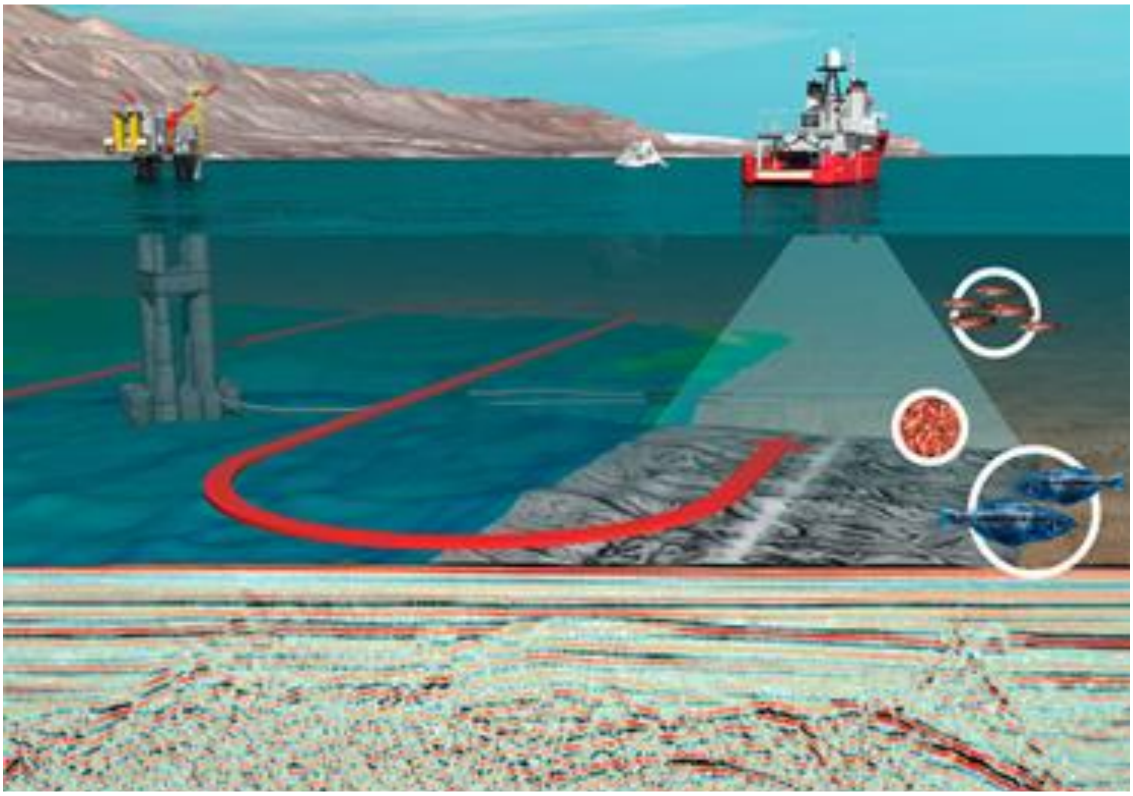
MapHab - Mapping Benthic Habitats in Greenland

pilot study in Disko Bay



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Geological Survey of Denmark and Greenland (GEUS)
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1. Introduction

The Greenland economy is by large dependent on marine resources, which is why a well-founded knowledge on marine bio environment is crucial for decision-making and their sustainable management. An important element in understanding the function of the marine ecosystem is the distribution of benthic habitats. Such knowledge with respective spatial datasets can be valuable to the management 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.

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 western coast of Greenland was published by Gougeon et.al. (2017).

In the DANCEA funded **MapHab** project, a research consortium consisting of four scientific institutions was established: Greenland Institute of Natural Resources (GINR, Greenland), Geological Survey of Denmark and Greenland (GEUS, Denmark), National Institute of Aquatic Resources (DTU Aqua, Denmark) and Institute of Zoology (IoZ, United Kingdom) in order to take the very necessary step towards developing a 'best practice' protocol for detailed seabed habitat mapping in Greenland. The GINR's survey ship R/V Sanna has recently been equipped with a multi-beam echo sounder (Reson SeaBat T50-ER) and ground-truth gear (video sled, drop camera and grab). This framework allows for an effective sampling program combining both acoustic survey with on-board processing and ground-truth sampling. The post-cruise mapping analysis forms the basis for identifying locations for in situ sampling, which again is used to verify the mapping analysis. The projected 'best practice' protocol was designed as a cost-effective and time-efficient mapping program of the strategically important areas of the Greenland shelf. The priority of this protocol is 'mapping for discovery', i.e. 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 and Lamarche, 2015). As a result of the **MapHab** project, the successfully developed 'best practice' protocol describes all the necessary steps from preparation through mapping activities to processing and interpretation of the final product, i.e. benthic habitat map from Disko Bay pilot area (Krawczyk et al. 2019). The protocol is available at GINR website.

Habitat mapping is the potential first step in establishing a seabed model portal for the Greenlandic shelf area as background for Marine Spatial Planning and decision-making. The #Modelling #Greenland #Seafloor program at GINR aims at building an online 3D platform with Greenland seafloor terrain model and associated information on habitats, sediments, geology and biology.

The **MapHab** project combined the experiences gained during research campaign, data processing and interpretation of the material collected in the pilot area, as well as harvesting existing data from the project area supplemented with knowledge transfer from international projects. The research consortium has worked with the key mapping components, i.e. bathymetry, geological setting, oceanographic modelling, seabed substrates distribution and benthic communities. Due to a rather small pilot area of the **MapHab** project, nearby existing sediment echo sounding data, vibrocore data, benthic trawl records, as well as large-scale hydrodynamic model data have been included in this report to illustrate the seabed environment of Disko Bay more accurately and in the broader context.

The following chapters describe geological setting, oceanographic modelling, seabed substrates and biological communities and finally, a benthic habitat map of the pilot area in Disko Bay and a new seabed classification scheme for Greenland.

2. Habitat mapping in EU

Benthic habitat mapping is a spatial representation of physically distinct areas of the seafloor that are associated with particular groups of flora and/or fauna. As an example, a stone reef area with its unique biodiversity or a sandbank in the photic zone with eelgrass distribution.

The need for high confidence and high-resolution benthic habitat maps is increasing in the European waters. The information provided by such maps can be effectively used in designing management plans for regulating human activities in the sea. After the industrial revolution and development of technologies, the increase in the human population causes uncontrolled and often destructive exploitation of the sea and its resources. Overfishing, trawling and raw material extraction are just some examples. The discovery of offshore hydrocarbon resources poses a major challenge to the marine environment and its habitats.

The seabed habitat map is an excellent tool that provides knowledge-based information for decision makers to develop plans for efficient and sustainable use of marine resources.

In the European Union, the Commission has formed several Directives to ensure the conservation of a wide range of habitats. The Habitat Directive proposal was launched in 1992 with the purpose of maintaining biodiversity in Europe, while considering the economic, social, cultural and regional requirements. The Directive aims at establishing a pan-European 'Natura2000' ecological network of protected areas. In 2018 the Marine Strategy Framework Directive (MSFD) was established with the objective of protecting marine environment and achieving a Good Environmental Status of the European waters by 2020.

Since the realization of the deteriorating state of the European marine waters, all member states included benthic habitat mapping in their national plan (in varying proportions). At the same time, they have acknowledged the fact that it is not realistic within the required timeframe. Therefore, the relationship between benthic physical habitats and their biological communities was studied. The most biologically relevant environmental parameters were extracted and used in modelling broad-scale benthic habitats. The previous *one nation – one approach* idea is not practical any more, as habitats do not recognize boarders or sectors. To have a unified pan-European seabed habitat map, a standardization protocol for classifying benthic habitats has been initiated under the name EUNIS (European Nature Information System). Despite its shortcoming in quite a few classes, EUNIS is under continuous development and soon the new EUNIS will be adapted in Europe.

The European Commission has funded several initiatives to produce seabed habitat models of the European waters, such as MESH (2004), BALANCE (2005), EMODnet/EUSeaMap 2009-now. These map productions were based on individual habitat mapping programs of all member states, as well as the available environmental parameters used for the modelling.

The broad-scale habitat maps are currently used for implementing the maritime spatial planning of the European waters. Despite their "broad scale" nature, they are still very useful for coherent management of the human activities, regulating the compaction for maritime space and energy sources and other uses to ensure a balanced economic growth and environmental protection of the European waters.

3. The Mareano program example

The Norwegian MAREANO program is an excellent example for benthic habitat mapping. It should be noted that MAREANO is a long-term program with large annual budget, whereas our **MapHab** project presents only fraction of such budget and was meant to start up a mapping program in Greenland, thus the two projects cannot be compared directly. The following chapter represents a summary of ICES RGMAREANO REPORT 2016 (ICES, 2016).

The MAREANO program collects data on seabed bathymetry, topography, sediment composition and biodiversity, as well as pollution in order to generate habitat and biotope maps of the Norwegian offshore areas including the Arctic waters. The program aims to provide answers to questions, such as:

What is the seascape of the Norwegian continental shelf?

What does the seabed consist of?

How is the biodiversity distributed on the seabed?

How are habitats and biotopes distributed on the seabed?

What is the relationship between the physical environment, biodiversity and biological resources?

How many contaminants are stored in the bottom sediments?

The Institute of Marine Research (HI) responsible for biological work, the Geological Survey of Norway (NGU) responsible for geological work and the Norwegian Hydrographic Service (NHS) responsible for bathymetric work, comprise the Executive Group carrying out the MAREANO field sampling and other scientific activities.

Bathymetric mapping is undertaken at least a year in advance of ground-truth sampling of geology and biology in order to provide an adequate time for data processing, interpretation and ground-truth planning. Most of the mapping is outsourced through tenders although NHS undertakes approximately one month of mapping effort with their own vessel. The tender documents focus on the delivery of multi-beam echo sounder data, while sub-bottom profiling is done as optional. NHS performs quality control of raw and cleaned bathymetric data before gridding into a digital terrain model (DTM) in manageable cell sizes of 0.5°cell or 5, 25, 50 m. Bathymetry data are also used to classify marine landscapes. NGU then performs analysis of sediment and terrain derivatives based on backscatter data from the multi-beam echo sounder. These data are quality controlled and calibrated based on measurements in a test area. When available, information on the nature of the seabed and sedimentation history are extracted from sub-bottom profiling data, though not systematically collected. Based on available bathymetry, backscatter and oceanographic data, the physical ground-truth sampling program is established. In the MAREANO program, visual and physical sampling is generally predefined in a density of 10 visual transect stations including 2 physical sampling stations per 1000 square km. The density and location of sampling stations is defined using automated analysis combined with expert judgement. The next step is carrying out physical sampling, samples for inorganic geochemistry and video observation of the seabed and the life inhabiting it. On a sampling station, a standard workflow is followed starting with video documentation in order to observe the undisturbed seabed and to optimize selection of grab and multi-corer positions, which are taken next. Finally, beam trawl and sled sampling is carried out. Video transects are used to obtain visual data for identification of megafauna and ground-truthing of surficial sediments. Video transects are taken in units of approximately 700 m length. Pre-annotation – a coarse analysis of substrates and megafauna - is performed on board. Further physical sampling is done for collection of benthic infauna and sediment samples. For collection of benthic fauna, up to three different gears are used – grab, epibenthic sled and beam trawl. In addition, density is recorded. The detailed biological analysis of video data includes annotation of all recognizable biological elements in order to obtain the lowest possible taxonomic level. Detrended Correspondence Analysis (DCA) ordination is used to define relationship between different benthic communities and environmental variables. A sampling grab and, in some cases, a gravity corer is used to obtain data to analyse the sediment composition and grain size. A multicorer or boxcorer is used to obtain data for geochemical analysis. The post-cruise analyses of data are used in producing maps of the present concentration of these components and, for some stations, the historical evolution.

NGU produces landscape maps from the bathymetry and derived data, as well as sediment maps based on backscatter and verifications from physical sediment samples and observations from video transects. The material is then, together with modelled oceanographic data, used by NGU and HI to produce biotope maps available at MAREANO webpage. HI also produces vulnerable marine ecosystem maps based on abundances/presence of species which have been classified as indicators of vulnerable marine ecosystems by, *inter alia* OSPAR (e.g. coral reefs, coral gardens and deep-seawater sponge aggregations), with extended grouping of sponge communities. HI also produces maps of distribution and density of trawl marks. Geochemistry maps are compiled based on analysis of inorganic and organic components.

4. Hydrographic data in habitat mapping

Mapping of marine habitats is typically done by predictive habitat models (PHM), which predict the likely distribution of species or habitats using environmental variables as predictors (ICES, 2019 *in prep*). The outputs of PHMs are habitat maps or species distribution maps based on the methods comprising a variety of statistical models, e.g. General Additive Models or General Linear Models and machine learning algorithms, e.g. Artificial Neural Networks, decision trees etc. Explanatory variables include data describing the physical properties of the sea-bed such as seabed topography, substrates and roughness. These are acquired from multi-beam surveys in combination with sediment sampling and observations, as demonstrated in this project. The environmental conditions of the overlying water are often correlated with temporal and spatial distribution of benthic species and/or communities in marine systems (Reiss et al., 2011, 2014; Snickars et al., 2014; Mohn et al., 2014). Examples of environmental conditions correlated specifically to the presence or abundance of benthic species or communities include measurements of bottom water currents, temperature and salinity, flux of organic carbon to the seabed, and oxygen concentrations. While observations of environmental conditions above the seabed are typically limited in both time and space, the ideal data source for a full spatial and temporal coverage of many environmental conditions can be retrieved from oceanographic models. These types of models include 3D hydrodynamic models used to simulate currents, temperature and salinity, and ecosystem models, applied on top of the hydrodynamic models to simulate biological and ecological processes in the water column, including the production and flux of organic matter, which is the primary food source sustaining benthic communities below the euphotic zone.

The water currents in shallow coastal waters (< 50-100 m) along the seabed are highly influenced by currents induced by surface waves, tides and wind stowing. The use of explanatory variables extracted from dynamic models covering coastal areas has been included in PHMs for many marine species, such as benthos, fish, marine mammals and seabirds (e.g. Skov and Thomsen, 2008; Reiss et al., 2011, 2014; Skov et al., 2014; Gilles et al., 2016; Heinänen et al., 2018) and the importance of hydrodynamic variables in species and habitat distribution is well established. In deeper waters, especially in areas with changing and complex seabed topography, internal waves may support strong turbulence and mixing (e.g. Klymak et al., 2012). As an example on how these deeper hydrodynamic processes may affect seabed habitats, a number of studies are briefly reviewed below. A particular example refers to hydrodynamic processes along deep-sea ridges, which may explain the presence/absence and abundance of cold-water corals (CWCs), e.g. *Lophelia sp.* reefs.

Hydrodynamic processes have been suggested to drive the flux of organic matter produced in the photic zone to the seabed that in turn sustains the presence and production of CWCs (e.g. Kiriakolulakis et al., 2005, 2007; White et al., 2005; Rengstorf et al., 2013; Mohn et al., 2014; Soetaert et al., 2016). White et al. (2005) presented a conceptual model suggesting deep-sea water motion around seabed ridges and coral mounds possibly increasing turbulence and mixing of the water column above and along these significant seabed structures. As a result, nutrient-rich water may be forced towards the surface, sustaining an increase in photic zone productivity and, at the same time, increasing the vertical downward transport of organic material produced in the photic zone to the seabed, in turn elevating the food source flux to CWCs. These processes have been suggested by other studies (e.g. Kiriakolulakis et al., 2005, 2007), that found elevated fluxes of fresh lipid-rich organic matter originating from the photic zone to the deep locations of CWCs based on analysis of molecular components of suspended organic matter.

Hydrodynamic processes are predominantly driven by tidal water movements, i.e. internal tidal waves interacting with seabed topography or oceanographic disturbances, such as fronts or storms creating "inertial" water motions (van Haren and Gostiaux, 2012). Internal tidal waves with heights of e.g. 10-100 meter (with low frequency and long periods) can induce strong turbulence when interacting with seabed topography and support both vertical mixing events, as well as sediment resuspension. Mohn et al. (2014) examined the correlation between CWCs and explanatory variables extracted from high-resolution hydrodynamic models (250-750 m horizontal resolution) from 3 sites in the NE Atlantic with CWCs habitats ranging from 500-1000 m water depths. They found a clear coupling between the presence of CWCs and the energetic, near-bottom flow dynamics largely controlled by tide-topography interaction generating and enhancing periodic motions such as trapped waves, freely propagating internal tides and internal hydraulic jumps (Figure 1). The near bottom flow dynamics showed high spatial variability and elevated energy levels found at locations with CWCs presence, compared to location with no presence. This suggests that internal wave's interaction with topography supports vertical mixing locally and is likely an important food supply mechanism to CWCs.

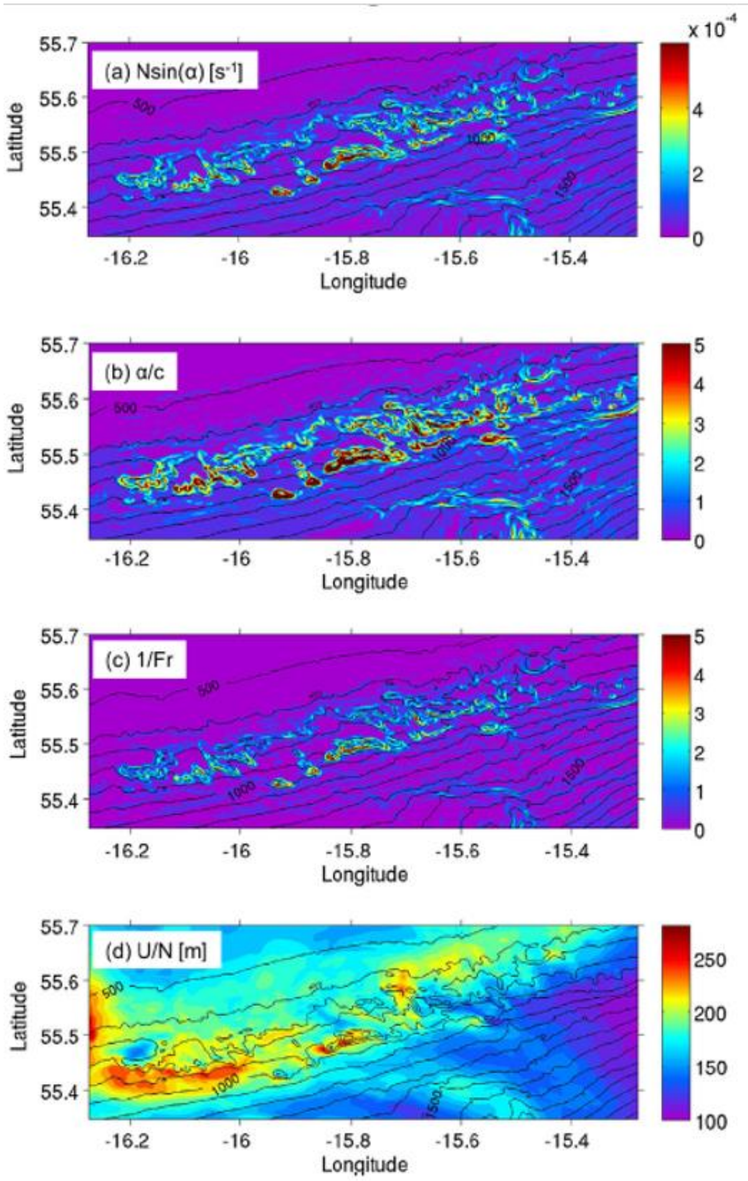

Figure 1. Figure from Mohn et al. (2014) showing calculated dynamical scaling parameters at the seabed relating to the internal wave–topography interaction at a location of the continental margins in Irish Sea. (a: maximum resonance frequency, b: internal tide slope parameter, c: tidal excursion inverse Froude number, d: vertical displacement scale).

These findings are also supported by Soetaert et al. (2016) who applied high-resolution modelling to quantify the vertical current distribution and the vertical distribution of the concentration of organic matter during a tidal period at 2 sites representing a coral mound and a coral ridge (Figure 2). The model results found elevated supply of organic matter to locations of CWCs induced by the hydrographic processes discussed above. Another study by Rengstorf et al. (2013) using PHM found slope, bottom temperature and shear stress to be the most important variables for for *Lophelia sp.* in the Irish continental margins using explanatory variables from hydrodynamic model with a spatial resolution of 2.5

km. High shear stress in this case is suggested as indication of elevated food supply and reduced sediment deposition.

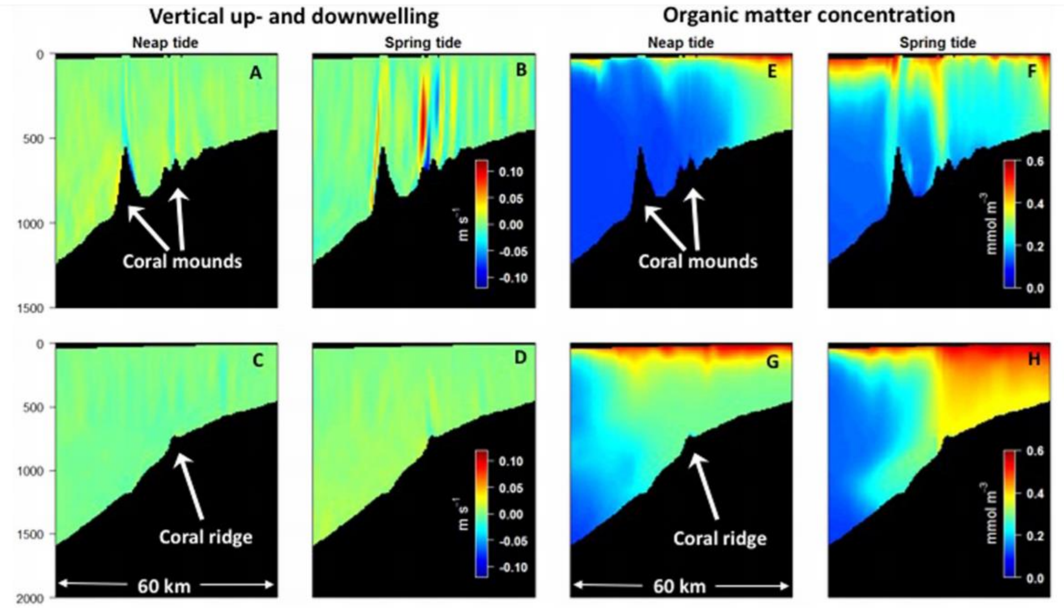

Figure 2. Model output of vertical current velocities (A–D) and organic matter concentration in the water column (E–H) along the coral mound (A,B,E,F) and coral ridge transect (C,D,G,H) at depths down to 1500 m during neap and spring tide (Soetaert et al., 2016).

Examples of other deep-sea species or groups of species where explanatory variables from hydrodynamic models have been used to predict species or habitat presence include sponges (Knudby et al., 2013a), black corals, gorgonian corals, sea pens and sponges (Knudby et al., 2013b).

The afore-mentioned studies provide a good evidence that hydrodynamic processes are important factors in predicting species occurrence, not only in shallow coastal waters, but also in deep-sea habitats. However, data from hydrodynamic models do not necessarily describe the physical processes governing the internal wave dynamics as described above. The hydrodynamic data available from global or regional hydrodynamic models are based on hydrostatic models (as opposed to non-hydrostatic models). Although the most energetic and widespread internal tides appear to propagate as linear or weakly non-linear waves, which may be approximately simulated by hydrostatic models (Carter et al., 2012), the non-hydrostatic pressure becomes important only when the horizontal scale of motion is lesser than the water depth (Vitousek and Fringer, 2011). In particular, the latter is the case when internal waves interact with rising seabed topography creating wave steepening and overturning eddies and this process cannot be solved explicitly using hydrostatic models (Wadzuk and Hodges, 2004).

In recent years, efforts have been made to implement more physically correct analytical approximations of these non-hydrostatic processes in hydrostatic models (Fox-Kemper et al., 2019) and, although a number of theoretical issues still remains, future applications of hydrostatic models are expected to provide good quantitative estimates of seabed energy derived from tide-topography interactions, such as reported by Mohn et al. (2014). More research for model validation are required, i.e. combining *in situ* measurements of internal wave interaction with sloping topography and high-resolution hydrostatic modelling including new methods and model implementations for approximating the high level energetic processes caused by internal waves–topography interactions. Currently, the global or regional models available from EU Copernicus Marine Environment Monitoring Service (CMEMS) do not include a representation of internal waves, however, the inclusion of internal wave processes at sub-mesoscale levels (1-20 km grid resolution) in CMEMS products are listed in the CMEMS service Evolution Strategy R&D priorities from 2018 (European Commission 2018). Thus, wherever there is a need to describe the tide-topography interaction, a dedicated model has to be setup for the study-specific area, ensuring that reasonable approximation of internal wave dynamics is resolved (see Wadzuk and Hodges, 2004; Carter et al., 2012, Mohn et al., 2014).

In general, outputs from global and regional hydrodynamic models available through the CMEMS include hydrodynamic variables, such as current speed and direction, temperature, salinity and mixed layer depth. Data are typically stored as daily means. Similarly, 3D biogeochemical models are available providing variables, such as nutrients, phytoplankton and oxygen. Explanatory variables for PHM in both shallow and deeper parts of the ocean may be extracted from this type of dynamic models. However, these data are typically only available at coarse scales (~ 10 km grid resolution or more). Hydrodynamic (and biogeochemical) models customised specifically for the purpose of providing high-resolution and more accurate predictor variables for PHMs (e.g. Mohn et al., 2014), can add considerable predictive power to these models. Rescaling, adjusting and calibrating a part of a regional hydrodynamic model (available from Copernicus or another data provider) to reflect e.g. a higher resolution for a study area, like in the studies mentioned above, is not a major task for an experienced modeller. This will require collaboration with physical and/or biological oceanographers as part of the future projects focused on mapping seabed habitats.

5. Disko bay - study area

The **MapHab** pilot area is located in SW Disko Bay covering about 600 km^2 in a 20x30 km square area (Figure 3.). The relatively small pilot area has been selected as a pioneer habitat mapping area in Greenland based on the pre-project knowledge on complex topography, hydrography and rich marine biodiversity including rare observations of Vulnerable Marine Ecosystem species. Disko Bay is also considered a biodiversity hotspot, identified as the Ecologically and Biologically Significant Area by the International Union for Conservation of Nature. Besides that, it is a highly economically relevant area with commercial shrimp fishery and marine traffic.

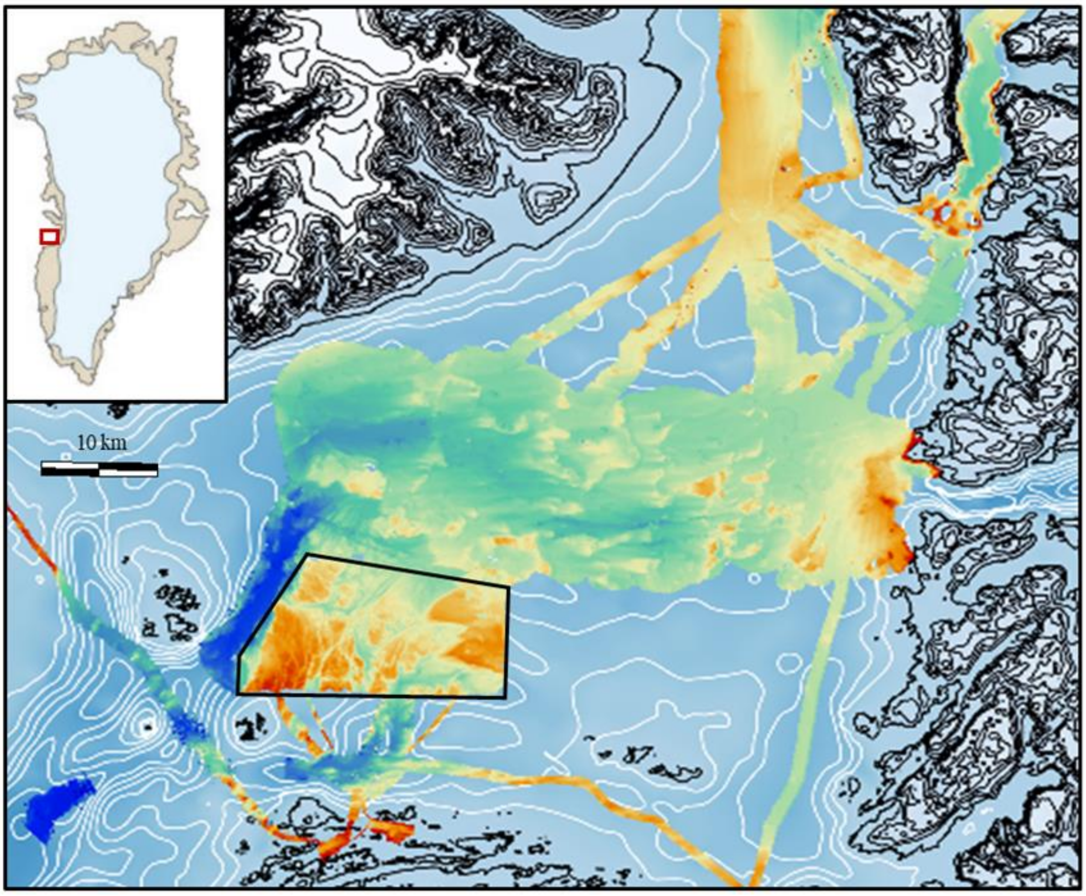

Figure 3. Location of Disko Bay and distribution of existing multi-beam data. The MabHap study area is within the southwest central black square.

5.1 Existing data

Due to a rather small pilot area, the general knowledge of the Disko Bay region is necessary. For this reason, the project-acquired data were supplemented with existing geological, hydrographic and biological information. Screening of existing data is a natural first step of a 'best practice' approach in order to design the field campaign and obtain the firsthand knowledge of the area.

In terms of geology, the marine areas around Disko Bay have been extensively studied by GEUS as part of the offshore Greenland mapping efforts and a number of international scientific marine cruises have taken place in the recent years. These studies were particularly focused on present and past deglacial history and long-term climate change. These efforts combined with the **MapHab** project produced multi-beam-based bathymetry map of a rather large part of Disko Bay (Figure 3). Previous surveys provided only bathymetry data in a moderate resolution (Hogan et al., 2012; Schumann et al., 2012) but no backscatter information, whereas the **MapHab** survey delivered high-resolution bathymetry and backscatter data. Backscatter is crucial for benthic habitat mapping, as it shows a direct relationship to sediment grain size and terrain ruggedness, thus can be used in providing information on bottom hardness (sediment types).

5.2 Geological setting

Geology of the area sets the scene for the present-day bathymetry, hydrography and distribution of sediments. It forms the background for a qualified interpretation of detailed habitat studies of the seabed morphology, recent sedimentation history and substrate distribution.

5.2.1 Tectonic setting

Tectonic setting west of Greenland (Figure 4) reveals that strike-slip movements predominate and are consistent with a NNE–SSW-oriented sinistral wrench system (Wilson et al., 2016). Extensional faults trending N–S and ENE–WSW (basement-parallel) and compressional faults trending E–W were also identified. The Labrador Sea–Davis Strait–Baffin Bay seaway and the wrench system played a dominant role in the development of the on and offshore fault patterns. Chapter 7.3.2 describes detailed tectonic interpretation of the study area, important for understanding the seabed depositional pattern.

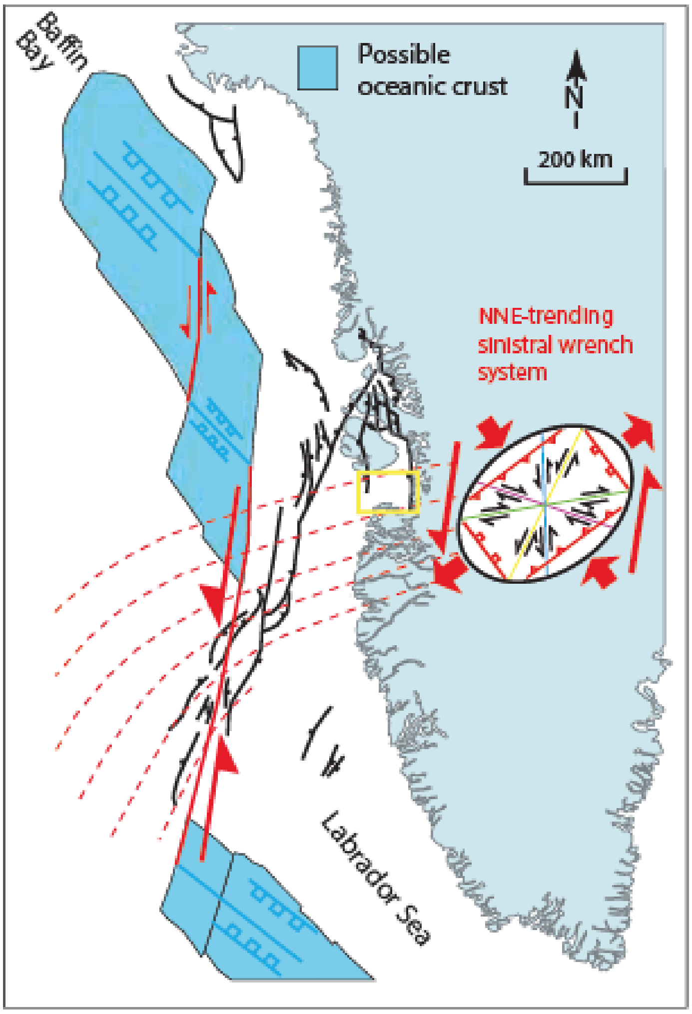

Figure 5. Model for the tectonic evolution of upper Mesozoic–Cenozoic west of Greenland (Wilson et al., 2016). N- and NNE-trending sinistral strike-slip faulting and associated strike-slip wrench tectonic systems with compressional structures (reverse faults) forming zones of basement anisotropy (e.g. shear zones in regional context, based on correlations between onshore and offshore fault structures). The Disko Bay pilot area is within a yellow square.

5.2.2 Pre-Quaternary geological surface

The pre-Quaternary geological surface setting in Disko Bay reveals that the faulting has divided the bay into a SW Precambrian granite basement surface and central to NE Upper Cretaceous fluviatile loosely cemented sandstones (Figure 5).

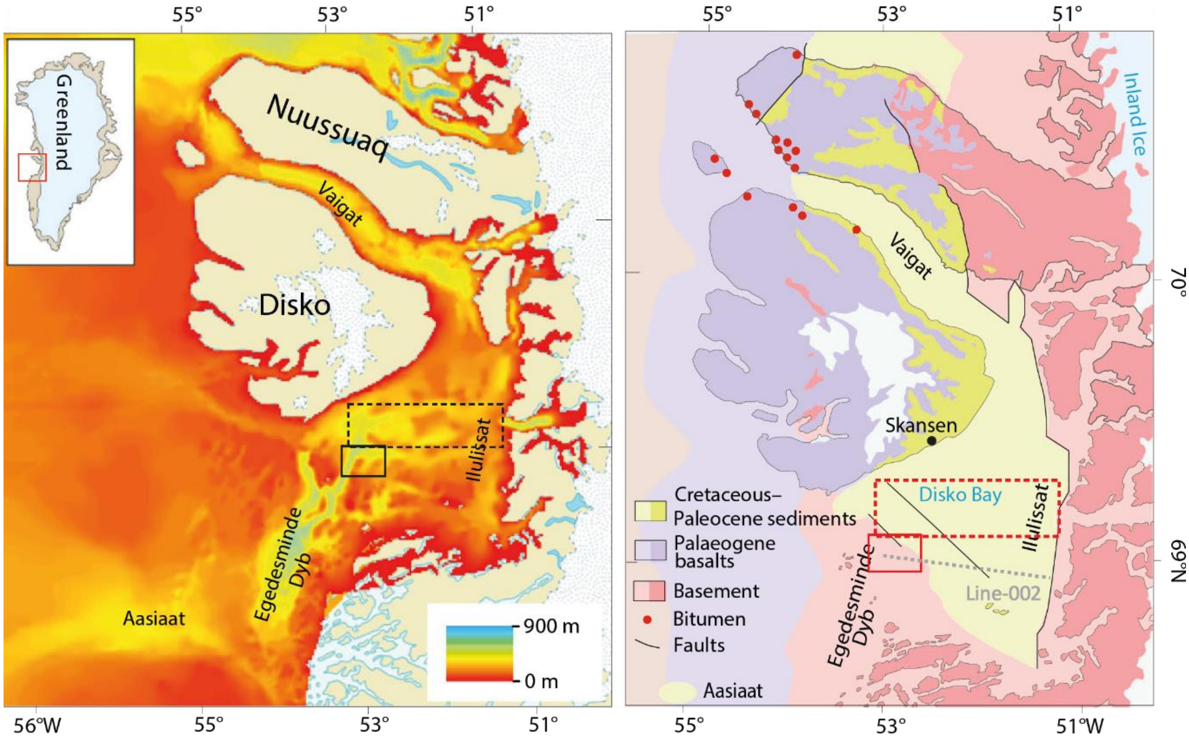

Figure 5. The Disko Bay region. Left: GEUS bathymetric map with location of MapHab study area (small full line square) and Hogan et al. (2012) study area (stippled square). Right: pre-Quaternary geological setting (adapted from Nielsen at al., 2014); full tones - onshore geology, half tones - offshore geology.

The **MapHab** pilot area is located in the border zone between the two bedrock types and with an only patchy coverage of Quaternary deposits (Figure 6). Along the southwestern coastline of Disko Bay the pre-Quaternary granites can be studied onshore, which shows a typical disrupted crystalline morphology with a combination of faults in granites and bedrock terrain indicative of fast ice flow lineation (Whaleback and Roche moutonée). The upper Cretaceous sediments can be studied onshore Disko Island around Skansen (see Figure 5), where 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) (Figure 6).

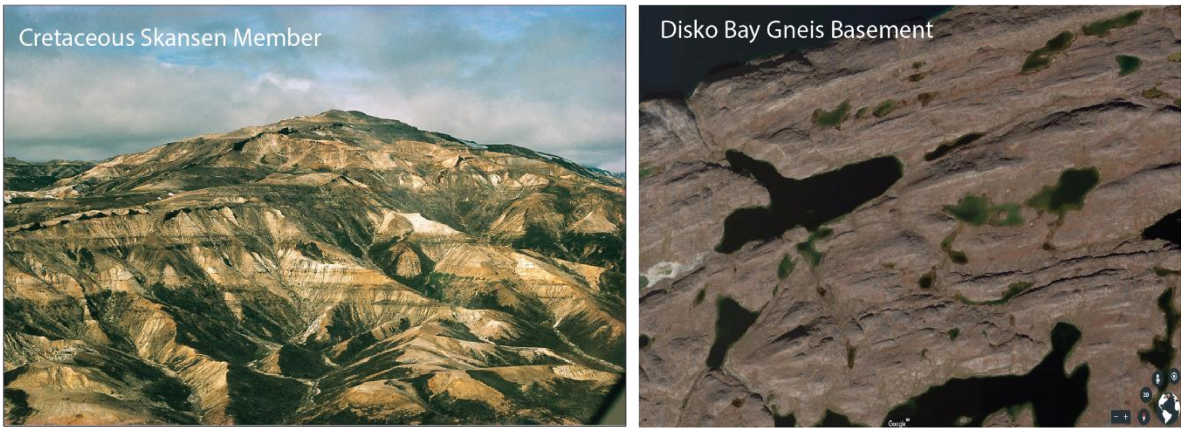

Figure 6. Presentation of the 2 major pre-Quaternary seabed deposits in Disko Bay (Dam et al., 2009). Left: The Upper Cretaceosu Skansen dominated by fluvial sandstones interbedded with fine-grained floodplain deposits and thin coal seams. Right: Precambrian basement granites.

5.2.3 Seismic data

In Disko Bay GEUS has acquired few seismic lines. The example below shows line GGU1995-line 002 (Figure 7 for location figure 5) crossing the **MapHab** pilot area. This line displays the fault zone delineating the boundary between western Pre-cambrian Gneiss and the eastern Upper Cretaceous sandstone.

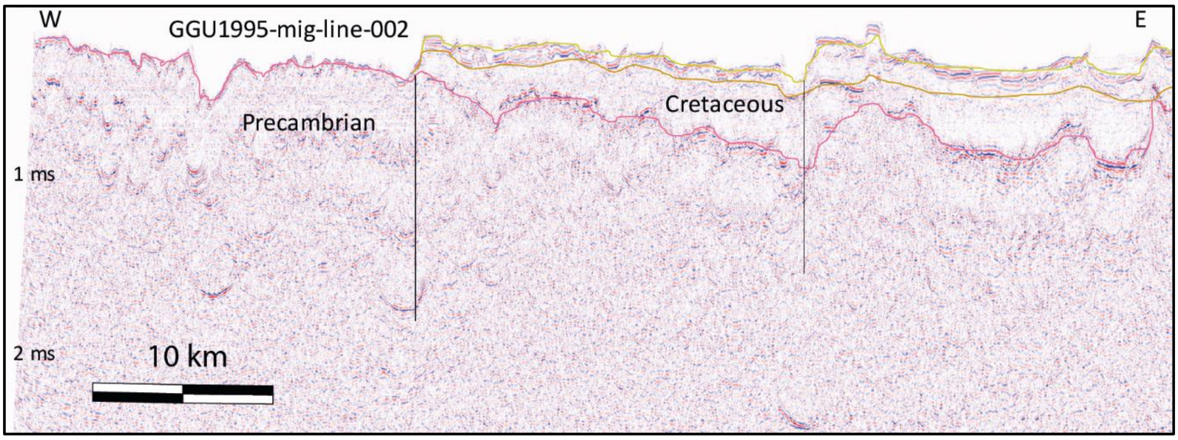

Figure 7. Seismic profile GGU1995 line 002 W–E profile. The line crosses Disko Bay and the NW–SE faults (represented by black vertical lines) reveals Precambrian granites and cretaceous sandstone.

Previous expedition by RRS James Clark Ross (JR175) to the West Greenland and Baffin Bay has provided bathymetric data (Hogan et al., 2012 and Streuff et al., 2017) collected with an EM120 multi-beam echo sounder. Data were processed and gridded at a cell size of 30 m. In addition, TOPAS PS18 parasound sub-bottom profiler data with a frequency range of 0.5–5 kHz were collected. The profiler records are generally of high quality with a resolution of 30–40 cm and were verified with 12 vibrocores. The existing bathymetric data from JR175 combined with the **MapHab** high-resolution bathymetry (10m grid) are described in chapter 7.

5.2.4 Quaternary sediments

Quaternary sediment thickness in Disko Bay, interpreted by Hogan et al. (2012; Figure 8), shows the interchange from large areas with practically no Quaternary sediment coverage to the pre-Quaternary bedrock, as well as thick Quaternary basins. Overall mixture of bedrock substrate, glaciomarine stony clay and mud basins are to be expected in benthic environment.

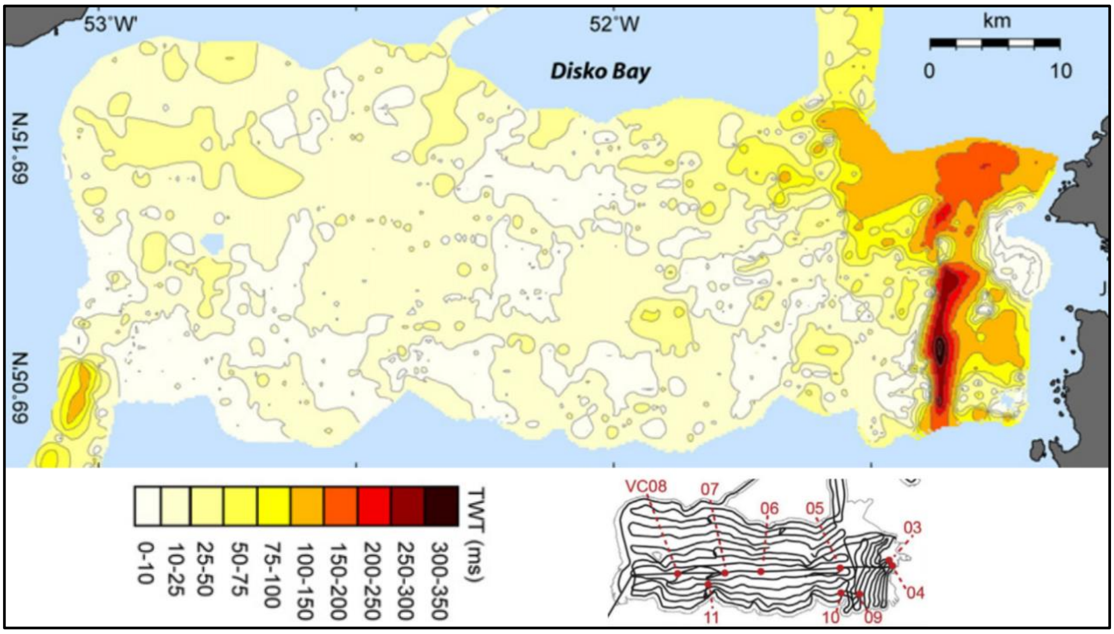

Figure 8. Isopach map of Quaternary sediment thicknesses from Hogan et al. (2012) given in ms TWT. Gridded sediment thicknesses are based on interpretation of seismic lines. Line distribution and vibrocore positions are shown at the bottom.

In Streuff et al. (2017) the parasound data were combined with multi-beam bathymetry into a geomorphological map (Figure 9) showing large areas of outcropping bedrock, possibly linked to topographically distinct transverse bedrock ridges, generally orientated in a north-south direction. The bedrock highs should be exposed at the seabed. The north-south orientated bedrock ridges are closely associated with East-West oriented elongated hills interpreted as bedrock highs, which were overridden and streamlined by glacial ice (glacial lineation). The characteristics of these landforms are consistent with formation of crag-and-tails, formed sub-glacially and in association with the bedrock highs, where the crag consists of bedrock with a lee-side tail of unconsolidated subglacial sediment. In addition, submarine channels and pockmarks were identified.

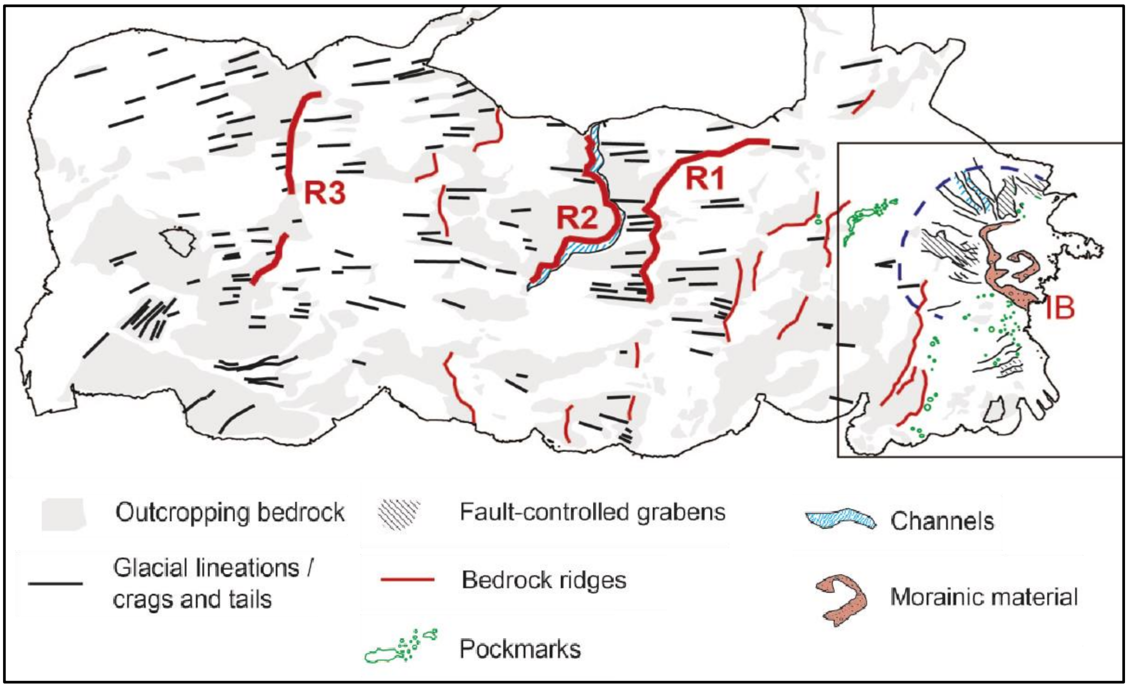

Figure 9. Geomorphological map of identified landforms in Disko Bay from Streuff et al. (2017). Landforms in the black rectangle indicate area mapped by Hogan et al. (2012) and Schumann et al. (2012).

General bathymetric and geological information together with high-resolution seismic data and ground-truth data are an important input for rectifying the acoustic multi-beam backscatter interpretation of seabed substrate.

5.3 Hydrography

5.3.1 Hydrographic conditions

The hydrographic conditions of Disko Bay are highly variable including complex and sloping seabed topography with maximum depths exceeding 900 m (outer parts of Disko Bay). In some places hydrographic conditions can change dramatically, such as along steep slopes and narrow submarine canyons to more shallow areas. The runoff of freshwater from melting glaciers during summer further contributes to the hydrographic complexity by introducing significant vertical and horizontal salinity gradients throughout the system (Hansen et al., 2012). Inertial water movements from tidal and meteorological forces are expected to interact with seabed topography driving turbulence and mixing along the seabed in Disko Bay, especially in the **MapHab** pilot area. This is supported by findings from the **MapHab** area showing a relatively thin layer of sediment deposits on top of otherwise hard (or consolidated) seabed substrates indicating that resuspension events occur at a frequency preventing long-term accumulation of clay, silt and organic matter at depths down to at least ca. 300 m.

5.3.2 Influence of seabed topography

Data on seabed topography of the entire Disko Bay area in a 150 m spatial resolution are available from BedMachine[1] (Figure 9; Morlighem et al., 2017a, 2017b). Bathymetry is highly variable in the outer western and south-western parts of Disko bay. Figure 10 shows high-resolution (10 m) bathymetry data for the pilot area collected during the **MapHab** survey (see chapter 6) and a low-resolution (150 m) bathymetry embedded in the BedMachine model. The comparison clearly shows that there are significant local variations in seabed topography at a scale less than 150 m and the high-resolution bathymetry data contributes a significant addition for characterisation of seabed habitats. The 150 m BedMachine bathymetry data are based on an agglomeration of various data sources, some of which may be of an original scale larger than 150 m, which contribute to

[1] This data set contains a bed topography/bathymetry map of Greenland based on mass conservation, multi-beam data, and other techniques. It also includes surface elevation and ice thickness data, as well as an ice/ocean/land mask.

the pronounced differences between the 10 m and 150 m resolution bathymetry data.

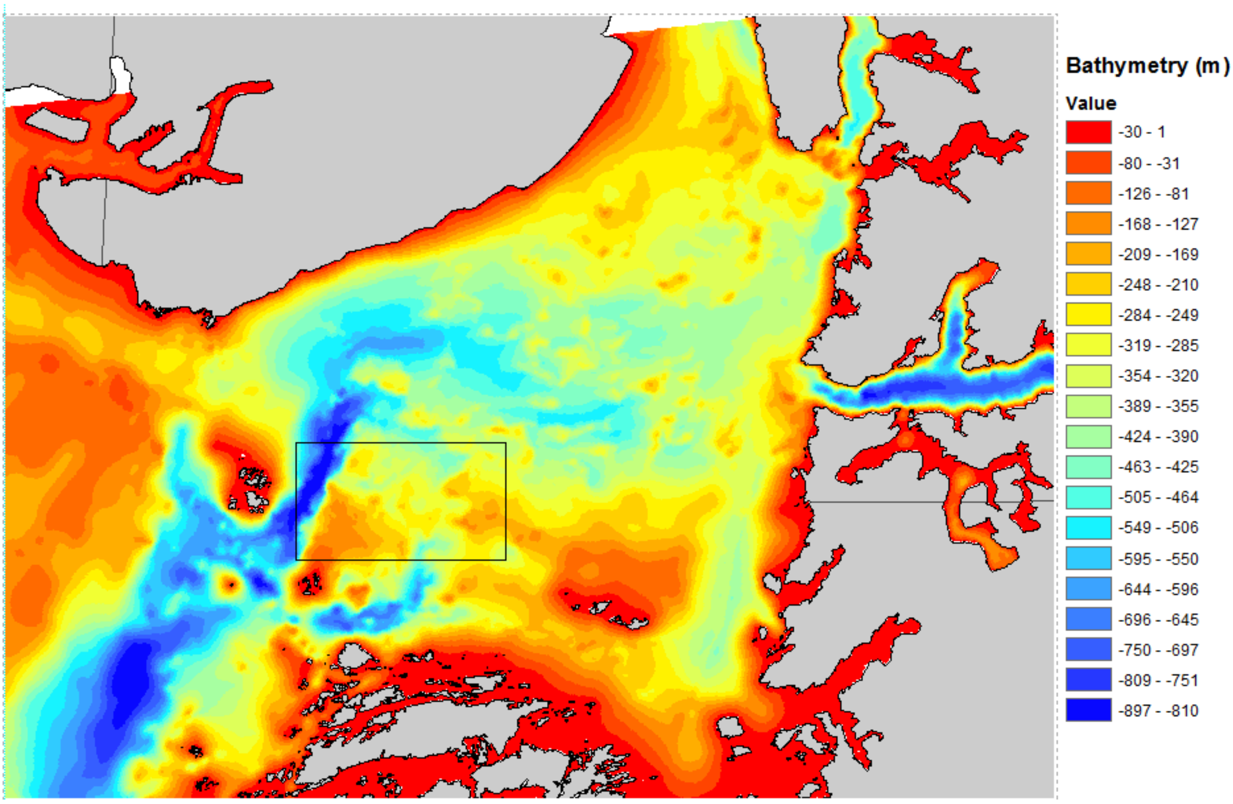

Figure 9. Bathymetry based on 150 m grid resolution (source: BedMachine). Black outline indicates the MapHab pilot area.

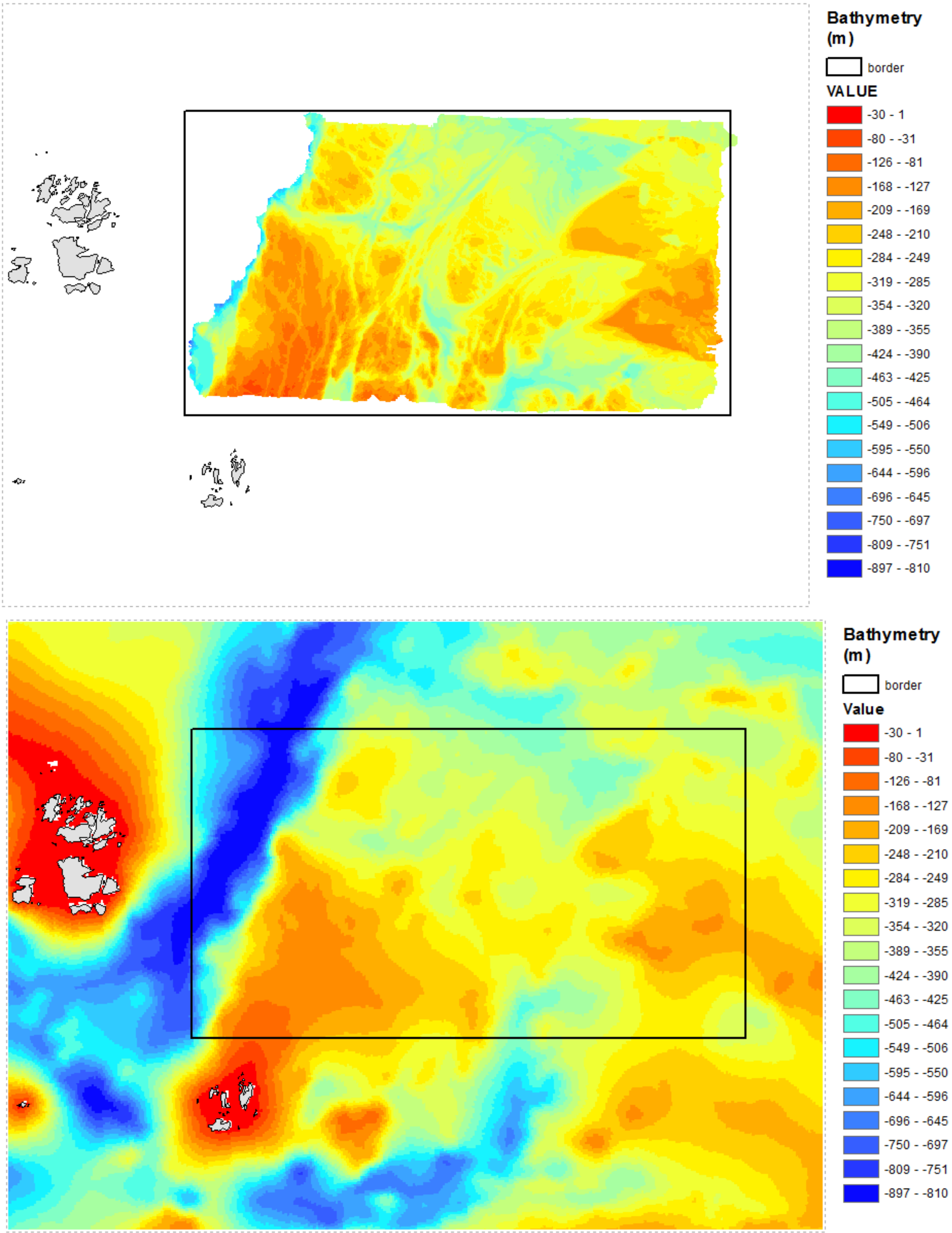

Figure 10. Bathymetry of pilot area (black outline) based on 10 m (top) and 150 m (bottom) grid resolution. Data from the multi-beam survey and Gridmachine.com.

The slope data extracted from the 150 m bathymetry data are shown in Figure 1111 emphasising the complexity of seabed topography at this scale. The combination of complex seabed topography, relatively large areas of varying water depths, tidal and meteorologically-induced currents, are expected to sustain a highly variable and complex hydrodynamic environment.

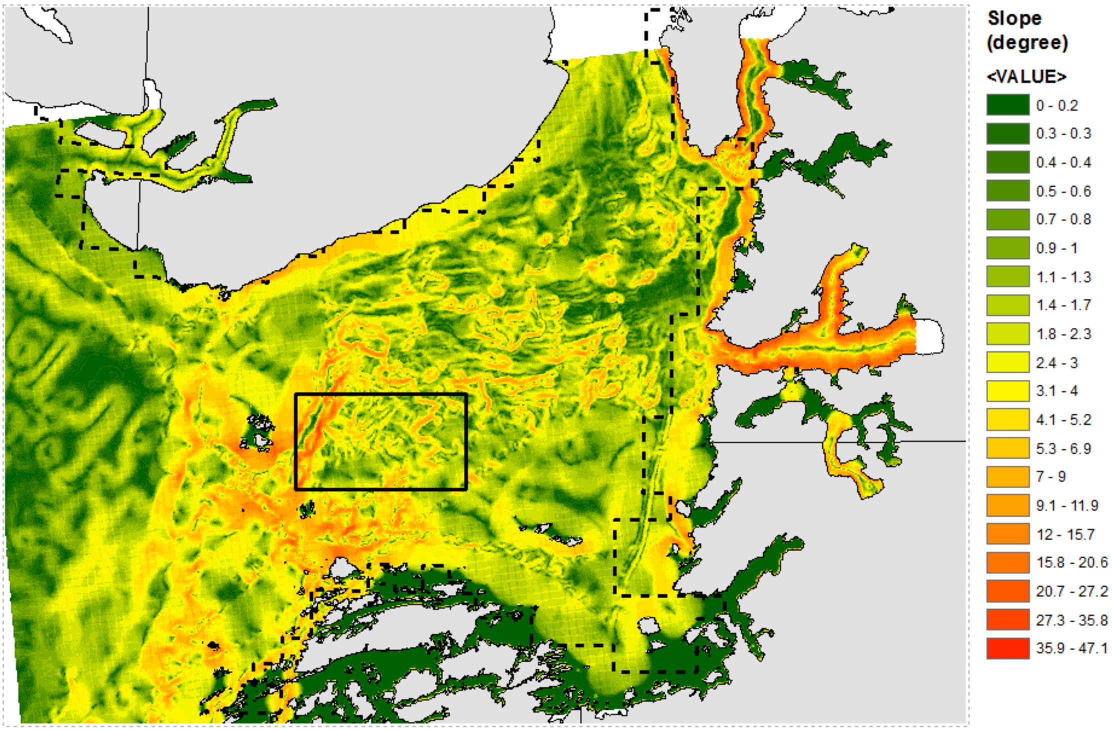

Figure 11. Calculated slope of seabed terrain from 150 m bathymetry data (Bedmachine). Colour scale represents slope in degrees. Black outline indicates the pilot area.

5.3.3 Hydrodynamic model

A high-resolution hydrodynamic model for the Disko Bay area that sufficiently resolves the complex seabed topography is not currently available and it was not possible within the framework of the **MapHab** project to create a customized high-resolution hydrodynamic model for the pilot area. Instead, to demonstrate the types of data that can be extracted from hydrodynamic models, hydrographic variables were extracted from a coarse hydraulic 3D model based on the COHERENS-modelling system covering the Baffin Bay with a horizontal resolution of ca. 5.3x5.3 km. The data were provided by Climatelab Aps and work on model calibration is still in progress, in particular the conditions close to glaciers and fjords are currently being optimized. However, this will only have minor effects on the hydrographic variables close to the seabed in more open areas of Disko Bay. The model simulation has been initiated by climatology data and forced by weather and sea ice data from reanalysis data with a 3-hour time interval. Turbulent mixing is described using a *k-epsilon* scheme, and fluxes at the open boundaries are based on climatological data. Since boundaries are located far from Disko Bay, deviation between climatology and real weather data will have no or minimal effect on the predicted conditions in Disko Bay. The tidal forcing at the open boundary towards the South originates from a barotrophic model. Simulated data for July 2013 were provided by Climatelab Aps and include water temperature, salinity and currents (u and v) covering the months of July 2013. These data have a grid resolution of ca. 5.3x5.3 km for the Disko Bay area, 25 vertical (sigma) layers, and all values represent daily means. The coverage of the Baffin Bay model and the horizontal grid resolution covering the Disko Bay are shown in Figure 1212; a comparison between simulated and observed water level at Ilulissat station in Disko Bay is shown in Figure 1313.

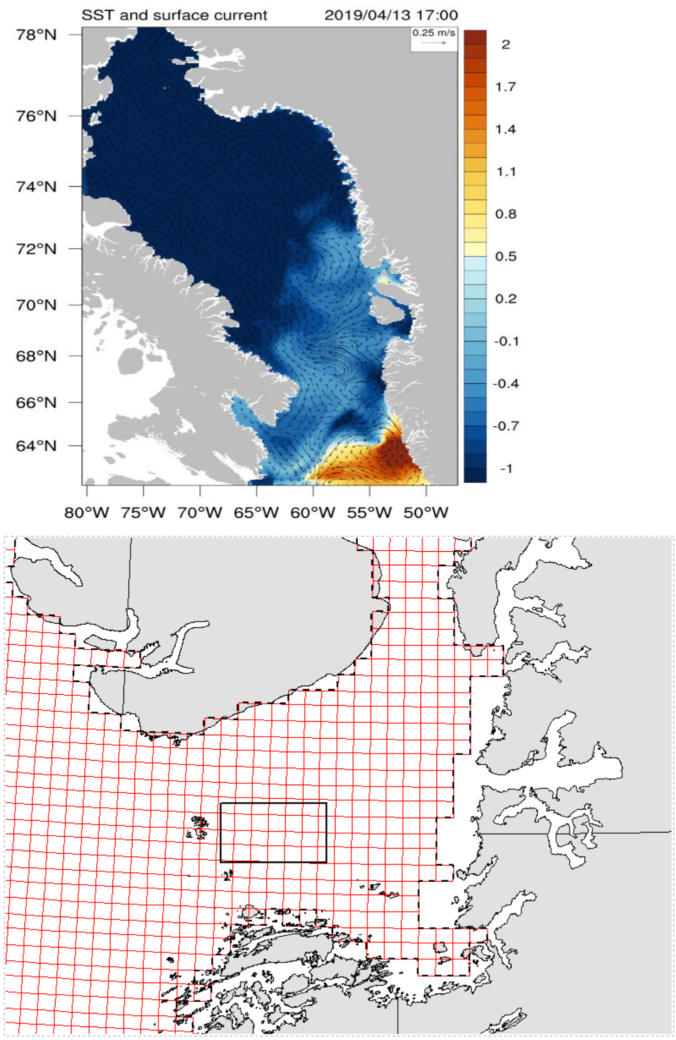

Figure 12. Top: Model domain of the hydrodynamic model COHERENS setup for the Baffin Bay. Colours indicate sea surface temperature on 2019-04-13, and arrows indicate sea surface currents direction and speed. Bottom: representation of

the computational grid (red outline) of the part of the Baffin Bay model domain covering the Disko Bay area. The pilot area is shown in black outline. Source: www.Climatelab.dk.

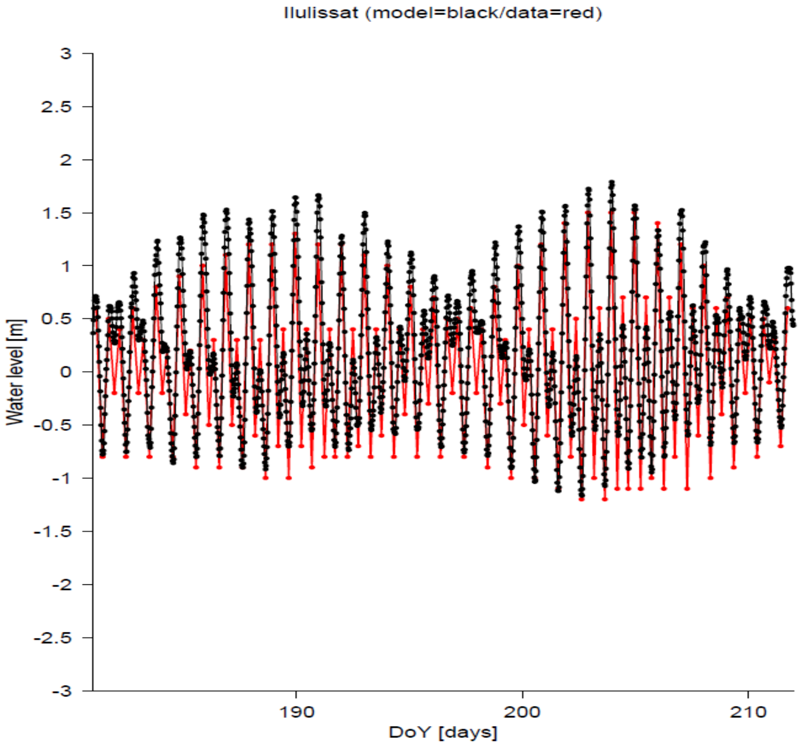

Figure 13. Comparison between simulated (black) and observed (red) water level at Ilulissat station in Disko Bay. Source: www.Climatelab.dk.

5.4 Biological communities

Knowledge of biological communities in the Disko Bay area is predominantly based on bycatch from stock assessment surveys of the northern prawn fishery, a limited number of beam trawl surveys conducted as part of the Long-Term Monitoring Benthos Network and drop camera/video surveys conducted by IoZ and GINR since 2011. Yesson et al. (2015) documented biological communities along the western continental shelf based on drop camera imagery (Figure 14). Four broad-scale communities were documented based on clustering of order-level taxa identified from imagery. Although this study did not include samples from within Disko Bay, it did include samples from Disko Bank and Store Helle-fiske Bank with similar depth and substrate profiles. The deeper, muddier com-munities were characterized by polycheat worms and the commercially fished cold-water prawn.

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).

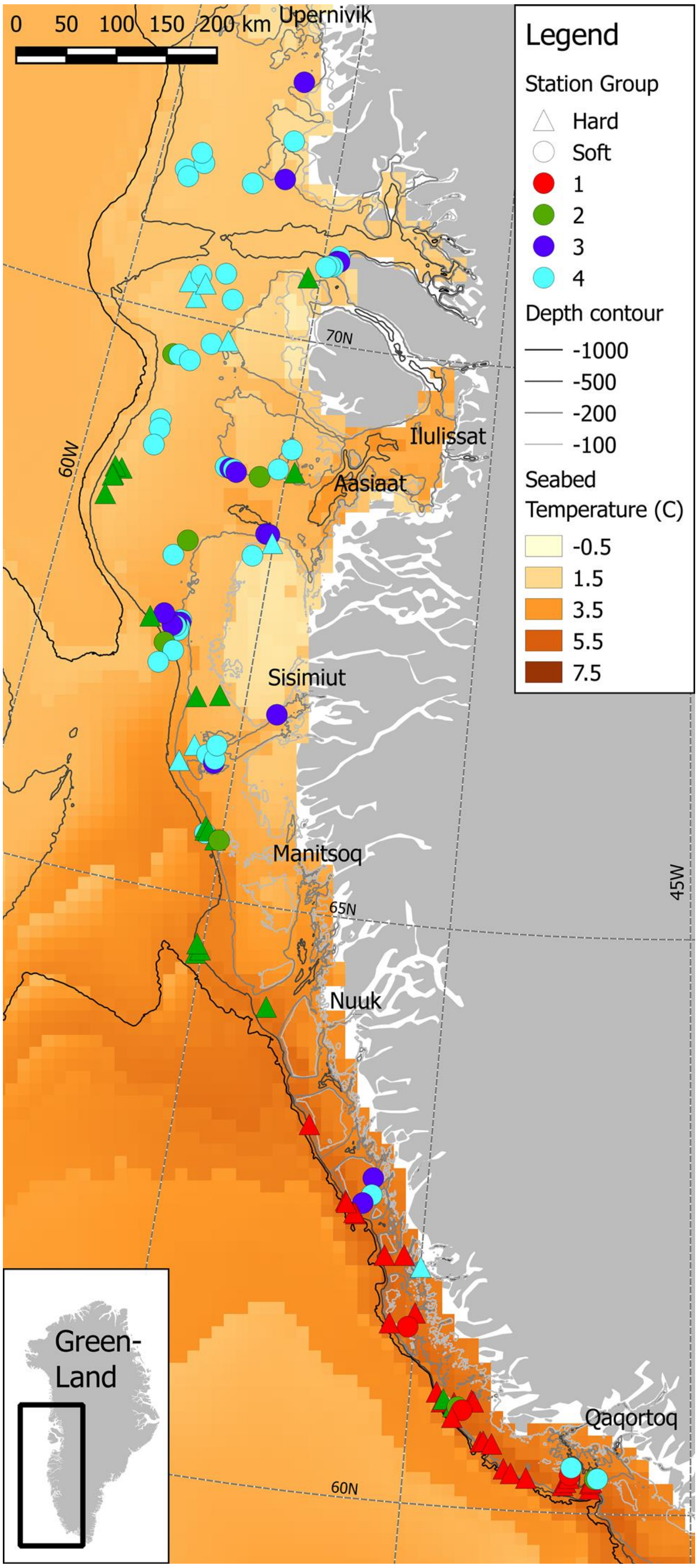

Figure 14. Reproduced from Yesson et al. (2015). Map of stations by faunal cluster groupings. Cluster 1&2 are on predominantly rocky/mixed substrate and are characterized by attached fauna such as ascidiaceas, bryozoa, porifera and an-

thozoa. Cluster 3&4 are soft sediment groups characterized by malacostraca including the commercially fished Pandalus borealis and Gastropoda. Approximate seabed temperatures are shown for reference.

6. MapHab survey

The 10-day **Maphab** survey was carried out in September 2018 with R/V Sanna covering an area of c. 30x20 km. The method combined acoustic survey (multi-beam echo sounder SeaBat T50-ER) with physical ground-truthing (benthic video sled, drop camera and grab) to characterize the seabed environment and habitats (see figure 15).

Operating frequency of multi-beam was constant throughout the survey (180 kHz), likewise power, gain, absorption and pulse length for reliable backscatter data. Unprocessed multi-beam data, i.e. bathymetry and backscatter were gridded on board and classified using unsupervised classification (histogram analysis) in ArcGIS software in order to choose the most optimal locations from the sampling points, based on distinct depth intervals, terrain features and backscatter intensity (grayscale). Ground-truthing is an important part of benthic habitat mapping. Samples of the seabed are required to calibrate and validate any interpretation of the acoustic data. We have deployed a combination of imaging and physical sampling of the area.

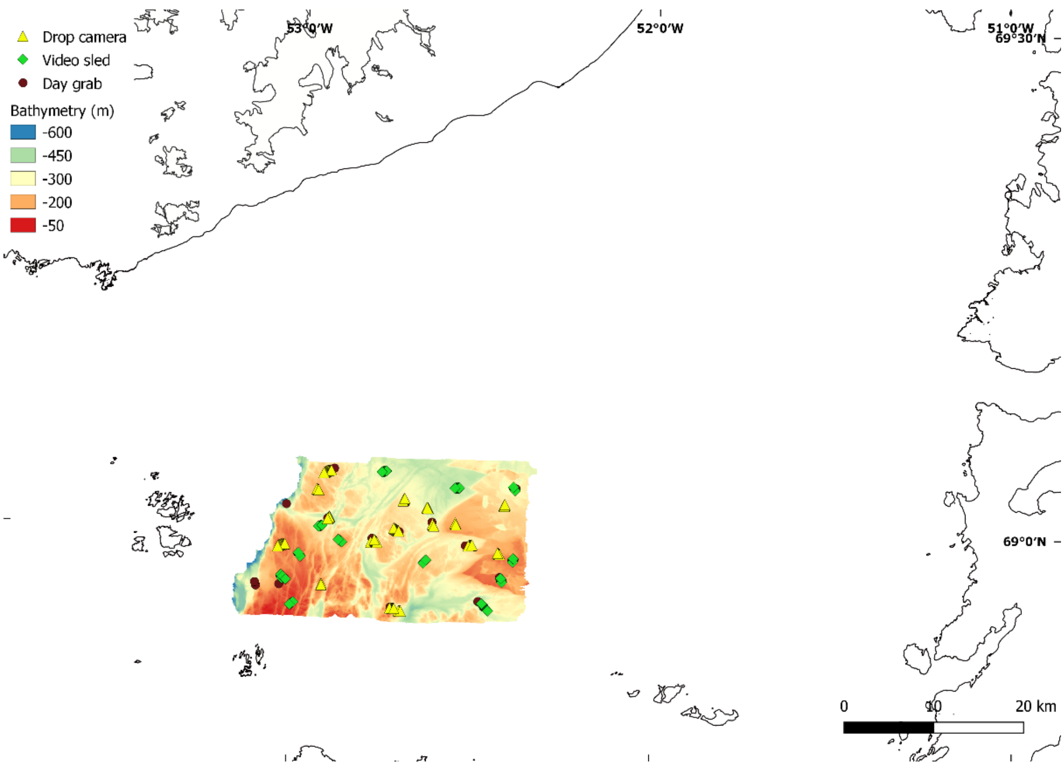

Figure 15. Location of physical ground-truthing stations from Disko Bay pilot area collected with video sled (green rhombus), drop camera (yellow triangle) and grab (red circle).

Imaging the seabed provided a broad overview of the seabed alongside pictures of benthic fauna over relatively wide geographic scale (~hundreds of meters per deployment). Images allowed classification of seabed into broad scale benthic habitats and were also used to assess benthic fauna, particularly epi-benthic megafauna. It can be difficult to identify fauna from images to detailed taxonomic resolution, but major habitat-forming groups can be determined. Physical sampling using grab enabled direct measurement of grain sizes, allowing more detailed calibration of sediment classes at the finer end of the size spectrum. Physical samples can also be used to identify and assess infauna but it was not a part of this study. Each physical sample, corresponding to a small (sub-metre) patch of the seabed, is more reliable on softer sediment habitats.

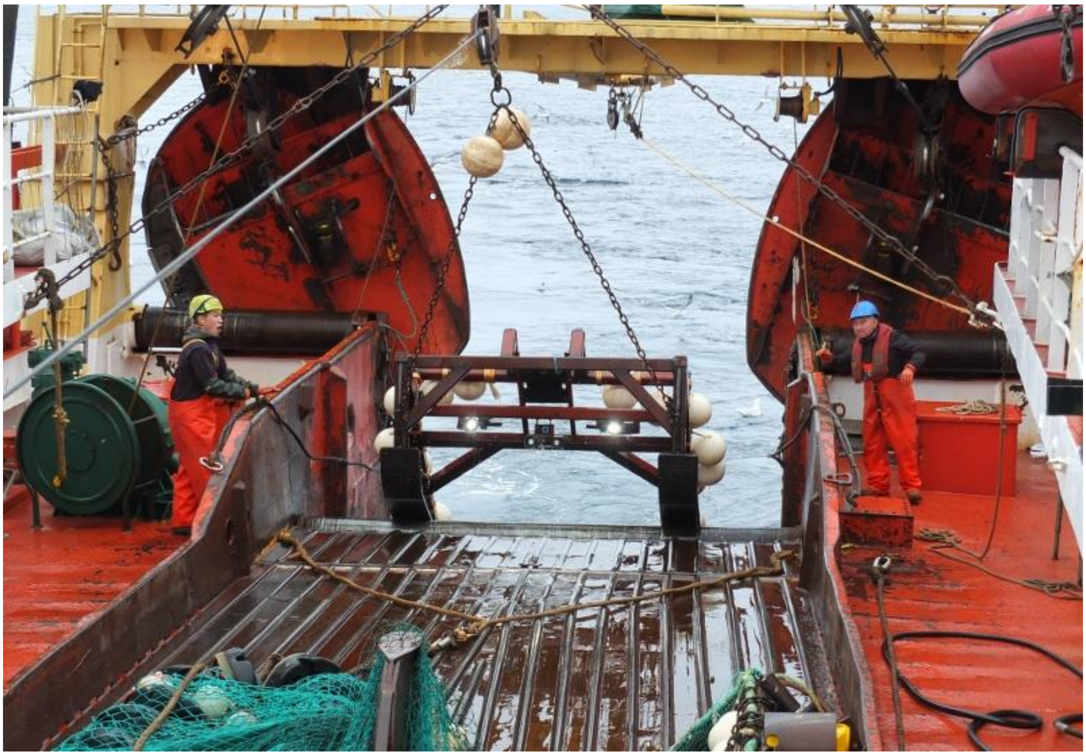

Figure 16. The towed video sled camera system being deployed.

The **MapHab** survey resulted in a set of high-resolution environmental data that were further processed. Multi-beam data provided a full coverage of the pilot area with bathymetry and backscatter signatures and derivatives, such as slope, ruggedness, morphology, whereas physical ground-truthing delivered videos, photos and physical samples of sediment types, as well as images of benthic communities. All these data were combined, classified, interpreted and digitized into coherent benthic habitat maps (see below). Detailed information on data acquisition, data formats, data processing, seabed classification and map production of the **MapHab** project can be found in the 'best practice' protocol at (Krawczyk et al., 2019).

6.1 Acoustic deliverables

<u>Bathymetry map</u> <u>and</u> **<u>3D terrain model</u>** showing seabed topography and water depth in the area; Disko Bay's complex topography is characterized by a large dendritic system of paleo-channels of the ancestral Jakobshavn Isbræ, multiple post-glacial valleys carved by glacial and fluvial activity; bathymetry data (Figures 17-19) are also used to calculate slope (Figure 20) and terrain ruggedness.

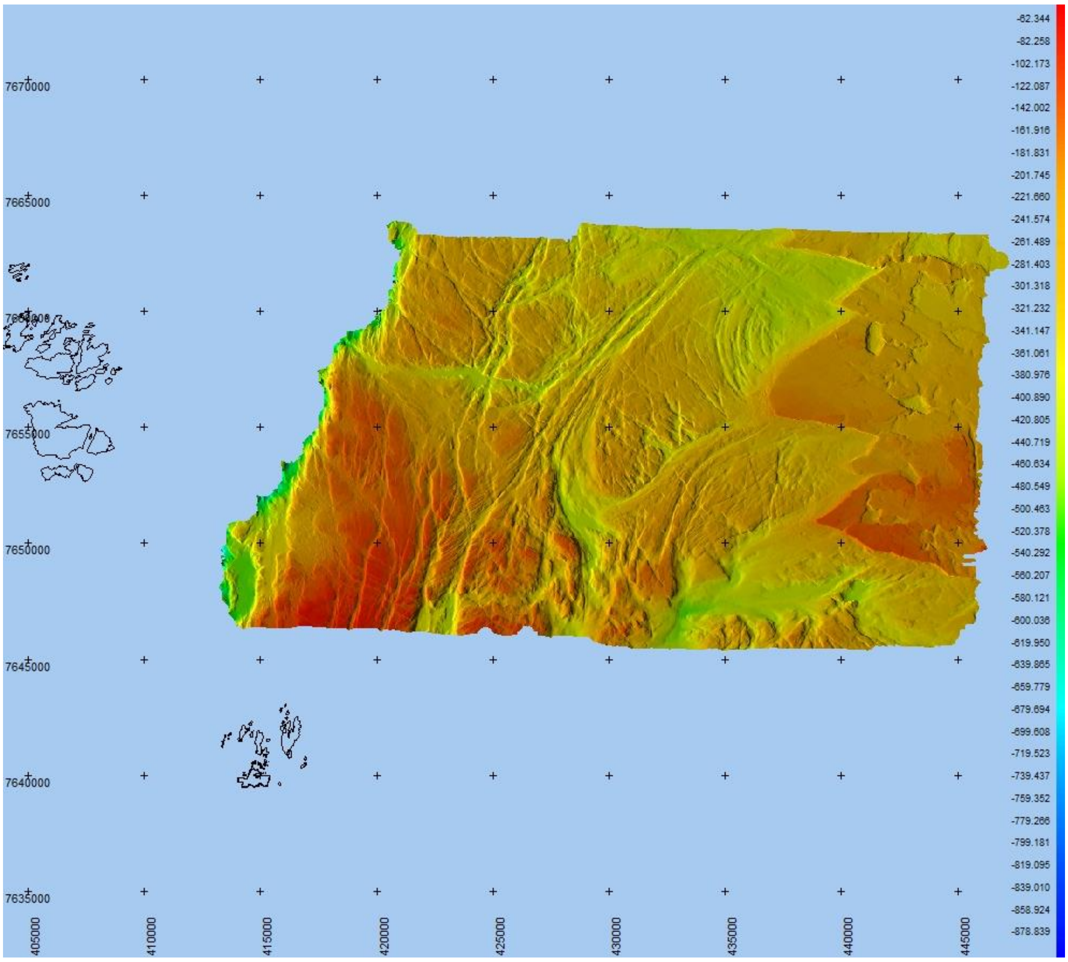

Figure 17. Disko Bay pilot area – bathymetry map (color scale: red – shallow waters, blue – deep waters); 10m grid.

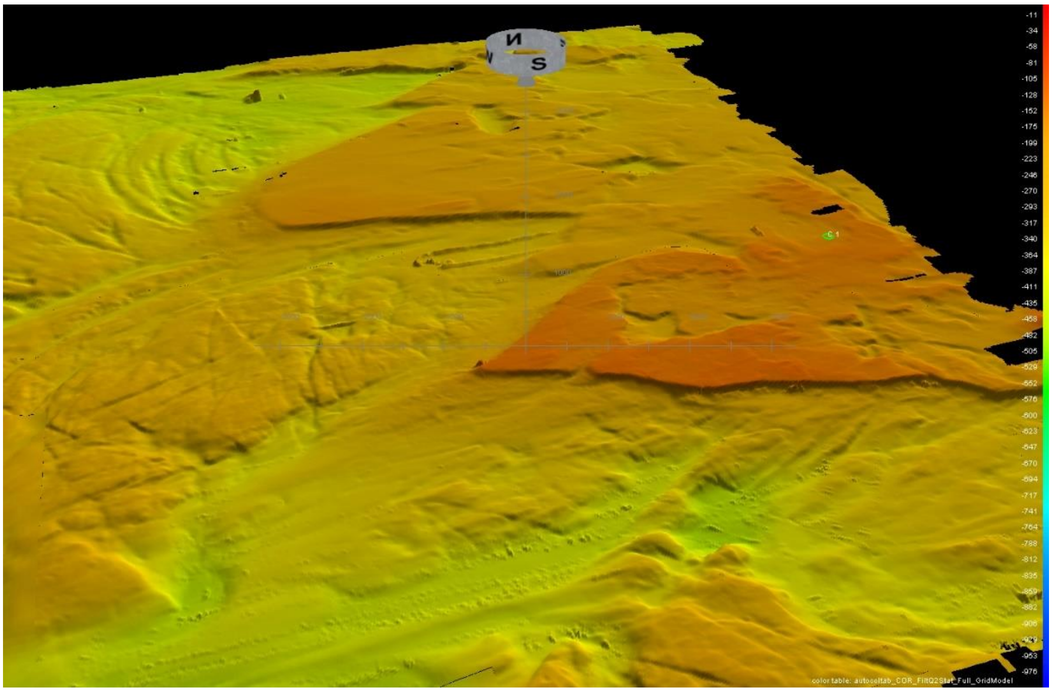

Figure 18. 3D terrain model (10m grid).

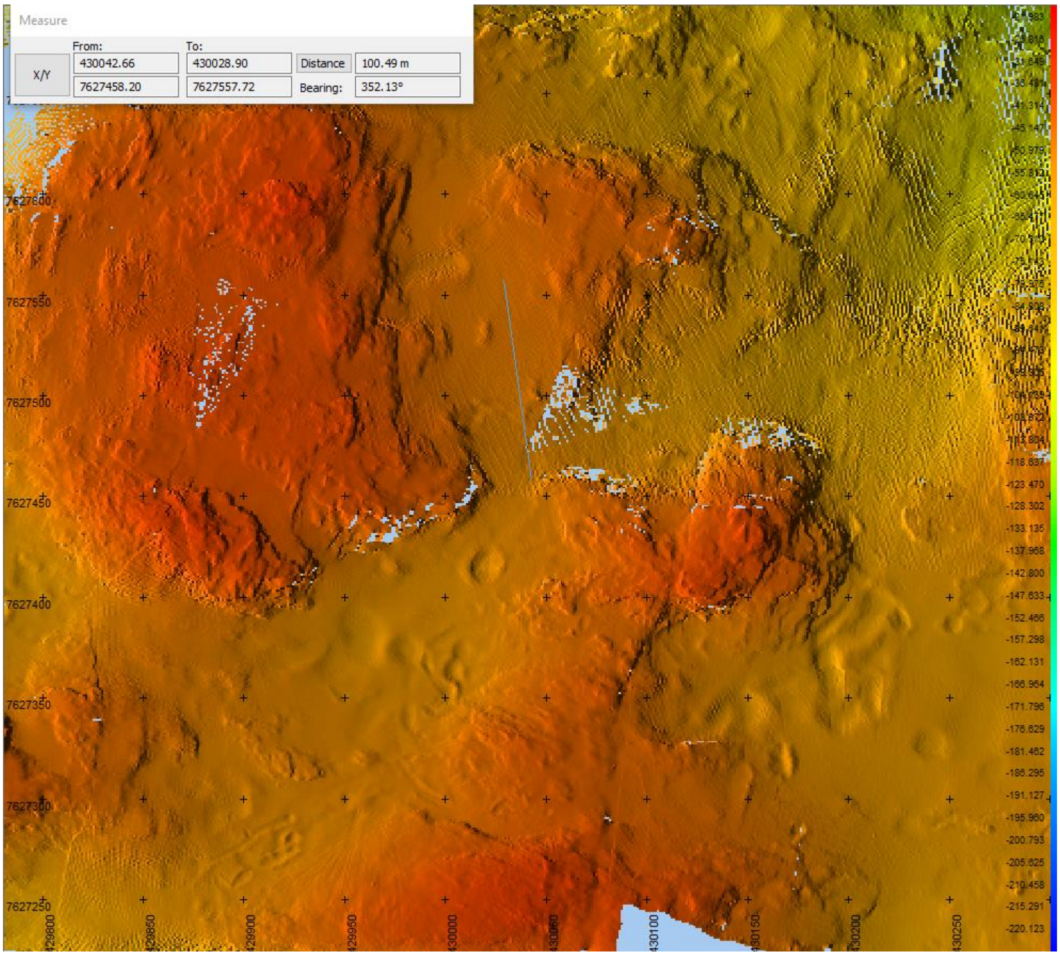

Figure 19. Example of ultra-high-resolution 3D terrain model (1m grid).

Figure 20. Slope – Disko Bay pilot area (color scale: green –flat bottom, brown – extreme slope).

<u>Morphology map</u> presenting distinct topographic features in the area, i.e. valley, mound, flat and slope (Figure 21). Morphology combines information on broad-scale and fine-scale bathymetric position index and slope.

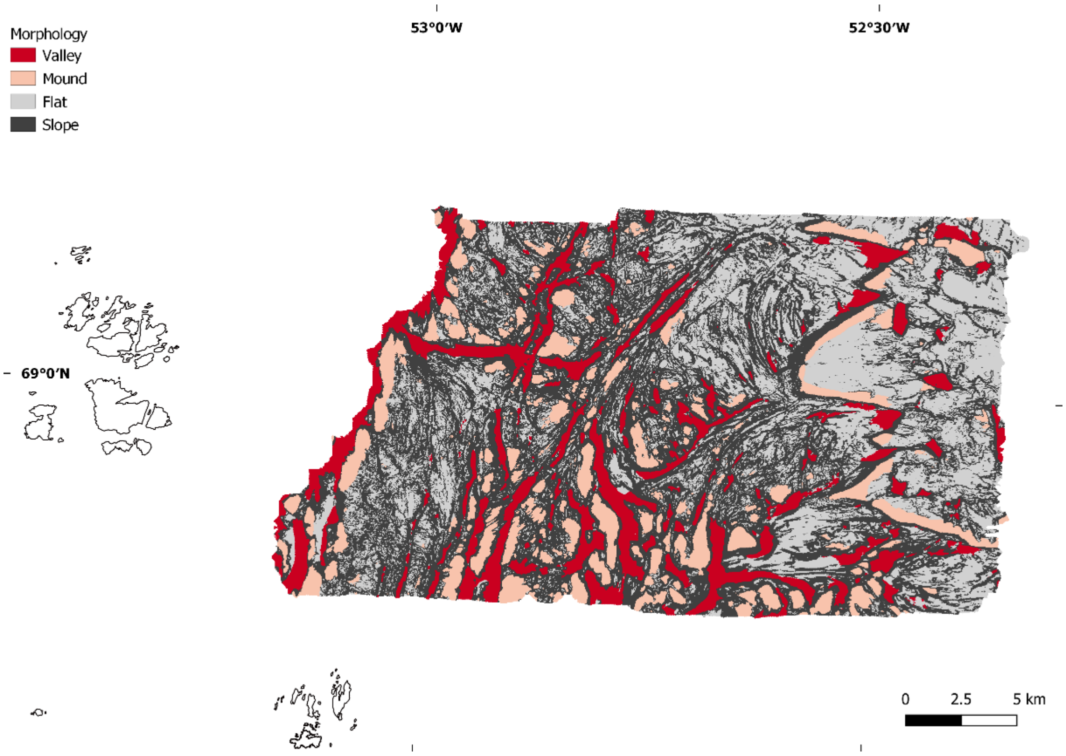

Figure 21. Morphology showing key topographic features in Disko Bay pilot area. Generated by Benthic Terrain Modeler (ArcGIS software).

Backscatter mosaic showing acoustic scatter intensity used as an indication of the seabed hardness and ruggedness used in sediment map processing. High intensity is indicative of hard bottom and low intensity is indicative of soft bottom (Figure 22).

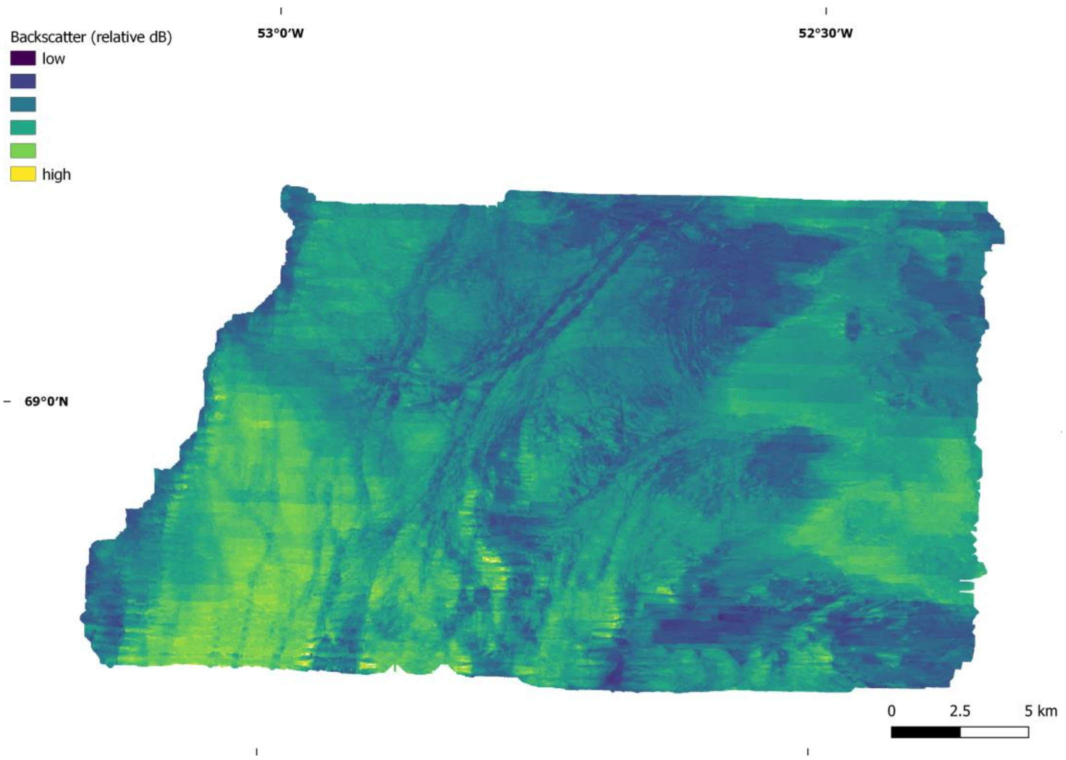

Figure 22. Backscatter mosaic – Disko Bay pilot area (color scale: yellow – hard bottom, black – soft bottom); 10m grid.

6.2 Ground-truth deliverables

Benthic images presenting benthic sedimentary environment and key fauna species inhabiting seabed. They were used to assess the substrata, benthic habitats and fauna of the survey areas; sediment classification was based on EUNIS-modified scheme (Gougeon et al., 2017). These were subsequently simplified into a three-class scheme: A6.1: Deep-sea rock and artificial hard substrata, A6.2: Deep-sea mixed substrata, A6.5: Deep-sea mud. Examples of these are presented in Figure 23.

Figure 23. Example stills from video sled imagery. These images were classified as top: Deep-sea mud; middle: Deep-sea rock and artificial hard substrata; bottom: Deep-sea mixed substrata.

The dominant taxa were recorded at the image level to record the habitat forming species in the area. Although a variety of habitats were observed (Figure 24), taxa were patchily distributed and sampling was insufficient to analytically segregate biotic habitats into anything more than two groups determined by substrate. These groups were:

1) soft seabed communities dominated by anemones, polychaet tubes and the cold-water prawn

2) mixed/rocky communities dominated by sessile attached fauna, such as bryozoan, ascidians and porifera

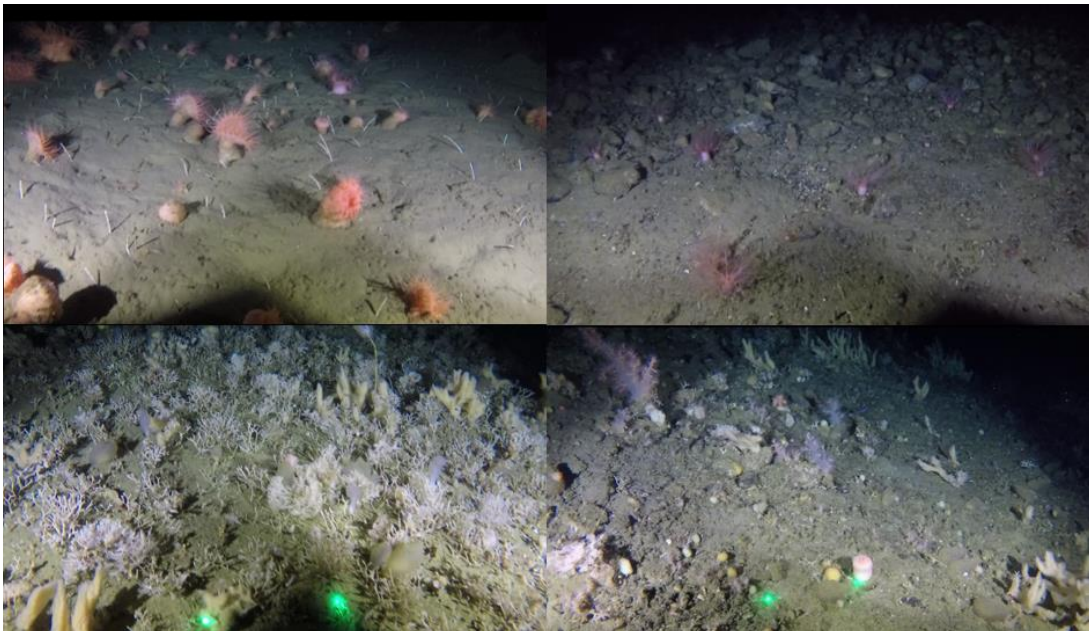

Figure 24. Example stills from video sled imagery highlighting a variety of benthic fauna. Top left: anemones and polycheat worms on muddy seabed; top right sea cucumbers on mixed seabed; bottom left bryozoan and sponges on mixed seabed, bottom right: sponge and corals on mixed seabed.

6.3 Baseline high-resolution maps

Simplified mapping workflow scheme showing combining acoustic layers with ground-truthing data:

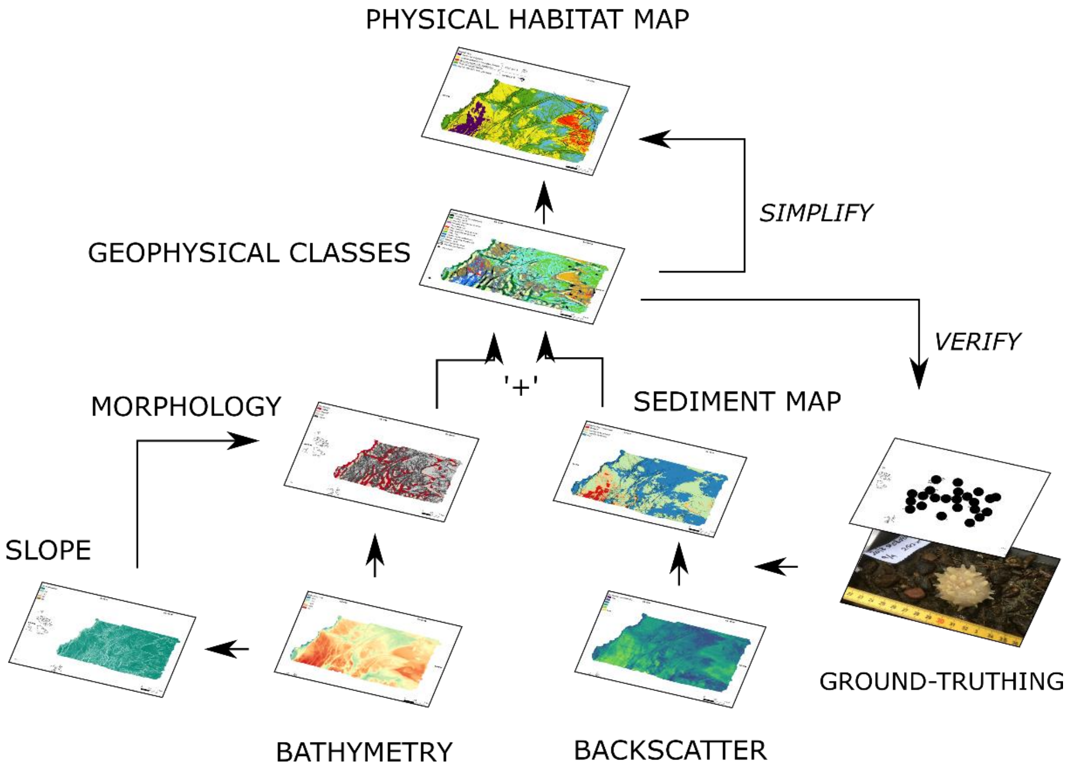

Figure 25. Simplified mapping workflow.

Sediment map presenting classified sediment types based on acoustic backscatter intensity and verified with the physical ground-truthing; the dominant fraction in the area is mud and gravelly sand/mud, to a lesser extent coarse rocky ground and bedrock (Figure 26).

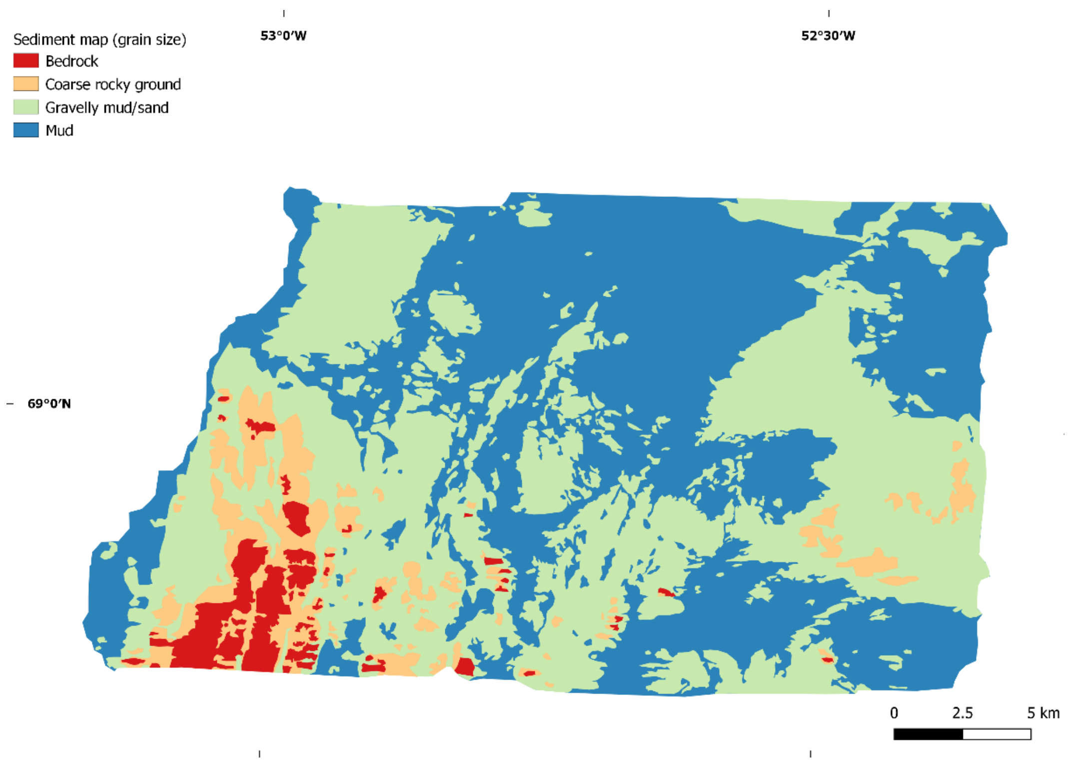

Figure 26. Sediment map based on classified backscatter mosaic.

Geophysical map presenting classified topographic features combined with sediment types in the area, as well as identified gas seeps and possible pockmarks. This map is a combination of morphology map and sediment map (Figure 27).

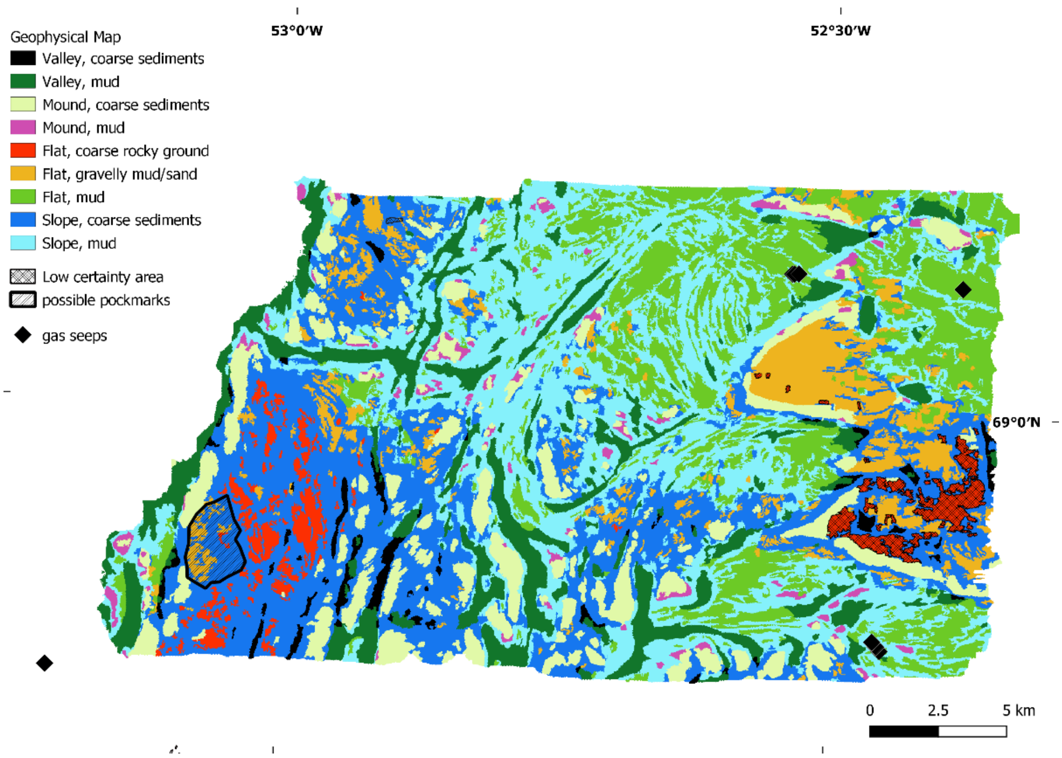

Figure 27. Classified geophysical map from Disko Bay pilot area, validated with ground-truthing data.

7. Map interpretation

7.1 Geological interpretation

For a more complete picture of the sedimentary environment of the **MapHab** pilot area, we have included profile data and vibrocorings from the RRS James Clark Ross Cruise - JR175 (Hogan et al., 2012) (Figure 28). This gives the opportunity for geological interpretation of seabed sediments and to generate a combined, semi-detailed bathymetry (cell size of 30 m) covering larger part of Disko Bay, in order to interpret the general morphological setting and transfer it to a more detailed pilot area.

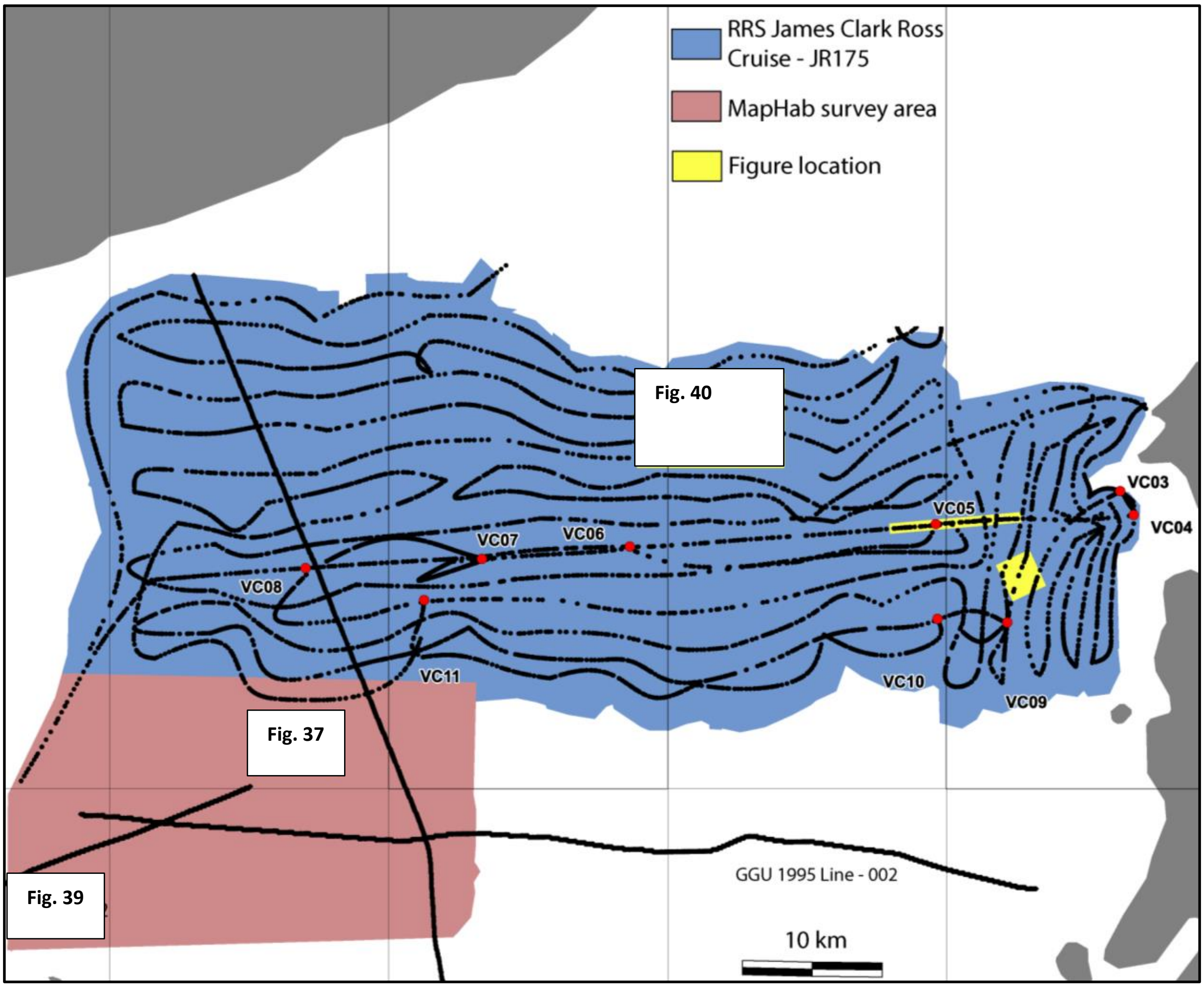

Figure 28. Blue area shows seismic survey lines from the RRS James Clark Ross Cruise (Hogan et al., 2012) including TOPAS sediment echo sounder data and multi-beam bathymetry, as well as vibrocores (red dots). Light red area shows the MapHab multi-beam survey area. Marked survey lines crossing the MapHab area represent archive seismic lines; GGU1995 Line – 002 is indicated. Yellow areas show locations of figures.

7.3.1 Semi-detailed bathymetry

The semi-detailed bathymetry (Figure 29) shows in a broad perspective an eastern shallow part (100–350m depth) outside the Ice Fjord (Isfjorden) followed by a central basin extending westward (300–500m depth) and interrupted by elongated ridges, a southern shallow (100-350m depth) plateau and a fare southwest oriented deep channel (450–900m depth).

Comparison between the general geological information from chapter 5.2 and the semi-detailed bathymetry indicates that Disko Bay shows a combination of bedrock structures, thin-skinned patchy glacial geology and postglacial deposition.

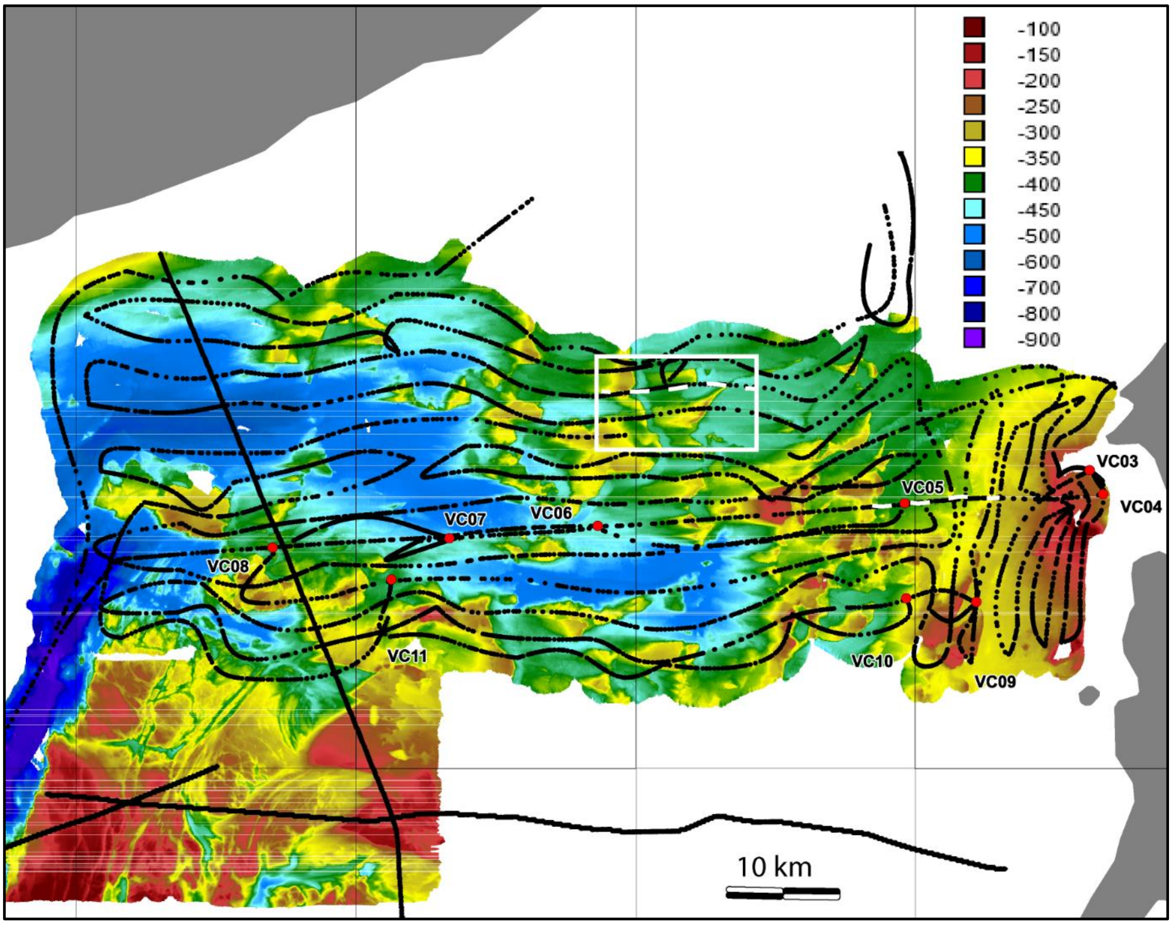

Figure 29. Combined multi-beam bathymetry of RRS James Clark Ross Cruise (Hogan et al., 2012) and MapHab survey area. Locations of seismic lines and vibrocores are also presented. The white square indicates location of figure 32, i.e. seabed surface sediment interpretation and location of figure 33, i.e. TOPAS sediment echo sounder profile crossing vibrocore VC5.

7.3.2 Tectonic interpretation

Tectonic surface setting (Figure 4) shows the general NNE–SSW-oriented sinistral wrench system. Figure 30 shows detailed extensional faults trending NE–SW and ENE–WSW (basement-parallel), and compressional faults trending SE–NW. The fault pattern is prominent in the southwestern Precambrian bedrock area with little to no topsoil, while the central and eastern Upper Cretaceous sandstone area is more modified by glacial processes, thus the bedrock tectonics is more unclear.

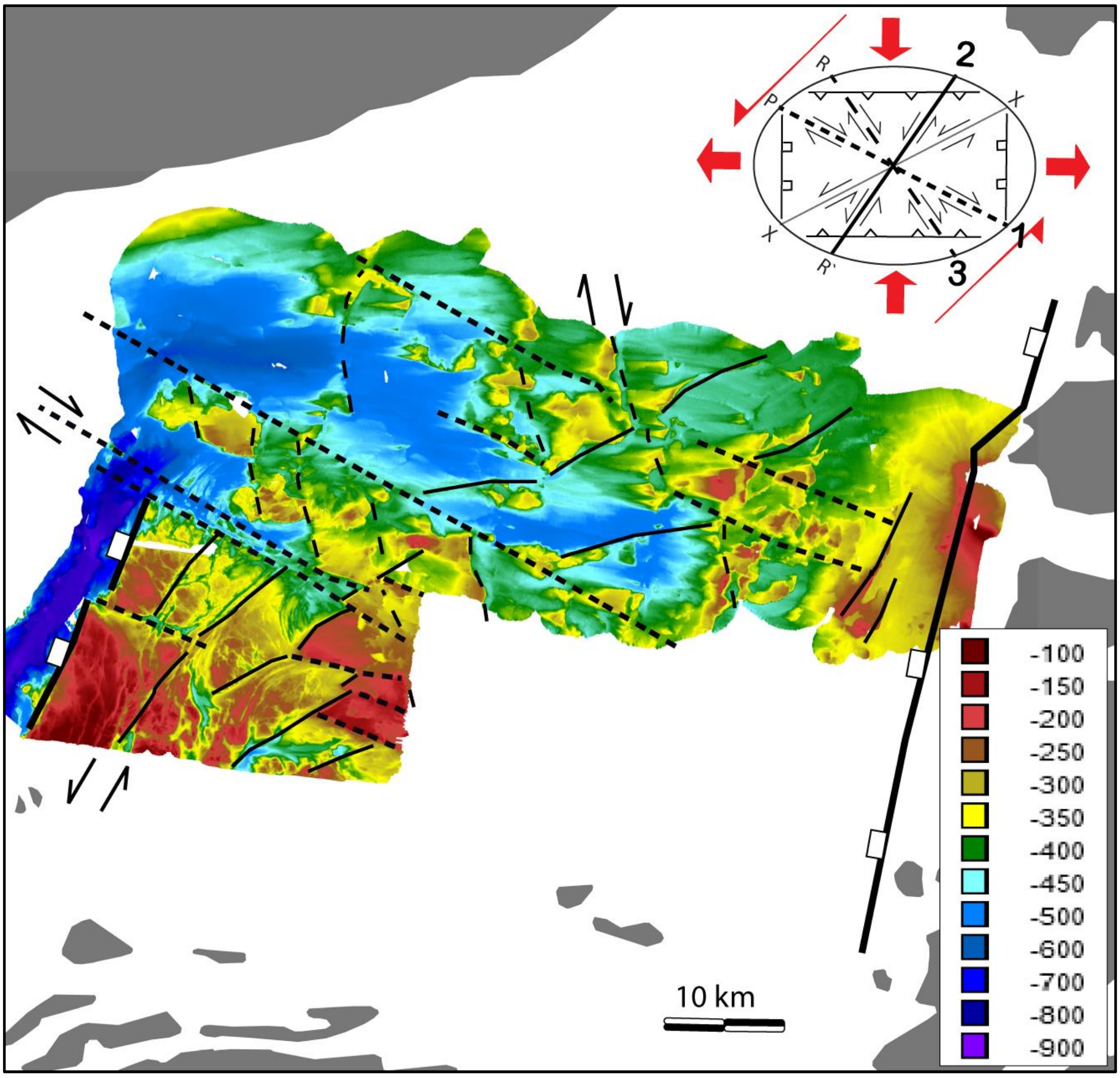

Figure 30. Detailed interpretation of possible major tectonic bedrock faulting (solid and dash lines) correlated with multi-beam bathymetry of RRS James Clark Ross Cruise-JR175 (Hogan et al., 2012) and MapHab survey area. For general tectonic model see figure 4. Color scale to the right indicated water depth (m).

7.3.3 Geological bedrock setting

The geological bedrock setting is presented in figure 31. The Precambrian bedrock is - besides the faulting - dominated by abraded streamlined terrain with fast ice flow lineation (Whaleback and Roche moutonée), which can be studied onshore near Aasiaat (Roberts and Long, 2005). The Upper Cretaceous sandstone can be studied onshore Disko Island around Skansen (see figure 5), 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 (Figure 6) (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). The large dimensions and the rugged appearance indicate that a purely glacial origin is unlikely.

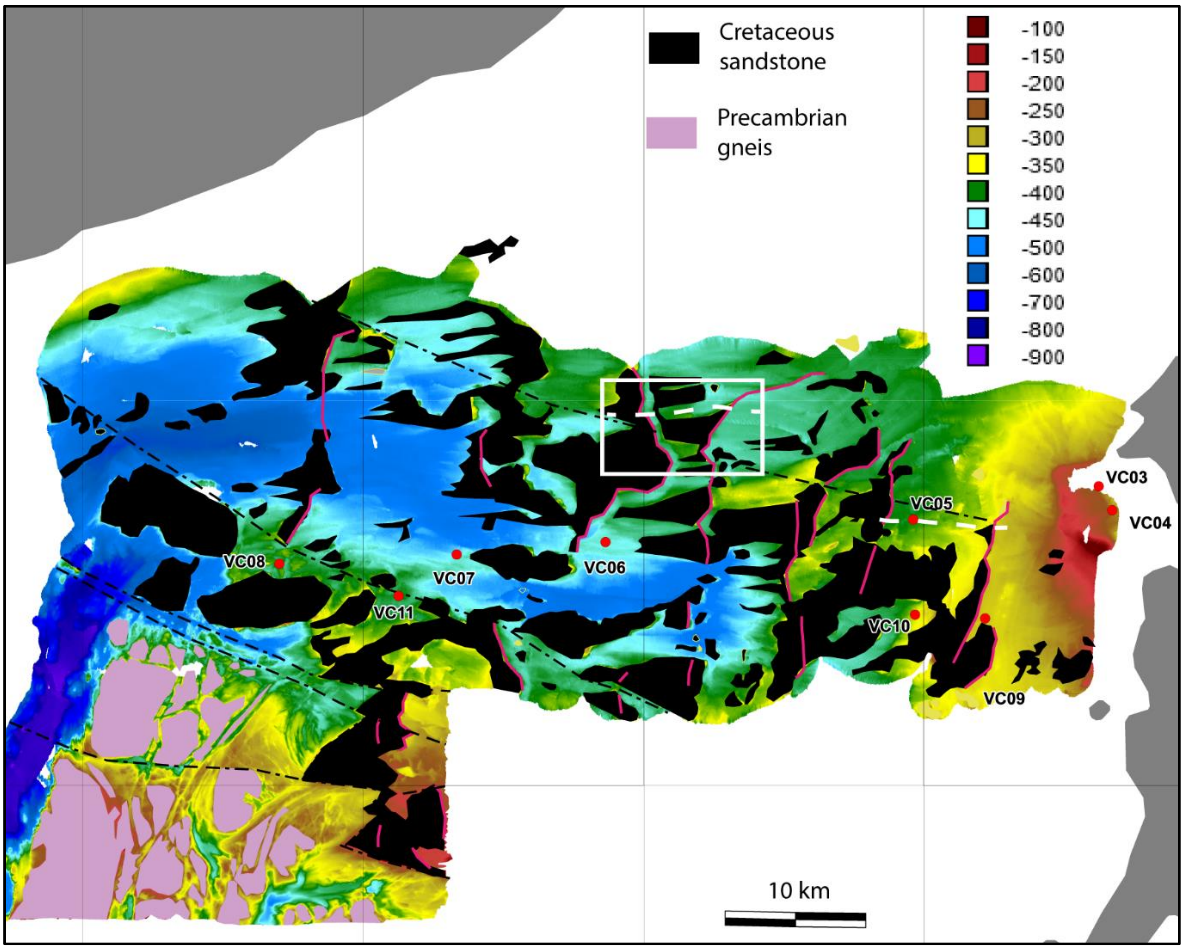

Figure 31. Distribution of interpreted near surface bedrock (topsoil thickness less than 10-20m) divided into Cretaceous sandstone and Precambrian gneiss superimposed on combined multi-beam bathymetry of RRS James Clark Ross Cruise-JR175 (Hogan et al., 2012) and MapHab survey area (color scale=water depth (m)). Major fault lines (dash lines) and vibrocores are marked. Red lines indicate bedrock ridges (see figure 9). The white square indicates location of figure 34, i.e. seabed surface sediment interpretation and location of figure 33, i.e. TOPAS sediment echo sounder profile crossing vibrocore VC5.

7.3.4 Glacier retreat history

The sub-bottom profiler data (see examples in figures 32 and 37) show that the majority of the topographically distinct highs are formed in bedrock, possibly streamlined by glacial ice. The absence of recessional moraine ridges suggests that retreat was so rapid that there was insufficient time for development of the ridges. The deglaciation history of Disko Bay is illustrated in figure 33. Radiocarbon dates from vibrocorings (see vibrocore VC5; Figure 32) constrain the retreat dynamics of Jakobshavn Isbræ. During deglaciation, retreat was relatively fast in the western parts of Disko Bay (~225-250 m a-1), all of which was deglaciated before 10.6 ka BP. Subsequent retreat through eastern Disko Bay was much slower (~50 m a-1) and likely interrupted by at least one still-stand due to pinning of the grounded glacier margin on submarine bedrock ridges. The ice margin paused again at Isfjeldsbanken before retreating into Isfjorden. Around 7.6-7.1 ka BP the ice margin had probably retreated far back into Isfjorden.

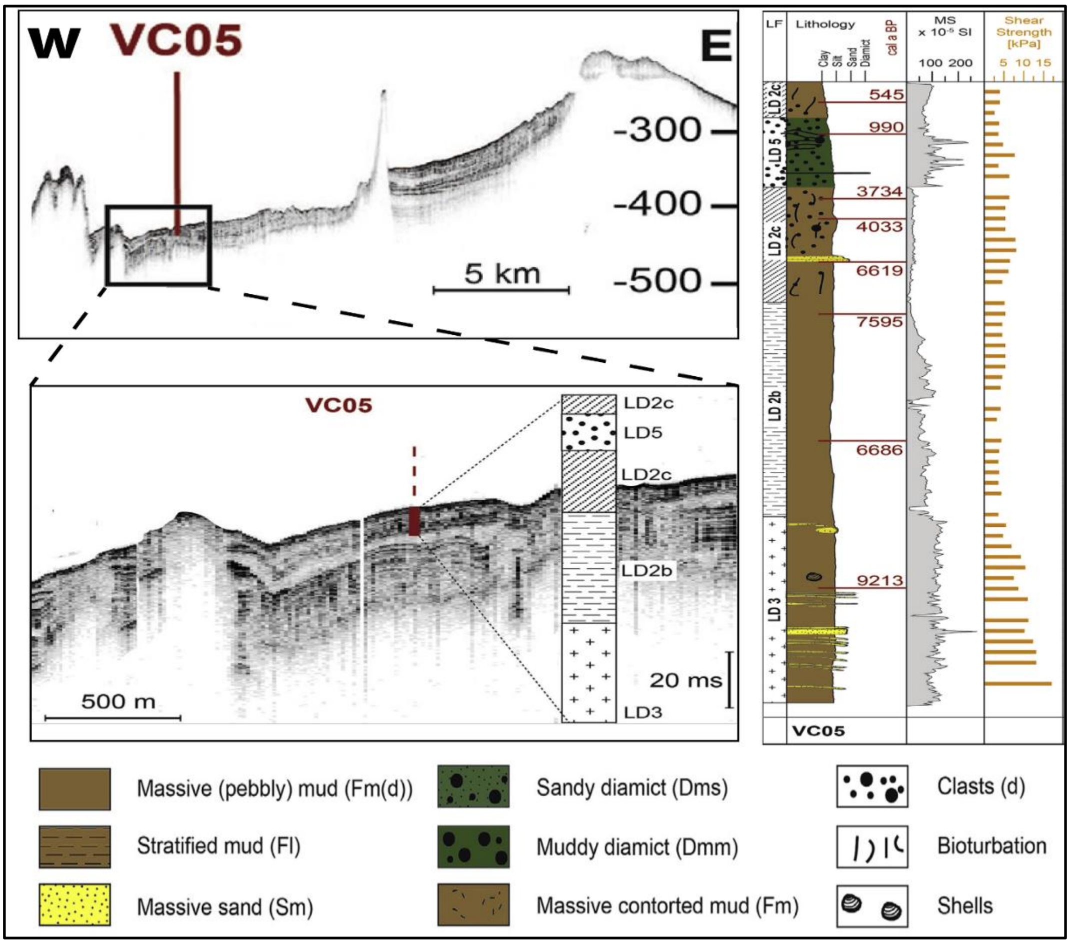

Figure 32. Example of TOPAS sediment echo sounder data crossing vibrocore VC05 from Streuff et al. (2017). Upper left shows general West-East profile (plough marks to about 300m), lower left shows zoomed in profile and vibrocore penetration; to the right vibrocore lithological profile with indication of calibrated radiocarbon dating, as well as magnetic susceptibility and shear strength log data. Map location of above example is located in figures 29, 31 and 34.

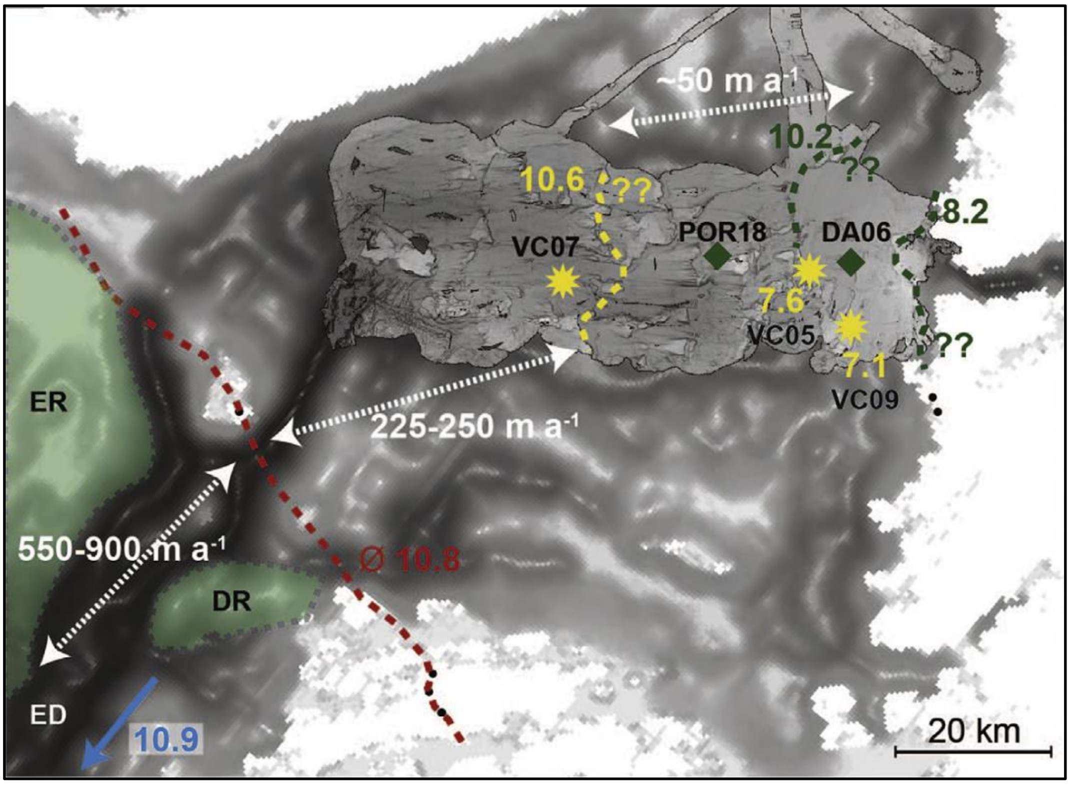

Figure 33. Deglaciation history from Streuff et al. (2017). Stippled red, yellow and green lines represent a rough estimation of where the ice front position could have been, based on dates from boulders/bulk sediment (red; Kelley et al., 2013) and sediment cores (yellow; this study and green; Lloyd et al., 2005). White arrows and numbers mark possible retreat rates.

7.3.5 Deglaciation sedimentation history

The deglaciation sedimentation history is illustrated in a model figure 34. Boxes A and B illustrate the early phase during and after deglaciation, dominated by glacial deposits, such as lodgment till and sandy diamict similar to glacial till. In general, 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 (IRD). The sub-bottom profiler data show abundant mass-flow deposits in Disko Bay, followed by Holocene sediment accumulation in the local basins defined by bedrock and glacial deposits. Three acoustic basin units are identified, representing Holocene sedimentary environment processes (Figure 34C-D):

(1) Mass–flows. The early phase after deglaciation was dominated by sediment gravity flows (i.e. mass–flows), reworking both fine- and coarse-grained deposits down the slopes of submarine basins and settling as stratified mud with sand laminae. The sand and mud layers appear contorted. Sediment accumulation likely relates to gravitational slump events

reworking and redepositioning the down-slope gravity flows, e.g. turbidity currents.

(2) Rainout. Meltout of coarser grains from icebergs (iceberg dumping/rainout) and sea ice settling as pebbly mud (Muddy diamict). The muddy matrix is interpreted as the product of hemipelagic or distal glacimarine suspension settling with the predominantly angular clasts, likely deposited from icebergs (Figure 35).

(3) Hemipelagic/IRD drape. Suspension settling of glacimarine mud (Massive-stratified pebbly mud) from meltwater and the water column. The meltwater derived sedimentation is the dominant process, as indicated by the exceptionally well-sorted mud (usually >95% of the mud has a grain size <63 mm) and sand. Based on its massive structure and the presence of bioturbation burrows, suggesting favorable living conditions for some benthic organisms, the unit is interpreted as ice-distal glacimarine mud. This is in accordance with the radiocarbon dates, which provide evidence for deposition after ~6.7 cal. ka BP in VC05 (see figure 32), while ice was retreating through Isfjorden. Post-glacial accumulation rates in Disko Bay are c. 0.24–1 mm a−1 (Lloyd et al., 2005; Lloyd, 2006).

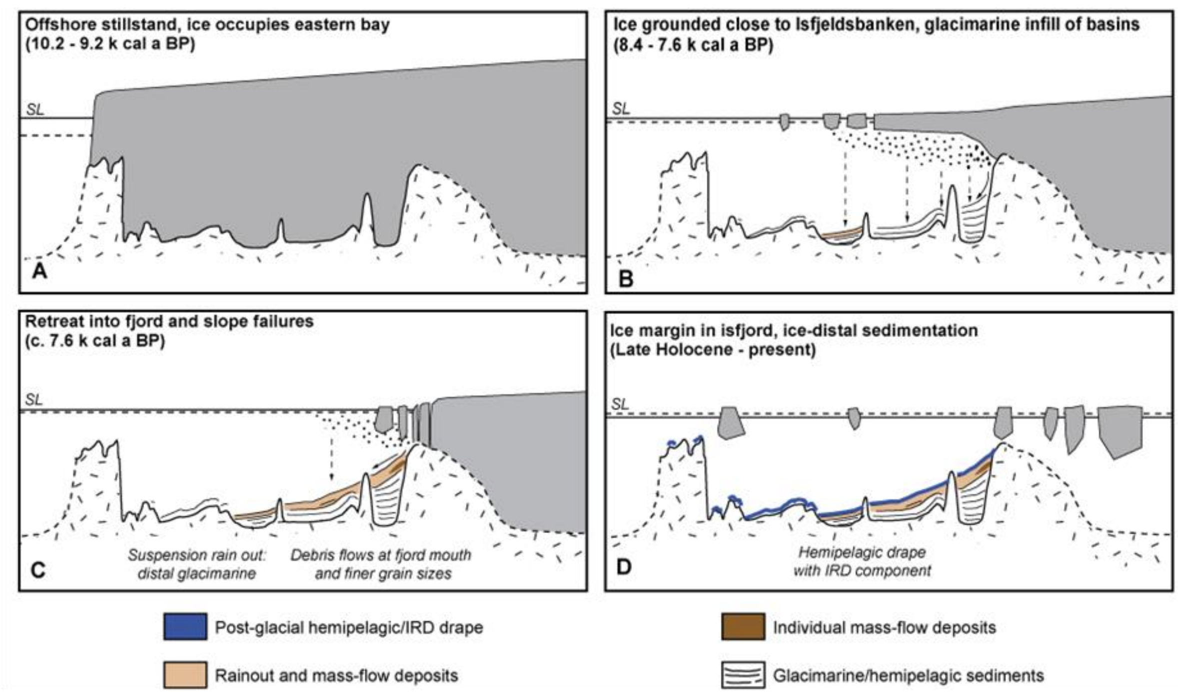

Figure 34. SW-NE Disko Bay profile showing interpretation of deglaciation sedimentation of near-surface sediments interpreted from TOPAS sediment echo sounder data and vibrocores (modified from Hogan et al., 2012).

7.3.6 Iceberg ploughing

Ploughing of sediments by grounded iceberg keels has been observed in the study area. The mean water depth in Disko Bay at which ploughmarks occur is 262 m (Thomson, 2011) with a relatively close range from 141-396 m. Large numbers of short ploughmarks observed at shallow water depths suggest that they were formed by icebergs with relatively small drafts (Figure 35). This makes sense, as the fjords draining into Disko Bay are fronted by shallow sills, which prevent icebergs with keels deeper than ~350 m from entering the bay (Rignot et al., 2010). Two types of ploughmarks have been observed in Disko Bay (Figure 36):

1. <u>Type I</u> ploughmarks are shallow depressions, with berms on either side of a narrow, v-shaped trough. 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.
2. <u>Type II</u> ploughmarks are shallow depressions flanked by small (1-2 m high) berms on either side of a u-shaped trough. In general, these features display similar lengths to Type I ploughmarks but their morphology is characterized by wide, flat-bottomed troughs, typically up to 100 m wide and ~10 m deep.

The majority of ploughmarks in Disko Bay are acoustically fresh; given the high rates of deglacial sedimentation in Disko Bay, i.e. 0.24–1 mm a^{-1} (Lloyd et al., 2005; Lloyd, 2006; Hogan et al., 2012) it implies a relatively young age for the observed ploughmarks.

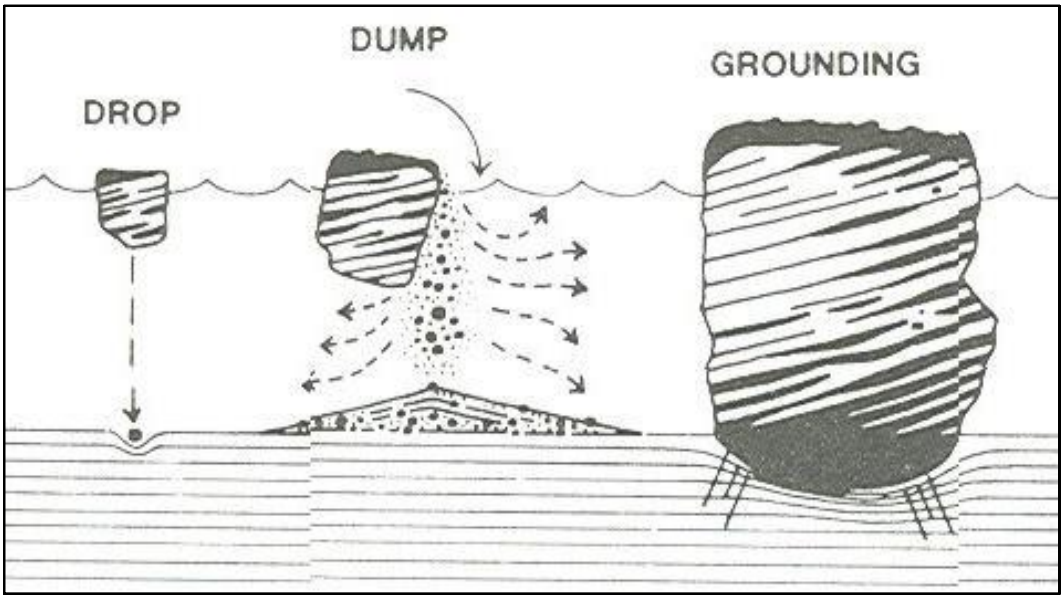

Figure 35. The effects of iceberg processes on the marine sedimentary record: deposition (dropping and dumping) of ice-rafted sediments, and deformation of seafloor sediments by an iceberg keel (Thomas and Connell, 1985).

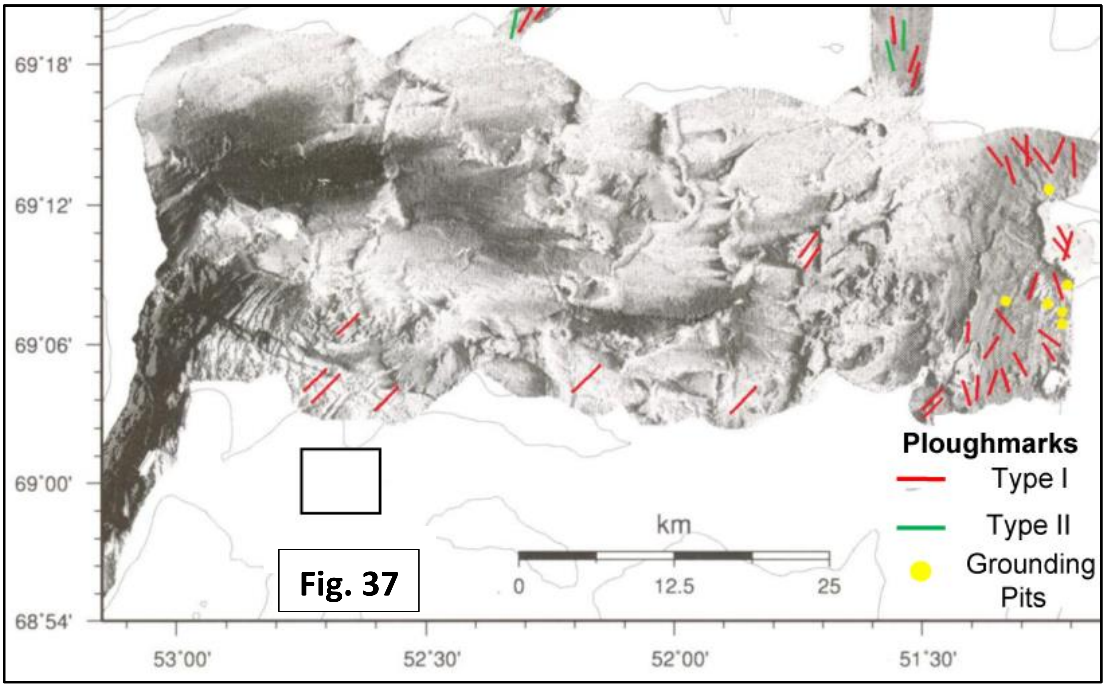

Figure 36. Grayscale swath-bathymetric map of ploughmark distribution in Disko Bay (Thomson, 2011). Red lines indicate type 1 ploughmarks and green lines type 2 ploughmarks. Location of figure 37 is indicated.

In relation to habitat mapping, iceberg ploughing is a natural disturbance of sea-bed integrity. Figure 34 and ploughmark studies by Thomson (2011; Figure 36) show existence of present-day grounding icebergs in the RRS James Clark Ross Cruise-JR175 area suggesting similar groundings in the **MapHab** pilot area. More detailed, high-resolution (3m) multi-beam data from the northeastern part pf the **MapHab** study area (Figure 37) show large areas with ploughmarks type 1.

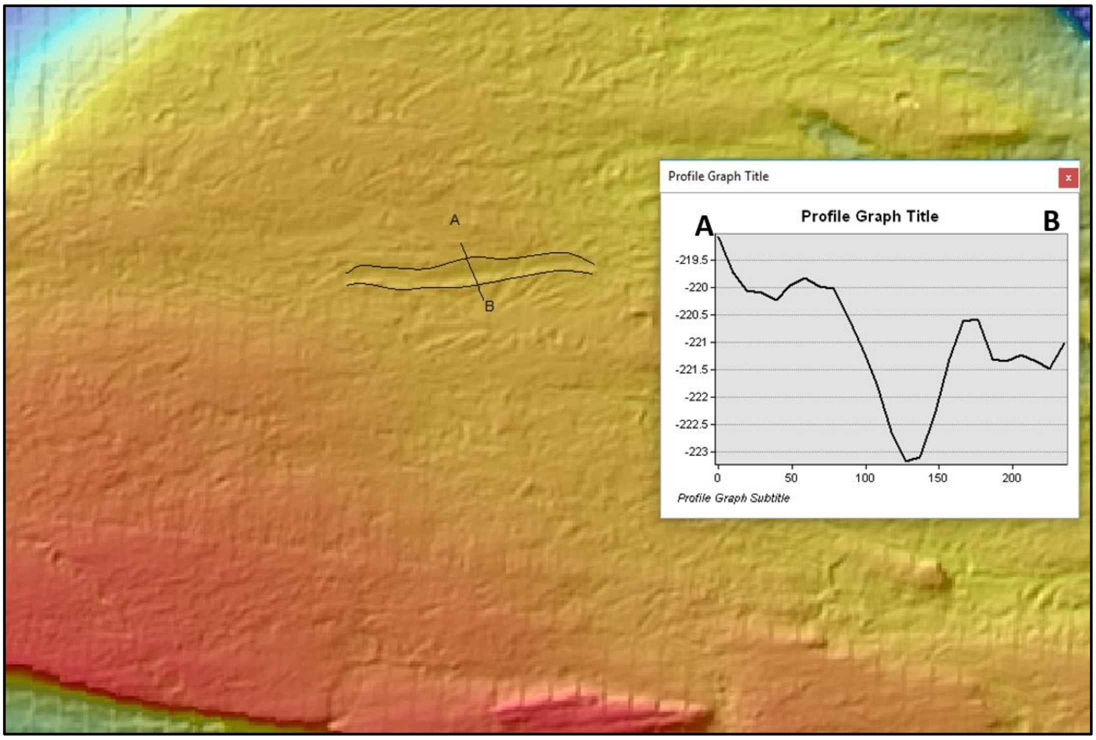

Figure 37. Example of MapHab ploughmark type 1. For location see figures 28 and 36.

7.3.7 Pockmarks

Circular pockmark depressions occur in Disko Bay and are especially common in the eastern part of the bay and on the distal flank of Isfjeldsbanken (Figure 38; see also figures 6 and 8 in Hogan et al., 2012). These depressions often occur in clusters and measure 5 to 300 m diameter and 7-30 m deep. On the sub-bottom profiler data these depressions are associated with a drawdown of the overlying reflections and occasional acoustic masking and are interpreted as pockmarks (Hogan et al., 2012). Pockmarks are formed as a result of gas or pore fluid seepage (e.g. Nielsen et al., 2014; Dowdeswell et al., 2016). Acoustic masking on the sub-bottom profiler data supports the gas seepage theory.

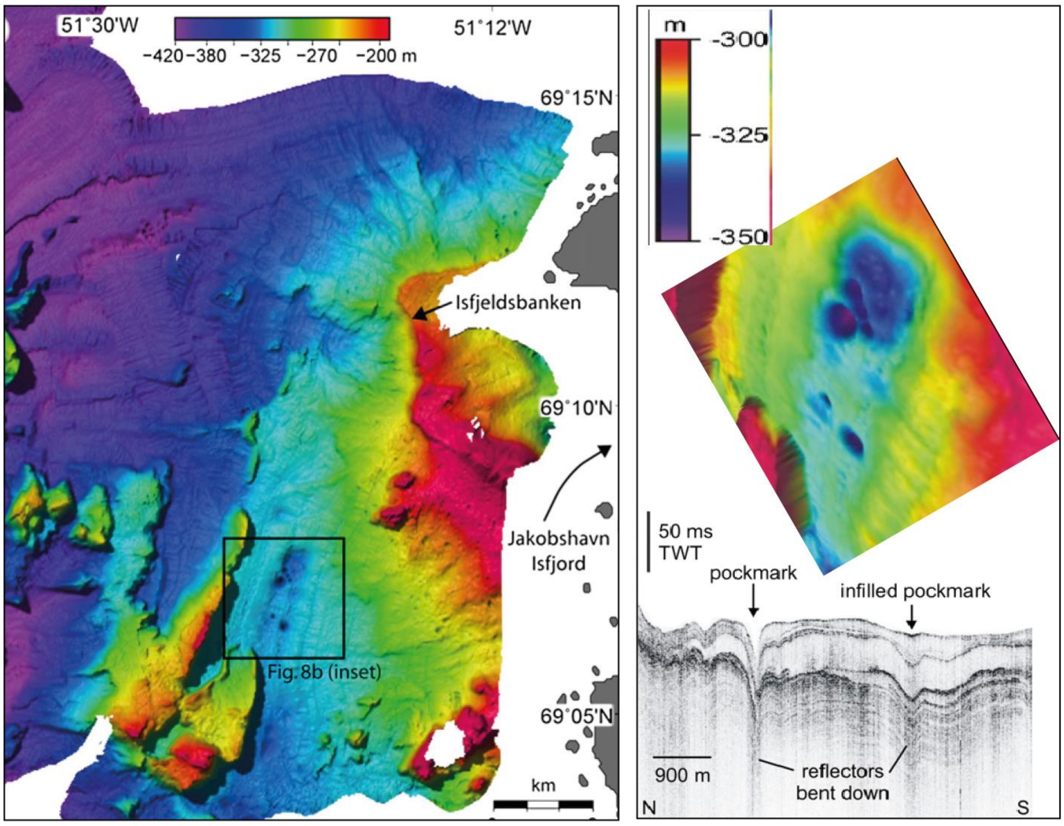

Figure 38. Pockmark area close to Jakobshavn Isfjord. For overall location see figure 28.

Prominent pockmarks have also been found in the southwestern part of the **MapHab** survey area (Figures 28 and 39) and in some cases mixed with iceberg ploughmarks.

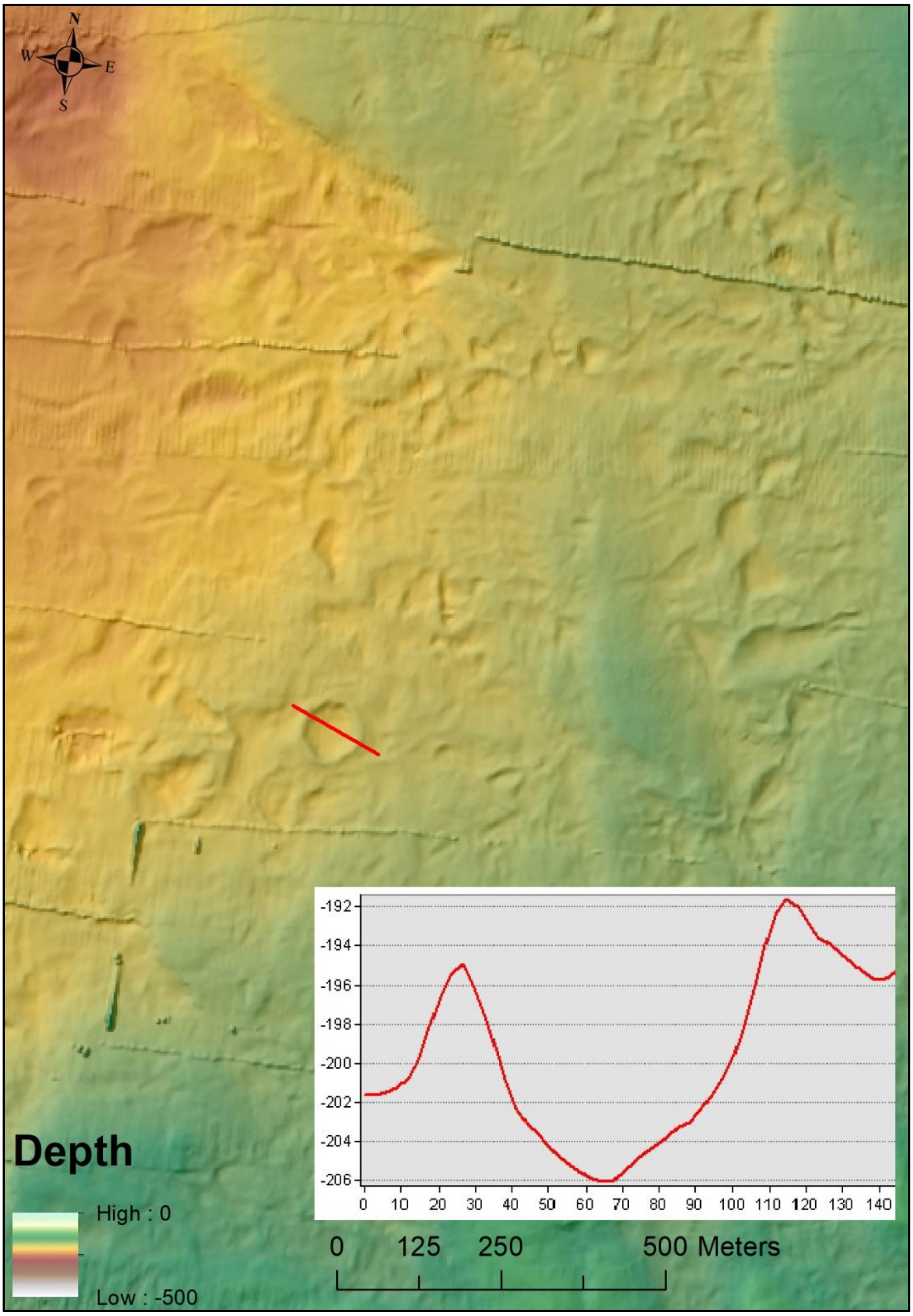

Figure 39. Pockmark example in the southwestern part of the MapHab survey area. Signs of presumable iceberg plough marks are also present. For location, see figure 28.

Schumann et al. (2012) suggested that pockmark formation in Disko Bay is driven by dissociation of gas hydrates. Their distribution may be related to faults, slides or disturbance caused by iceberg-keel plough marks. The pockmark areas in Disko Bay are found at water depths at which gas hydrates in the Arctic become unstable at the bottom-water temperatures (~3 °C).

7.3.8 Geological surface sediments

Geological mapping of the seabed surface sediments includes sediment echo sounder and sediment cores as support data to the habitat substrate mapping carried out in the **MapHab** project, i.e. multi-beam and physical ground-truthing using grab and photo/video footage. Previous chapters use Disko Bay as an example of the useful geological background information that can be acquired. This chapter focuses on sediment echo sounder and sediment sampling in the RRS James Clark Ross Cruise-JR175 area, north of the **MapHab** survey area. While the multi-beam backscatter measures the return signal from the seabed surface (down to several cm), the sediment echo sounder profiler penetrates into 30–40 cm of the seabed. Figure 40 shows an example of digitized seabed and the classified map along the survey lines.

1. Bedrock**.** The bedrock seabed type is characterized by no acoustic penetration and is mostly related to topographical highs.
2. Till. Diamict, poorly sorted stony clay sediments showing a chaotic internal seismic reflection pattern is interpreted as till.
3. Mud. Mud sediments including stones to a varying degree is the most prominent sediment type as shown in figure 32. The seismic signature is stratified to homogeneous with internal structures that can reveal age relations distinguishing recent from ancient sediment layers and thereby map recent depositional basins.
4. Slumped. Destabilized slumped sediment can be identified from internal contorted stratification.
5. Eroded surface /ploughmarks. Erosional surfaces can be identified on the seismic profiles as well as iceberg ploughmarks (see figures 34 and 40).

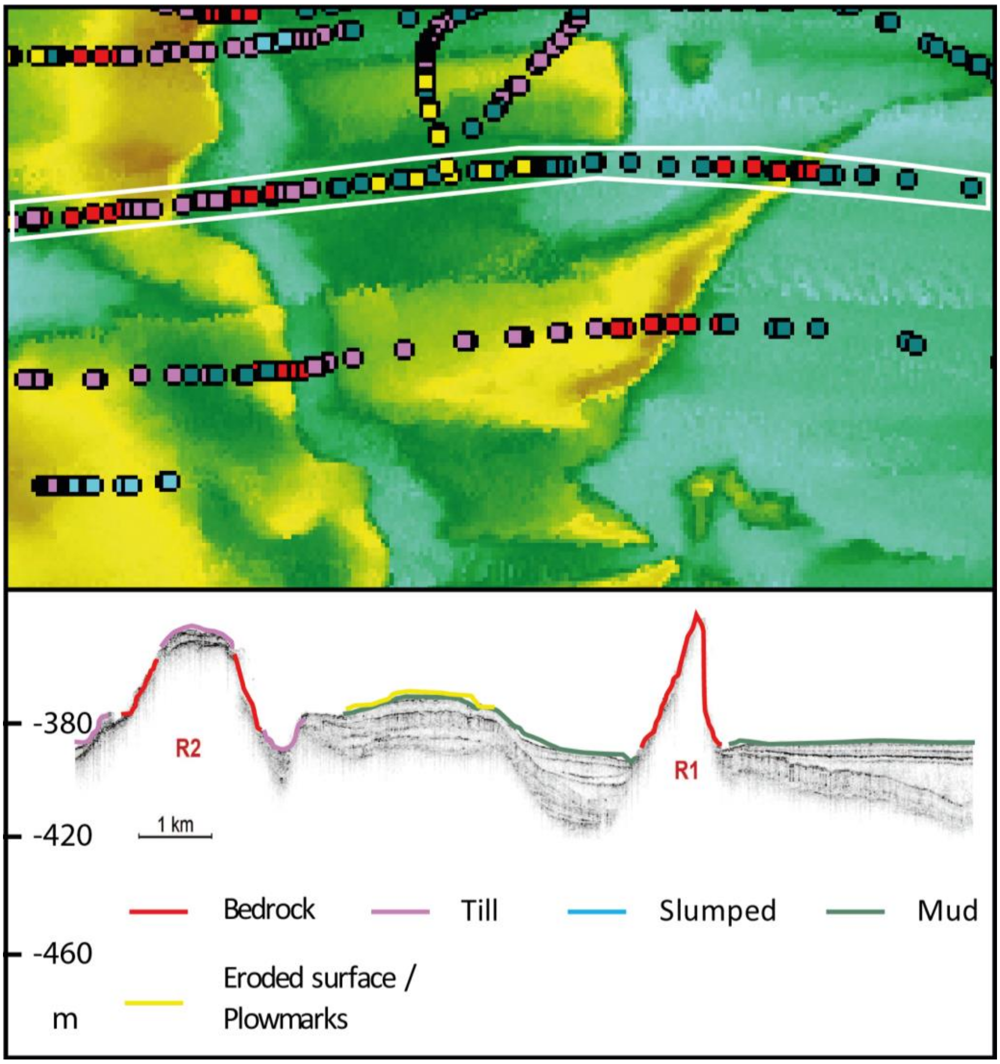

Figure 40. Example of interpreted seabed surface sediments from TOPAS sediment echo sounder data (Streuff et al., 2017). Upper figure shows multi-beam bathymetric map section (for depth legend see figure 29); data points framed in white line are interpreted in the bottom figure. Map location of example is located in figures 29 and 31.

On the basis of broad-scale profile mapping, geological seabed sediment map is produced (Figure 41). Hard bottom sediment types are represented by coarse rocky ground and gravelly mud/sand and soft bottom is shown as mixed mud with signs of slump or surface erosion and mud, mainly representing mud depositional areas.

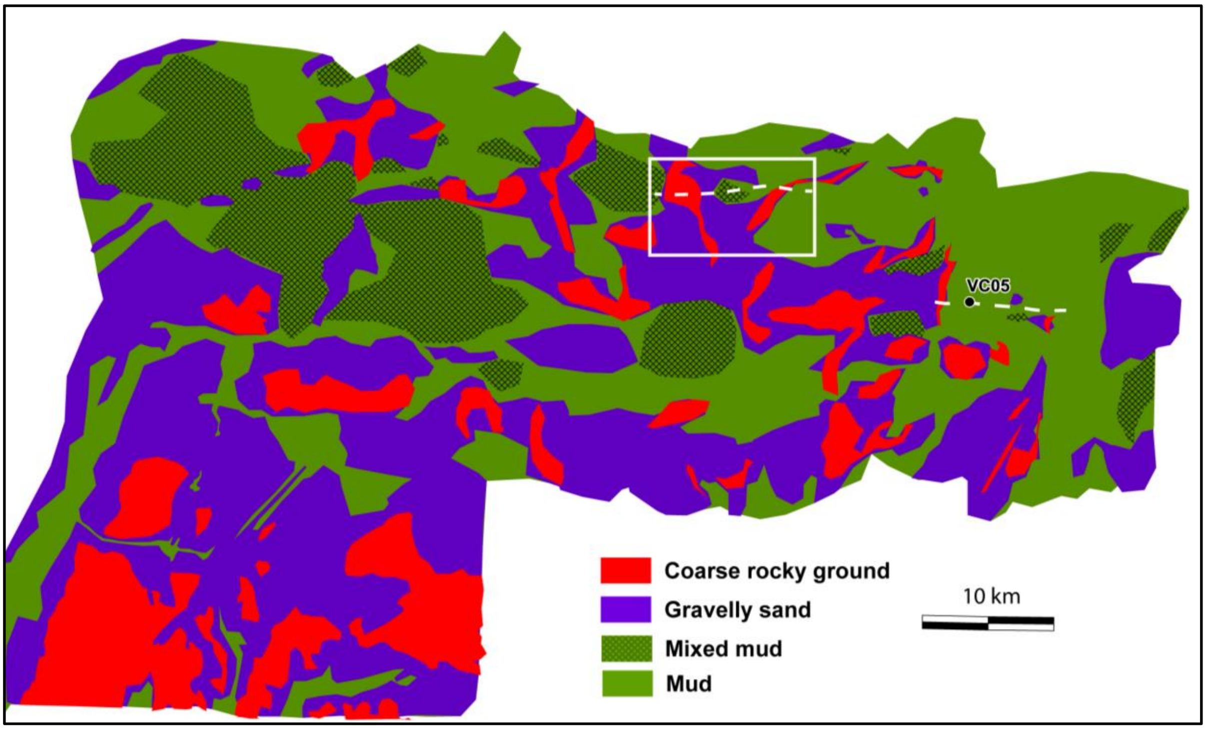

Figure 41. Distribution of seabed sediments in the RRS James Clark Ross Cruise-JR175 (Hogan et al., 2012) and MapHab survey area based on sediment echo sounder and sampling data. Location of figure 40 seabed surface sediment interpretation is indicated in the white square frame area and location of figure 32 TOPAS sediment echo sounder profile crossing vibrocore VC5 is indicated.

Below, high-resolution sediment map of the **MapHab** pilot area based on classified backscatter and physical ground-truthing (Figure 42). The map shows combined information on the detailed distribution of sediments obtained from the **MapHab** survey with main geological features identified in the larger Disko Bay area.

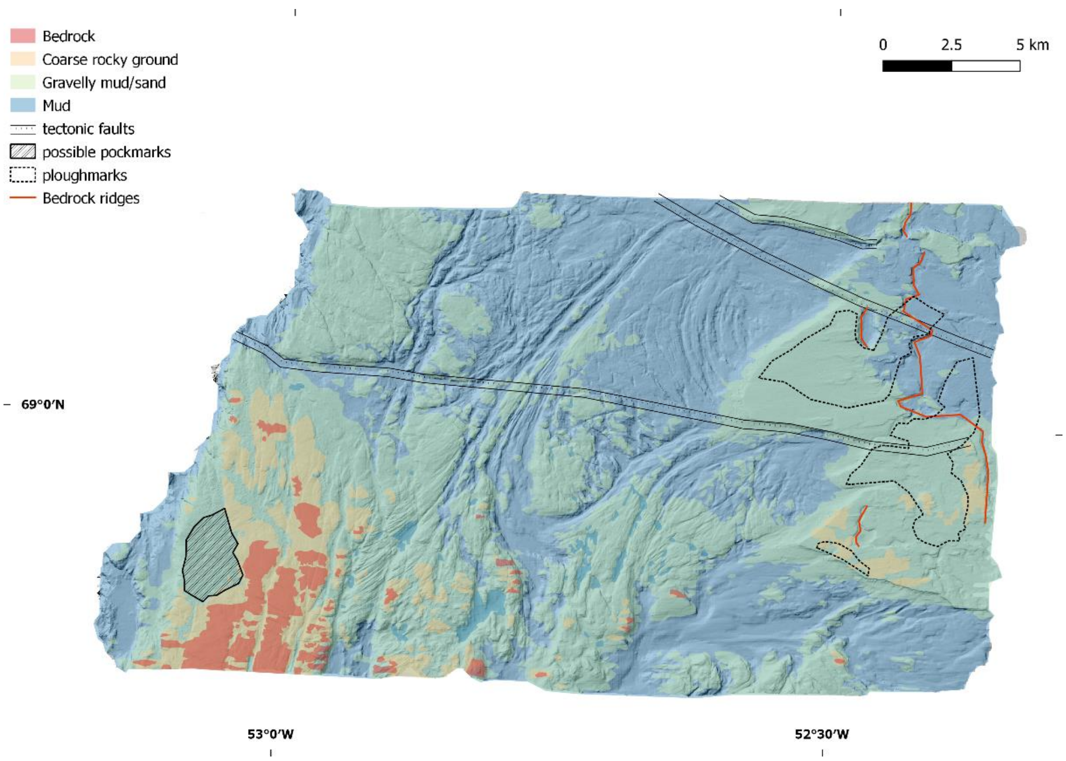

Figure 42. Sediment map from the MapHab survey dataset (backscatter combined with ground-truthing) with main geological structures, i.e. ploughmarks, possible pockmarks, tectonic faults and bedrock ridges.

7.2 Hydrographic interpretation

7.2.1 Extraction of explanatory variables

Examples of explanatory variables were extracted from the COHERENS model for the Disko Bay area as mean values for each horizontal grid cell and for 1 month simulation, i.e. July 2013. This was done to demonstrate how different hydrographic variables may vary in Disko Bay area. For future applications using explanatory variables from a high-resolution hydrodynamic model, extraction of explanatory variables will have to be done for a longer simulation period and preferably for more than 1 year to ensure that the variability in hydrographic processes is sufficiently captured.

The following variables were extracted:

- Mean Current slope bottom layer (horizontal fronts)
- Mean Current slope surface layer (horizontal fronts)
- Mean Current speed bottom layer
- Mean Salinity bottom layer
- Mean Temperature bottom layer

The variables are shown in Figure 43-47 below.

While horizontal current slope is an indicator of location of frontal zones, often associated with high primary and secondary productivity, current speed itself may identify areas with high input or flux of food sources, hence high productivity potential, as well as areas where net deposition and net resuspension of suspended material, respectively may occur. Decrease in salinity levels is an indication of freshwater or brackish water inflow often associated with elevated nutrient inputs potentially sustaining a higher primary production in the vicinity. Temperature at the seabed plays a major role in the speed of biological processes and areas with somewhat higher mean temperature may potentially support higher production rate and biomass. Differences between bottom and surface temperature indicate vertical stratification and may be used to locate areas with fully mixed water column, likewise expected to be linked to variability in species diversity and/or abundances. Temperature averages and extremes, as for salinity, may also limit the distribution of some species due to limited physiological tolerance.

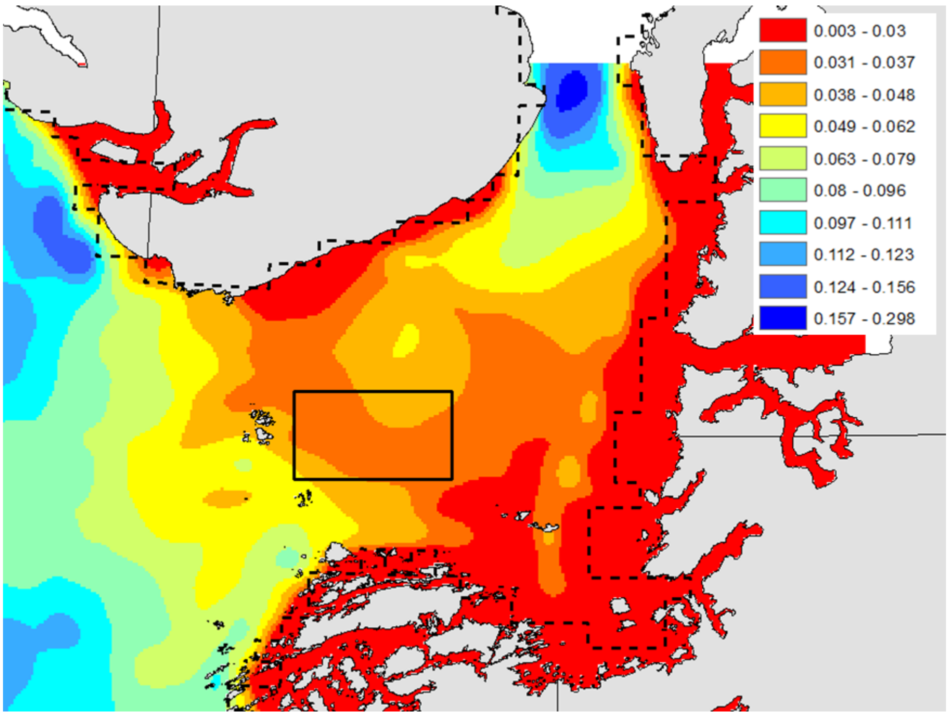

Figure 43. Mean bottom current speed (m/s) for July 2013 for Disko Bay area extracted from the COHERENS model setup for Baffin Bay and subsequently interpolated. Black outline is the pilot study area. Black dotted outline is the COHERENSE land-water boundary. Source: www.climatelab.dk.

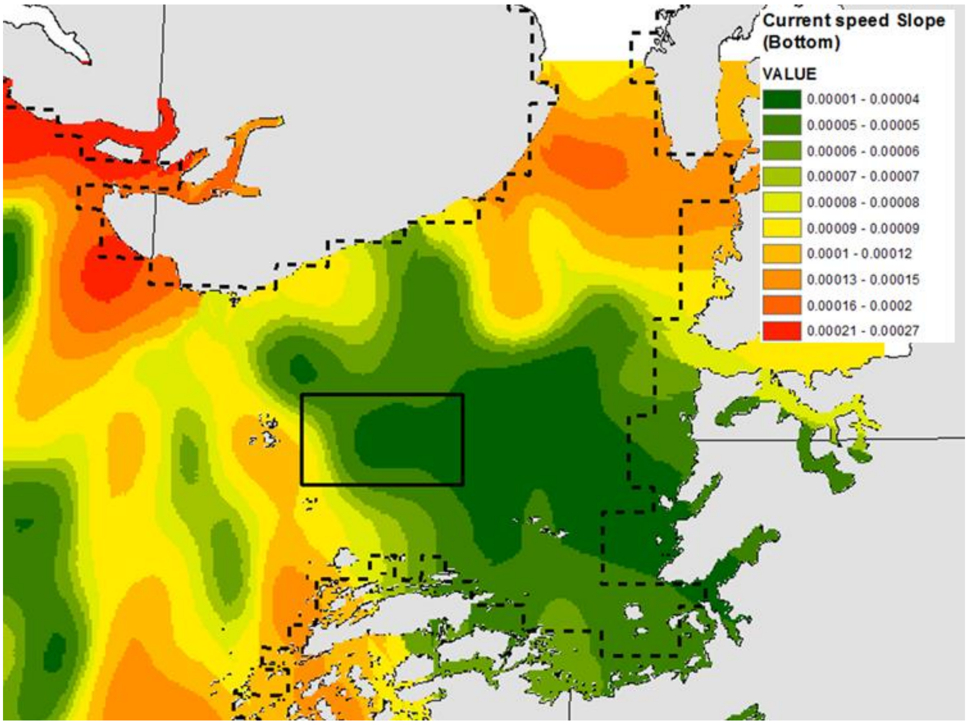

Figure 44. Bottom current speed slope (unit-less) based on mean bottom current speed (m/s) for July 2013 for Disko Bay area extracted from the COHERENS model setup for Baffin Bay and subsequently interpolated. Black outline is the pilot study area. Black dotted outline is the COHERENSE land-water boundary. Source: www.climatelab.dk.

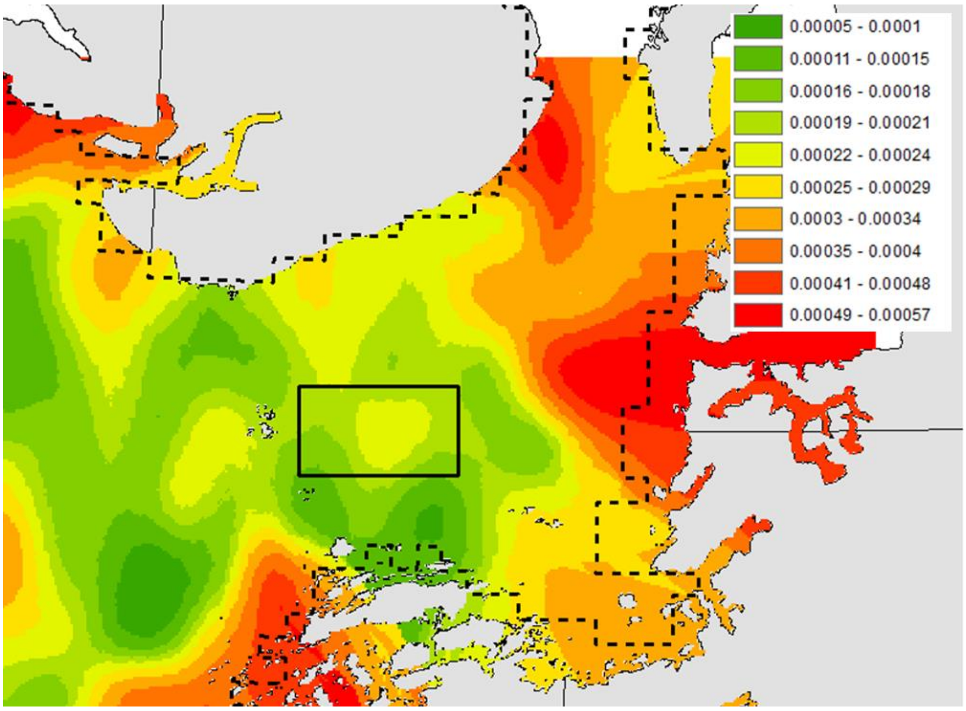

Figure 45. Surface current speed slope (unit-less) based on mean surface current speed (m/s) for July 2013 for Disko Bay area extracted from the COHERENS model setup for Baffin Bay and subsequently interpolated. Black outline is the pilot study

area. Black dotted outline is the COHERENSE land-water boundary. Source: www.climatelab.dk.

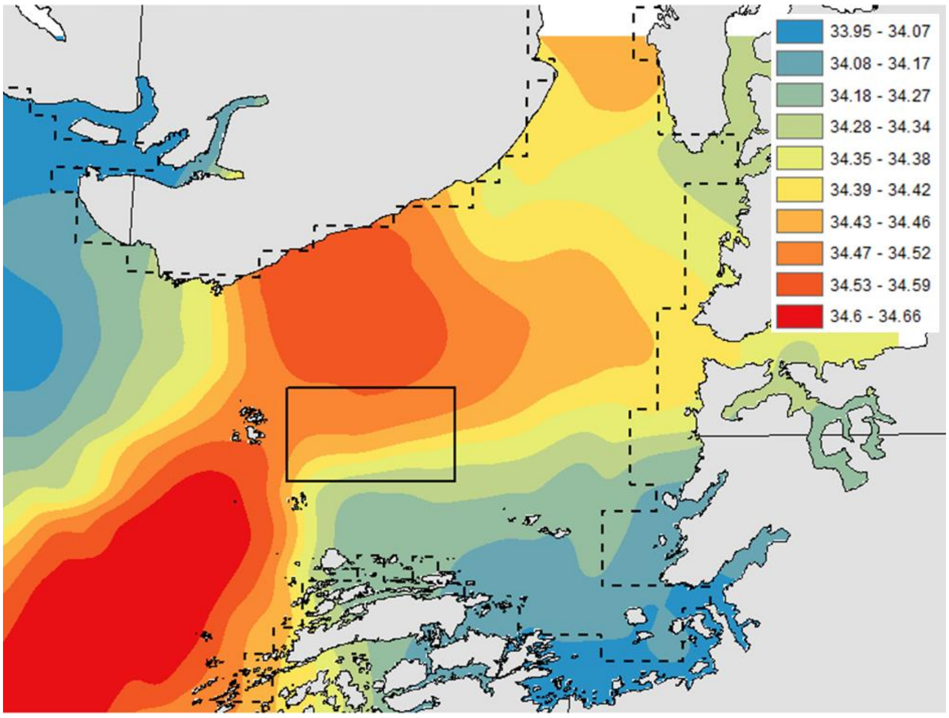

Figure 46. Mean bottom salinity (PSU) for July 2013 for Disko Bay area extracted from the COHERENS model setup for Baffin Bay and subsequently interpolated. Black outline is the pilot study area. Black dotted outline is the COHERENSE land-water boundary. Source: www.climatelab.dk.

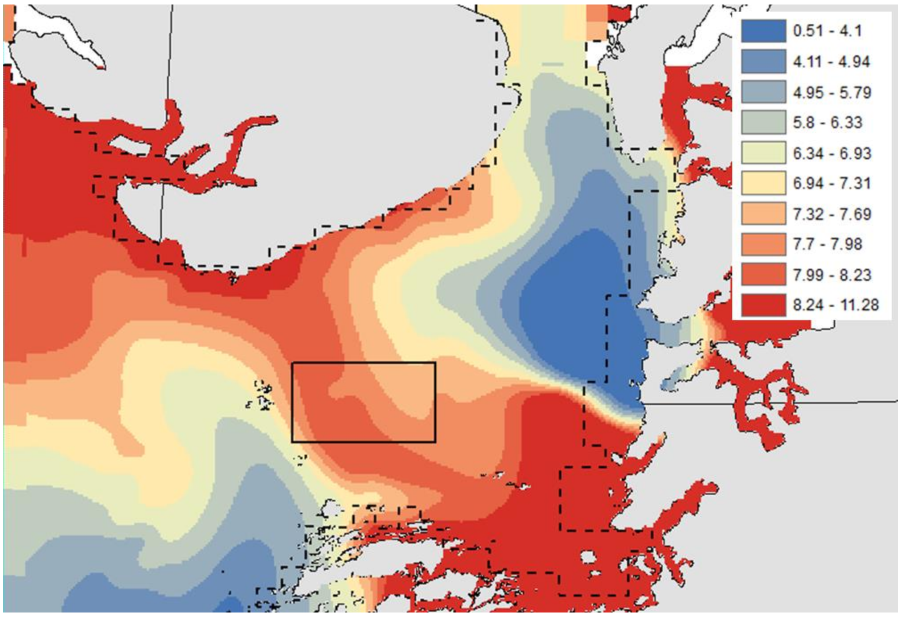

Figure 47. Mean bottom temperature (degree Celsius) for July 2013 for Disko Bay area extracted from the COHERENS model setup for Baffin Bay and subsequently

interpolated. Black outline is the pilot study area. Black dotted outline is the CO-HERENSE land-water boundary. Source: www.climatelab.dk.

7.2.2 Other available data

Other data that may be of relevance include biological variables, such as primary and secondary productions and indices hereof, such as chlorophyll concentrations from biogeochemical models or surface observations from satellites. Figure 48 shows an example of monitored seasonal progression of chlorophyll concentrations from satellite data for the Disko Bay area showing high seasonal and spatial variations. Spatial and temporal variability in primary production in the upper water column (photic zone) is likely to sustain a similarly high spatial and temporal variable flux of organic carbon to the seafloor, in turn potentially affecting both seabed secondary production and species presence, absence and abundance. This link between the surface production and the seabed may be further complicated in systems with complex hydrographic processes, such as varying spatial and temporal occurrences of vertical stratification and the magnitude (and direction) of currents, as described in previous sections.

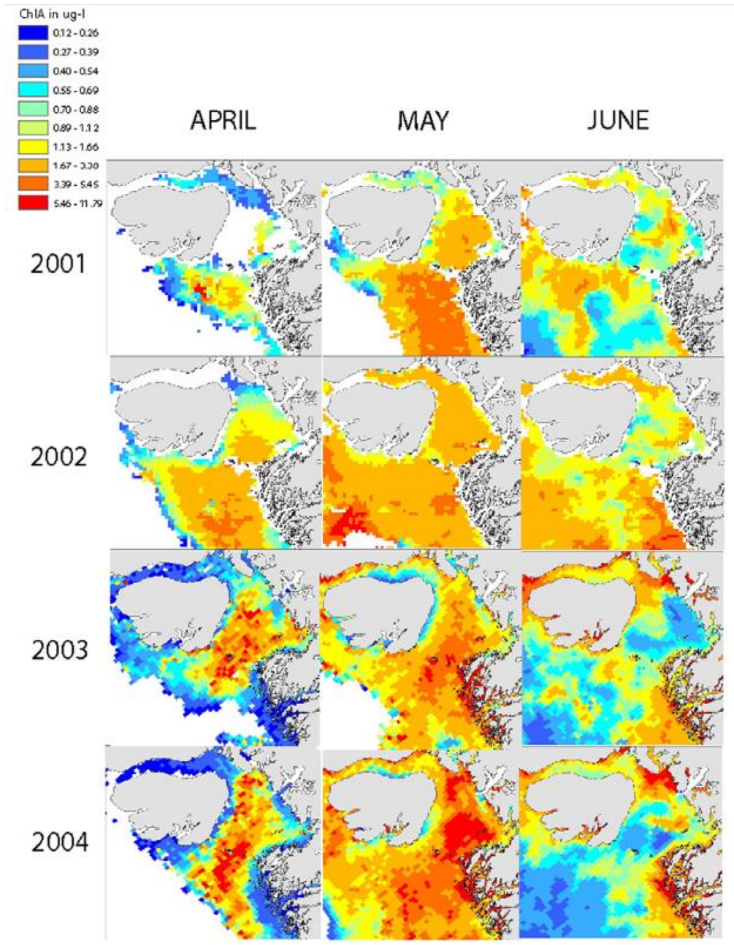

Figure 48. Monthly progression of chlorophyll a production in Disko Bay between 2001 and 2004. Data are presented as monthly averages from MODIS level 3 Terra (2001 and 2002) and level 3 Aqua (2003 and 2004) with adjustment of the Terra data to ensure compatibility. White areas are ice covered (Heide-Jørgensen et al., 2007).

7.2.3 Data synthesis

The lack of full coverage of species data for the Disko Bay area means that it was not possible to link data on species presence/absence and/or abundance to explanatory variables extracted from the coarse hydrodynamic model for Disko Bay using methods of predictive habitat modelling. Instead, we applied a so-called unsupervised classification of the selected set of explanatory variables covering the larger Disko Bay (see previous section) and including 5 hydrodynamic variables and 2 seabed topographic variables (depth and slope). Two types of classification were applied: 1) ISO clustering and 2) maximum likelihood classification using normalised values of the seven explanatory variables (Figure). Another analysis included the same clustering and classification technique but using the 3 dominant components from the Principal Component Analysis of the 7 variables (Figure 30). This was done to minimise the influence of variable covariance on the output.

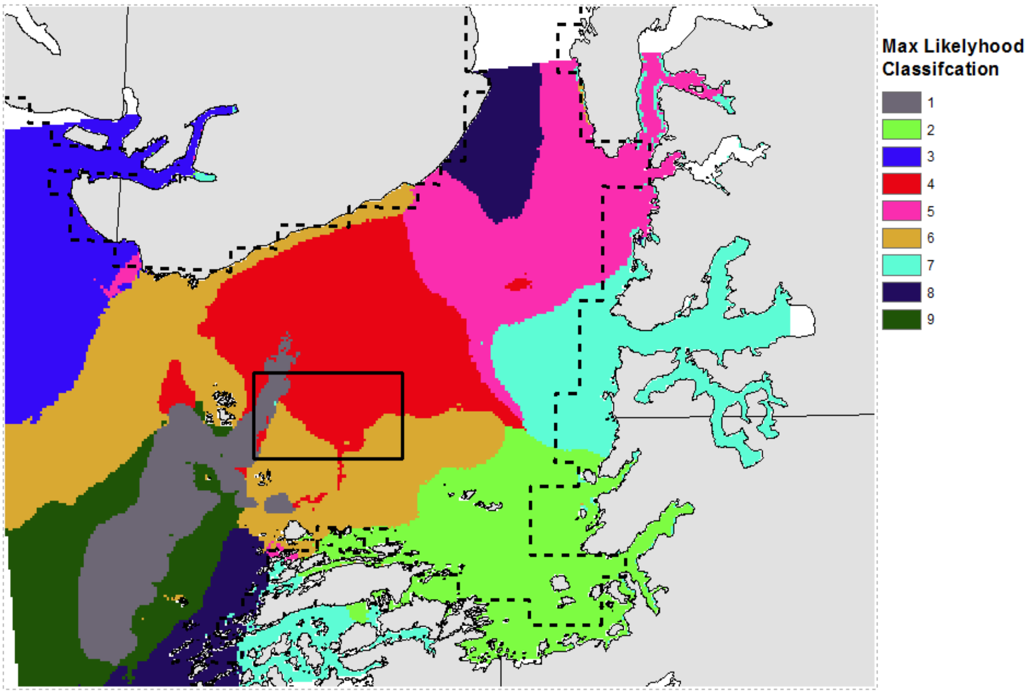

Figure 49. Unsupervised classification based on 7 hydrographic explanatory variables using ISO clustering and maximum likelihood classification.

The output of these classifications gives an indication that the seabed physical environment can be grouped into distinct classes and these are likely to explain some of the regional and local variability in species and habitat presence/absence and abundances. Together with additional explanatory variables, such as seabed substrate and seabed roughness from multi-beam surveys, and the use of high-resolution hydrodynamic modelling (as well as biogeochemical modelling) for resolving the hydrodynamic currents (and biogeochemical variables) at a fine scale, a much more detailed classification can be done, providing an ideal basis for predicting species and habitat distribution using PHMs.

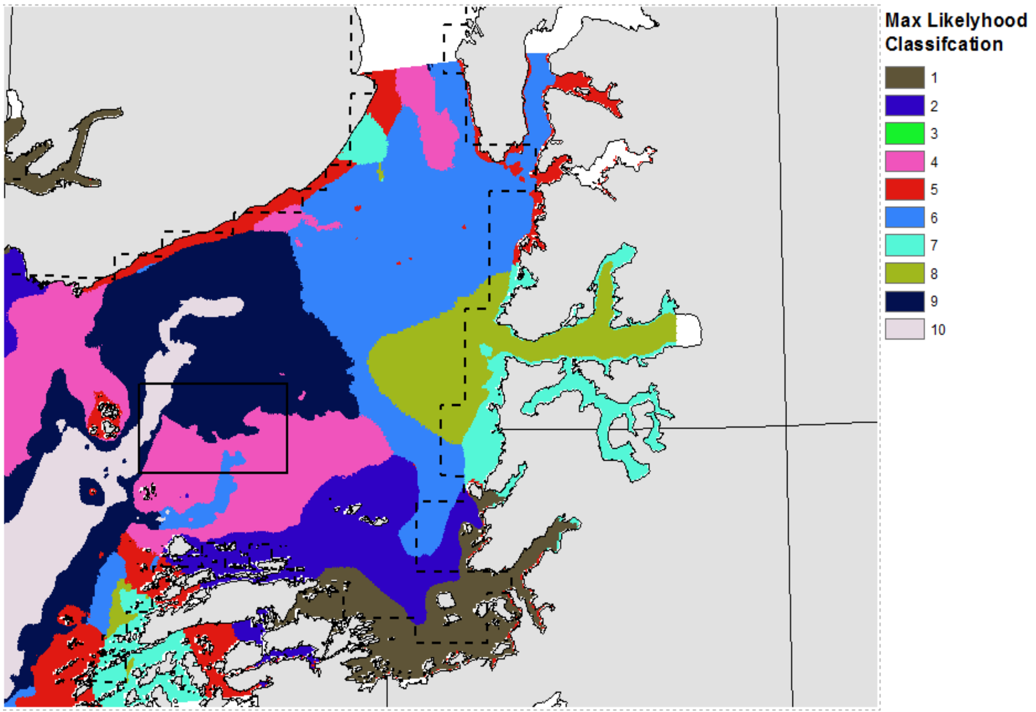

Figure 3. Unsupervised classification based on the top 3 most important components from the Principal Component Analysis of 7 hydrographic explanatory variables using ISO clustering and maximum likelihood classification.

8. Habitat map – EUNIS example

Production of a benthic habitat map requires knowledge of the relationship between the biotic and abiotic habitat types. In order to compare the mapped seabed habitats in Disko Bay with the standard of the European Union, we applied EUNIS classification to our **MapHab** 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). The afore-mentioned study covered a large area of the western coast of Greenland and was based only on ground-truthing sampling at selected points of the seafloor. The EUNIS classification falls short in describing the deep-sea habitats, i.e. areas beyond the continental shelf: Bathyal and Abyssal deep zones, and instead, the deep-sea habitats are considered to be >200m water depth. This, among other things, comprises a challenge that was discussed in an open workshop organized by Mesh Atlantic project in April 2012. The Joint Nature Conservation Committee (JNCC) proposed to take this task and developed a new deep-sea classification for the UK waters (JNCC, 2015). It is also expected that the new updated EUNIS classification will take into consideration these proposals to become standard EU classes.

The geophysical map produced in this work (see chapter 6.3 and figure 27), using bathymetry map, backscatter-derived sediment map and the ground truthing data, was used as a lookup table to translate the geophysical components into EUNIS classes. Four classes were established:

1. EUNIS class A6.1 : Deep-sea rock and artificial hard substrata
2. EUNIS class A6.2 : Deep-sea mixed substrata
3. EUNIS class A6.2 or 6.5 : Deep-sea mixed substrata or Deep-sea mud
4. EUNIS class A6.5 : Deep-sea mud

EUNIS class A6.3 and A6.4 were not included as sand or muddy sand did not dominate in the mapped seabed. This example using EUNIS classification in the pilot study area (Figure 51) highlights the need for a more comprehensive approach to standardizing habitat mapping and classification in Greenland region.

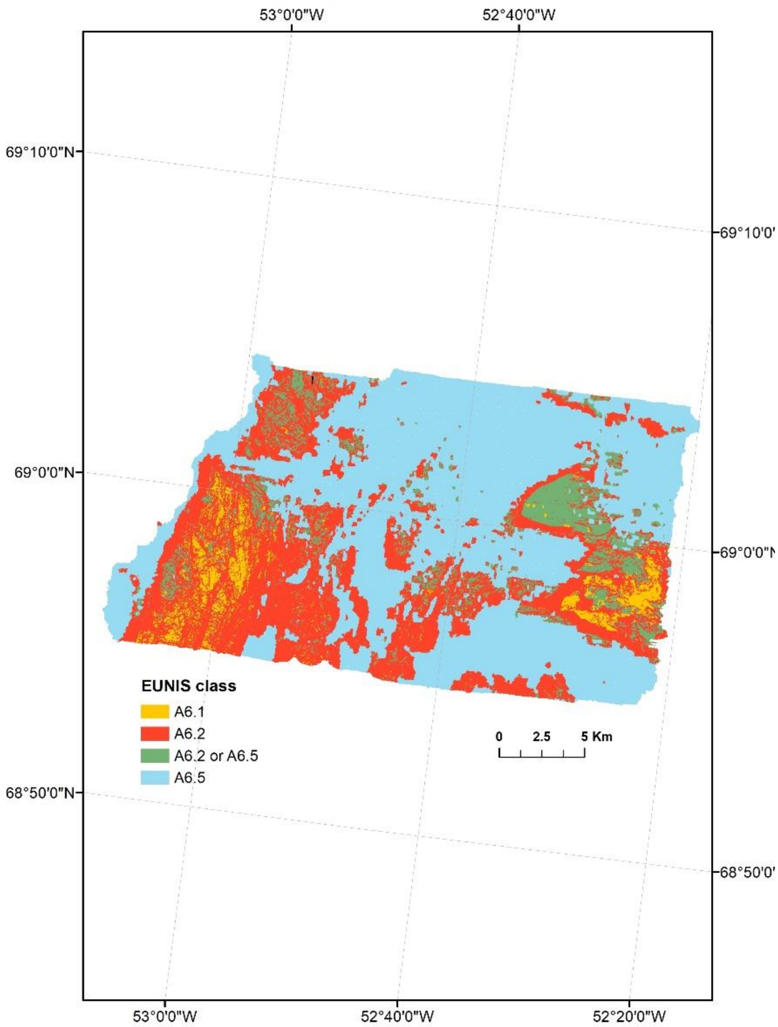

Figure 51. Habitat map of the Disko Bay pilot area classified after the EUNIS classes.

9. Standardized habitat classification for Greenland

Using 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 developed a habitat classification suitable for Greenland's highly complex topography of the coastal and offshore areas within the continental shelf, i.e. Greenland Ocean floor Classification of Habitats (GOCH). This classification is based on the **MapHab** project and will be subject to continuous improvement based on the new incoming data and information collected during ongoing and planned surveys (see table 1). GOCH is currently composed of 5 key factors (i.e. descriptors) defining/shaping benthic environment:

1) (Geo)morphology (seafloor structure)
2) Sediments (seafloor texture)
3) Oceanography (water masses)
4) Chemistry (chemical conditions)
5) Biota (benthic flora/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 (e.g. morphology map; Figure 21) with geological interpretation of the features whenever possible (=geomorphology).

(2) Sediment factor is based on a combination of acoustic sub-bottom profiling and physical ground-truthing used to classify and validate acoustic backscatter data.

(3) Oceanography factor is based on bathymetry data and number of oceanographic studies describing key water masses around Greenland and validated with the CTD profiles, regularly collected by GINR. Fjord waters are typically more complex due to seasonal circulation modes and are adapted to the local CTD measurements and monitoring.

(4) Chemistry factor is based on observations of chemical processes, such as gas seeps.

(5) Biota factor includes presence/absence of the key benthic epifauna and flora species/communities identified from underwater footage and beam trawl surveys.

FACTORS	SUB-FACTOR	AREA	CLASS	DESCRIPTORS			REFERENCE
(GEO)MORPHOLOGY	Morphological feature	Shelf	Mound	IHO hill			GINR & GEUS database
			Flat/Floor				classification: CMECS, EMODnet, BGS
			Slope				
			Valley	Depression			
			Rugged terrain				
	Geomorphological feature		Trough				
			Ploughmarks	Iceberg			
			Pockmarks	Fluid-escape			
SEDIMENTS	Grain size	Shelf	bedrock	Bedrock w. Mud, boulder and pebbles	mR		GINR & ZSL database
			coarse rocky ground	Course rocky ground	R		classification: EUNIS-modified
				Course rock ground with thin layer of mud	Rm		
			gravelly sand	Gravelly sand	gS		
			gravelly mud	Gravelly mud	gM		
				Mud with dropstones	Md		
			mud	Mud	M		
	Genesis		gneis	precambrian			GEUS database
			sandstone	cretaceous			
OCEANOGRAPHY	Water mass	Shelf	surface water	>2	<33	0-50m	GINR & DMI database
			Polar Water	0-2	33-34	50-200m	
			Subpolar Mode Water	>2	>34	200-400?m	
			Irminger Water	>4	>34.9	400-600m	
CHEMISTY		Shelf	Gas seeps	cold seeps?			
BIOTA	Taxa	Shelf	bryozoan				GINR & ZSL database
			brittle star				
			kelp				
			mollusks				

Table 1. Preliminary GOCH classification scheme based on Disko Bay pilot area.

Following the GOCH classification, five different (physical) habitats were identified in Disko Bay pilot area (figures 52-53):

1) Rocky bank habitat – morphologically rugged terrain consisting of bedrock and coarse rocky sediments, most likely of metamorphic origin, i.e. Precambrian gneiss covering area in the upper 200 m water depth; habitat influenced by Polar Water mass (T>0 C; 33<S<34) and dominated by sessile fauna (biotope A), i.e. ascidians, sponges, soft corals, sea cucumbers and bryozoans;
2) Coarse rugged habitat – area covering rugged terrain mostly consisting of gravelly mud/sand and admixture of coarse rocky ground; majority of the area has Precambrian gneiss as building block and covers areas between 150-300 m water depth influenced predominantly by Polar Water, and dominated by biotope A;
3) Sandy floor habitat – vast flat areas with dominant fraction of gravelly sand/mud with building block of Cretaceous sandstone; habitat represented by biotope A in a water depth interval of 150-300 m and influenced by Polar Water mass;
4) Muddy rugged habitat – morphologically rugged terrain, covered by mud in the water depth interval of 300-500 m; habitat dominated by shrimp and Polychaeta (biotope B) and influenced by the Subpolar Mode Water (T>2?; S>34.8?);
5) Muddy floor habitat with seeps – morphologically flat area covered by mud with numerous seep observations; habitat dominated by biotope B in deeper water, i.e. 300-500 m water depth, influenced by the Subpolar Mode Water;

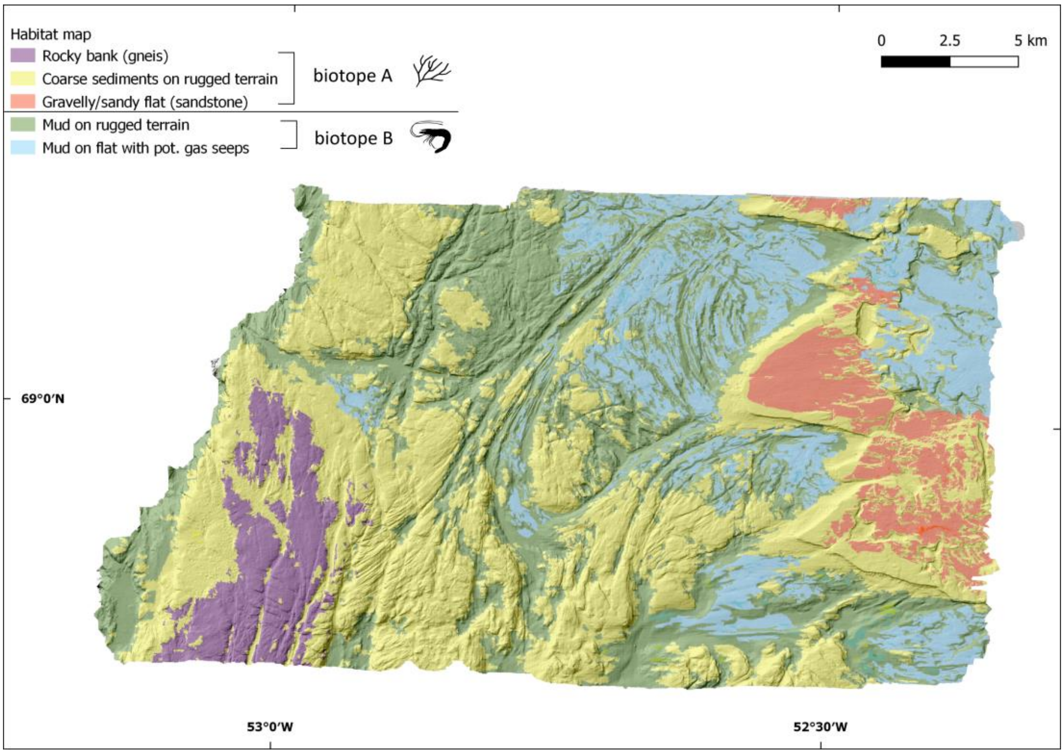

Figure 52. Habitat map of Disko Bay pilot area superimposed on the bathymetry map (hillshade with semi-transparent habitats).

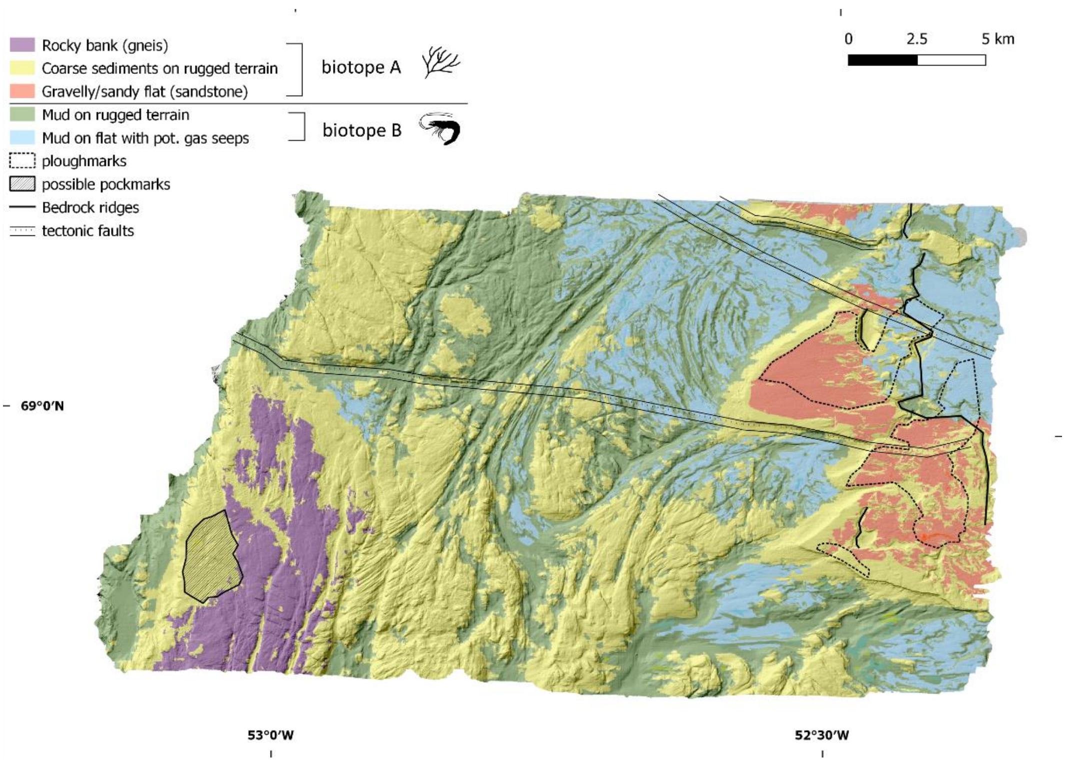

Figure 53. Habitat map of Disko Bay pilot area with key geological features identified in the area superimposed on the bathymetry map (hillshade with semi-transparent habitats).

10. Summary

The objective of the **MapHab** project was to develop a 'best practice' protocol for mapping benthic habitats in Greenland and produce the first high-resolution benthic habitat map. The project resulted in successful data collection using combined multi-beam and ground-truthing gear during a single survey, processing and map production with guidelines and recommendations, all described in detail in the 'best practice' protocol available at GINR website. We collected large datasets of acoustic data, underwater images and physical samples of the seafloor environment with associated information on sediments and benthic communities. Through co-operation we put the relatively small pilot area in the bigger context of Disko Bay's geology and sedimentary environment by integrating new and historical data collected within the research consortium. This project provided geophysical and biological datasets as baseline knowledge necessary for the sustainable management of benthic resources. The generated digital terrain models, sediment map, geophysical and habitat maps, as well as benthic imagery will help better understand the physical and biological habitats of the central Disko Bay, which in turn will promote our better understanding of its' unique marine environment and ecosystem. The **MapHab** project is the first attempt to produce a high-resolution benthic habitat map in Greenland territory and is the cornerstone to large scale mapping of the West Greenland shelf as part of the #Greenland #Seafloor #Modelling program.

11. Literature

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