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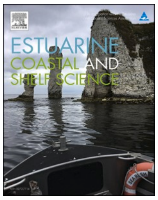

Seafloor habitats across geological boundaries in Disko Bay, central West Greenland

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ABSTRACT

In this paper we describe seafloor terrain of nearly the entire Disko Bay region and provide scientific baseline information about surface geology and sedimentary environments that can support the seafloor management plan in Greenland. Our study utilized multiple datasets of multibeam bathymetry and backscatter, seismic profiles and ground-truthing consisting of video footage from drop camera and benthic video sled, as well as sediment samples from grab and corers. Our results revealed that the key geological units in Disko Bay characterize the scale of geomorphic features, which in turn affects the distribution and complexity of habitat zones. The NE sub-region is underlain by Cretaceous sandstone and characterized by large-scale landforms, mainly vast flat areas draped by glacial lineations, bedrock ridges and pockmark fields. This setting promotes less topographically complex habitats, i.e. coarse plain, muddy/sandy plain with dropstones, and muddy plain. The SW sub-region is characterized by Precambrian Gneiss and Paleoproterozoic metasedimentary rocks with complex system of small-scale geomorphic features, such as cross-cutting channels. This results in topographically complex habitats in the area, such as rocky bank, coarse rugged terrain, and rocky slopes. Two distinctive habitat areas, associated with potential gas seeps, i) southern pockmark field and ii) western zoanthid-sponge wall, were discovered at the geological boundary separating the two sub-regions. Our study highlights the importance of seafloor habitat mapping and analyses by providing fundamental geophysical knowledge necessary to comply with long-term sustainable use of marine resources in Greenland.

1. Introduction

The seafloor topography of the glaciated shelf of Greenland reveals a wide variety of landforms and structures formed by geological processes and past ice stream activity associated with dynamics of the Greenland Ice Sheet (GrIS). During the Last Glacial Maximum (c. 21.000 yrs BP), GrIS extended to the adjacent continental shelf break and since then the ice sheet has lost approximately 40% of its area and volume (Funder et al., 2011). The retreat and re-advances of ice streams and outlet glaciers associated with glacial and interglacial cycles have shaped the geomorphology of the continental shelf, broadly characterized by alternating system of deep troughs and shallow banks (Ryan et al., 2013; Hogan et al., 2016; Hofmann et al., 2016).

Disko Bay forms one of the Greenland's largest paleo-ice stream outlets with a seafloor characterized by a large dendritic system of paleo-channels of the ancestral Jakobshavn glacier, spanning hundreds of kilometers across the shelf (Brett and Zarudzki, 1979). The Jakobshavn glacier underwent major fluctuations since the Last Glacial Maximum (Hogan et al., 2016). Recent studies (Hogan et al., 2012; Streuff et al., 2017) suggest a rapid retreat of the glacier into central Disko Bay by c. 10.600 yrs BP with a subsequent slower retreat through eastern Disko Bay, based on seafloor topography likely related to erosion of grounded glaciers. During the Holocene thermal optimum (c. 7.600–7.100 yrs BP) the ice sheet retreated behind its present margin into Ilulissat Icefjord (Weidick et al., 1990). Presumably, the variation of the Jakobshavn glacier reflects the overall drainage and mass balance of the central western GrIS, similarly to the present-day ice flow near Ilulissat Icefjord (Hogan et al., 2016).

The Disko Bay of West Greenland forms a geologically and topographically complex region that is ideally suited for investigating

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linkages between Arctic benthic habitats and physiographic conditions of the seafloor (Hogan et al., 2012; Krawczyk et al., 2021). A better understanding of how marine seafloor environment and associated biodiversity relate to geology and geomorphology is highly important in terms of present-day concerns of ocean-climate change and the stability of the GrIS. Moreover, given the impact of commercial fishing on seafloor integrity and habitats of Disko Bay there is a need for seafloor habitat studies that can support a sustainable use of marine resources (Yesson et al., 2017). A Canadian study by Todd and Kostylev (2011) have shown a link between geological environments of German Bank seabed and associated benthic habitats providing a scientific context for the management plan of a scallop fishing ground in Canada. Investigating seafloor habitats is required for the improved understanding of environmental drivers enabling predictive models to estimate wider distributions and inform Marine Spatial Planning (e.g. Brown et al., 2011). Thus, benthic habitat mapping is the necessary tool providing crucial information on physical environment and biota aiding the environmental and economic sustainability.

In this study, we combine the historical and new datasets of spatial geophysical measurements (seismic and multibeam) and of ground-truthing sampling (sediments and partly benthic fauna) to delineate different geological units and features of the complex seafloor environment of the Disko Bay region. Subsequently, we discuss and compare the geomorphic elements, or geodiversity to the existing, general biological information in the area. We followed the hypothesis and approach proposed by Harris and Baker (2012), stating that geomorphic features, such as submarine canyons, sandy banks or fjords are typically associated with specific types of benthic habitats. They underline that the natural diversity of seabed geological features has a value of its own and should be included in seabed management plans. The recommended approach requires the comparison of both physical and biological data as a key element of a case study. In classifying the habitat zones, we primarily focus on the physical elements of seafloor, i.e. water depth, terrain features and bedrock/sediment types. Secondary, a rough identification of benthic communities was carried out only for the selected areas, i.e. extreme slopes, following the assumption that steep slopes will promote high biodiversity, compared to more flat areas affected by benthic trawling, as observed during the recent monitoring and research cruises around Greenland (e.g. Yesson et al., 2017; Long et al., 2021).

This paper provides a new seafloor habitat map for a large area of Disko Bay with description of geological structure, geomorphic features and sedimentary environment providing a background map for biodiversity hotspots and fishing grounds in the West Greenland region. We illustrate the applicability of seafloor habitat characterization through examples of benthic fauna observations, seismic profiles, and mapping of geomorphic features. The integration of both faunal and physical (geology, geomorphology) parameters in benthic habitat characterization can improve the basis for building benthic habitat suitability models and their utility for environmental management.

2. Physiographic setting

Disko Bay is a large, open marine bay (68°30′ N and 69°15′ N and 50°00′ W and 54°00’ W, Fig. 1) located in central West Greenland. The overall geological setting is represented by three main units, which can be found both onshore and offshore, i.e. Precambrian rocks in the

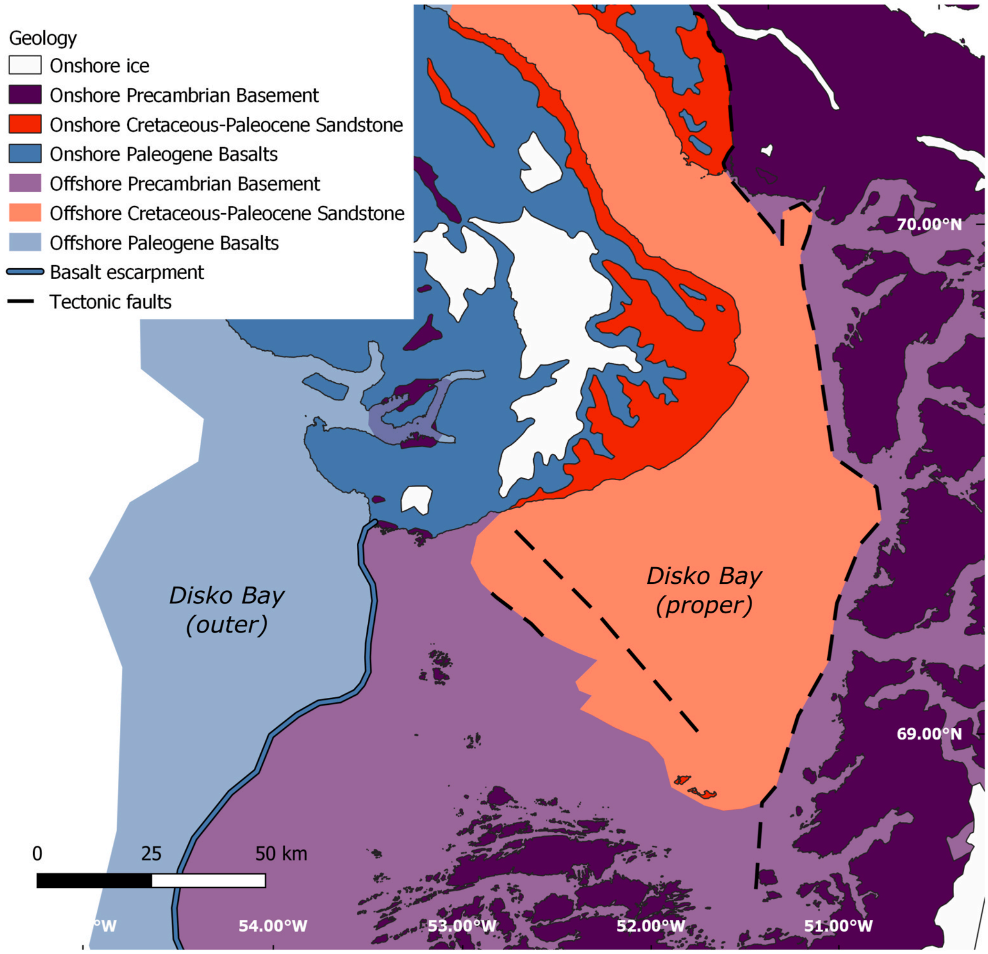

Fig. 1. Geological setting of the Disko Bay region (modified from Nielsen et al., 2014). Coordinate Reference System (CRS): WGS 84/NSIDC Sea Ice Polar Stereographic North.

southwestern area, Cretaceous sandstone in the central and eastern area and Paleogene Basalts to the west (Fig. 1). The regional bedrock tectonics reveal a strike-slip wrench tectonic system with a prominent fault pattern (Wilson et al., 2006). The terrain topography of the Disko Bay region is largely modified by glacial processes. The Precambrian terrain is dominated by an abraded streamlined terrain with fast ice flow lineations (Whaleback and Roche moutonée), whereas the Cretaceous sandstone, as a softer sedimentary-layered bedrock type, shows a more homogeneous, continuous morphology between the faults with outcropping bedrock ridges (Dam et al., 2009). These have a relief of several tens of meters to about 100 m and have been streamlined by glacial ice (Hogan et al., 2012).

The near-surface Quaternary succession of Disko Bay is dominated by proximal glacial deposits, overlain by a Holocene mud blanket (Krawczyk et al., 2019a). Lodgment till, sandy diamicts and glacimarine mud are commonly observed and associated with sediment gravity flows and intense meltwater activity during the last deglaciation of the GrIS. These mass-flows reworked glacimarine mud and ice rafted debris down the slopes of submarine basins, which are currently delineated by bedrock and local topography (Lloyd, 2006; Streuff et al., 2017; Krawczyk et al., 2019a).

In Disko Bay proper, the seabed depth mostly varies between 300 and 500 m, with a U-shaped deep trough, Egedesminde Deep (>900 m water depth) bounding the western side of the 'proper' bay to the southwest (Fig. 2A) (Buch, 2000). The outer Disko Bay is mostly shallow water banks within the depth range of 50–300 m (Fig. 2A). Present-day oceanographic conditions are governed by seasonal sea ice cover, the West Greenland Current and freshwater input from the GrIS (Boertmann et al., 2013). The relatively warm and saline Atlantic-sourced water from the West Greenland Current enters the bay from the south and leaves both to the north (via Vaigat Strait) and south of Disko Island (Söderkvist et al., 2006; Hansen et al., 2012) (see Fig. 2A). This Atlantic-sourced water is also known as the Subpolar Mode Water (Rysgaard et al., 2020) and is found below the cold and low-saline Polar Water, i.e. below the upper *c.* 200 m (Tang et al., 2004). Regionally, the oceanographic conditions can change dramatically, such as along steep slopes and narrow submarine canyons to more shallow areas. The freshwater runoff from melting sea ice and glaciers during summer introduces significant vertical and horizontal salinity gradients throughout the system (Hansen et al., 2012). Icebergs originate from calving outlet glaciers, mainly through Ilulissat Icefjord (a UNESCO world heritage site) and Torsukattak (Buch, 2000) (Fig. 2A). These major tidewater glaciers seem to be influenced by the inflow of the West Greenland Current (Holland et al., 2008; Rignot et al., 2010). During autumn-winter, the oceanographic structure changes to a rather well mixed water column due to the wind and cyclone activity (Andersen, 1981).

3. Materials and methods

The datasets used in this study are a compilation of multibeam data, seismic data and ground-truthing from novel and various historical surveys (Fig. 2B). Table 1 summarizes overall information on all datasets described below. A list of all ground-truthing locations with information on gear, depths and annotations is provided in Table A1.

3.1. Multibeam data

Four sets of multibeam data, which were collected during four different cruises: GN, BAS, IOW, NASA over the last two decades, were included in this study (Table 1; Fig. 2B). All sets provided detailed information on bathymetry, whereas one set (GN) provided additional information on backscatter (Figure A1-A2); water column data were not collected during the cruises.

GN, BAS and IOW surveys combined continuous multibeam data acquisition with intermittent stops for collection of ground-truth data. GN and BAS surveys have covered the largest areas of Disko Bay region of 2157.81 and 5557.63 km^2, respectively. Detailed information on acquisition settings (e.g. operating frequency is given in Table 1), positioning, sailing speed, and calibrations for GN surveys can be found in the 'best practice' report (Krawczyk et al., 2019b, 2021), and for BAS, IOW and NASA surveys in the respective cruise reports (Hogan and Ó Cofaigh, 2019; Harff et al., 2016; OMG Mission, 2020).

GN, BAS and IOW datasets were available as original measurements

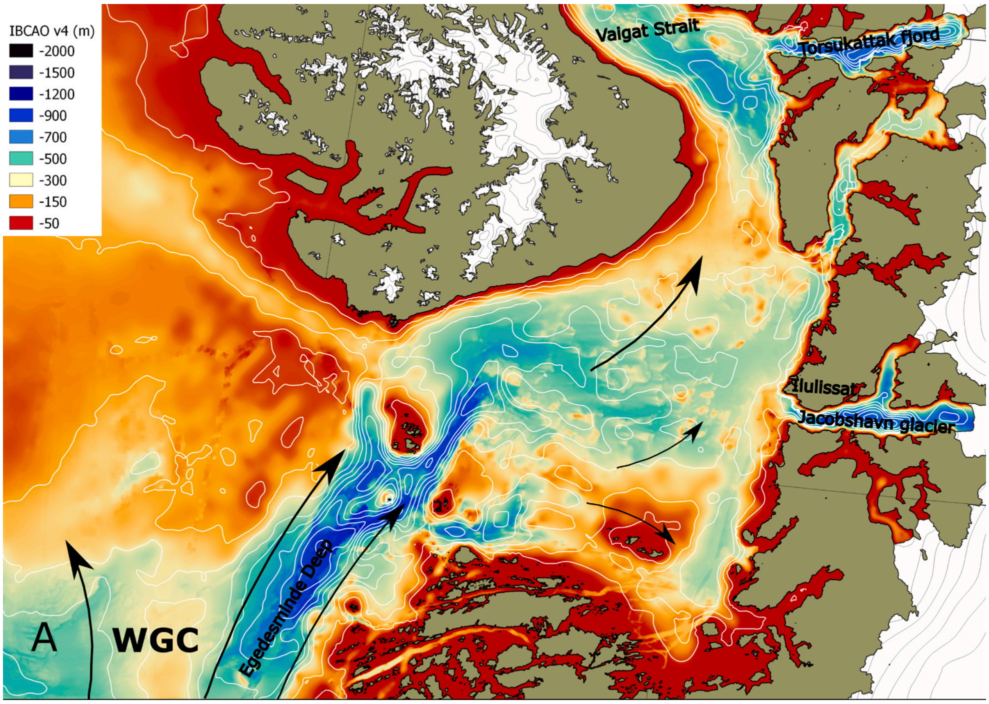

Fig. 2A. Broad-scale, low-resolution bathymetry map (water depth) of the Disko Bay region for reference (IBCAO v4; Jakobsson et al., 2020). The approximate route of the West Greenland Current (WGC) is indicated. Coordinate Reference System (CRS): WGS 84/NSIDC Sea Ice Polar Stereographic North.

Table 1
A list of all datasets used in this study, including data type, corresponding cruise and sampling gear, data resolution and data source (report/reference).

Dataset	Data type	Cruise (Year)	Gear	Data/resolution	Source/Reference
Multibeam	bathymetry and backscatter	RV Sanna (2018–2019)	Teledyne SeaBat T50 ER (fq = 180 kHz)	25 × 25m grid	Grønlands Naturinstitut (GN); Krawczyk et al. (2021); this study: Figure A1-2
Multibeam	Bathymetry	RRS James Clark Ross (2009)	Kongsberg EM120 (fq = 12 kHz)	25 × 25m grid	British Antarctic Survey (BAS); Hogan and Ó Cofaigh (2019)
Multibeam	Bathymetry	RV Maria S Merian (2007)	Kongsberg EM120 (fq = 12 kHz)	50 × 50m grid	Leibniz-Institut für Ostseeforschung Warnemünde (IOW); Harff et al. (2016)
Multibeam	Bathymetry	MV Cape Race (2015)	Teledyne SeaBat 7160 (fq = 44 kHz)	50 × 50m grid	The National Aeronautics and Space Administration, Jet Propulsion Laboratory (NASA); Fenty et al. (2016); OMG Mission (2020)
Seismic	multichannel seismic profiles	Danish Navy Thetis (1995)	Single airgun array; digital streamer (240 channels)	GGU/95-1 and GGU/95-2 lines	Geological Survey of Denmark and Greenland (GEUS); Chalmers et al. (1998)
Ground-truthing	GoPro video/stills	MT Paamiut (2017)	Video sled	7 transects	Grønlands Naturinstitut, Zoological Society of London (ZSL); Krawczyk et al. (2021); this study: Table A1
Ground-truthing	GoPro video/stills	RV Sanna (2018)	Video sled	12 transects	Grønlands Naturinstitut, Zoological Society of London; Krawczyk et al. (2021); this study: Table A1
Ground-truthing	GoPro video/stills	RV Sanna (2018–2019)	Drop camera	72 deployments	Grønlands Naturinstitut, Zoological Society of London; Krawczyk et al. (2021); this study: Table A1
Ground-truthing	Sediment samples	MT Paamiut (2014)	Grab	9 samples	Grønlands Naturinstitut; Krawczyk et al. (2017); this study: Table A1
Ground-truthing	Sediment samples	RV Sanna (2018–2019)	Grab	54 samples	Grønlands Naturinstitut; Krawczyk et al. (2021); this study: Table A1
Ground-truthing	Sediment samples	RV Dana (2000)	Piston corer	1 sample	Geological Survey of Denmark and Greenland; Kuijpers et al. (2001); this study: Table A1
Ground-truthing	Sediment samples	RV Maria S Merian (2007)	Gravity corer/multicorer	2 samples	Leibniz-Institut für Ostseeforschung Warnemünde; Harff et al. (2016); this study: Table A1
Ground-truthing	Sediment samples	RRS James Clark Ross (2009)	Vibrocorer	12 samples	British Antarctic Survey; Streuff et al. (2017); this study: Table A1

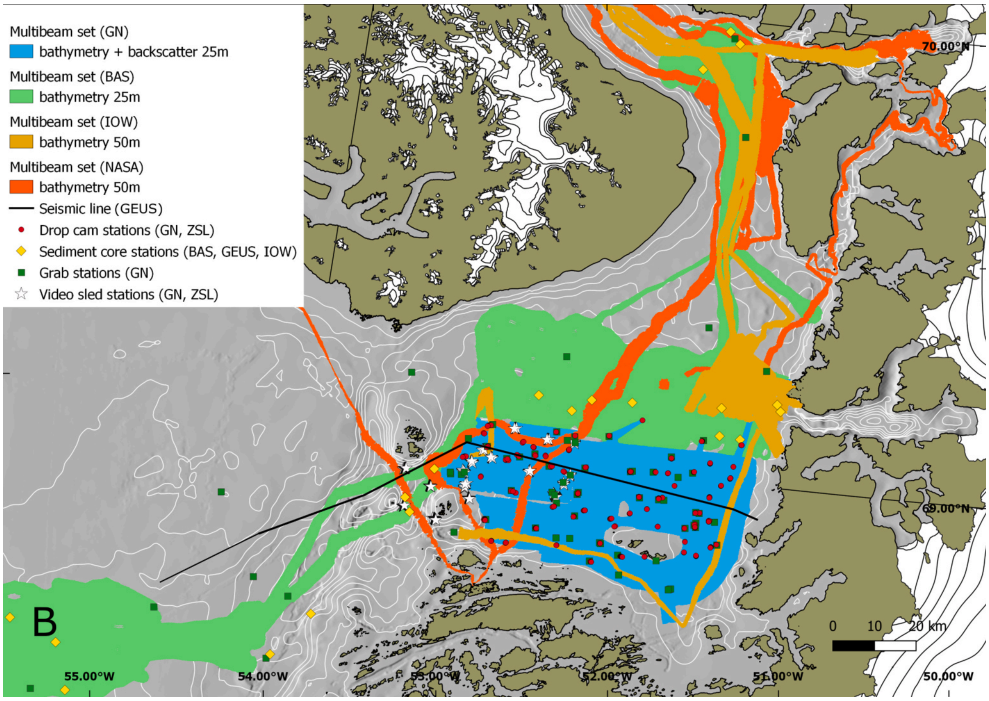

Fig. 2B. Geological and geophysical datasets used in this study. Shortcuts in legend: GN - Grønlands Naturinstitut, BAS - British Antarctic Survey, IOW - Leibniz-Institut für Ostseeforschung Warnemünde, NASA – The National Aeronautics and Space Administration, ZSL - Zoological Society of London, GEUS - Geological Survey of Denmark and Greenland.

in .xyz point cloud format and were further gridded and exported to ESRI ASCII grid format (.asc) at a resolution of 25 × 25 m or 50 × 50 m, depending on quality (in Table 1). NASA dataset was available as gridded points (.asc) with a resolution of 50 × 50 m. All multibeam data were modelled in Teledyne software PDS (Teledyne, 2019), gridded and analyzed in QGIS (QGIS Development Team, 2022) and ArcGIS (Walbridge et al., 2018) software.

3.2. Seismic data

The study area is covered by widely spaced 2D seismic-reflection lines collected by GEUS in 1995 (then GGU) (Table 1; Fig. 2B). A seismic interpretation was carried out using conventional stratigraphic principles (Mitchum et al., 1977) with particular focus on the seabed and sub-seabed reflection patterns. The GGU-95 survey in Disko Bay was acquired using a sleeve-gun source and a 240-channel digital receiver array (Christiansen et al., 1996). The data were processed to yield 3x32 fold migrations with a 12.5 m trace spacing. Seismic interpretation was carried out using the Petrel 2019 software platform (www.software.slb.com).

3.3. Ground-truthing

Ground-truthing samples were collected throughout seven cruises, most of which were collected by GN. Ground-truthing consists of drop camera deployments, video sled transects, surface sediment samples collected with piston corer, gravity corer, multicorer, vibrocorer, and grab (Table 1; Fig. 2B). These data are used to validate any interpretation of the multibeam data, as well as characterize seafloor environment and habitats. Detailed information on sediment core lithologies and geochemical analyses are described in Kuijpers et al. (2001), Harff et al. (2016) and Streuff et al. (2017).

Underwater imaging systems (72 drop camera deployments and 19 video sled transects; GN, ZSL), equipped with GoPro camera and 1–2 Nautilux torches (GroupBinc) and georeferenced using ships GPS, were used to extract still photos (Long et al., 2020). The drop camera employed a yo-yo sampling protocol, drifting for 1 min. (c. 30–50 m) between drops, employed at undulating/sloping terrain, unsuitable for a towed sled. Stills were examined at the point the camera touched the seabed (Yesson et al., 2017). The video sled was used for flat seabed, taking a continuous video 1 m above the seabed for 15-min transects with stills taken at 30 s intervals (Long et al., 2020). Each still was classified into sediment classes following the EUNIS-modified seabed classification scheme (Gougeon et al., 2017; Krawczyk et al., 2021). Table A1 shows all sediment types for all stations, as well as final sediment classes identified in Disko Bay area: 1) Bedrock (with admixtures of boulders, pebbles and mixed sediments), 2) Coarse rocky ground (with admixtures of mixed sediments), 3) Gravelly sand/mud, 4) Mud with dropstones (i.e. observed at the seafloor surface), and 5) Mud. In addition, observations of apparent gas seeps were recorded, where continuous plumes of fluid emerging from muddy seabed were observed in videos (following Krawczyk et al., 2021). Selected stations identified during cruises as ‘vertical slopes’ or ‘rock walls’, i.e. areas covering slopes steeper than 45°, were inspected for presence of benthic communities, based on dominant, habitat-forming taxa (after Nicoll, 2020).

Physical samples of surface sediment were collected by GN with grab (63 samples) and by BAS, GEUS and IOW with sediment cores (15 top core samples). Samples were subject to visual description of sediment type. In addition, some samples were dried and subject to grain size analysis using the available mesh sizes and following the size classes described in Wentworth (1922) (see Table A1). Identified sediment classes were labeled as silt and clay (mud), fine sand, medium sand, coarse sand, gravel, and cobbles. Final sediment classes were adapted to the above-mentioned sediment classes obtained from the underwater imaging (Table A1).

3.4. Classification

All multibeam data were used to generate 3D terrain models and bathymetry grids, which were used to generate seafloor environmental descriptors with Benthic Terrain Modeler (BTM) toolbox in ArcGIS software. The BTM toolbox produces morphology maps by combining several layers, including bathymetry, broad scale Bathymetric Position Index (BPI) (default settings of inner radius 25 units and outer radius 250 units), fine scale BPI (default settings of inner radius 3 units and outer radius 25 units) and slope (Wright et al., 2005). We used a classification dictionary consisting of eight classes, i.e. narrow depression, depression, local crest in depression, crest, local depression on crest, narrow crest, flat, and slope (Krawczyk et al., 2021). All bathymetry and bathymetry-based slope grids together with backscatter grids were classified using unsupervised classification, i.e. histogram analysis using natural breaks in ArcGIS software, followed by expert judgement to validate multibeam-derived classes with sediment classes identified from ground-truthing (see chapter 3.3.). Further, the classified multibeam data were combined and validated with morphology map, seismic data, and again ground-truthing data to produce final habitat classes following the Greenland Ocean floor Classification of Habitats (GOCH; Krawczyk et al., 2021).

4. Results and interpretation

4.1. Bathymetric data

Water depth (m) of the studied region varies between several to tens of meters in coastal and near-island areas to c. 1100 m in the deepest point of Egedesminde Deep, in its middle section (Fig. 3). Average water depth of this deep channel is c. 800–900 m. The second deepest area is in the northern part of Diso Bay, i.e. Torsukattak fjord (average of c. 700–800 m water depth), then the entrance to the Vaigat Strait (c. 600 m water depth). The Disko Bay is connected to the Vaigat Strait via a shallower plain of c. 250 m water depth (Fig. 3). Medium water depth, between 400 and 600 m covers a large part of the central Disko Bay (Fig. 3). The southern Disko Bay area displays the largest shallow water areas (less than 200 m water depth) (Fig. 3). Most of the mapped area lies within the 250–450 m water depth interval.

4.1.1. Seafloor characteristics

All bathymetry data were used to produce morphology map (BTM classification) to inspect seafloor topography and describe seafloor environment (Figs. 4–5). Morphological classes were homogenized for simplicity and a better overview of the large study area, i.e. depression, crest, narrow crest, flat, and slope (Fig. 4). Fig. 4 displays morphology map combined with the interpreted geomorphic features, which were first described by Streuff et al. (2017) and corresponded only to the BAS survey area (see Fig. 2B). Here, we compliment these data with a new bathymetric map and interpretation of geomorphic features identified farther south over the GN dataset and supported by the seismic and ground-truthing data (sub-chapter 4.2.-4.3.). However, seismic data did not contain sufficient resolution to provide information on small-scale features, such as ploughmarks, pockmarks and seeps, while the high frequency multibeam used in this study recorded a degree of noise in deeper, soft bottom areas. Therefore, such features stand as an independent observation from bathymetry and verified with video footage records, as well as previous identifications from Disko Bay region (Streuff et al., 2017; Krawczyk et al., 2021).

Depressions represent the deepest channels or basins in the area, mostly below c. 500 m water depth (Fig. 4). These are most prominent in the central-western part of Disko Bay, at the entrance to Vaigat Strait and in Torsukattak fjord (Fig. 4A). Crests and more streamlined, narrow crests are non-uniformly spread throughout the entire area, typically less than c. 300 m water depth (Fig. 4). Slopes dominate in the western and southwestern parts of Disko Bay and together with numerous small-scale depressions and crests form rugged seafloor terrain (Figs. 4 and 5C). Vast flat areas cover most of the Disko Bay area, in particular northern, central and southeastern parts (Fig. 4).

Geomorphic features were primarily identified from 3D terrain models, as well as bathymetry and slope layers, and verified with the video footage. The most pronounced and numerous features in the area are crag-and-tails or glacial lineations, bedrock ridges, and pockmarks, as well as ploughmarks (Figs. 4–5). Crag-and-tails/glacial lineations are concentrated in the central and northern Disko Bay and at the entrance to Vaigat Strait, typically between 200 and 500 m water depth (Fig. 4 and -5A). These have been described as east-west oriented elongated hills (1500–7000 m long, 100–1000 m wide, and c. 10 m high), formed sub-glacially from deposition of sediment, grinded from the crag, typically bedrock (see Streuff et al., 2017). Thus, crag-and-tails in Disko Bay are associated with bedrock ridges. Numerous bedrock ridges characterize the central, northern and eastern part of Disko Bay (Figs. 4 and

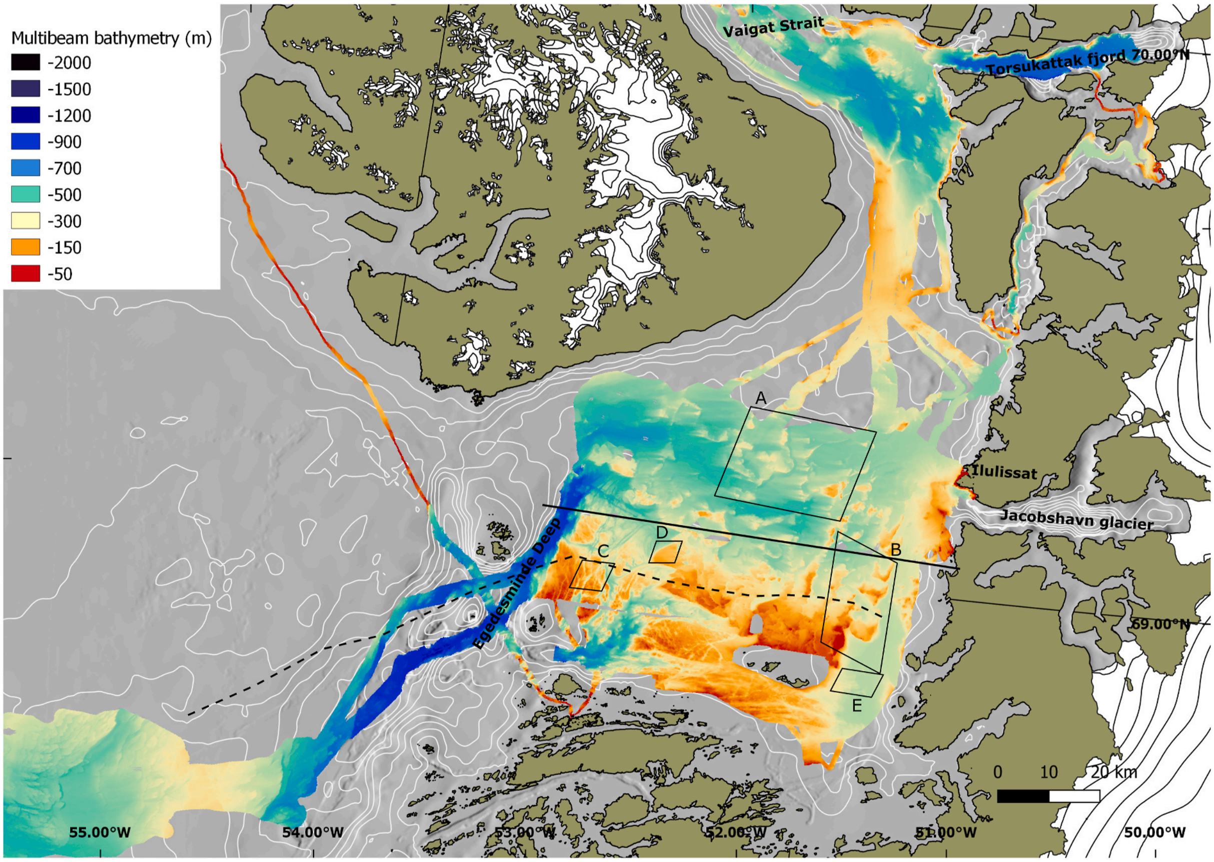

Fig. 3. New bathymetry dataset for Disko Bay. Black boxes indicate locations of digital terrain models; black dash line indicates location of seismic profiles. Black line indicates approximate border between the key datasets, i.e. GN and BAS datasets, also marking an approximate center of Disko Bay. The source for background relief map: IBCAO v4 (Jakobsson et al., 2020). Coordinate Reference System (CRS): WGS 84/NSIDC Sea Ice Polar Stereographic North.

5B). These are north-south oriented with sharp crests imparted by eastward steep slopes and westward gradual flanks, streamlined in the direction of former ice flow (Streuff et al., 2017). Iceberg ploughmarks formed by grounded iceberg keels are mostly located on the flats, in the southeastern part of Disko Bay area, where water depths range from c. 150–300 m (Figs. 4 and 5D). Ploughmarks in Disko Bay are typically shallow depressions with berms on either side of a narrow, V-shaped trough and range from tens of meters to several kilometers long. Circular depressions occurring in clusters, called pockmarks have been identified previously at the entrance to Vaigat Strait and Ilulissat Icefjord (see Fig. 4A). New, large pockmark fields were found in the flat areas of southeastern Disko Bay, often in the vicinity of iceberg ploughmarks and sporadic observations of gas seeps (Figs. 4B and 5E).

4.2. Seismic data

A seismic-stratigraphic interpretation of seismic lines has identified three units above a corrugated horizon interpreted as Archean basement (red horizon; Fig. 6). West of Egedesminde Deep, the topmost unit (Unit 1; below purple horizon in Fig. 6) represents Early Cenozoic volcanic extrusives, e.g. lava flows, while the eastern part of Disko Bay has Cretaceous sandstone exposed at the seabed (Unit 2; below blue horizon in Fig. 6) (Chalmers et al., 1998; Henriksen et al., 2009). Fault structures are observed that appear to be connected to seafloor escarpments and ridges associated with the Cretaceous sandstone terrain and farther into the Egedesminde basin (Figs. 6 and 4). Both top units are underlain by a unit expressing a dispersed seismic character with vague, discontinuous internal reflections resting on basement (Unit 3; below yellow horizon in Fig. 6). Unit 3 is exposed at or close to the seabed and heavily incised in the western parts of Disko Bay, notably expressed by the Egedesminde Deep. Multibeam-derived surface maps (Fig. 5C) and seismic data (Fig. 6) indicate that the rugged and incised surface of Unit 3 is more prone to erosion than the surrounding basalt and sandstone lithologies. Thus, it seems unlikely that the near-surface bedrock in the western parts of the bay, where Unit 3 is exposed at seabed, is formed by Archean Gneiss. The more erosive character of Unit 3 compared to the sandstone terrain is more readily explained by the presence of meta-sedimentary rocks extending offshore into the western bay area (Garde and Hollis, 2010). However, more data, e.g. ground-truthing samples and high-resolution seismic data is needed to determine the origin of the incised seabed west of the Cretaceous strata.

4.3. Sediments and habitats

Eight seafloor habitat classes were identified in the Disko Bay region based on a combination of multibeam, seismic and ground-truthing data, and they are displayed together with their descriptors in Table 2. Backscatter data were only collected within the GN dataset, and thus included in the habitat classification only for the southern and south-western Disko Bay area (see Fig. 2B and Figure A2).

4.3.1. Hard bottom

In Disko Bay region we can distinguish five habitats associated with the hard bottom, i.e. rocky bank, shallow rocky slope, coarse plain, coarse rugged terrain, and rocky/muddy slope. The shallow water areas (<200 m water depth), i.e. rocky bank and shallow rocky slope were characterized by presence of solid rock. Rocky bank is morphologically a crest and may be associated with Gneiss and/or volcanic intrusives. Shallow rocky slopes cover areas steeper than 20° and are linked to rocky bank, as well as narrow crests and shallow bedrock ridges in Disko

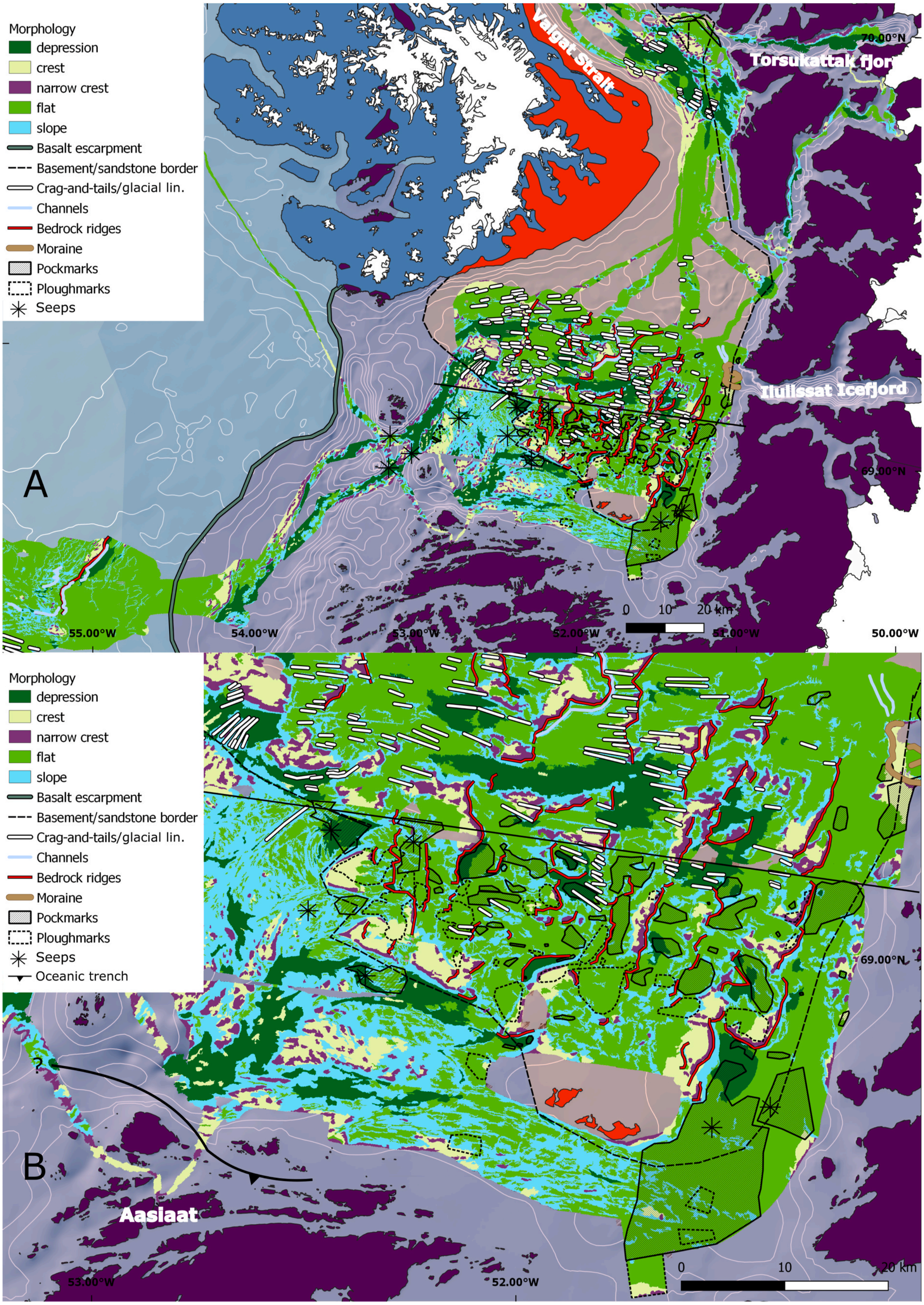

Fig. 4. Morphological map with interpreted geomorphic features (following interpretation from the BAS dataset; in Streuff et al., 2017). Black line indicates approximate border between the key datasets, i.e. GN and BAS datasets, also marking an approximate center of Disko Bay. Onshore and offshore geology is referred to in Fig. 1. Coordinate Reference System (CRS): WGS 84/NSIDC Sea Ice Polar Stereographic North.

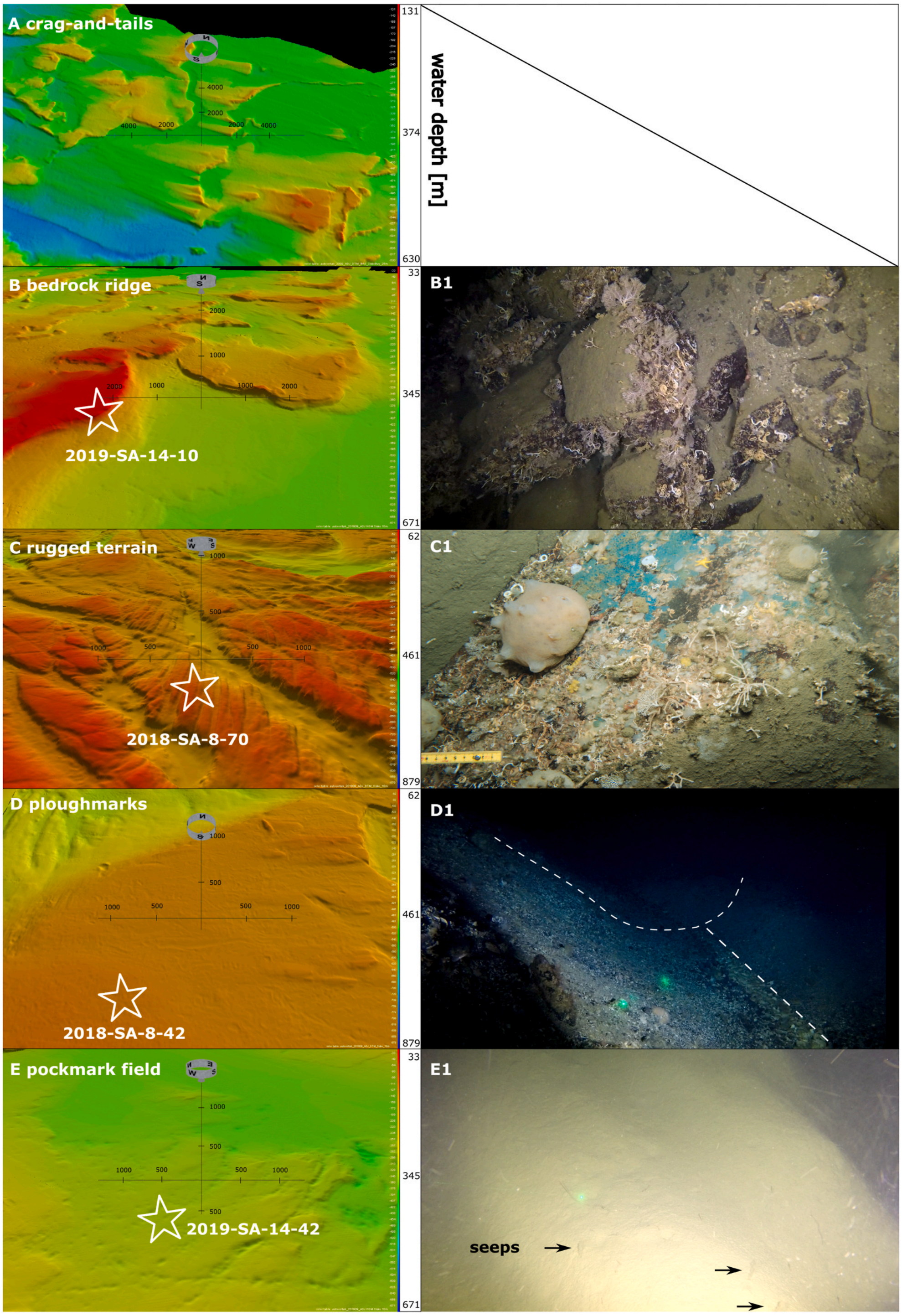

Fig. 5. Example digital terrain models showing pronounced geomorphic features in Disko Bay, identified as (A) crag-and-tails, (B) bedrock ridges, (C) rugged terrain, (D) ploughmarks and (E) pockmarks with corresponding still images from ground-truthing stations (B1-E1; station number and location is marked with a white star). General locations of these terrain features are boxed in Fig. 3.

Bay. Coarse sediments, i.e. coarse rocky ground were too observed in these shallow habitats, as well as in deeper areas, i.e. coarse plain and coarse rugged terrain, where this sediment class was mixed with gravelly sand/mud. Coarse plain is associated with Cretaceous sandstone and is characterized by flats and crests with occurrence of iceberg ploughmarks in shallow and medium deep areas (<300 m water depth). Coarse rugged terrain is associated with Unit 3, likely meta-sediments/volcanics, characterized by slopes and crests in shallow to medium deep areas. Coarse rocky ground mixed with mud characterized rocky/muddy slopes, which covered areas deeper than 200 m water depth and steeper than 20°. This habitat was associated with bedrock ridges and glacial lineations (crag-and-tails). Within this habitat we can distinguish a sub-habitat, i.e. extreme slope, steeper than 45°, and mostly linked to bedrock ridges. All the hard bottom habitats were characterized by the presence of sessile epifauna, whereas the extreme slopes were characterized specifically by dominance of taxon pairs, i.e. ascidian-sponge, ascidian-bryozoan, ascidian-hydroid, bryozoan-sponge, and a unique observation of zoanthid-sponge aggregations (Fig. 7).

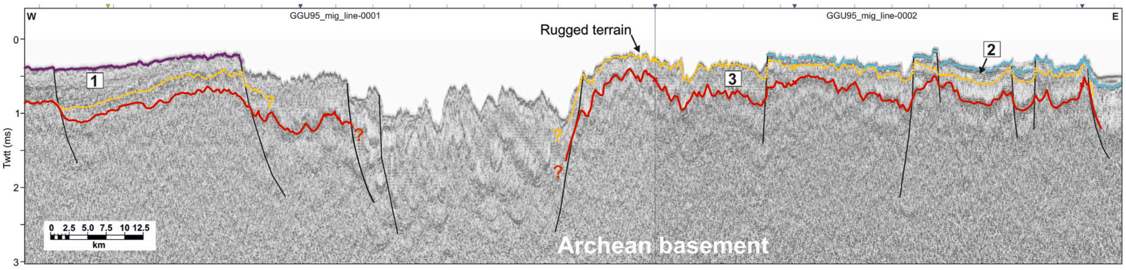

Fig. 6. Interpreted seismic transect which is a composite of GGU/95-1 and GGU/95-2 lines (see Figs. 2–3 for location). Unit 1 (purple horizon) – Early Tertiary Basalt; Unit 2 (blue horizon) – Cretaceous sandstone; Unit 3 (yellow horizon) – Paleoproterozoic meta-sediments and meta-volcanics. Red horizon – Archean basement. Area corresponding to 'rugged terrain' in Fig. 5C is marked with a blue arrow.

Table 2
Seafloor habitat classification of the Disko Bay region with descriptors (following the GOCH scheme in Krawczyk et al., 2021). Sediment classes are listed in text, chapter 3.3.

Bathymetry	Morphology (BTM class)	Slope (steepness)	Geomorphic feature	Sediment class	Bedrock type	Biota	Habitat
<200m	Crest		Bank	1 2	Gneiss & Meta-sediments/ volcanics	sessile fauna	**Rocky bank**
<200m	Narrow crest Slope	 >20°	Bedrock ridges	1 2		sessile fauna	**Shallow rocky slope**
<300m	Flat Narrow crest Crest		Ploughmarks	2 3	Sandstone	sessile fauna	**Coarse plain**
<300m	Narrow crest Crest Slope			2 3	Meta-sediments/ volcanics	sessile fauna	**Coarse rugged terrain**
>200m	Slope	>20°	Crag-and-tails/glacial lineations, bedrock ridges	2 5		sessile fauna	**Rocky/muddy slope**
		>45°	bedrock ridges	2		ascidians, sponges, bryozoans, hydroids, zoanthids	**Extreme slope**
200–300m	Flat		Pockmarks	3 4 5		sessile fauna/shrimp	**Muddy/sandy plain with dropstones**
>300m	Flat		Pockmarks	5		shrimp	**Muddy plain**
>500m	Depression		Trough	5			**Muddy trough**

4.3.2. Soft bottom

Mixed and soft bottom areas represent three habitats in Disko Bay, i.e. muddy/sandy plain with dropstones, muddy plain, and muddy trough. Muddy/sandy plain with dropstones is morphologically flat and composed of mix of sediment classes, i.e. gravelly sand/mud, mud with dropstones, and mud. This habitat covers medium deep areas (200–320 m water depth) with numerous pockmark fields. Mud as the main sediment class was identified in muddy plain and muddy trough. The muddy plain is distributed on flat and deeper areas (>300 m water depth) with records of pockmarks and apparent gas seeps, while muddy trough is characterized by larger depression in areas deeper than c. 500 m, also with some gas seep observations (Fig. 4). Muddy/sandy plain with dropstones and muddy plain were notable for the presence of shrimp. Regional distribution of habitats is discussed further.

5. Discussion

Large spatial datasets of bathymetry, backscatter and seismic profiles were integrated with stations containing video footage and sediment samples to investigate seafloor environment of the Disko Bay region. Approximately half of the studied region included backscatter data allowing more accurate representation of seafloor habitat types. As a result, we combined information on broad-scale geology and geomorphology with new high-resolution models of bathymetry, terrain features and distribution of bedrock/sediment types. These detailed information were classified into seafloor habitats to provide an overall link between physical environment and known benthic communities in the area. In this study we followed Harris and Baker (2012), emphasizing that different geomorphic seafloor structures may delineate different benthic habitat zones. In addition, a preliminary analysis was done for habitat suitability for settlement of different types of benthic taxa on the extreme slopes, as potential biodiversity hotspot areas.

5.1. Geological outline

Disko Bay region is generally characterized by largely varying water depths within c. 1000 m range, encompassing deep-water troughs and shallow plains or banks (Fig. 3). Our new high-resolution data improve the understanding and outline of the submarine geological units in the area. Chalmers et al. (1998) considered the central Disko Bay to be underlain by basement corresponding to the 'Disko Gneiss Ridge', inferred beneath Disko Island. A more recent study by Garde and Hollis (2010) invokes the presence of an oceanic trench suture across Disko Bay (Fig. 4B), separating the Rinkian fold belt from orthogneisses of the Aasiaat Domain. In this context, the rugged terrain revealed by the multibeam bathymetry data is likely underlain by rocks similar to the Paleoproterozoic meta-volcanics and meta-sediments, e.g. schists, exposed north-east of Aasiaat and in the western Disko Bay. Thus, Disko Bay can be geologically divided into two sub-regions: NE represented by Cretaceous sandstone unit and SW represented by Precambrian Gneiss and Paleoproterozoic meta-sediments/volcanics (Figs. 1 and 6). Both sub-regions contain areas of soft sediments annotated as 'mud', most

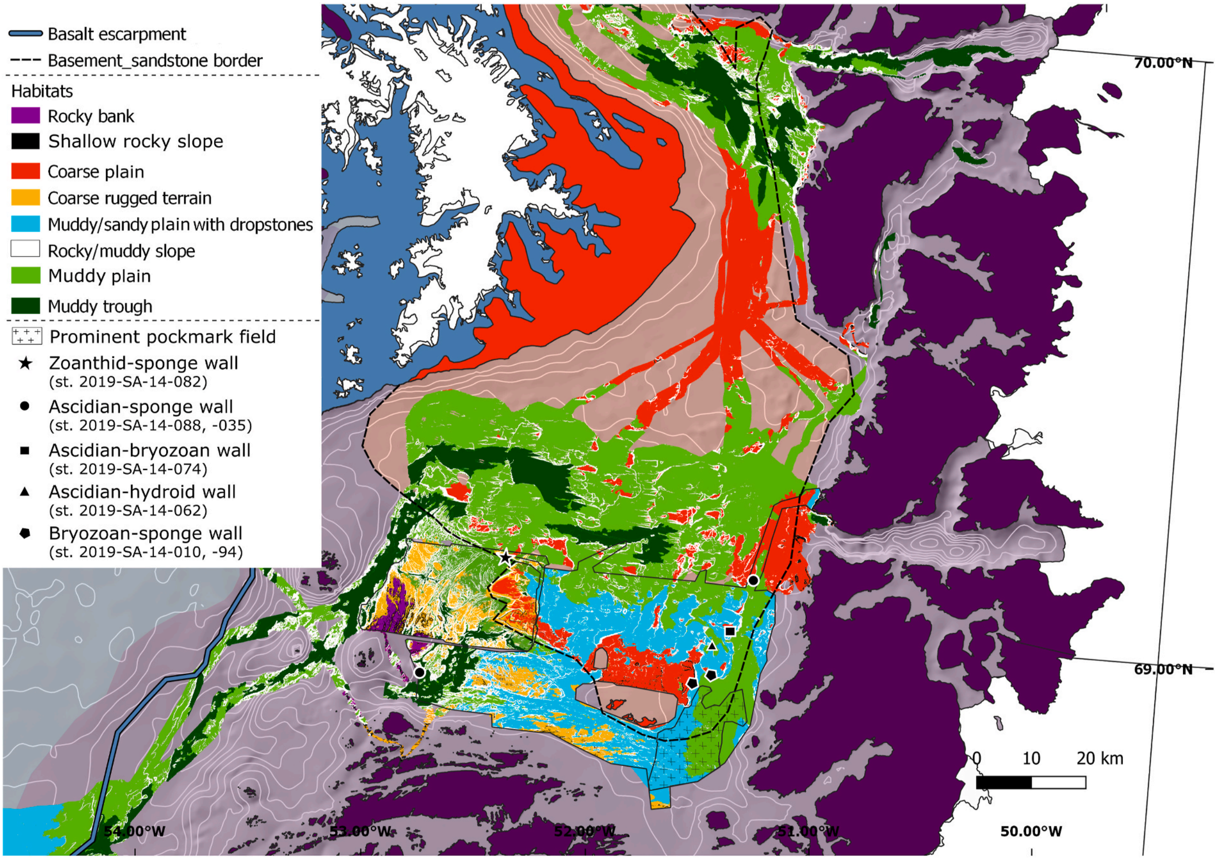

Fig. 7. Map showing distribution of the defined habitats, prominent pockmark field and locations of the ‘extreme slope’ biotopes (station numbers are given in legend; see Table A1). High-resolution data collected by GN and containing backscatter information are outlined (black line) on the map (see Figure A1-A2). Onshore and offshore geology is referred to in Fig. 1. Coordinate Reference System (CRS): WGS 84/NSIDC Sea Ice Polar Stereographic North.

likely glacial deposits with more recent Holocene sedimentation, mainly ice rafted debris from calving icebergs (Lloyd, 2006; Streuff et al., 2017).

Combining historical data with new high-resolution data reveal that the regional distribution of geological units in Disko Bay shapes the scale of the identified geomorphic features, i.e. large-scale structures in the NE sub-region of sandstone versus small-scale complex structures in the SW sub-region of the Gneiss/metasedimentary rocks. This in turn affects the distribution and complexity of habitats, i.e. ‘flat-type’ habitats in the NE sub-region, whereas ‘rugged-type’ habitats in the SW sub-region (Fig. 7).

5.1.1. ‘Flat-type’ habitats

The NE sub-region (sandstone area) is characterized by vast plains and numerous large-scale glacial lineations (crag-and-tails) and bedrock ridges (narrow crests), as well as large fields of pockmarks and iceberg ploughmarks (Fig. 4). This sub-region is predominantly covered by three habitats: coarse plain, muddy/sandy plain with dropstones and muddy plain, including potentially chemosynthetic habitats, all of which cover large areas (Fig. 7). We must assume that due to the lack of backscatter data in much of the NE sub-region (i.e. a non-outlined area in Fig. 7), the coarse plain and muddy plain classes are overgeneralized there and they might contain more mixed sediment, e.g. muddy/sandy plain with dropstones that would have been otherwise reflected by changes in backscatter intensity. Rocky/muddy slopes and shallow rocky slopes can be associated with, commonly observed in this sub-region, bedrock ridges as they represent outcropping bedrock in the vicinity of narrow crests (Fig. 4). Moreover, rocky/muddy slopes clearly outline the distribution pattern of crag-and-tails (Figs. 4 and 7). Pockmark fields were distributed mainly in the muddy/sandy plain with dropstones and partly in muddy plains (Figs. 4B and 7). These are trending south with the largest continuous coverage discovered in the SE section of Disko Bay, at the border of geological units (Fig. 7). The identified pockmark field in the SE section of Disko Bay, along with gas seep observations, coincides with the commercial shrimp fishery as one of the highest catch areas (Boertmann and Mosbech, 2021). In addition to the SE border of geological units, pockmarks with gas seeps were identified in the western border of geological units (Fig. 4B) (Krawczyk et al., 2021). Gas seeps were also observed in deeper muddy trough areas, such as Egedesminde Deep, in agreement with other reports (Mikkelsen et al., 2012). Previous study by Schumann et al. (2012) suggested that pockmark formation in Disko Bay may be driven by dissociation of gas hydrates and their distribution may be related to faults, slides or disturbance caused by iceberg-keel ploughmarks. Pockmarks, gas seeps, as well as iceberg scouring (see Fig. 4) are commonly observed in surface sediments across glaciated margins of the Arctic region, e.g. Beaufort Sea (Pickrill and Kostylev, 2007), and are considered potential geohazards (Hough et al., 2010). We note that our seep observations are biased by camera gear and our reports are mainly observations from the towed video sled, which was deployed in areas of flat seabed. This equipment was not available during the 2019 surveys, so the scarce observations of gas seeps from drop camera (e.g. station 42; Fig. 5E1) should not be interpreted as an absence of seep hazard.

5.1.2. ‘Rugged-type’ habitats

The SW sub-region towards Egedesminde Deep is characterized by an incised relief (‘rugged terrain’) displaying a complex small-scale system of cross-cutting channels and curvi-linear features with diverging/converging trends (Figs. 4 and 5C). The geomorphic zone was likely formed by glacial erosion of Paleoproterozoic meta-sediments and volcanics. It is likely that the relief is partly inherited from variations between meta-sediments and meta-volcanics and the superimposed tectonic deformation within the suture zone (Garde and Hollis, 2010). This sub-region is characterized by coarse rugged terrain and a shallow rocky bank (Fig. 7) with bedrock exposed at the surface. In addition, highest density of shallow rocky slopes and rocky/muddy slopes is a characteristic of this sub-region. The largest relief in the Disko Bay area of nearly 1000 m is observed in the western part, where rocky bank (one of the shallowest areas) transitions directly to muddy trough, Egedesminde Deep (deepest area) (Figs. 7 and 3). This sub-region is also covered by soft sediments, particularly along the geological boundary, represented by muddy/sandy plain with dropstones in the south and muddy plain to the west.

5.2. Benthic taxa

The identified range of sediments and habitat classes in Disko Bay are expected to contain a wide variety of benthic fauna, based on our previous assessments of benthic habitats in the region (Yesson et al., 2017; Long et al., 2020; Blicher and Arboe, 2021). Our observations of faunal communities are limited by our survey equipment. We did not attempt to sample or characterize infauna, which can play a significant ecological role on muddy seabed. The quality of images from our camera setup also limits the size and detail of faunal observations (Long et al., 2020). Previous high-resolution benthic habitat study from central Disko Bay (outlined area to the west in Fig. 7) revealed that hard bottom habitats are represented by sessile epifauna, such as sea anemones, sponges, bryozoans, soft corals, sea cucumbers and ascidians, whereas soft bottom habitats are represented by shrimp and tubeworms (Krawczyk et al., 2021). The video footage used in this study for sediment/habitat classification from the entire southern Disko Bay region (both outlined areas in Fig. 7) will be used in further studies to document and analyze biological characteristics of habitats in the area. However, provisional observations confirm the hard-soft bottom biotope pattern for the larger area of Disko Bay (e.g. Yesson et al., 2017; Krawczyk et al., 2021) (Table 2). Special attention was given to the steepest areas (extreme slopes), where benthic communities were represented by two-dominant taxa, mostly a mix of ascidians with sponges, ascidians with bryozoans/hydroids, and bryozoans with sponges (Fig. 7). Of these, only the sponges are currently considered indicators of Vulnerable Marine Ecosystem by the Northwest Atlantic Fisheries Organization (NAFO,

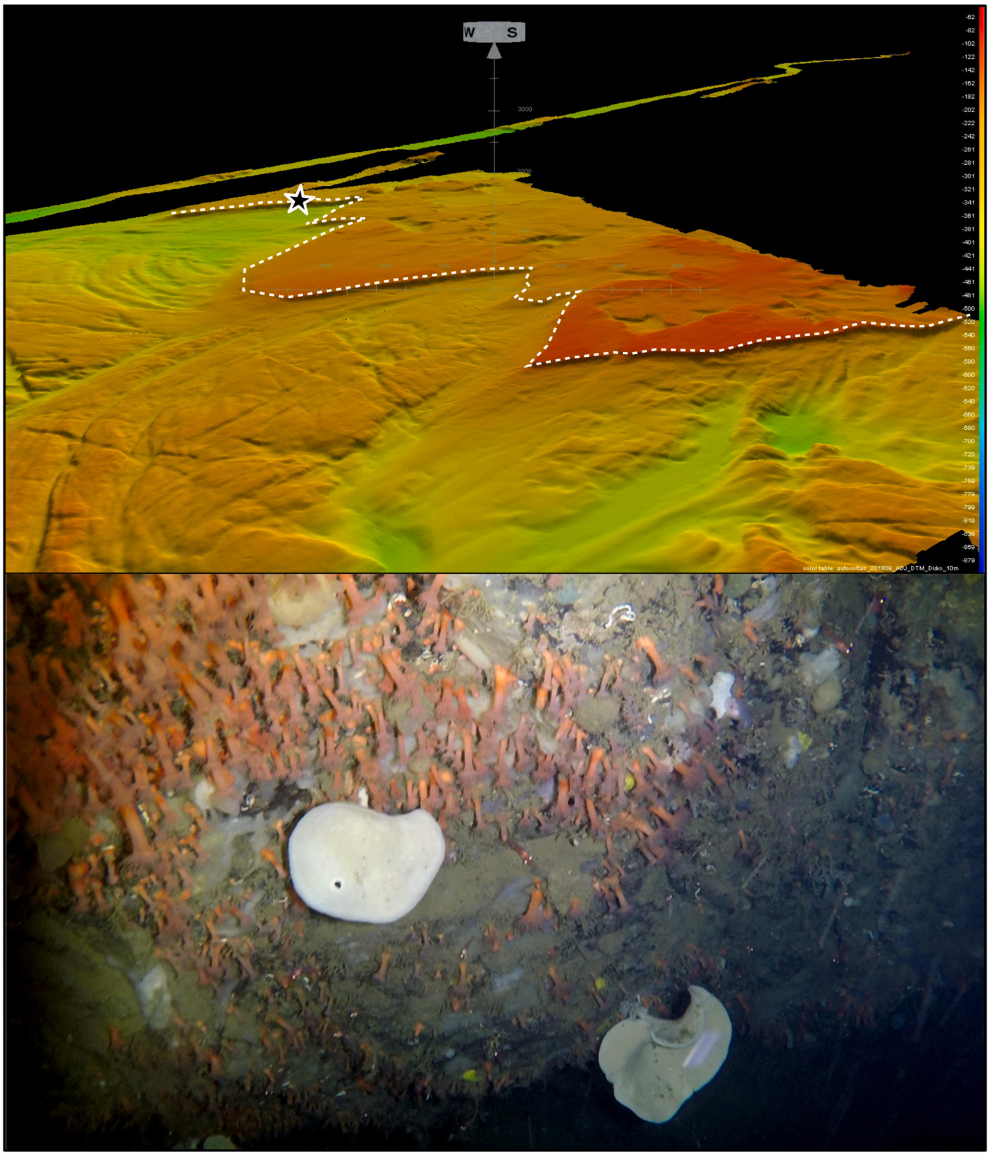

Fig. 8. A unique zoanthid-sponge wall identified in this study, shown in a digital terrain model (top; solid star) and video footage (bottom; still). Geological boundary is marked with white dashed line. Color scale: red – 50–100 m, blue – 700–900 m. For exact location, see Fig. 7.

2012). One station showed a rich zoanthid-sponge wall (Fig. 8). It should be noted that these extreme slope stations were biased towards southern area of the drop camera surveys (Fig. 2B). Nevertheless, they were mostly associated with bedrock ridges and some proximity to pockmark fields (compare Figs. 7 and 4B), whereas the zoanthid-sponge wall was additionally located along the geological boundary and seeps in western Disko Bay (Figs. 7–8). Similar zoanthid dominated communities have been observed in other steep-slope Arctic environments, such as the Bering Sea (Rybakova et al., 2020).

The unique zoanthid-sponge biotope was not observed in any other inspected video station, despite the presence of numerous steep slopes of bedrock ridges in the eastern Disko Bay area (e.g. Fig. 5B-B1), which were extensively sampled (see Fig. 2B). Thus, this biotope was not associated with the locations of bedrock ridges, typical of the rocky/muddy slope habitats in Disko Bay; instead, it might be associated specifically with geological boundary and potential gas activity. While it is difficult to draw any conclusions from this isolated observation, it is noteworthy that some sponge habitats have been associated with seeps (e.g. Thurber et al., 2010; Rubin-Blum et al., 2019). Moreover, methane seeps can be the energy source and foundation of ecologically important chemosynthetic ecosystems (Åström et al., 2020). However, we have not observed any taxa in these areas that we recognize as specialist chemosynthetic organisms and our provisional assessment does not show any taxa uniquely observed in these seep areas, although our inferences are limited by the quality of our imagery and inability to collect samples for examination. Further work is required to establish a link between these potential seep sites and the fauna observed at these locations.

5.3. *Implications for Marine Spatial Planning*

The current study builds on the pilot project from central Disko Bay, which was focused on developing benthic habitat mapping protocol and classification for the Greenland region (Krawczyk et al., 2021). Here, we provide an up-scaled habitat map for nearly the entire Disko Bay with a long-term prospect to generate broad-scale, high-resolution seafloor habitat maps in Greenland suitable for the different management sectors in Greenland. The classified habitat map (Fig. 7) contains important information on characteristics of the (1) physical environment, including distribution of key geological units with associated sediment types in different depth strata and geomorphic features, such as large-scale glacial lineations. In addition, we outline areas with pockmarks and gas seep observations, which are considered potential geohazards. These geohazard areas, together with detailed distribution of terrain features, such as extreme slopes or tectonic faults are particularly useful for the management sectors responsible for mining and fishing, in terms of optimizing deployment of benthic gear and possible ecosystem implications (e.g. Harris and Baker, 2012). Distribution of distinct sediment classes, including mixed sand and gravel can help plan the sand dredging activities. Another set of useful information concerns the overall (2) benthic community structure recognized in the area and linked to the physical environment structure. In particular, sessile benthic megafauna, typically formed of mixed communities characterize hard bottom habitats, mostly older rock formations, whereas shrimp characterize muddy and muddy/sandy habitats (Table 2), most likely composed of recent sedimentation processes. This species-environment relationship is highly relevant for producing predictive models of the distribution of commercially important species (e.g. Pickrill and Kostylev, 2007), such as shrimp on the one hand, and of protected areas containing vulnerable species, such as coral gardens on the other hand. In this study, all the 'muddy habitats' in Disko Bay within the upper 500 m water depth, namely muddy/sandy plain with dropstones and muddy plain (Fig. 7) may represent a potential shrimp habitat, based on their affinity to water depth and sediment type in the area (in Krawczyk et al., 2021). Commercial fisheries could benefit from such predictive modelling to maximize fishing effort (cf. Harris and Baker, 2012; Todd and Kostylev, 2011), especially that Disko Bay is known for shrimp fishery operating within the Northwest Atlantic Fisheries Organization statistical area 1A (Burmeister and Riget, 2019). On the other hand, unique habitats, such as rich zoanthid-sponge wall observed in the extreme slope of western Disko Bay (Fig. 8) could be a nursery, feeding, and breeding ground for many benthic and pelagic species. Therefore, such unique habitats would require to be protected from destructive anthropogenic impact, such as benthic trawling (Yesson et al., 2017; Long et al., 2021); although we note the observations were on steep slopes that are inaccessible to trawlers. While many of the observed habitats formed by sessile benthic megafauna may meet one or more of the 5 criteria defining Vulnerable Marine Ecosystems (e.g. vulnerable or structurally complex), at present only sponges and corals are recognized by Northwest Atlantic Fisheries Organization as regional indicators of Vulnerable Marine Ecosystems (NAFO, 2012; Long et al., 2021). Both, the areas of conservation interest and those of commercial interest are necessary to be delineated in the high-resolution habitat maps, such as the one generated in this study, in order to better identify conflicting seabed areas in the overall scope of sustainable use of the oceans and marine resources in Greenland.

6. Conclusions

Our data confirm that geomorphic features largely contribute to delineating seafloor habitat zones, which in our study focus on the physical environment. However, bedrock characteristics and sedimentary processes controlling the distribution of sediment types in Disko Bay are nonetheless important in the glaciated shelf region. Combination of the new high-resolution and historical datasets has allowed to delineate geological boundaries in the area with higher accuracy. In particular, we find that an incised topographic relief forming complex, rugged-type habitats is generated by Precambrian Gneiss and Paleoproterozoic meta-sediments and meta-volcanics (geological unit 3), exposed in the SW area of Disko Bay. In contrast, the vast, flat-type habitats are generated by indurated Cretaceous sandstone (geological unit 2) that characterize the NE area of Disko Bay.

The overall biotic structure in Disko Bay follows the typical hard-soft bottom pattern, however more detailed benthic analyses could help answer the question, whether bedrock characteristics and origin are important for biodiversity or faunal compositions. In this study, a unique biotope was found at the western geological boundary, in the vicinity of pockmarks and seeps, which highlights the need for further work linking geology, seafloor habitats and the associated biotopes in West Greenland shelf region.

The study demonstrates how the use of multiple datasets, e.g. multibeam bathymetry, backscatter, seismic profiles and ground-truthing sampling, which combine spatial seafloor with sub-surface geological information is important for characterizing habitat zones and understanding the underlying factors for the distribution of benthic ecosystems in West Greenland. Such detailed knowledge can be further extrapolated over similar topographically complex regions spanning across the large Arctic maritime area.

CRediT authorship contribution statement

Diana W. Krawczyk: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Chris Yesson:** Validation, Formal analysis, Data curation. **Paul Knutz:** Visualization, Validation, Formal analysis. **Nanette H. Arboe:** Data curation. **Martin E. Blicher:** Data curation. **Karl B. Zinglersen:** Data curation. **Jukka N. Wagnholt:** Resources.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Diana Krawczyk reports financial support was provided by Greenland Institute of Natural Resources.

Data availability

Data are shared as supplement, deposited at PANAGEA, IBCAO and other public sources

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2022.108087.

Appendices.

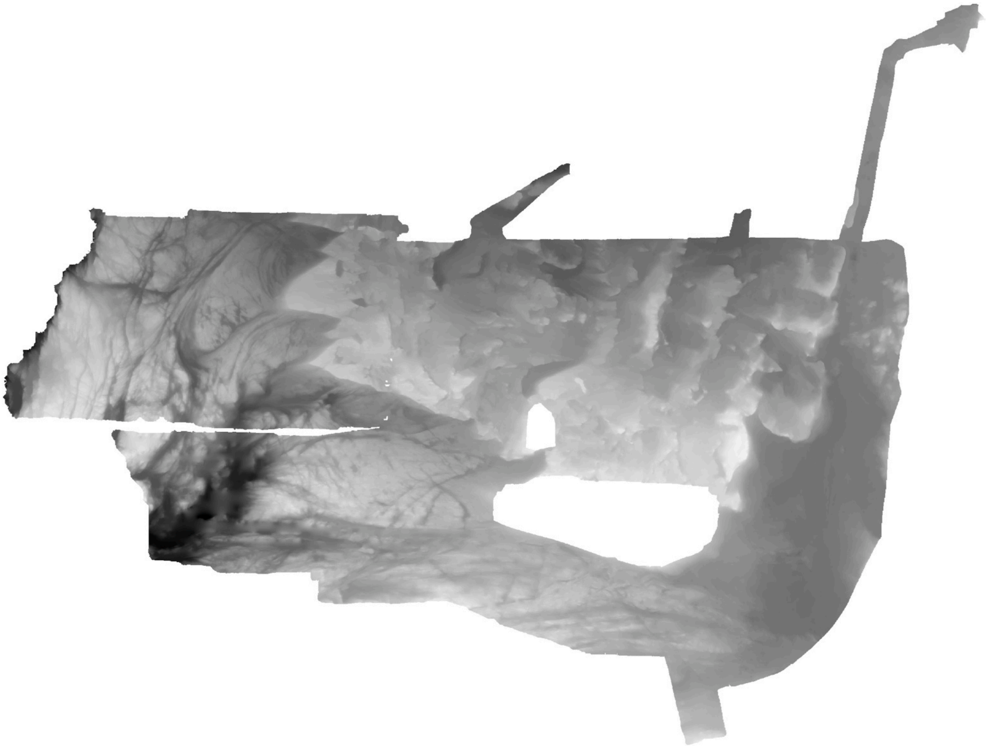

Fig. A1. Georeferenced bathymetry grid (.tif; scale in m) of 25 × 25 m resolution in Disko Bay (data collected by Grønlands Naturinstitut). CRS: WGS 84/UTM zone 22N.

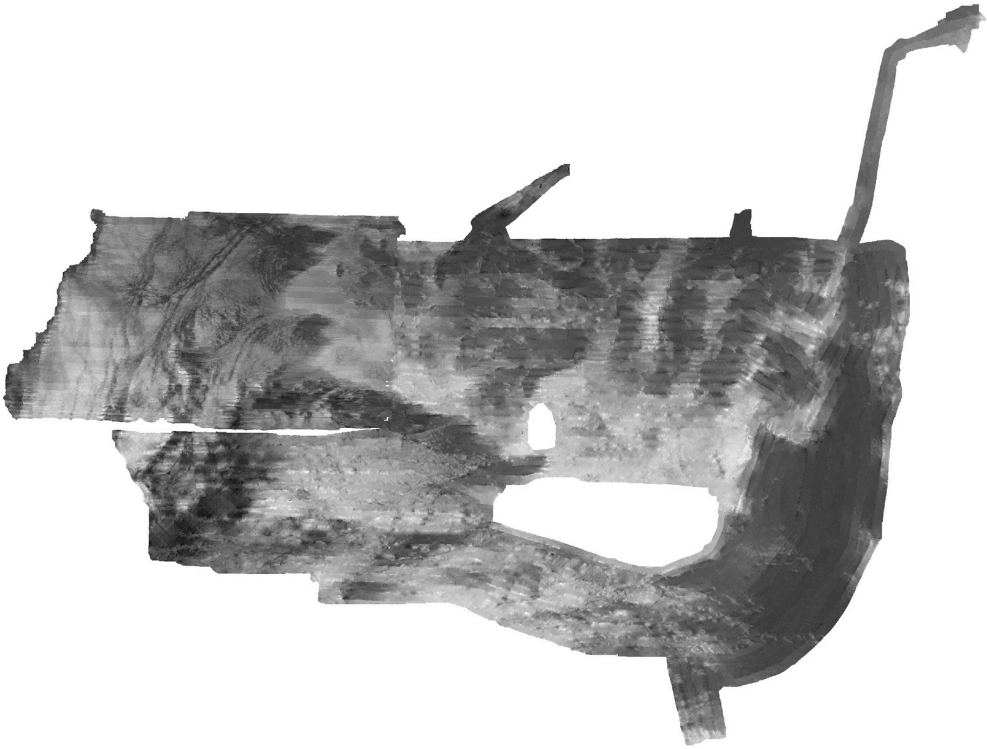

Fig. A2. Georeferenced backscatter mosaic (.tif; scale in dB) of 25 × 25 m resolution in Disko Bay (data collected by Grønlands Naturinstitut). CRS: WGS 84/UTM zone 22N.

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