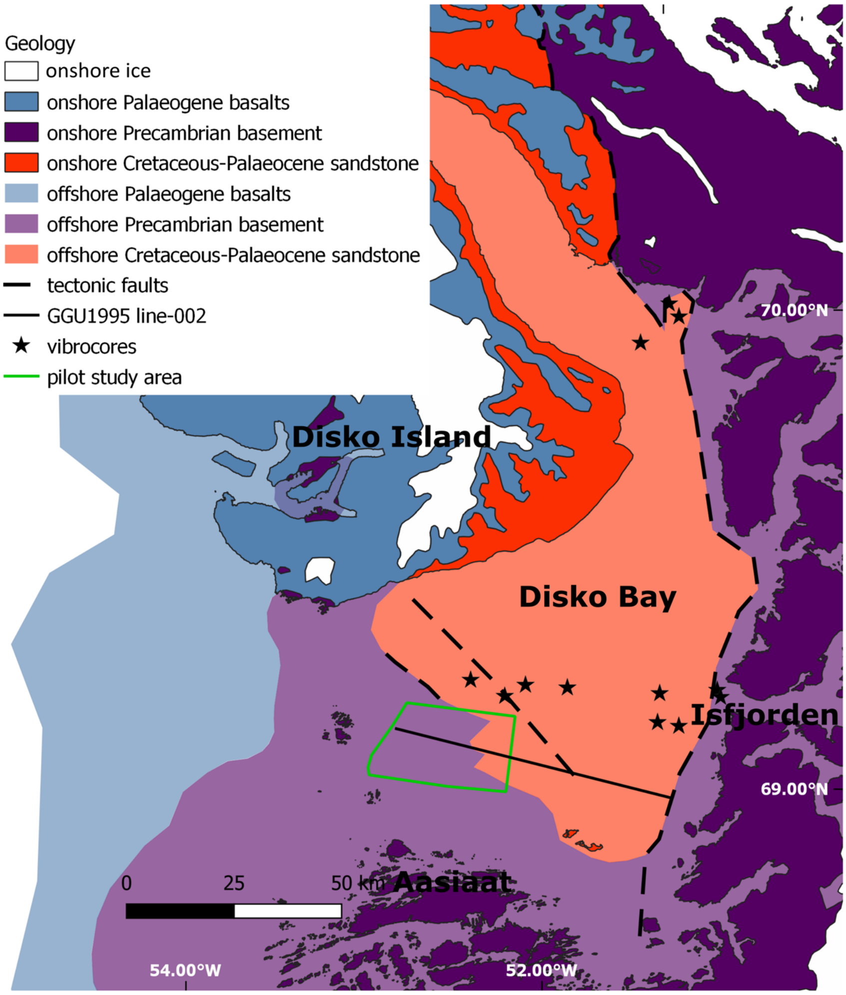

Figure 1. Pre-Quaternary geological setting of the Disko Bay region (modified from Nielsen et al., 2014). Full tones represent onshore geology and half tones represent offshore geology. Dashed black lines indicate tectonic faults. Solid black line indicates position of the seismic profile GGU1995 line-002 and solid black stars indicate locations of vibrocores from RRS James Clark Ross cruise (JR175; in Streuff et al., 2017). Green box marks the outline of the pilot study area. Coordinate Reference System (CRS): WGS 84.

2. Study Area

2.1. Geology

Disko Bay is an open marine bay (68°30' N and 69°15' N and 50°00' W and 54°00' W, Figure 1) located in central West Greenland. The overall geological setting, both onshore and offshore is governed by the regional bedrock tectonics in a strike-slip wrench tectonic system with a prominent fault pattern (Wilson et al., 2006). The southwestern area consists of Precambrian basement with little to no topsoil, while the central and eastern area consists of Upper Cretaceous sandstone (Figure 1), modified by glacial processes, thus the bedrock tectonics is more unclear. The Precambrian basement is dominated by an abraded streamlined terrain with fast ice flow lineation (Whaleback and Roche moutonée), which can be found onshore near Aasiaat (Roberts & Long, 2005; Figure 1). The Upper Cretaceous sandstone can be studied onshore Disko Island (Figure 1), where the softer sedimentary-layered bedrock type shows a more homogeneous, continuous morphology between the faults, cut by several consolidated sandstone dykes that create ridges in the landscape (Dam et al., 2009). The outcropping bedrock ridges have a relief of several tens of meters to about 100 m and appears to have been streamlined by glacial ice (Hogan et al., 2012).

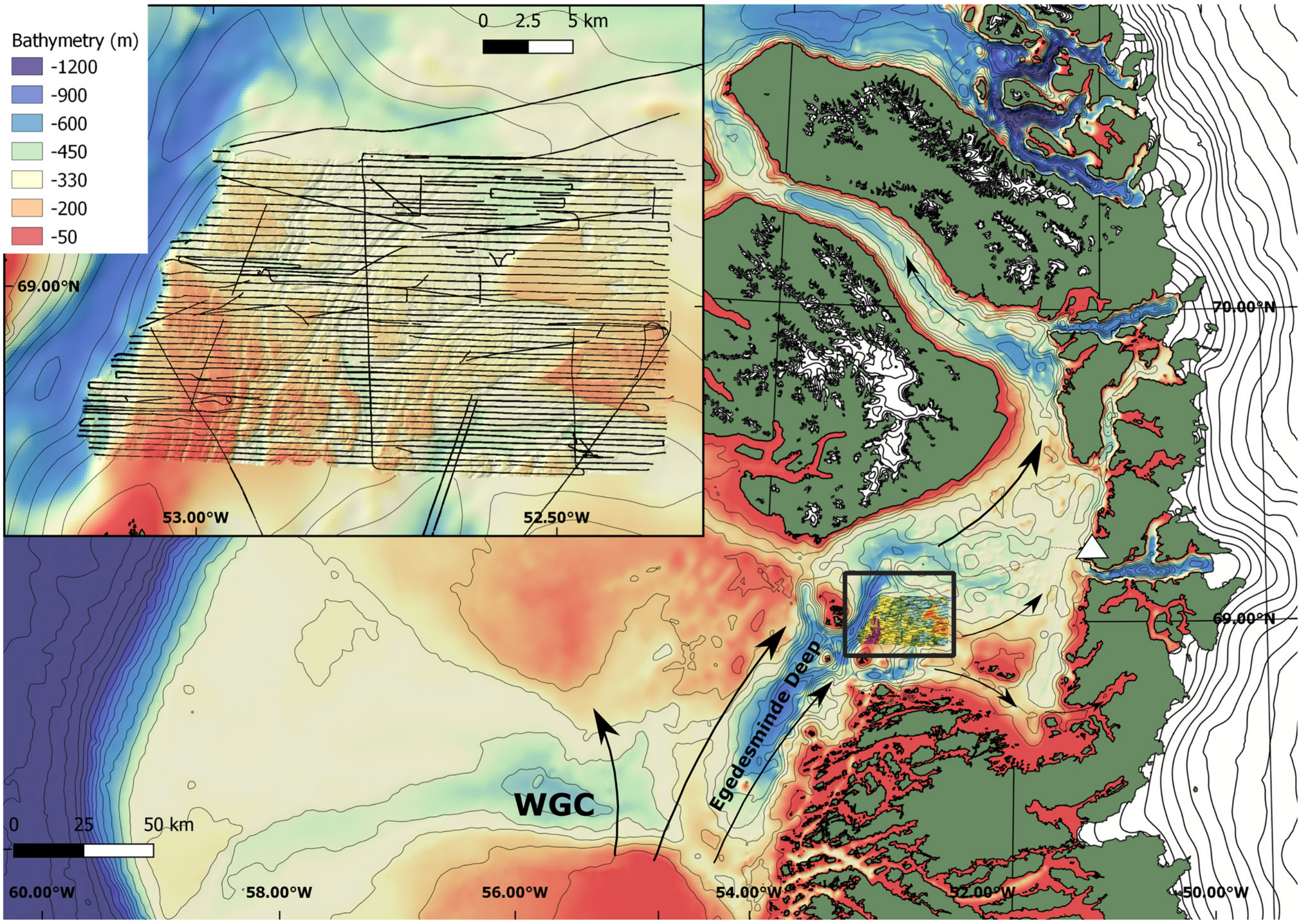

Figure 2. Bathymetry (m) of central West Greenland shelf, that is, Disko Bay region superimposed on a relief map. Source: BedMachine v3 (Morlighem et al., 2017). The arrows indicate the approximate flow of the West Greenland Current (adapted from Andersen, 1981). The white triangle shows Ilulissat harbor. White color on land indicates ice. Insert map shows the tracklines of this pilot study survey overlaying the survey bathymetric grid (see Figure 3). CRS: WGS 84.

Deglaciation of the Greenland Ice Sheet was so rapid in the western parts of Disko Bay (by *c.* 10.600 years BP) that there was insufficient time for development of recessional moraine ridges (Hogan et al., 2012; Weidick & Bennike, 2007). Subsequent glacial retreat through eastern Disko Bay was much slower and likely interrupted by at least one still-stand period due to pinning of the grounded glacier margin on submarine bedrock ridges. Around 7.600–7.100 years BP the Greenland Ice Sheet margin had probably retreated far back into the present-day Isfjorden (Hogan et al., 2012; Jennings et al., 2014; Weidick & Bennike, 2007; Figure 1). The deglaciation sedimentation history in the early phase after deglaciation, is dominated by glacial deposits, such as lodgment till and sandy diamict. These glacial deposits are interpreted as mass-flow deposits, which occurred from meltwater and/or the water column and melting icebergs, reworking glacimarine mud, and ice rafted debris. Mass-flow deposits are abundant in Disko Bay, covered by more recent sediment accumulation in local basins and defined by bedrock and glacial deposits (Hogan et al., 2012).

2.2. Oceanography

The overall circulation pattern in Disko Bay is dominated by relatively warm and saline Atlantic-sourced water from the West Greenland Current entering the bay from the south and leaving again both to the north and south of Disko Island (Hansen et al., 2012; Söderkvist et al., 2006; see Figure 2). A recent study by Rysgaard et al. (2020) identifies this Atlantic-sourced water as Subpolar Mode Water along the West Greenland shelf. The Subpolar Mode Water is found below the cold and low-saline Polar Water, that is, below the upper *c*. 200 m (Buch, 1981; Tang et al., 2004). The oceanographic conditions are highly variable, supported by complex and sloping seabed topography with maximum depths exceeding 900 m, that is, at a deep-water trough, Egedesminde Deep located at the outer part of Disko Bay (Figure 2). In Disko Bay proper, the topography varies with depths of 300–500 m (Buch, 2000) (Figure 2). In some places oceanographic conditions can change dramatically, such as along steep slopes and narrow submarine canyons to more shallow areas. The runoff of freshwater from melting sea ice and glaciers during summer further contributes to the oceanographic complexity by introducing significant vertical and horizontal salinity gradients throughout the system (Hansen et al., 2012). Distinct and dynamic vertical temperature gradients have been reported with temperatures in a surface layer (<50 m) highly controlled by atmospheric and seasonal conditions (−1.8°C–6.7°C), and with more stable conditions at greater depths (<−0.5–3.4°C) with some indications of periodically slight increase in water temperature with depth (Hansen et al., 2012). Indications of inertial water movements driven by internal waves from tidal forces and meteorological events have been reported (Söderkvist et al., 2006) with the potential to interact with seabed topography driving turbulence and mixing between productive surface layers and benthic communities below the photic zone.

2.3. Biology

Knowledge of epibenthic megafaunal communities in the Disko Bay area is limited. Greenland Institute of Natural Resources (GINR) initiated a monitoring program for benthos in 2015, based on bycatch of benthos in the bottom trawl stock assessment surveys conducted annually by GINR. In addition, beam trawl hauls are performed during the same surveys (Blicher & Arboe, 2017).

Yesson et al. (2015) used drop camera surveys to document biological communities along the western continental shelf. Four broad-scale communities were documented showing strong affinity to seabed substrate. Although this study did not include samples from within Disko Bay, it did include samples from the offshore area, west of Disko Bay with similar depth and substrate profiles. These were predominantly muddy communities characterized by polychaetes and the commercially fished Northern Shrimp *Pandalus borealis* (Burmeister & Rigét, 2019).

A study conducted in 2009 west of Disko Island, on Store Hellefiske Banke and in Disko Bay using Haps and Van Veen grabs showed a very species-rich benthic community with more than 600 different invertebrate species, and dominated by polychaetes on stations with soft sediment and deeper than 200 m (Boertmann et al., 2013).

Commercial fishing has a major influence on seabed habitats in West Greenland. Sustained demersal trawling can dramatically reduce the diversity and abundance of sessile attached fauna. The West Greenland cold-water prawn fishery has operated demersal trawls in the area since the 1950s, although central Disko Bay has not been the main target of this fishery, there is likely to be an impact on the benthos in the region (Yesson et al., 2017).

3. Materials and Methods

The 10-day mapping survey was carried out in September 2018 with R/V Sanna covering about 600 km^2 in a *c*. 30 × 20 km square in central Disko Bay, West Greenland as part of the "MapHab" pilot study. The survey combined continuous multibeam data acquisition with intermittent stops for collection of ground-truth data (Figures 2 and 3). The ground-truth dataset was supplemented with two stations collected during M/T Paamiut cruise in summer 2017. Table S1 in Supporting Information S1 presents details of exact ground-truth locations and sampling information.

3.1. Multibeam Data

The area was mapped using a hull-mounted multibeam echo sounder Reson SeaBat T50-R with extended range projector to achieve 1000 m water depth range. The system has 512 beams per ping arrayed over an arc of 150° and a high-resolution beam width (0.5° in shallow water and 1.5° in deep water). The swath of seafloor imaged on survey lines was typically 2–4 times the water depth with most optimal results achieved on flat area at *c*. 300 m water depth, that is, over 1 km footprint. Bathymetry and backscatter data were acquired

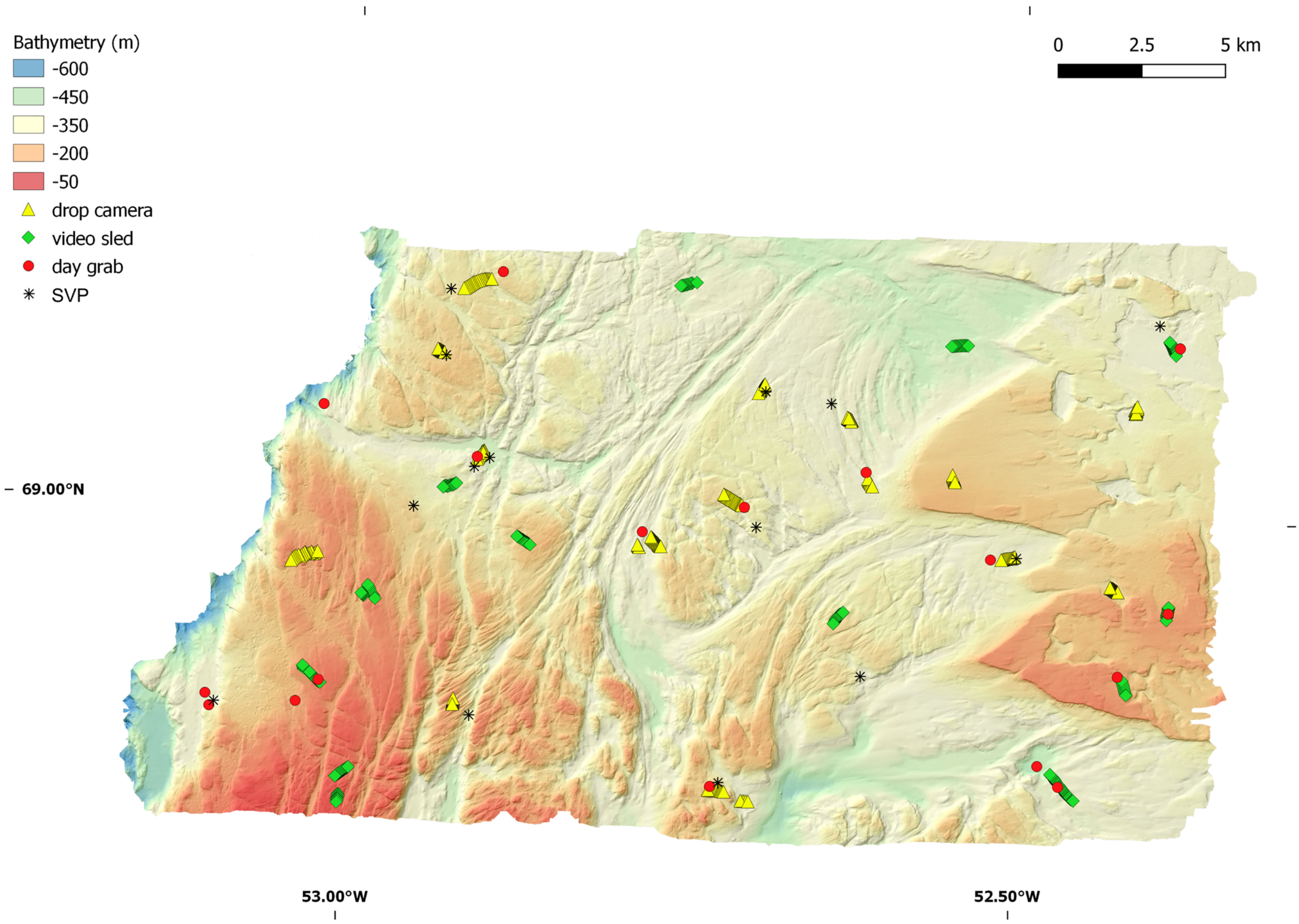

Figure 3. Bathymetric grid (m) of 10 × 10 m resolution superimposed on a hillshade terrain model with locations of ground-truth stations/transects including Sound Velocity Profiles (SVP) in Disko Bay study area (see legend). CRS: WGS 84.

at 0.3 km line spacing between latitudinal oriented tracklines at speed *c.* 7.5 knots. Average ping rate at this speed and at *c.* 300 m water depth was 1–3 pings/sec. Swath overlap provided optimal *c.* 30% overlap between tracklines. Positioning and movements of the vessel were calculated directly with the Applanix POS MV WaveMaster II receiving data from an Inertial Motion Sensor, Teledyne INS Type-20, and two Trimble GNSS (DGPS) antennas. The accuracy of the observations is generally within 0.5–2 m horizontally and up to 0.03° roll, pitch and heading of the vessel (Applanix, 2020). Positioning and motion data from Applanix POS MV are transferred directly to the Teledyne Marine PDS Real Time acquisition software. Sound Velocity Profiles (SVP) were periodically collected (along with water temperature) to correct the effect of sonar beam refraction due to water density changes (Figure 3).

The time-efficient approach involved first, sailing several tracklines, second, converting unprocessed multibeam data to a preliminary height grid model (HGM = bathymetric grid) and backscatter mosaic (BM = backscatter grid) using Teledyne acquisition software PDS (Teledyne, 2019). Finally, gridded data were roughly classified using unsupervised histogram analysis (i.e., natural breaks) in ArcGIS software (ESRI, 2020) in order to choose the most optimal locations for the ground-truth sampling, based on distinct depth intervals, terrain features, and the preliminary backscatter intensity. Additional tracklines were collected to fill the gaps and cross-lines for azimuth validation (Figure 2).

Operating frequency of multibeam was constant throughout the survey (180 kHz; continuous wave), likewise settings of power, gain, absorption, and pulse length for reliable snippets, that is, series of amplitude values in the signal reflected from a beam's footprint of the seafloor (for detailed settings see Krawczyk, Zinglersen, et al., 2019). During survey, multibeam echo sounder was calibrated on flat and sandy floor for good

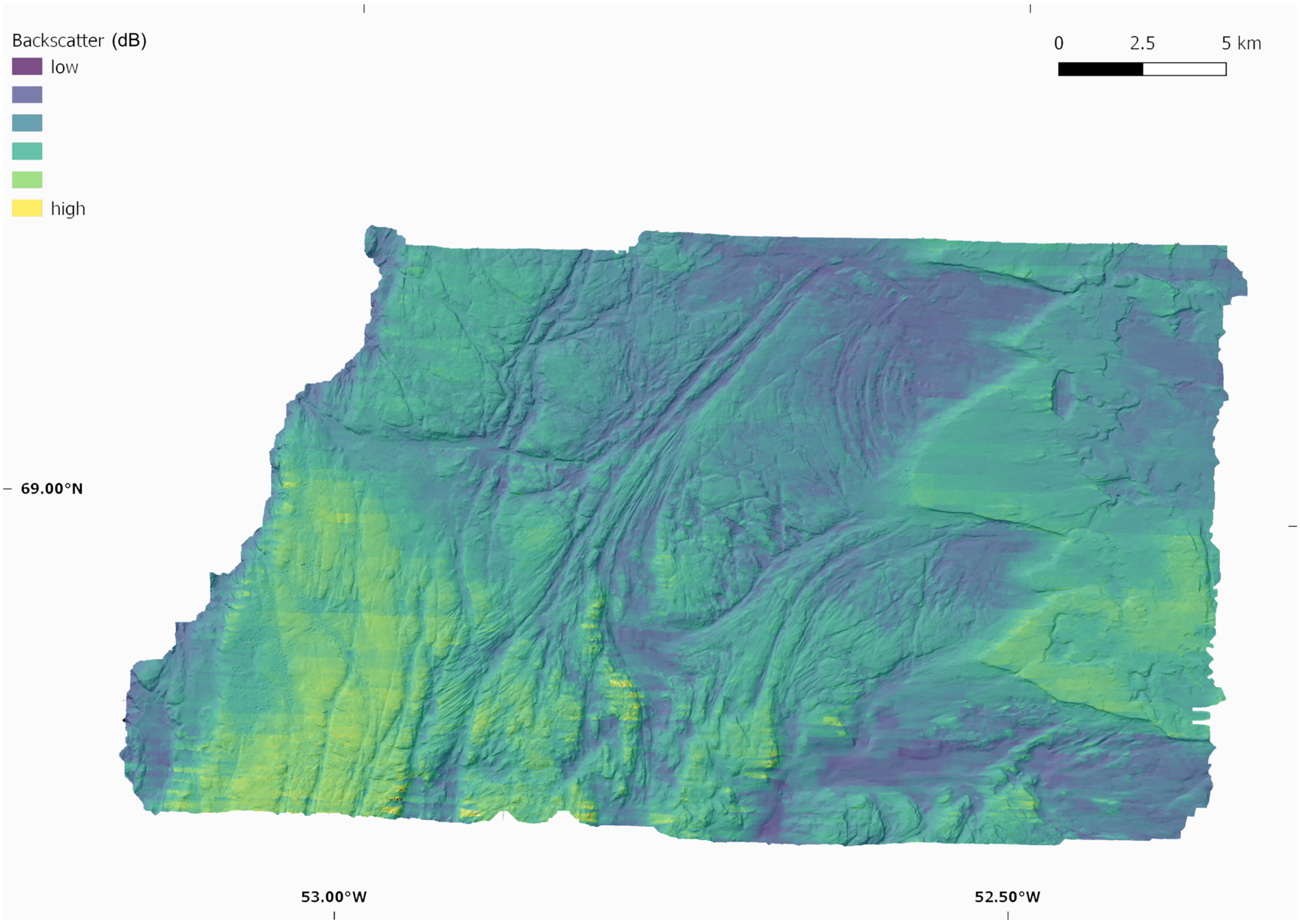

Figure 4. Backscatter mosaic (dB) of 10 × 10 m resolution superimposed on a hillshade terrain model in Disko Bay study area. Maximum backscatter intensity is −9 dB and minimum backscatter intensity is −56 dB. CRS: WGS 84.

quality snippets (i.e., backscatter data), as recommended by manufacturer. Backscatter is known to show direct relationship to sediment grain size and terrain ruggedness, thus can be used in providing information on physical attributes of the seabed (Kostylev et al., 2001; Lurton & Lamarche, 2015).

Post-survey processing of data was carried out using Teledyne software PDS and data were corrected for true heave, sound velocity, and tidal variation (tide model: Ribergaard, 2020). Automatic filters were applied (e.g., detection quality, statistic, and nadir) together with manual spike removal to subsequently generate HGMs of different resolutions. In this study we use two HGMs, 1 × 1 m and 10 × 10 m resolution. The HGM of a smaller cell size of 1 × 1 m was used to build a BM to a final resolution of 10 × 10 m, instead of a HGM of larger cell size of 10 × 10 m, as this would minimize uncertainties in calculating backscatter corrections for insonification area related to slope and angular dependency (Malik, 2019). In PDS software, BM is automatically corrected for radiometric and geometric distortions (gain, power, pulse width, beam pattern, absorption and spreading, beam position, difference angular dependency, area of insonification, Lambert) resulting in backscatter intensity in dB grayscale. In the study area, backscatter intensity ranged from −9 to −56 dB. Backscatter intensity is useful in differentiating seafloor sediments (Kostylev et al., 2001). Furthermore, HGM and BM (both 10 × 10 m resolution; Figures 3 and 4) were exported to ESRI ASCII grid format (.asc) compatible with GIS. Bathymetric grid was used to generate seafloor environmental descriptors with Benthic Terrain Modeler (BTM) toolbox in ArcGIS software (Walbridge et al., 2018). The BTM toolbox produces layers, such as broad scale Bathymetric Position Index (BPI) (inner radius 25 units and outer radius 250 units), fine scale BPI (inner radius 3 units and outer radius 25 units), slope, and morphology. Broad BPI data are used to identify larger benthic zones features, such as slopes and depressions, whereas fine

BPI are used to identify smaller benthic features, such as narrow crest and lateral midslope depressions (Wright et al., 2005). For building the morphology layer we used two classification dictionaries consisting of eight classes, that is, narrow depression, depression, local crest in depression, crest, local depression on crest, narrow crest, flat and slope, and four classes, that is, depression, crest, flat, and slope (modified from Wright et al., 2005).

3.2. Ground-Truthing

Ground-truthing is required to calibrate and validate any interpretation of the multibeam data. We have deployed a combination of imaging using video sled (i.e., 14 transects) and drop camera (i.e., 17 deployments) and physical sampling using day grab (i.e., 17 deployments) to characterize the seabed environment and habitats (Figure 3).

Drop camera sampling employed a Nikon D80 digital SLR in DSC-10000 Digital Ocean Imaging Systems deep-sea camera housing and 200 W-S Remote Head Strobe flash unit (Model3831) in a steel frame with the camera, 65 cm above seabed (see Yesson et al., 2015). Also attached is a GoPro camera in an underwater housing with 1–2 Nautilux torches (GroupBinc). GoPro is positioned at 85 cm at an angle of 49.5°. The camera is lowered to the seabed to trigger an image; it is then raised *c.* 5 m above the seabed between drops and lowered again at 1–2 min intervals (dependent on the drift of the ship). Camera position is assumed the same as the ship and is logged for each image, along with water depth and drift speed (following Yesson et al., 2015).

The benthic video sled is a towed camera structure equipped with GoPro camera and two Nautilux torches in GB-PT 1750 GroupBinc underwater housing; camera height is at *c.* 85 cm positioned at 31° angle (details in Long et al., 2020). The camera was deployed for 15 min on the seabed at a speed of approx. One knot covering an approximate transect of 500 m. Position is logged on the ship GPS at the start and end of the transect, along with water depth and length of wire deployed. Camera position is inferred as being directly behind the ship (direction inferred from start and end position of survey) at a distance X, where $X = (W^2 - D^2)^{0.5}$ (W-wire length, D-water depth).

Video from the sled was sampled into a series of images for analysis. Stills were extracted at 30-s intervals for analyzable sections of video. When stills are not analyzable due to silt clouds obscuring the view or steeply undulated terrain dramatically changing the camera angle, the video is played until the next analyzable section is found, with intervals continuing from that point (following Long et al., 2020).

Each still (video sled and drop camera image) was classified into sediment classes following the scheme of Gougeon et al. (2017), which is an adapted version of the EUNIS (European Nature Information System) seabed classification scheme (Davies et al., 2004). Sediment categories identified in Disko Bay pilot area with underwater imagery are mR–bedrock with mud, boulder and pebbles, R–coarse rocky ground, Rm–coarse rocky ground with thin layer of mud, gS–gravelly sand, gM–gravelly mud, Md–mud with dropstones, and M–mud (Figure 5). Additionally, observations of prominent (most abundant) taxa, including potentially habitat forming taxa were registered, as well as chemical activity, that is, apparent gas seeps.

Physical samples of sediment enable direct measurements of grain sizes, allowing more detailed calibration of sediment classes at the finer end of the size spectrum, thus more reliable on identified soft bottom habitats. A single sample per station was collected, typically accompanying a video transect or drop camera station (see Figure 3). They were dried in the oven and subsequently sieved with mesh sizes of 0.063, 0.25, 0.5, 2, and 64 mm following the size classes described in Wentworth (1922), that is, mud (silt and clay), fine sand, medium sand, coarse sand, gravel, and cobbles, respectively. Each sieved sediment fraction of each sample was weighted to define grain size class and percentage was calculated. Final sediment classes were assessed based on the majority fraction and adapted to follow the scheme of Gougeon et al. (2017), that is, R (class consisting of gravel and/or cobbles), gS, gM, and M (Figure 5; see also Krawczyk, Zinglersen, et al., 2019). Class "bedrock" cannot be identified from a grab sample.

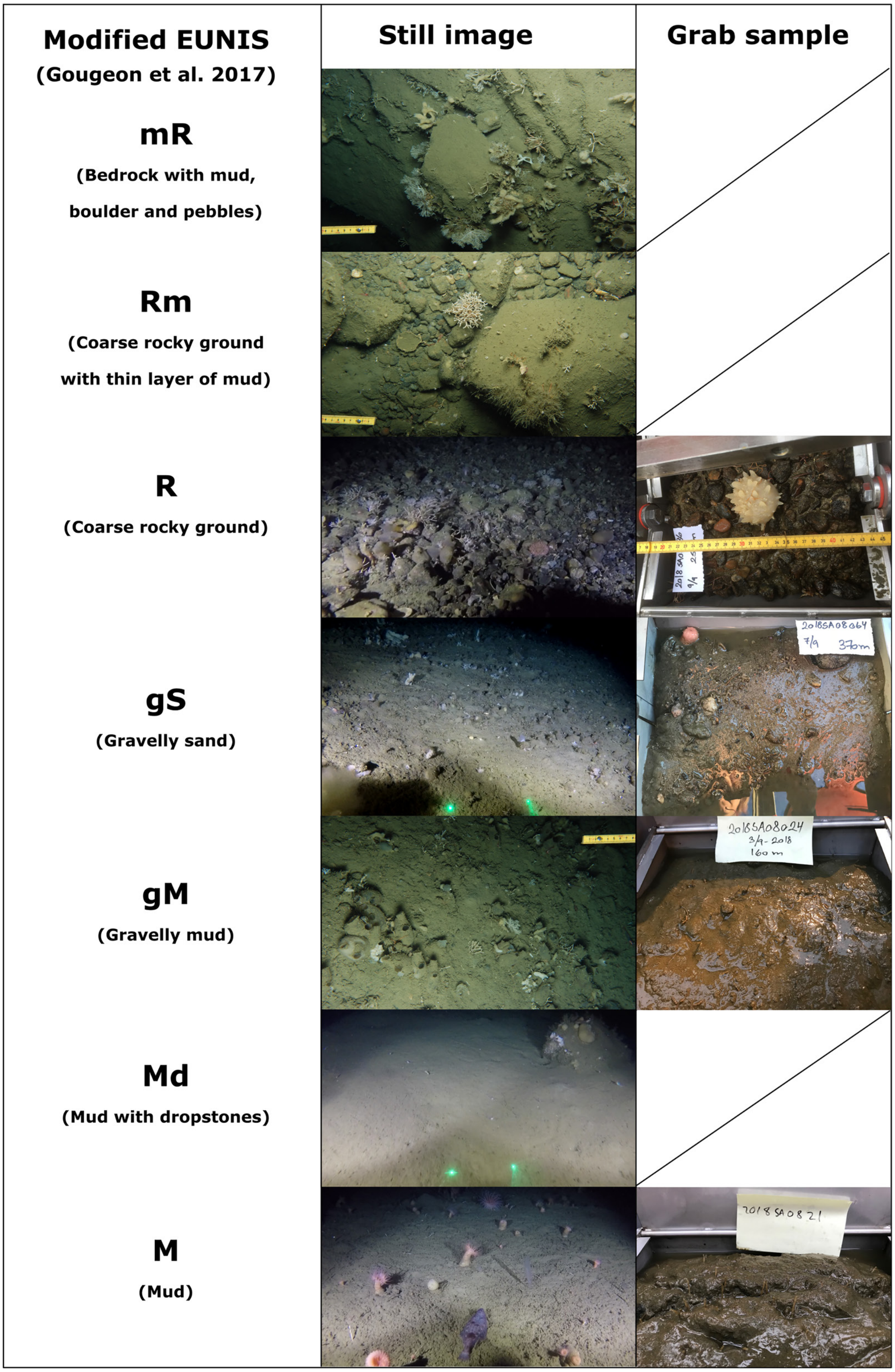

Figure 5. Images illustrating each of the seven sediment categories identified in Disko Bay pilot area, consisting of still images from drop camera/video sled and pictures of grab samples. Sediment categories follow the scheme of Gougeon et al. (2017).

3.3. Statistical Analyses

We registered benthic taxa that were identified consistently throughout the image material (see Table S1 in Supporting Information S1). Canonical Correspondence Analysis (CCA) was used to investigate the relationship between benthic taxa and environmental variables, that is, bathymetry (m), backscatter (dB), slope (degrees), broad BPI, and fine BPI. Prior to CCA, simple linear regression was performed for all combinations of environmental variables to test potential inter-correlation. The independence and relative strength of individual variables were estimated using CCA and a Monte Carlo permutation test (1000 permutations) in order to estimate the statistical significance (*p* values) of relationships between environmental variables and benthic taxa. CCA was carried out using the Addinsoft XLSTAT program.

Single-image presence-absence data of benthic taxa were combined into an estimate of "relative abundance" per camera station/transect. Bray-Curtis similarity of square-root transformed relative abundance data were used to build similarity matrices. To identify natural group structure in the samples, we applied a similarity profile test (SIMPROF). The SIMPROF routine conducts a series of permutation tests to find clusters of samples with statistically significant internal structure (*p* value set at 0.05). This was performed using Primer 6.

4. Results and Interpretation

4.1. Morphology

Bathymetry-derived grid of the area was classified using BTM classification (following procedure described in Wright et al., 2005) in order to produce a seafloor morphology grid for better understanding of the benthic environment and its topography. Four broad morphological classes were produced, that is, depression, crest, flat, and slope (Figure 6). These classes are used together with other parameters, such as the backscatter intensity and ground-truth sampling results to model the seabed habitat of the area. Depressions represent the deepest features in the area, mostly channels located below *c*. 350 m water depth (Figures 3 and 6). Crests and slopes dominate in the western section of the area and together with numerous depressions form rugged seafloor terrain (Figure 6). In contrast, vast flat areas cover mostly the eastern sector in two water depth intervals, that is, 150–300 m and 300–500 m (Figures 3 and 6). The shallowest area was identified in the southwestern part as slopes and flats in the range of 50–150 m water depth (Figures 3 and 6).

Ploughing of sediments by grounded iceberg keels has been observed in the study area. Iceberg ploughmarks are mostly located on the flats in the eastern part, where water depths range from 150 to 300 m (Figures 3 and 6). Ploughmarks in Disko Bay are typically shallow depressions with berms on either side of a narrow, v-shaped trough (Figure 7). These features typically range from tens of meters to several kilometers long, with widths of 10–70 m at the seabed, depths of up to 5 m and berm heights in the order of 1 m. The mean water depth in the Disko Bay region at which ploughmarks occur is 262 m (Thomson, 2011). Numerous bedrock ridges also characterize the eastern part of the area (Figure 6). Features resembling pockmarks have been identified in the eastern part of the study area as well, in the vicinity of tectonic faults (Figure 6). They mostly occur in clusters (Figure 7). Schumann et al. (2012) suggested that pockmark formation in Disko Bay is driven by dissociation of gas hydrates and their distribution may be related to faults, slides, or disturbance caused by iceberg-keel ploughmarks.

4.2. Sediments

Benthic images (597 stills) and sediment samples (17 samples) were used to assess the sediment types in the study area. Sediment classification was based on EUNIS-modified scheme (Gougeon et al., 2017) and in total, seven sediment classes were identified as shown in Figure 5 and Table S1 in Supporting Information S1. These classes were used to validate the backscatter intensity and translate the BM (dB) to a preliminary sediment map. We used the on-board generated unsupervised classification of the unprocessed BM, that is, simple histogram analysis using five classes based on natural breaks to crosscheck between original data and processed data. Expert interpretation was used to compare sediment type information obtained from ground-truthing with backscatter intensity in order to define the final sediment classes and their threshold (Figure 8). It should be noted that it is very difficult to distinguish between mud and sand in this area using

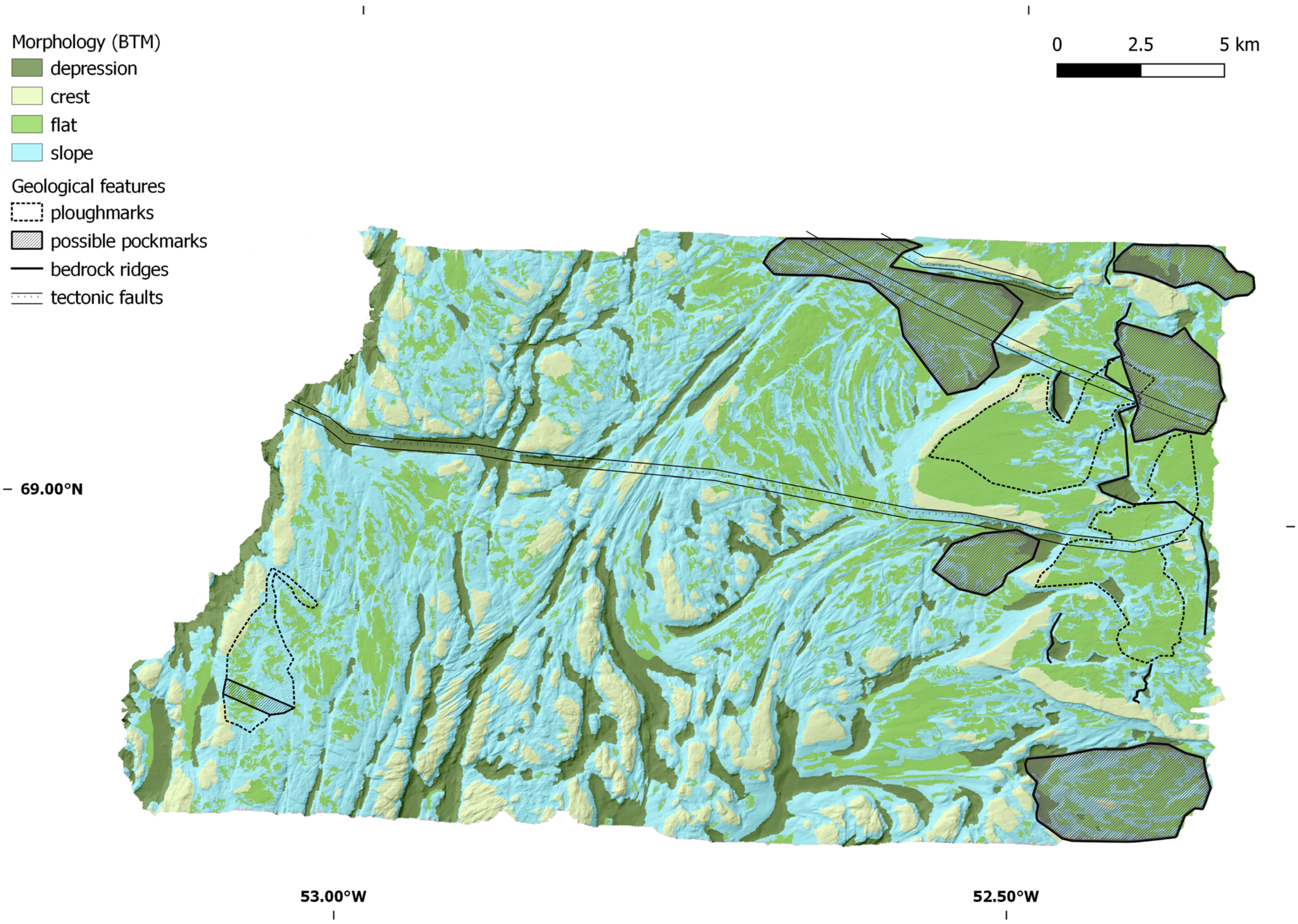

Figure 6. Morphology map showing distinct terrain features using broad BTM classification together with geological features identified in Disko Bay study area (Krawczyk, Jensen, et al., 2019). CRS: WGS 84.

solely camera footage, comprising majority of the data, thus we generalized fractions containing gravelly mud and/or gravelly sand, that is, gravelly mud/sand.

Finally, a preliminary sediment map was generated by reclassifying BM, followed by verification with ground-truthing (Figure 9). Backscatter may underperform in hard bottom areas, compared to soft bottom areas (Mohammadloo et al., 2017), thus it is recommended to validate classified sediment types with ground-truthing. The dominant fraction in the study area is mud and gravelly mud/sand. To a lesser extent, coarse rocky ground and bedrock are distributed mostly in southwestern area (Figure 9). There are some inconsistencies between the ground-truthing and reclassified BM, that is, coarse rocky ground was observed in part of the NW and SW area but backscatter intensity revealed gravelly mud/sand-like signal in the NW area, whereas bedrock-like signal in the SW part (Figure 9). This may result from different water depth strata (see Figure 3). Such hard bottom-backscatter inconsistencies may require further validation with other seafloor descriptors, such as slope (Bellec et al., 2017), which we have taken into account in generating the final benthic habitat map (Krawczyk, Zinglersen, et al., 2019). In addition, gas seeps were observed at stations corresponding solely to mud on a flat bottom (see Figures 6 and 9).

4.3. Benthic Communities

Benthic images also were used to assess benthic fauna of the Disko Bay pilot study area. The dominant taxa were recorded at the image level to record the habitat forming species in the area (see Table S1 in Supporting Information S1). 10 key benthic taxa were documented in this study: Actiniaria (mostly family

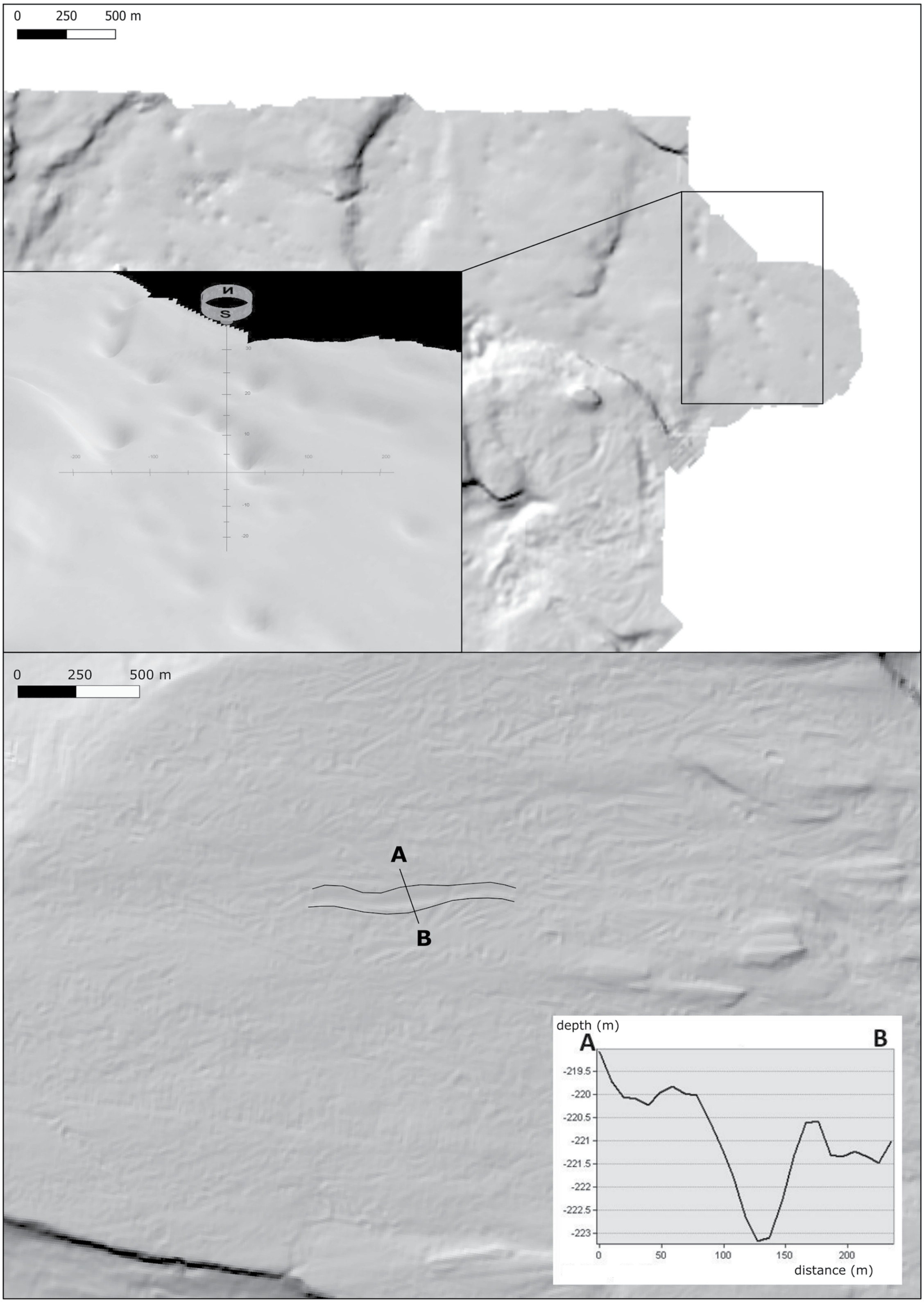

Figure 7. Examples of pockmarks (top) and iceberg ploughmarks (bottom) in the eastern part of the study area (hillshade terrain model). Insert image on top shows 3D terrain model of the NE corner of the study area.

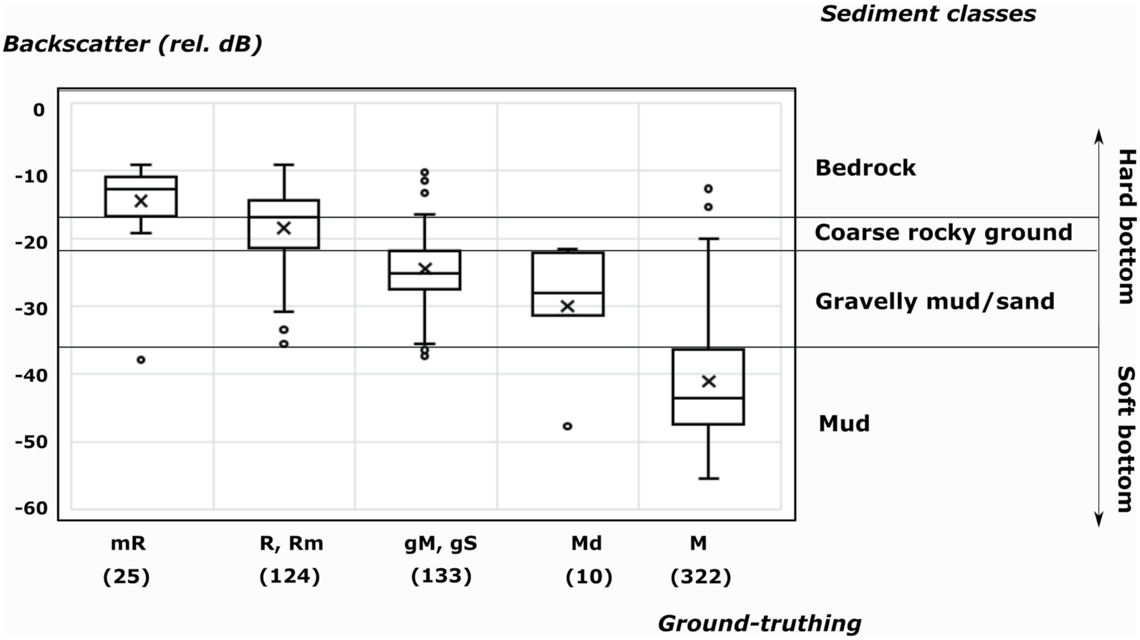

Figure 8. Box plot showing sediment classes identified from ground-truthing in relation to backscatter intensity (dB). Horizontal lines in boxes indicate median values and crosses are at mean values; boxes indicate quartiles, whiskers indicate standard deviation and black circles are outliers. Sample numbers for each category are shown in the brackets (bottom). Ground-truth labels: mR–bedrock with mud, boulder and pebbles, R–coarse rocky ground, Rm–coarse rocky ground with thin layer of mud, gS–gravelly sand, gM–gravelly mud, Md–mud with dropstones, M–mud.

Hormathidae), Alcyonaria (Nephtheidae), Ascidiacea solitary (mostly *Halocynthia*), Bryozoa erect (Horneridae, Tubiliporidae, and Myriaporidae), Bryozoa soft (Flustridae), Crinoidea (Antedonidae), Decapoda (*Pandalus borealis*), Holothuroidea (Cucumariidae), Polychaeta, and Porifera (a variety of large sponges including Polymastiidae, Geodiidae, Rosselidae).

A cluster analysis (Bray-Curtis) with SIMPROF test on similarity of taxon composition (relative abundances) indicated two main biotopes, which are driven by the underlying substrate. Polychaeta and Decapoda dominate the soft bottom, that is, mud. In areas with hard bottom, that is, mixed/gravelly/rocky seabed the dominant biota is a mixed selection of attached fauna, such as Bryozoa erect, Porifera, and Ascidiacea.

The ordination diagram of benthic taxa and independent environmental variables along the CCA Axes 1 and 2 is shown in Figure 10. Water depth (m) variable was excluded from CCA analysis as it was correlated with backscatter ($R^2 = 0.85$). For easier interpretation of the backscatter in CCA diagram, backscatter was additionally coded as "hard bottom" (0–(−36.4) dB) and "soft bottom" ((−36.5)–(−60) dB), based on image analysis (i.e., sediment categories; see Figure 8). CCA results show that the backscatter (hard bottom and soft bottom) explains the most variance in the data (26%). Slope, broad BPI and fine BPI have only minor influence on distribution of benthic taxa (1% each). The correlation of variables with Axes 1 and 2 indicates that backscatter and broad BPI are positively correlated with Axis 1 and slope with fine BPI are negatively correlated with Axis 2 (Figure 10). Benthic taxa can be divided into two communities, that is, biotope A plotting to the right and associated with hard bottom (i.e., high backscatter values) and biotope B plotting to the left and associated with soft bottom (i.e., low backscatter values) (Figure 10). Benthic taxa belonging to the "hard bottom" biotope A are Holothuroidea, Nephtheidae, Porifera, Ascidiacea, Bryozoa erect, Actiniaria, and Crinoidea and the ones belonging to the "soft bottom" biotope B are Decapoda, Polychaeta, and Bryozoa soft (Figure 10).

4.4. Benthic Habitats

The key seafloor descriptors delivered from multibeam data and verified with ground-truth samples were used to classify benthic habitats in Disko Bay pilot area (see Table S1 in Supporting Information S1), following the workflow described in Krawczyk, Zinglersen, et al. (2019). The following descriptors were used in

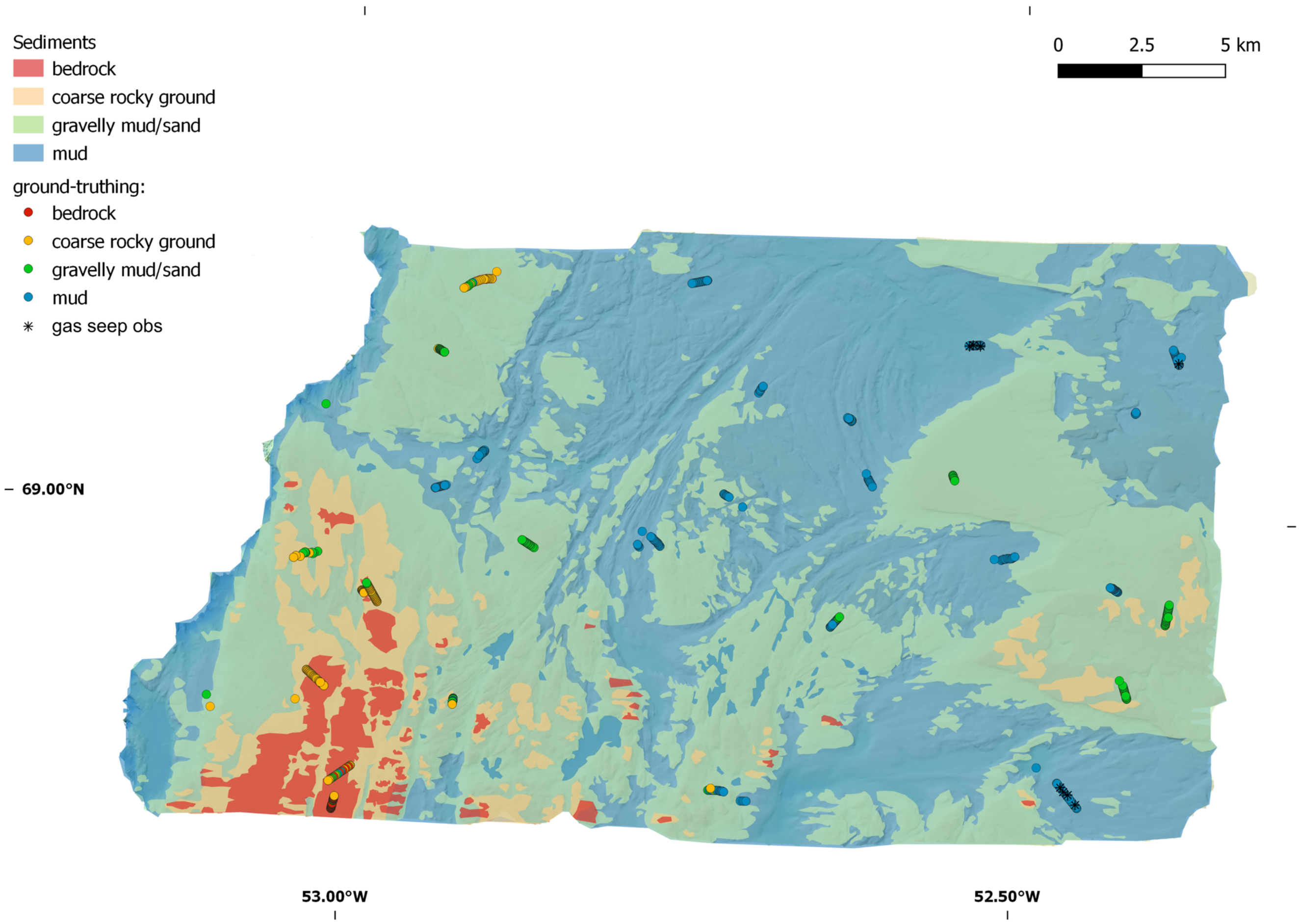

Figure 9. Backscatter-derived sediment map superimposed on a hillshade terrain model, showing distribution of identified sediment types in Disko Bay study area together with ground-truth stations and gas seep observations (see legend). CRS: WGS 84.

the mapping process, that is, bathymetry (water depth), morphology (including slope), backscatter-derived sediment types, and benthic communities. In addition, we included descriptive information on the general water mass characteristic in Disko Bay (Rysgaard et al., 2020), associated with the measured water depths in the study area and cross-checked with survey temperature loggers. Our data were compared with the existing geological data (Hofmann et al., 2016; Krawczyk, Jensen, et al., 2019; Streuff et al., 2017) to provide a more accurate interpretation of the geological setting and seabed sedimentation environment (see Figure 1). Altogether, we have distinguished five benthic habitats in the Disko Bay pilot area (Figure 11):

1. Rocky bank habitat–morphologically undulated terrain consisting of bedrock and coarse rocky sediments, most likely of metamorphic origin, that is, Precambrian Gneiss, covering shallow water area in the upper 150 m water depth; habitat influenced by surface Polar Water mass and represented by sessile fauna (biotope A). Habitat located in the SW part of pilot area
2. Coarse rugged habitat–area covering undulated terrain mostly consisting of gravelly mud/sand and admixture of coarse rocky ground (likely Precambrian Gneiss); habitat covers areas between 150 and 300 m water depth and is influenced predominantly by Polar Water. Habitat is represented by biotope A and spread throughout the pilot area
3. Sandy floor habitat–morphologically flat areas with dominant fraction of mixed gravelly mud/sand, most likely Cretaceous sandstone; habitat represented by biotope A in water depth interval of 150–300 m and influenced by Polar Water mass. Habitat located in the eastern part of pilot area. This habitat is associated with iceberg ploughmarks (Figure 6), which represent a natural disturbance of seabed integrity

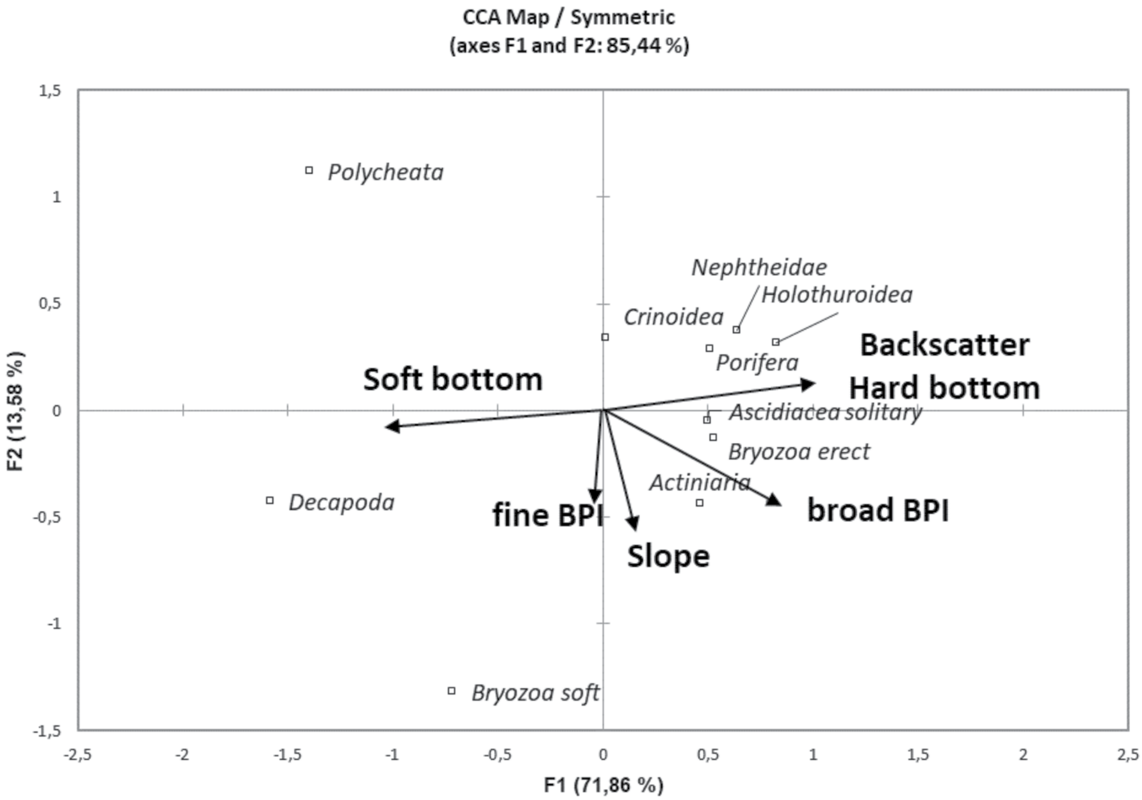

Figure 10. Ordination diagram of benthic taxa and independent environmental variables along two CCA axes. Groups plotting to the right are associated with hard bottom (i.e., biotope A) and groups plotting to the left are associated with soft bottom (i.e., biotope B).

4. Muddy rugged habitat–morphologically undulated terrain, dominated by mud in the water depth interval of 300–500 m; habitat represented by biotope B (shrimp/polychaetes) and influenced by the subsurface Subpolar Mode Water, also known as the sub-surface component of the West Greenland Current. Habitat spread throughout the pilot area
5. Muddy floor habitat with potential seeps–morphologically flat areas dominated by mud with numerous features resembling pockmarks (Figure 6) and gas seep observations (video footage; Figure 9); habitat represented by biotope B in deeper water, that is, 300–500 m water depth, influenced by the Subpolar Mode Water. Habitat located mostly in the eastern part of pilot area

5. Discussion and Conclusions

Our Disko Bay pilot study was designed to create the "best practice" protocol for a novel project in Greenland focused on high-resolution benthic habitat mapping. In the relatively small area, bathymetry and backscatter data were collected by the multibeam echo sounder. These remote sensing data were validated with ground-truthing, both physical and imagery in order to describe seafloor sediment environment. In addition to physical environment, epifauna were observed with video sled and drop camera and used to describe benthic communities. In this section we discuss the methods applied in this study for data collection and data gaps, the new habitat classification compared with other studies, and future plans for upscaling and broad-scale mapping in Greenland.

5.1. Data Collection and Data Gaps

Generally, a good agreement was achieved between the results obtained from the remote sensing method and the ground-truth samples. However, we observed some discrepancies. Imagery is dependent on the resolution of images, but is unlikely to differentiate sediment classes on the smaller end of the sediment

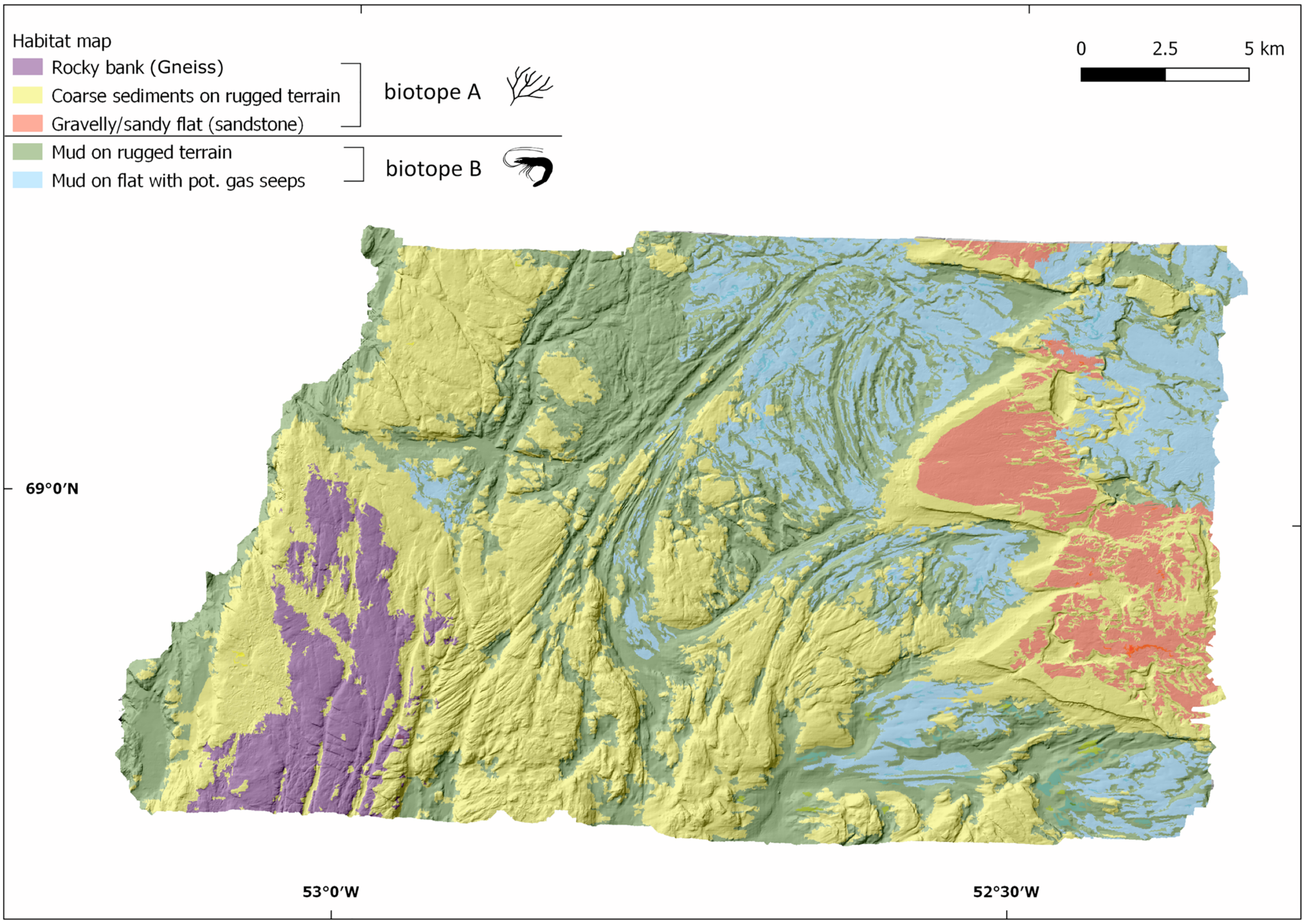

Figure 11. Benthic habitat map superimposed on a hillshade terrain model, showing distribution of identified habitats and associated biotopes in Disko Bay study area. CRS: WGS 84.

size scale and cannot reliably distinguish mud and sand classes. Thus, it is more reliable on the hard bottom habitats, such as large grain, surface-exposed sediments, like gravel and boulders. However, some hard-ground locations proved difficult to identify from imagery, particularly places where a thin surface sediment obscured underlying hard ground. This leads to conflicting signals from video ground-truthing and backscatter profiles, as the former picks up the visible surface where the latter shows the underlying substrata (i.e., SW study area, see Figure 9). This problem is exacerbated when classifying from extracted still photos, while watching entire video sequences can give a greater sense of the underlying substrata.

In contrast, the grab sampler is designed to collect sediments and operates best on areas at the smaller end of the grain size spectrum. Areas with cobbles or larger rocks often result in "failure" of the grab, as rocks get caught in the "teeth" leaving the grab partially open and allowing smaller sediments to wash through. Combining ground-truth methods is more time consuming but can often be worth the effort, particularly on intermediate seabed types where both methods can have difficulties.

Ideally, the benthic habitat mapping should be conducted with remote sensing instruments including surface mapping systems and sub-bottom profiling sediment echo sounders. The latter provides information on the deposition and erosion history, as well as the thicknesses of the deposited layers under the seafloor. In this study the sub-bottom profiler data were not available. However, geological information from previous studies (i.e., Hofmann et al., 2016; Hogan et al., 2012) for the area north of our pilot study area were used to build an idea on the geological setting and the geological model of the area. The interpretation from previous study and from the new dataset obtained in this pilot study were compared and showed a good agreement in the overlapping areas (for details see Krawczyk, Jensen, et al., 2019).

5.2. Habitat Classification

In this study we combined abiotic map layers to provide a model representing primarily physical properties of benthic environment, and biotic information were used to check and rectify the relationship between biota and the modeled physical environment. We followed the two basic assumptions that were used to define boundaries between different habitat types, (i) environmental gradients show discontinuities and (ii) distinct benthic communities can be paired with distinct environmental factors (Lurton & Lamarche, 2015). Synthesis of layers was first subject to unsupervised classification (simple histogram analysis), followed by supervised classification, that is, verification with ground-truth data and manually digitizing of physical habitat classes and community-level entities.

The generally small pilot area (*c.* 30 × 20 km) shows highly complex topography with rather mixed sedimentary environment and composed of two different geological units, Precambrian Gneiss and Cretaceous sandstone (Figure 11). This benthic environment was shaped by depositional dynamics, tectonics and glacial transgression/regression (Hogan et al., 2012) producing morphologically complex features at different depths. Five benthic habitat classes clearly reflect the bathymetric, topographic and sedimentary complexity of the area (Figure 11). The two identified biotopes, (1) sessile fauna and (2) shrimp/polychaetes cover approximately half to half of the studied area. These benthic communities are associated with sediment types, where sessile fauna represent hard bottom and shrimp/polychaetes represent soft bottom.

In order to compare the mapped seabed habitats in Greenland shelf region with the standard European Union habitat classes, we applied EUNIS classification (Davies et al., 2004) to our pilot area. The EUNIS classification has already been successfully used in describing surface substrate of Greenland's seabed in a broad-scale study by Gougeon et al. (2017). That study spanned *c.* 1.500 km of the western shelf using a coarse grid with pixel dimensions of 3500 × 3500 m. In contrast, our high-resolution grid has dimensions 10 × 10 m and spans around 10 × 5 pixels on the Gougeon grid. This scale mismatch limits the value of direct comparison, but there is broad agreement in that the majority of the region is classed soft sediment (mud/gravelly mud), while the SW section is differentiated as rockier substrates (see Figure S1 in Supporting Information S1). Nevertheless, the results of our comparison revealed that the EUNIS classification scheme considers areas >200 m water depth as deep-sea habitats and offers three habitat classes matching our ground-truthing interpretation, that is, (A6.1) deep-sea rock and artificial hard substrata, (A6.2) deep-sea mixed substrata, and (A6.5) deep-sea mud (see Krawczyk, Zinglersen, et al., 2019). Thus, the EUNIS scheme falls short of classifiers to describe benthic habitats and highly complex topography in Greenland shelf region; it is however a useful reference for classifying sediments after some modifications.

Using comparison and adaptions of the existing standardized seabed (habitat) classifications, such as EUNIS, US Coastal, and Marine Ecological Classification Standard (CMECS, 2012) and British Geological Survey two-part classification (Bradwell et al., 2016), we have developed seabed habitat classification suitable for Greenland shelf region, that is, Greenland Ocean floor Classification of Habitats (GOCH; Krawczyk, Zinglersen, et al., 2019). This classification focuses on the highly complex topography and sedimentary environment of the glaciated Greenland shelf, prioritizing the detailed geophysical information from the high-resolution multibeam data. GOCH is composed of five key factors (descriptors) defining/shaping the benthic environment (Figure 12):

1. (Geo)morphology (seafloor structure)
2. Sediments (seafloor texture)
3. Oceanography (water masses)
4. Chemistry (chemical conditions)
5. Biota (benthic fauna)

1. (Geo)morphology factor includes general and more region-specific information on underwater landforms (=morphology) derived from acoustic bathymetry data and their post-analyses; future work will include geological interpretation of the features (=geomorphology) and in-depth information on seabed geology using sub-bottom profiler data
2. Sediment factor is based on analyses of ground-truthing samples used to classify and validate acoustic backscatter data combined with acoustic sub-bottom profiling from a neighboring region (i.e., Hogan

Factor 1		Factor 2		Factor 3		Factor 4	Factor 5	Region	Subregion	Habitat
Morphology	Geomorphology	Sediment type	Genesis	Bathymetry	Water mass	Chemistry	Biota			
Flat Mound Slope	Bank	bedrock, coarse rocky ground	Gneiss	<200m	Polar Water		ascidians, sponges, soft corals, sea cucumbers, bryozoans	shelf	Disko Bay	**Rocky bank**
Flat	Iceberg ploughmarks	gravelly mud/sand	Sandstone	150-300m	Polar Water		ascidians, sponges, soft corals, sea cucumbers, bryozoans	shelf	Disko Bay	**Sandy floor**
Mound Flat Slope Valley		bedrock, coarse rocky ground, gravelly mud/sand	Gneiss, Sandstone	150-300m	Polar Water		ascidians, sponges, soft corals, sea cucumbers, bryozoans	shelf	Disko Bay	**Coarse rugged**
Mound Slope Valley		Mud		300-500m	Subpolar Mode Water		shrimp, polychaetes	shelf	Disko Bay	**Muddy rugged**
Flat		Mud		300-500m	Subpolar Mode Water	gas seeps	shrimp, polychaetes	shelf	Disko Bay	**Muddy floor/gas**

Figure 12. Example of classified benthic habitats with the description of the key factors using GOCH in the Disko Bay pilot study.

et al., 2012; Hofmann et al., 2016); future work will include sub-bottom profiler data collected simultaneously with multibeam data

3. Oceanography factor is strongly linked to bathymetry data and is based on the number of oceanographic studies describing key water masses around Greenland (most recently Rysgaard et al., 2020) and validated with the CTD profiles
4. Chemistry factor includes observations of chemical processes at seabed (e.g., video footage), such as gas seeps; future work will include additional geochemical analyses of sediments, such as organic material content and other chemical compositions that influence habitat spatial extent and distribution
5. Biota factor includes presence/absence of the key benthic epifauna identified from underwater footage and trawl surveys

5.3. Upscaling

Our habitat classification will be subject to continuous improvements based on the new incoming data and information collected during the ongoing surveys. Next step in the process will focus on upscaling the new high-resolution habitat map for the entire Disko Bay region to provide meaningful knowledge on the potential distribution of shrimp habitat, as well as possible vulnerable species for a future application in seafloor management plans to sustainably use the oceans and marine resources in Greenland. Further efforts of the Greenland mapping classification will involve the use of sub-bottom profiling to obtain geological information and extending the research area to off the continental shelf in order to provide more information on the deep-sea environment and habitats. The new Greenlandic R/V Tarajoq is already equipped with deep water multibeam and sub-bottom profiler which will be utilized in the long-term mapping strategy. This strategy will implement the "best practice" protocol to generate broad-scale, high-resolution benthic habitat maps, and seafloor models, following the examples of the large European programs (e.g., MESH, 2004), to be applied in strategic areas for the end-users in Greenland, such as marine resources management, commercial fisheries, and Marine Spatial Planning authorities.

Data Availability Statement

All ground-truth data along with corresponding measurements and analyses used in this study are provided in Table S1 in Supporting Information S1. Table S1 in Supporting Information S1 together with the gridded multibeam data, that is, bathymetric ESRI ASCII grid and backscatter ESRI ASCII grid (10 × 10 m resolution) are deposited at PANGAEA data archiving and publication (PDI-28870; DOI:

https://doi.pangaea.de/10.1594/PANGAEA.935642). Bathymetric grid (100 × 100 m resolution) was also submitted to the International Bathymetric Chart of the Arctic Ocean; IBCAO (http://seabed.geo.su.se/ibcao).

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