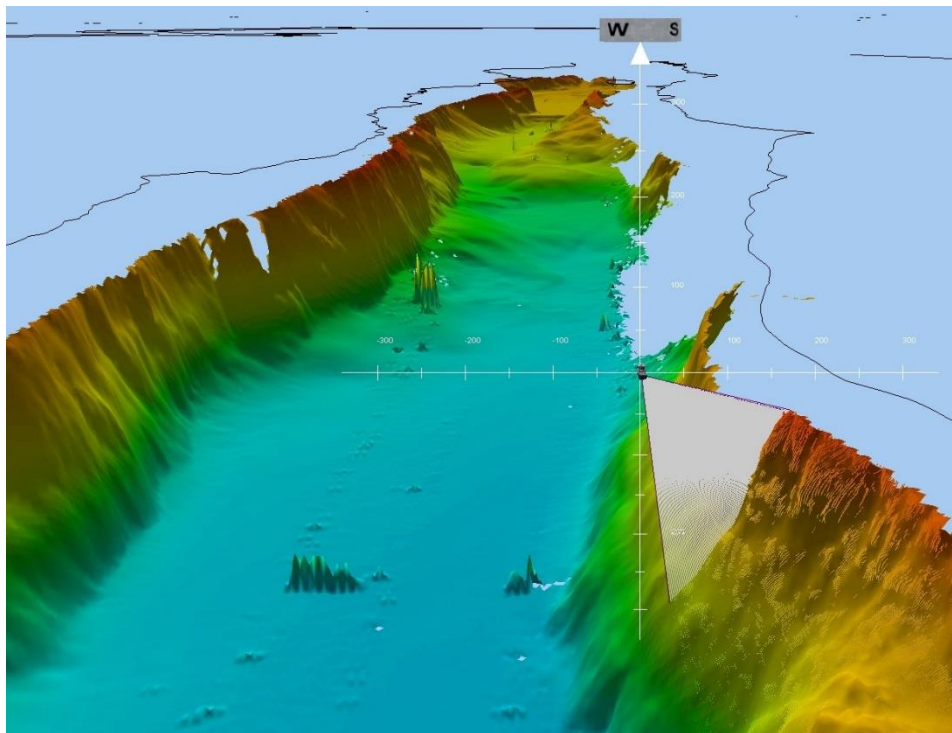


PINNGORTITALERIFFIK · GRØNLANDS NATURINSTITUT

# MapHab - Mapping Benthic Habitats in Greenland

*Best practice protocol*



**Technical report no. 108**



**Title:** MapHab – Mapping Benthic Habitats in Greenland. *Best practice* protocol.

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**Project consortium:** Greenland Institute of Natural Resources (GINR)  
Geological Survey of Denmark and Greenland (GEUS)  
Institute of Zoology (IoZ)  
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# 1 Introduction

Habitat is a combination of physical properties of environment and information on biological communities/assemblages in a given area. Benthic habitat, as the subject of the **MapHab** project, can therefore be defined by the physical environment elements, i.e. seafloor bathymetry, morphology, sediment types and water mass characteristics (hydrography), as well as the occurrence/distribution of the benthic flora and fauna species.

The marine environment surrounding Greenland poses several challenges for planning and conducting field campaigns focused on habitat mapping, such as seasonal sea ice cover, icebergs, highly complex topography (e.g. hundred meter steep slopes) and strong winds. Such demanding environment requires extra efforts before and during data acquisition. In the **MapHab** project, we recognized 'the potential of using remote-sensing data as proxy of biophysical indicators', thus we created the 'best practice' protocol for novel in Greenland, high-resolution benthic habitat mapping procedure. The proposed 'best practice' protocol is a cost-effective and time-efficient mapping guide for 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).

The advantage of this protocol is the effective sampling program combining acoustic survey with on-board processing and ad hoc data interpretation in order to select the optimal ground-truthing sampling in one go (instead of separate acoustic survey followed by ground-truthing sampling a year after). For that, the Greenland Institute of Natural Resources (GINR) developed a suitable scientific framework, i.e. a remote research platform 'Sanna' equipped with multi-beam echo sounder and ground-truthing tools. In addition, the projected offshore 'New vessel' is being prepared for a similar setup but with a deep-water multi-beam and a sub-bottom profiler for the more in-depth geological mapping. The following 'best practice' protocol is based on the pilot study in Disko Bay (**MapHab** project; Krawczyk et al., 2019), where we carried out a 1-survey, baseline high-resolution habitat mapping using multi-beam with physical ground-truthing sampling on a relatively small area (c. 30x20 km).

All the acoustic mapping-related descriptions in this protocol follow the example of GINR multi-beam system on R/V Sanna (i.e. Reson SeaBat T50-R-ER with PDS software) and the recommendations by Teledyne Reson (online technical assistance), GeoHab report (Lurton and Lamarche, 2015) and Field manual for Monitoring Australia's Commonwealth Waters (Lucieer et al., 2018). Workflow of the

map synthesis is inspired by workflow described in the Norwegian mapping program (Buhl-Mortensen et al., 2012; Bellec et al., 2017) and the Canadian mapping program (Kostylev et al., 2001; Todd & Kostylev, 2011).

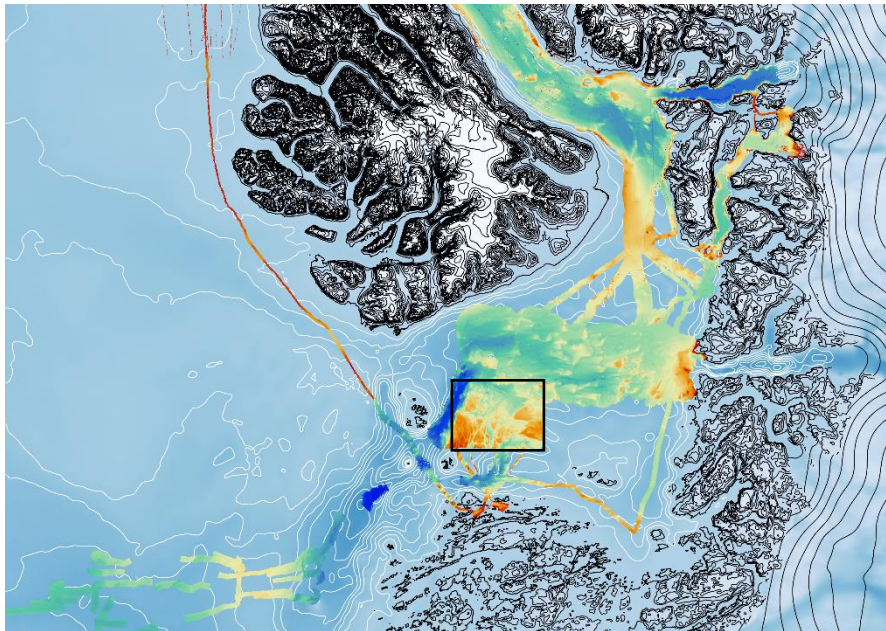
## 2 Data acquisition

A well-planned survey is crucial to the quality of the final product. It is important to account for all the necessary calibrations, corrections, verifications and additional measurements prior to the survey. Environmental parameters, such as water column characteristics affect the multi-beam data measurement and this will vary depending on e.g. freshwater inflow from the Greenland Ice Sheet in the fjords and on the ocean current in the continental slope area. Therefore, acquiring good multi-beam data requires sound velocity profiles for accurate reflection of water mass during survey. Suspended sediment, gas seeps, biology and bubbles can also absorb or redirect the acoustic signal, and thus need to be documented during the survey. Compared to bathymetry, the scatter of echo from seafloor (=backscatter) is more complex and requires more parameters to be measured (Lurton and Lamarche, 2015).

In this chapter, we describe mapping activities for the high-resolution habitat mapping survey type, defined by the purpose to collect spatially continuous acoustic signature of the desired area and physical ground-truthing samples. In the Disko Bay pilot study, acoustic data, i.e. bathymetry and backscatter were collected by the multi-beam echo sounder. The backscatter data require validation with physical ground-truthing (sediments) in order to describe seafloor sediment environment, thus sediment information and samples were obtained with benthic video sled, drop camera and grab. In addition, video sled and drop camera registered data on epifauna to describe benthic communities.

### 2a Preparation for survey

- Select designated survey area boundary with datum and coordinate system identified
- Collection of all available geophysical data (bathymetry and backscatter, if available) and ground-truthing data from opportunistic surveys for the area overview



**Figure 1.** Example of bathymetric data collected by multi-beam systems from opportunistic surveys (source: IBCAO, GINR & GEUS database) and MapHab pilot area (black box).

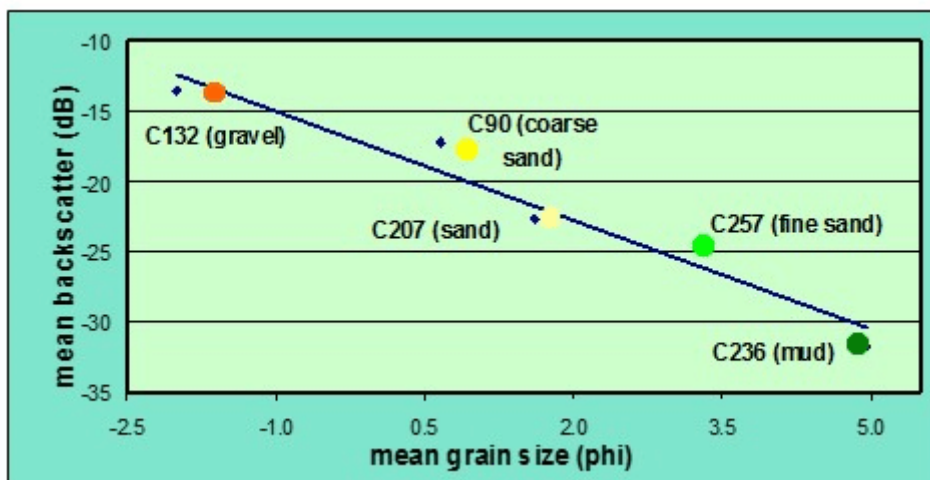
- Information on the sea ice conditions and weather forecast
- On-board equipment list with necessary utensils (e.g. batteries, zip-lock bags, markers, external hard drives etc.)
- GPS positioning system on board – accuracy greater than 1m
- Logbook for registering survey activities, i.e. multi-beam transects, ground-truthing points, Sound Velocity Profile casts
- Sonar head cleaning in advance (biofouling)
- Application to Geodata Agency of Denmark for permit to collect and process multi-beam data

Detailed manuals for multi-beam data acquisition and processing are available at GINR

## 2b Multi-beam settings

- For habitat mapping, focus is on good quality snippets (=backscatter) but good quality sensor (=bathymetry) data is important, especially resolution and consistency of bathymetry, e.g. small features or rapid changes in slope
- **Survey type: habitat mapping** – optimal settings for good quality sensor and snippets data in Greenland environment:
  - Tick sensor data and snippets

- Power: full (226 dB)
  - Pulse length: 300  $\mu$ s/CW mode; pulse length should remain constant throughout the survey so that all data are standardized
  - Gain: 30 dB for shallow water; 50 dB for deeper water (gain needs to be controlled to avoid saturation in shallow, hard bottoms)
  - Max rate (ping): 50 p/s
  - Beam mode: equi-distant
  - Pulse type: CW (constant wavelength) - simple reception process limits the risks of level biasing; FM (frequency modulation) is accepted as long as a fixed center frequency is applied throughout the survey at a minimum FM sweep (1 kHz)
  - Center Frequency: 180 kHz
  - Absorption: 35 dB/km<sup>-1</sup> for T: 0-3; S: 33; Depth: 0.1-0.9km; pH: 8
  - Spreading: 30 dB
  - Effective depth range: 0.8 km
- 
- Backscatter shows direct relationship to sediment grain size and terrain ruggedness, thus can be used in providing info on bottom hardness (sediment types)
  - Assumption: backscatter values increase with grain size, though backscatter strength does not provide a direct measure of grain size (Bellec et al., 2017)
  - Backscatter signal can penetrate into the seabed (depending on the frequency) from several up to c. 10 cm, thus reflect the sediment composition in the uppermost c. 10 cm of the seabed (Bellec et al., 2017)



**Figure 2.** Example of relationship between backscatter strength (dB) and sediment grain size (phi) – New Zealand study (Lamarche et al., 2011).



- Rule of thumb: minimize changes for maximized backscatter products

### multi-beam calibration for good quality snippets

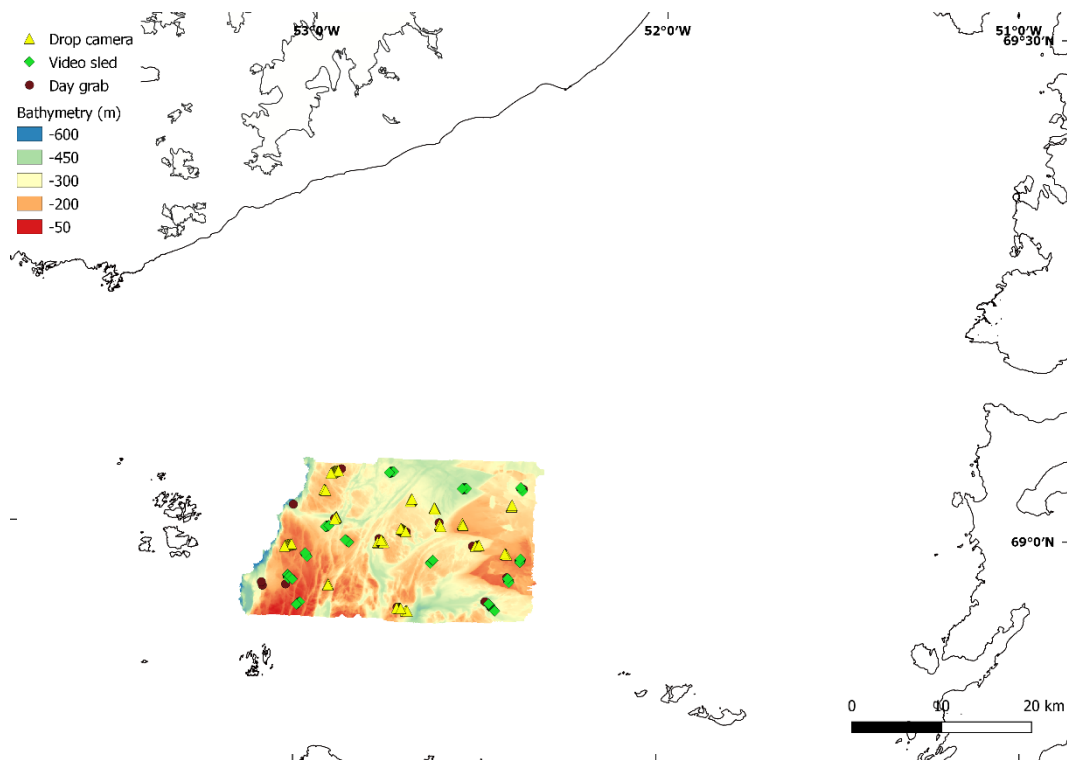
- Reference (known) area: flat and sandy
- Recommended 1x year due to aging of multi-beam

## 2c Ground-truthing

- ✓ Benthic gear (GINR) : video sled (imaging), drop camera (imaging), day grab (physical sample)
  - Video sled sampling:
    - Equipped with GoPRO camera and two Nautilux torches in GB-PT 1750 group binc underwater housing; camera height is at c. 85 cm positioned at 31° angle
    - Deployment: winch on the aft deck
    - Sampling time: c. 15 min. at c. 1 kn speed covering c. 500 m transect
    - GPS position is logged at start and end of the survey along with water depth and winch wire length
    - Camera position is inferred as being directly behind the ship at a distance  $X$ , where  $X=(W^2-D^2)^{0.5}$  (W-wire length, D-water depth); layback calculation required
  - Drop camera sampling:
    - Nikon D80 digital SLR in DSC-10000 Digital Ocean Imaging Systems deep-sea camera housing and 200 W-S Remote Head Strobe flash unit (Model3831) in a steel frame (camera 65cm above seabed). Also attached is a GoPro camera in a groupbinc underwater housing with 1-2 Nautilux torches. GoPro is positioned at 85cm at an angle of 49.5°
    - Deployment: winch on the side of the aft deck
    - Sampling time: c. 10-20 drops at 1-2 min. intervals while ship is allowed to drift. Camera is raised c. 5m above the seabed between drops. Camera automatically triggers image capture on contact with the seabed



- GPS position is logged at every drop along with water depth and drift speed
- Camera is assumed to be directly beneath the ship
- Grab sampling:
  - Deployment: from winch on the side of the aft deck
  - Sampling time: immediate at contact with seabed
  - Grab is assumed to be directly beneath the ship
  - Sediment sample is photographed, labeled and stored in zip-lock bag in cold room for further lab analyses

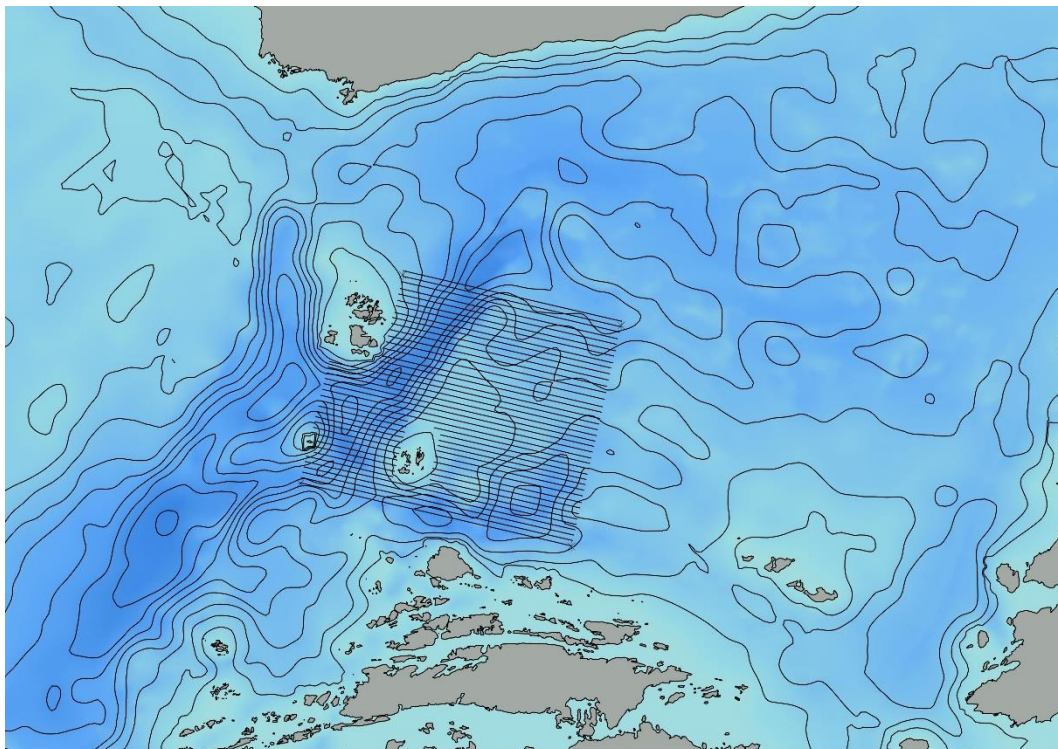


**Figure 3.** Multi-beam based bathymetry map with locations of physical ground-truthing stations from Disko Bay pilot area collected with video sled (green rhombus), drop camera (yellow triangle) and grab (red circle).

- Imaging the seabed provides a broad overview of the seabed alongside a picture of the benthic fauna over relatively **wide geographic scales** (~hundreds of metres per deployment) allowing classification of seabed into broad scale habitats
- Imagery can also be used to assess benthic fauna, particularly epi-benthic megafauna, on a relatively coarse taxonomic level (i.e. species groups)
- Physical grab samples can be used to identify and assess infauna

## 2d Survey techniques for quality data

- Survey lines (transects) predetermined with optimal line spacing depending on water depth:
  - E.g. 0,3 km spacing at depths 100-300 m
  - Swath overlap: optimal 30% overlap between transects; for reconnaissance surveys aiming at targeting specific locations, the overlap is not crucial
  - Transect lines parallel to the seafloor contours (if known)
  - Navigation direction: preferred unidirectional on complex topography
  - Sharp turns are excluded
  - Cross-lines (orthogonal)
  - For changes in settings – use the same transect line and log changes



**Figure 4.** Example of transect lines spaced at 0,3 km in Disko Bay pilot area.

- Sailing speed: 6-8 knots
- Time-efficient mode: sail several 'multi-beam' transects -> convert raw multi-beam data to on-board digital terrain model (bathymetry) and backscatter mosaic (e.g. 1 m grid resolution for depth<100m and 10m)

grid resolution for depth>200m) -> depict ground-truthing points based on distinct terrain features and mosaic grayscale tones

- On-board terrain model and backscatter mosaic should be generated for cross-check between original data and modelled data (e.g. to check for consistency between different seafloor types)
- Optimal points for ground-truthing:
  - drift must be accounted for when selecting sampling location
  - cover as many backscatter grayscale tones as possible/aid with unsupervised classification (e.g. natural breaks, histogram analysis in ArGIS)
  - cover same backscatter grayscale tones at different depth intervals
  - cover different topographic features (bathymetry/slope)/ aid with unsupervised classification (e.g. natural breaks, histogram analysis in ArGIS)
  - cover transition areas
  - Imagery is dependent on the resolution of the images, but is unlikely to differentiate classes on the smaller end of the sediment size scale and cannot reliably distinguish mud and sand classes, thus is more reliable on the **hard bottom** habitats
  - Physical samples enable direct measurements of grain sizes, allowing more detailed calibration of sediment classes at the finer end of the size spectrum, thus more reliable on **soft bottom** habitats
  - It is recommended to first collect a physical sample (e.g. grab) from undisturbed habitat before deploying imaging gear; it is recommended to collect triplicates of sediment samples due to potential variations between the samples, especially in mixed substrate areas
  - best to use both sampling techniques, i.e. imagery and physical sampling per station for a more complete and precise picture of benthic habitat



**Figure 5.** Example of raw backscatter mosaic generated on board showing bottom reflectivity as a manifestation of bottom hardness: lighter tones-stronger reflectivity-harder bottom. Red circles indicate recommended areas for ground-truthing that cover homogeneous tones of grayscales.

- Sound Velocity Profiles (SVP; at least at the start and end of the survey); optimal solution:
  - SVPs can be collected in between ground-truthing sampling, i.e. after imaging, while inspecting footage and assessing best location for the physical sample
  - Reson multi-beam has SVP sensor built onto the head of transducer that informs on sound speed below the water surface

## 3 Data formats

Data type	Equipment	Raw format	Processed format	Software
Sensor data (bathymetry)	Reson SeaBat T-50 ER	.s7k; .pds	Digital Terrain Model: .dtm; .asc; .tif, .kmz	PDS, QGIS, ArcMap
Snippets (backscatter)	Reson SeaBat T-50 ER	.s7k; .pds	Backscatter/Phi Mosaic: .dtm; .asc; .tif	PDS, QGIS, ArcMap
True Heave	Reson SeaBat T-50 ER	Applanix ATH	-	PDS
Tide	10 min. model (Danish Meteorological Institute)	.txt	.tdg	PDS
Sound Velocity Profile (SVP)	Valeport mini Sound Velocity Probe	.txt	.svp; .csv	PDS
Images, videos	GoPRO camera	.jpeg, .mp4	.jpeg (stills), .mp4 (videos), .txt (annotations)	Bigle (any image viewer is suitable)

**Table 1.** Data types produced in the mapping procedure with their raw and processed formats.

## 4 Data processing

From raw data to map layers:

- Bathymetry (=Z average) data (multi-beam) -> Digital Terrain Model
- Bathymetry+backscatter (=snippets) data (multi-beam) -> backscatter mosaic and phi mosaic (sediment grain size)
- Sediment types (ground-truthing) -> validation of backscatter/phi mosaic
- Benthos (ground-truthing) -> biotic layer

## 4a Multi-beam data decoding

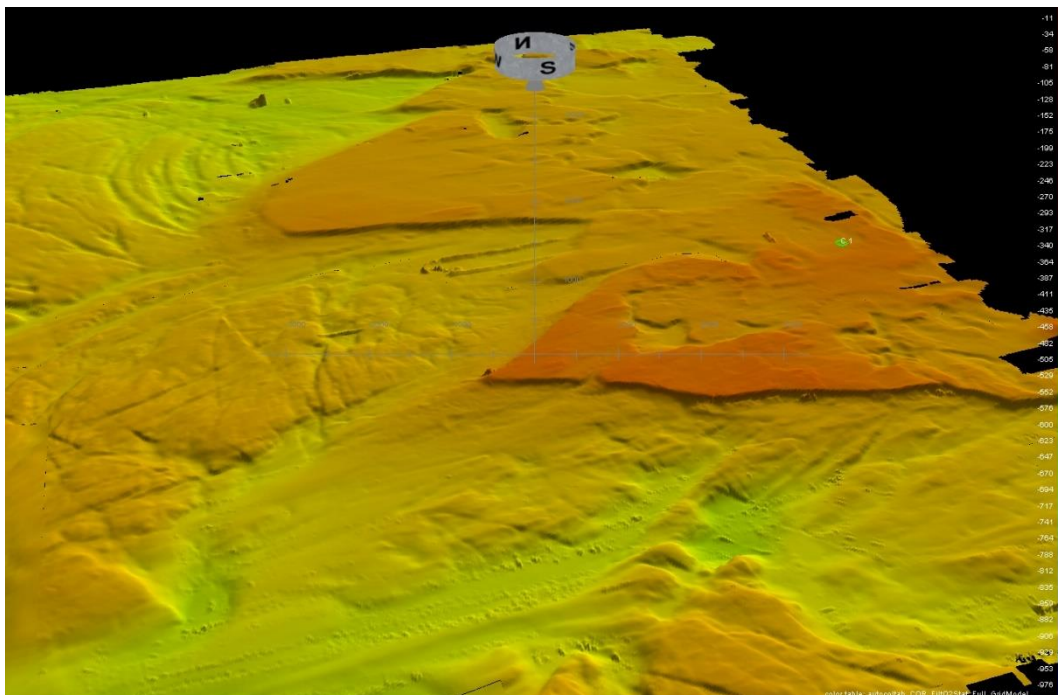
Decoding raw data (Z average):

- Geodetic settings: assign UTM zone to project
- Apply system-dependent corrections (PDS: True Heave, Tide, SVP)
- Create grid model (raw data) and inspect by standard deviation
- Draw profiles and inspect data for mismatches
- Apply automatic filters (e.g. detection quality, statistic, nadir)
- Manual editing (optional CUBE/Combined Uncertainty and Bathymetry Estimator processing)
- Create grid model (clean data) and inspect again
- Choose low cell size: 1m, 5m, 10m for high-resolution gridding

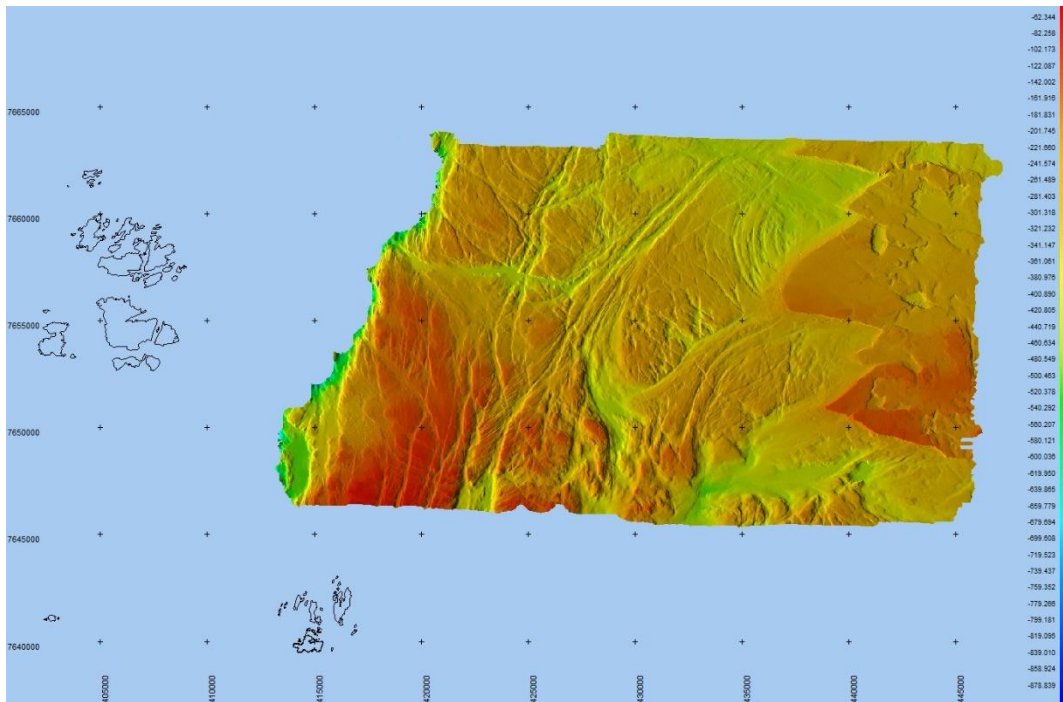
## 4b Multi-beam data gridding

Data gridding (Z average and snippets):

- Create final grid model (Z average) from clean data = Digital Terrain Model (DTM)



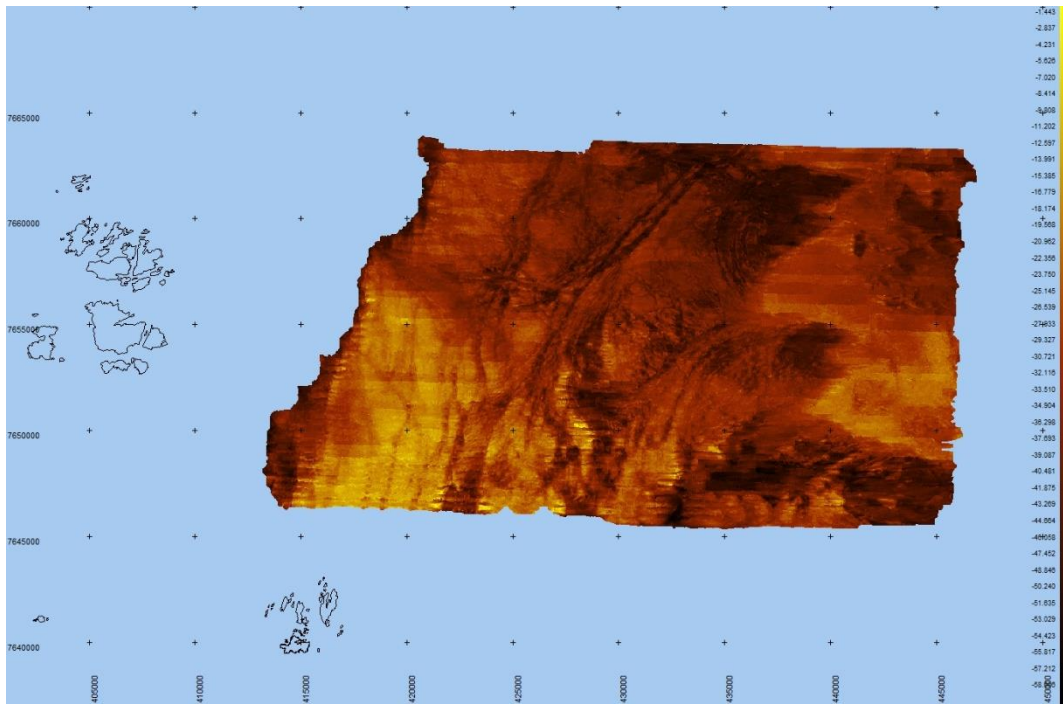




**Figure 6.** DTM – Disko Bay pilot area (color scale: red – shallow waters, blue – deep waters); 10m grid.

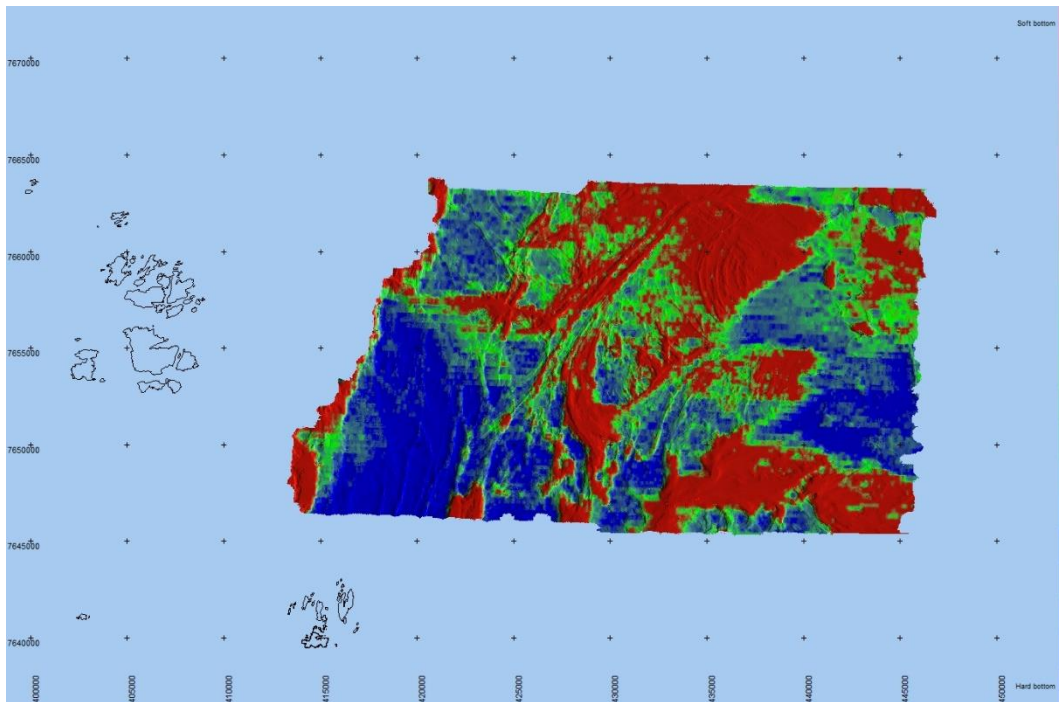
- Create final backscatter mosaic (snippets) via height grid model (Z average) = backscatter mosaic
  - Compute calibration offset for the reference area (flat and sandy) and apply to data
  - Backscatter mosaic is corrected for radiometric and geometric distortions (gain, power, pulse width, beam pattern, absorption and spreading, beam position, difference angular dependency, area of insonification, Lambert)





**Figure 7.** Backscatter mosaic – Disko Bay pilot area (color scale: yellow-hard bottom, black – soft bottom); 10m grid.

- Create phi mosaic via backscatter mosaic
  - Phi mosaic uses method called Angular Response Analysis (ARA) that corrects for the variations in amplitude for different angles of incidence; a compensation of angular dependency is necessary for a usable geographical representation of backscatter
  - Phi mosaic represents different bottom types corresponding to Wentworth scale (grain size: from gravel to clay)



**Figure 8.** Phi mosaic – Disko Bay pilot area (color scale: blue – hard bottom, red – soft bottom).

- Optional: spike removal, interpolation, clipping
- Export Digital Terrain Model /backscatter mosaic/phi mosaic to GIS formats (.asc, .tif., etc.) for map production

Steps towards backscatter normalization:

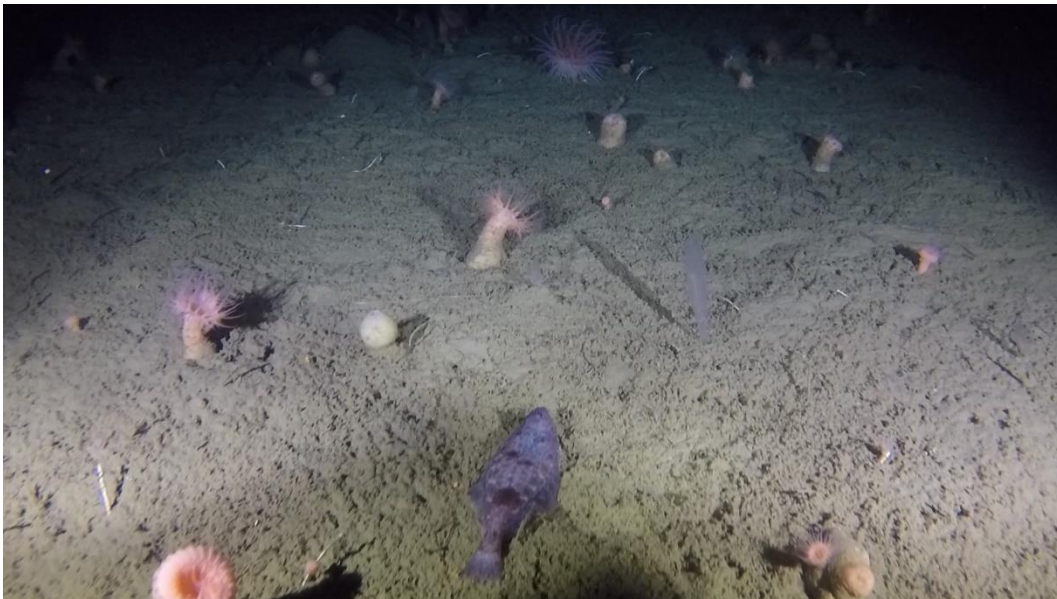
- Step 1: calibration routine ensures optimum beam forming
- Step 2: backscatter should account for slope
- Step 3: backscatter product should be angle-compensated to avoid along-track banding artefacts
- If change of settings occur during survey (CW/FM) it is recommended not to combine different frequencies into a single mosaic
- For projects focusing on ‘mapping for discovery’, such as the **MapHab** project, the backscatter is mostly analyzed as qualitative reflectivity (relative dB scale), i.e. descriptive image of the seafloor

- Highest possible resolution is recommended for more accurate gridding/mosaicking; high resolution of input bathymetry grid reduces uncertainties on the corrections for insonification area and angular dependency (Malik, 2019)

- Backscatter data collected over long time during different surveys should be annotated rather than merged in one file, due to changes in seafloor scatters over time. It is recommend to combine final classified products if there is lack of normalized backscatter data (Lacharité et al., 2018).

## 4c Ground-truthing classification

- ✓ Two types of data: underwater imagery (video sled and drop camera) and physical sample (grab).
- Underwater imagery: image analysis -> steps:
  - Stills are extracted at 30 sec intervals for analyzable sections of video; for drop camera stills are taken at 1-2 min. intervals (camera is triggered each time it hits the bottom)



**Figure 9.** Example still from video sled imagery highlighting a variety of benthic fauna in Disko Bay pilot area (sea anemones and polychaet worms on muddy seabed).



**Figure 10.** Example still from drop camera showing ascidians and sponges on mixed seabed in Disko Bay pilot area.

- When stills are not analyzable due to silt clouds obscuring the view or steeply undulation terrain dramatically changing the camera angle the video is played until the next analyzable section is found
- Each still is classified into sediment classes following the scheme of Gougeon et al. (2017) which is an adapted version of the EUNIS seabed classification scheme (Davies et al., 2004); sediment categories identified in Disko Bay pilot area with underwater imagery are marked with asterisk
- For each image, observations of prominent (most abundant), potentially habitat forming taxa are registered

EUNIS		Modified EUNIS categories (Gougeon et al. 2017)	
<b>A Marine habitats</b>			
<b>A6 Deep-sea bed</b>			
<b>A6.1 Deep sea bedrock and artificial hard substrate</b>			
			A6.1.1 Bedrock with mud, boulder and pebbles (mR)*
			A6.1.2 Bedrock with sand, boulder and pebbles (Rs)
			A6.1.3 Coarse rock ground with thin layer of mud (Rm)*
			A6.1.4 Coarse rocky ground (R)*#
			A6.1.5 Coarse rocky ground with boulders (Rb)
<b>A6.2 Deep-sea mixed substrata</b>			
			A6.2.1 Gravelly mud (gM)*#
			A6.2.2 Gravelly mud with boulders (gMb)
			A6.2.3 Gravelly sand (gS)#
<b>A6.4 Deep-sea muddy sand</b>			
			A6.4 Muddy sand (mS)
<b>A6.5 Deep sea mud</b>			
			A6.5.1 Mud (M)*#
			A6.5.2 Mud with dropstones (Md)*

**Table 2.** Modified EUNIS categories used in annotating images obtained from video sled and drop camera footage from the West Greenland region. Sediment categories identified in the MapHab pilot area are marked with asterisk (\* - from underwater imagery) and hashtag (# - from grab samples).

- Physical sample: grain size analysis -> steps:
  - Dry sediment samples in the oven
  - Sieve sediments using appropriate mesh sizes, e.g. 0,063 mm, 0,25 mm, 0,5 mm, 2 mm, 64 mm
  - Weigh each sediment fraction separately defined by grain size class (after Wentworth scale):

Grain size class (mm)	<0,063	0,063-0,25	0,25-0,5	0,5-2	2-64	>64
Sediment type	Silt & clay	Fine sand	Medium sand	Coarse sand	Gravel/Pebbles	Cobbles

**Table 3.** Grain size classes with sediment types after Wentworth scale

- Calculate % of each sediment fraction per sample
- Assess sediment type (majority %) and adapt class to the modified-EUNIS classification (see table 2; categories identified in Disko Bay pilot area from grab samples are marked with hashtag
- It is recommended to use a simplified procedure of sediment type assessment from grab samples involving visual inspection of the physical sample on board, to better match photo/video assessment, thus compromise different sampling techniques

Ground-truthing classification needs some modifications due to different accuracy of the different sampling techniques, i.e. imagery provides a more reliable description of **hard bottom** habitats, whereas physical samples provide more accurate assessment of **soft bottom** substrate; most optimal solution will require incorporating more detailed information on the grain size (Wentworth scale) into the EUNIS-modified classes and a more unified terminology, e.g. gravel=pebbles?

## 5 Data synthesis – map production

The key components of benthic habitat maps are high-resolution seafloor bathymetry, backscatter, slope and morphology together with sediment types and information on benthic species/assemblages/communities derived from multi-beam data and the ground-truthing sampling. Combination of abiotic map layers provides with geophysical map representing the physical properties of the benthic environment, whereas combination of abiotic and biotic layers provides with a habitat map representing the relationship between biota and the physical environment. Two basic assumptions are used in order to define boundaries between different habitat types, i.e. i) environmental gradients show discontinuities and ii) distinct benthic communities can be paired with distinct environmental factors (Lurton and Lamarche, 2015). Syntheses of abiotic and biotic layers is first subject to unsupervised classification (segmentation, similarity clustering etc.), followed



by supervised classification, i.e. verification with ground-truthing data and manually digitizing of physical habitat classes and community-level entities.

## 5a Map layers

- Export all map elements from processed survey data to GIS formats (.asc, .tif., .txt, etc):
  - Multi-beam-based layers (.asc): terrain model=bathymetry, backscatter (mosaic type of data) and/or Phi mosaic (angular type of data)
  - Ground-truthing points (.txt): sediment types & benthic communities info
  - GIS-generated layers (QGIS/ArcGIS) from bathymetry layer: slope, rugosity, bathymetric position index (BPI), and classified morphology (e.g. standardized classification using ArcGIS benthic terrain modeler tool)



**Figure 11.** Slope – Disko Bay pilot area (color scale: green –flat bottom, brown – extreme slope).



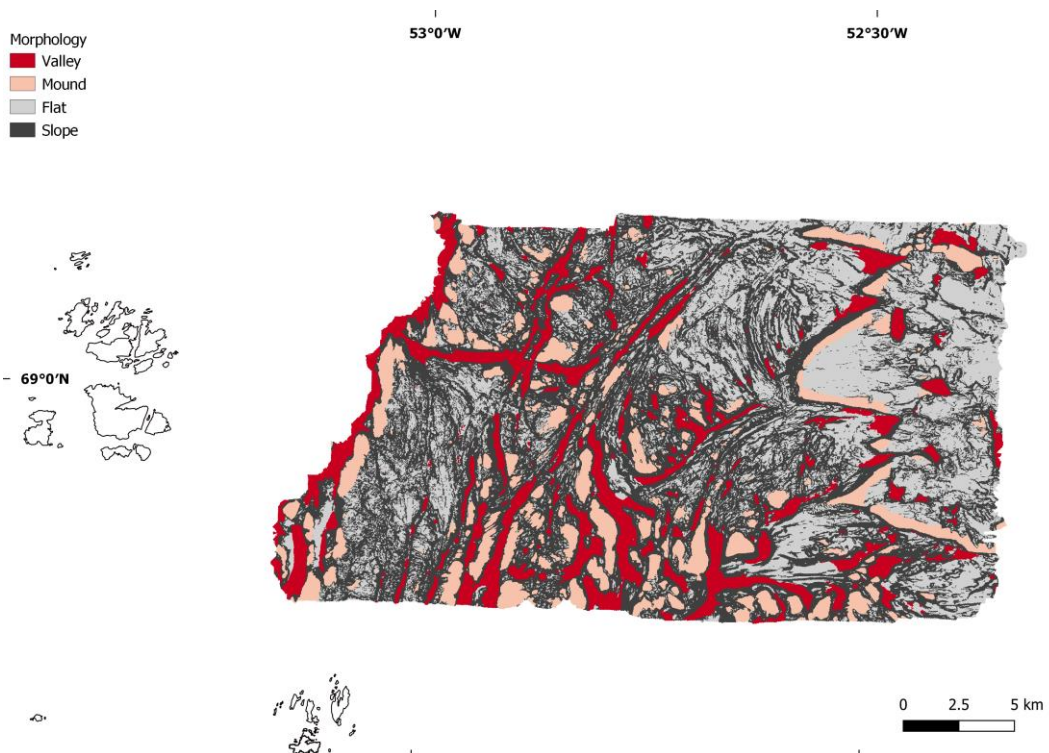


Figure 12. Morphology showing key topographic features in Disko Bay pilot area.

- Produce sediment layer; steps:
  - Unsupervised classification: e.g. simple histogram analysis derived from backscatter/phi intensity pixel (ArcGIS)

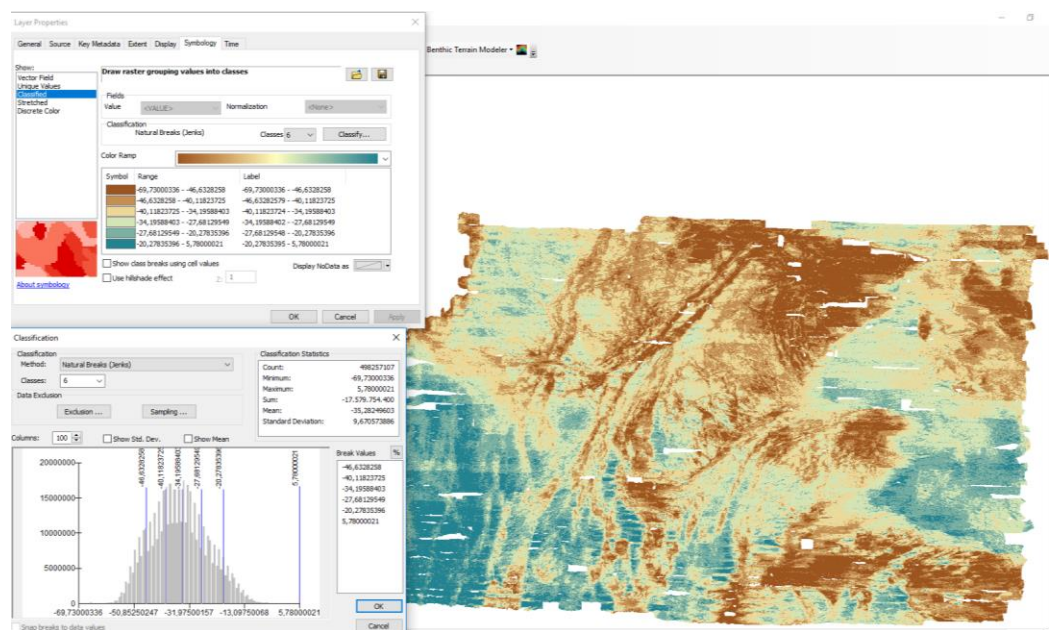
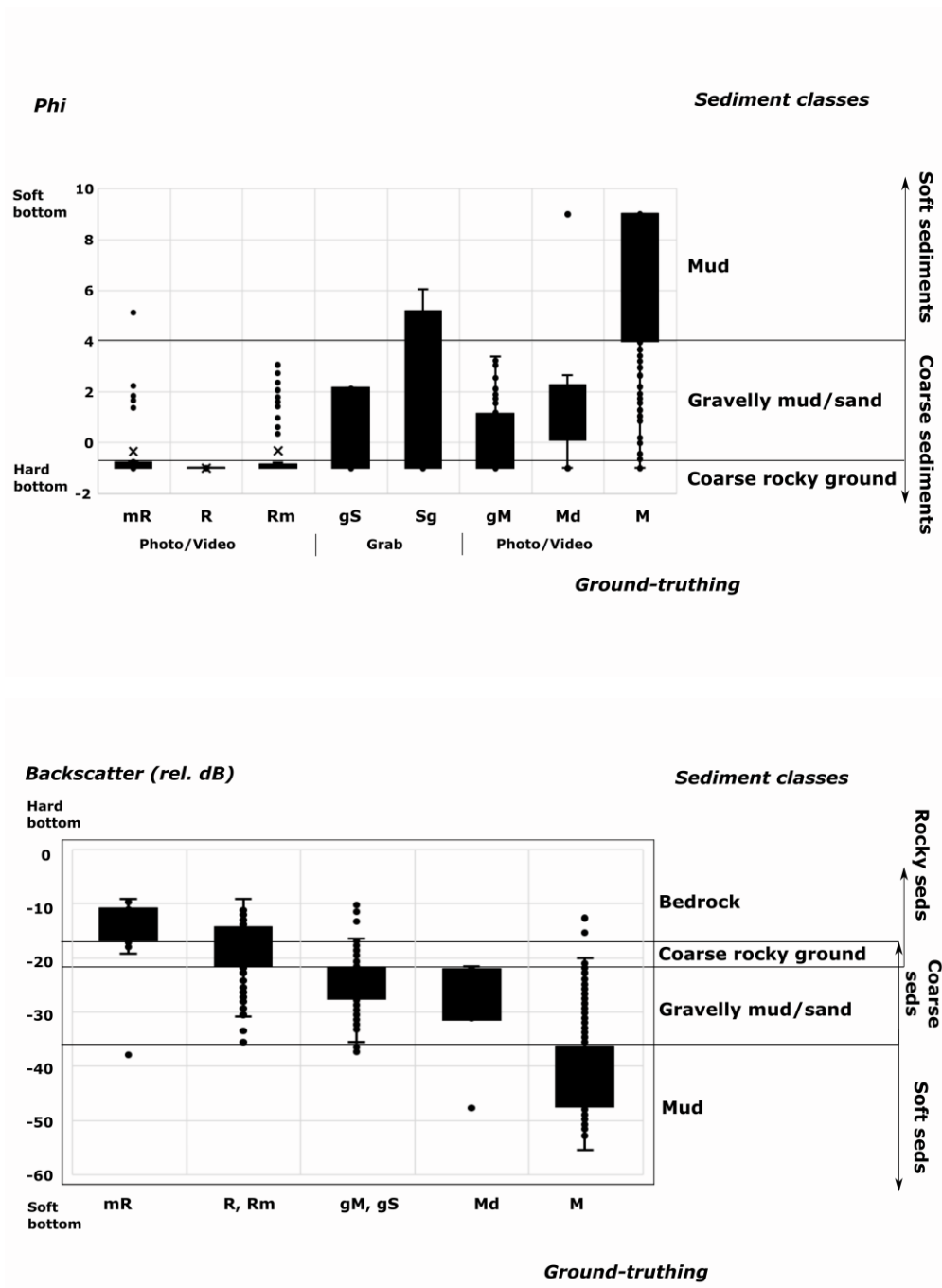


Figure 13. Example of unsupervised classification of 'raw' backscatter mosaic using histogram analysis (natural breaks).

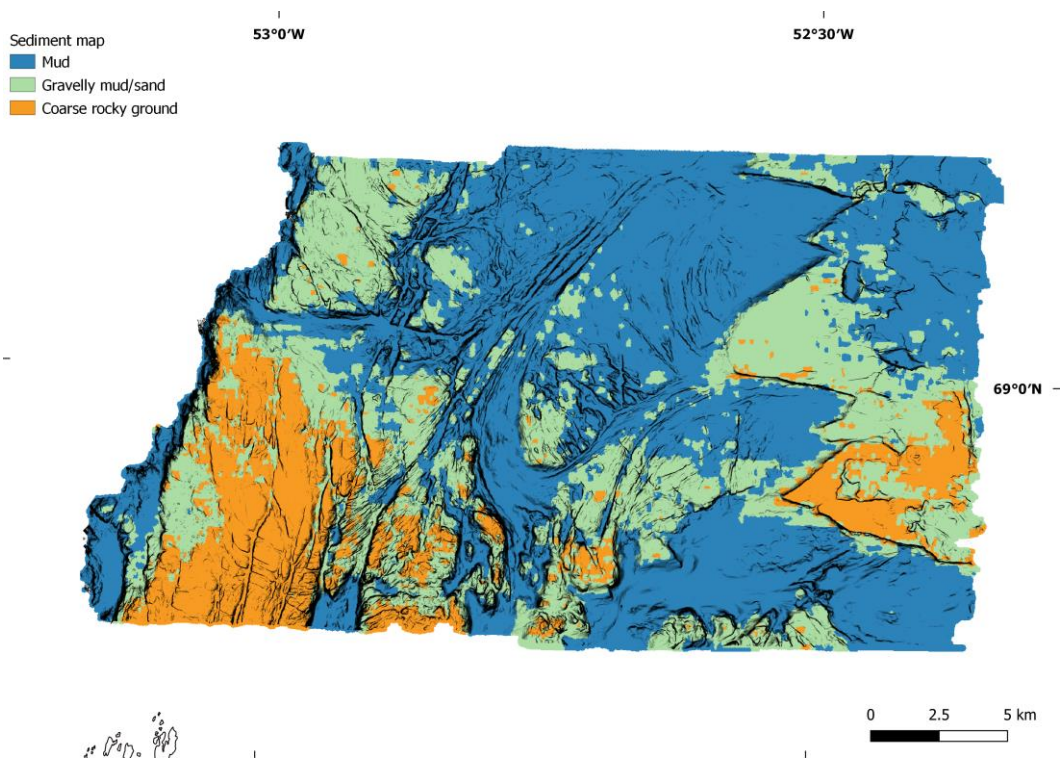
- Supervised classification: compare sediment type info obtained from ground-truthing with backscatter/phi mosaic data ranges
- Define sediment classes and threshold



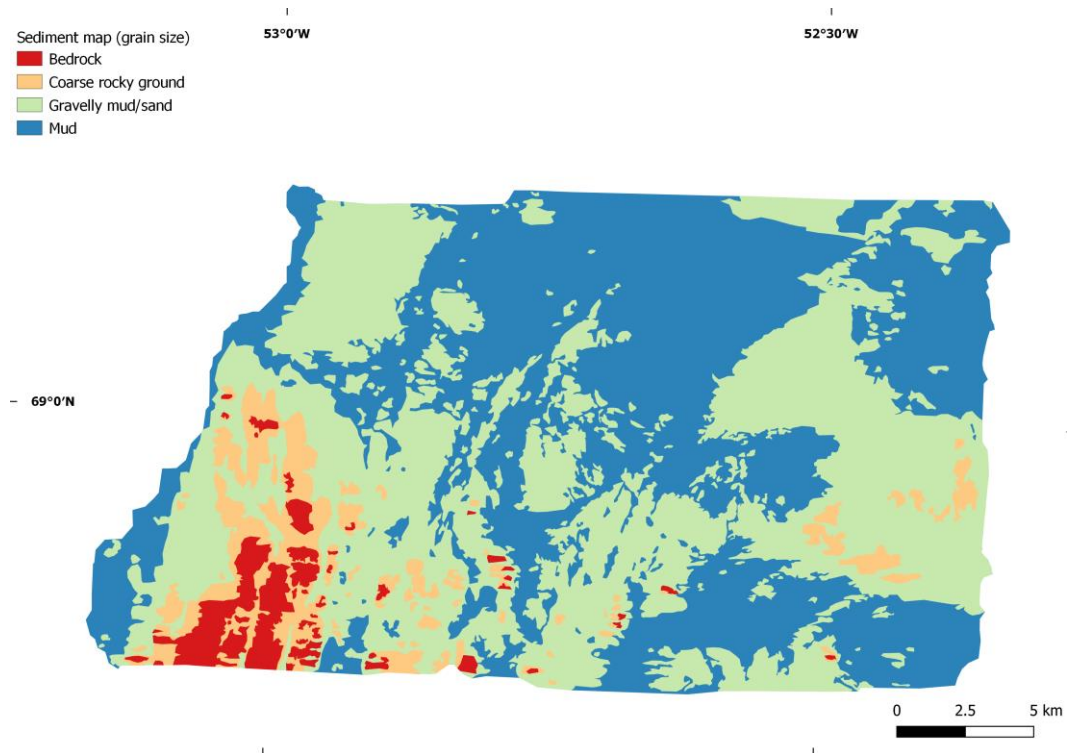
**Figure 14.** Box plots showing relationship between sediment types identified from ground-truthing (see table 2 for sediment codes) and Phi (grain size; top plot) and backscatter intensity (relative dB; bottom plot). Defined sediment classes with threshold are to the right.

➤ Backscatter mosaic produces more reliable and accurate representation of seabed sediments when validated with ground-truthing observations, compared to ARA-based Phi mosaic.

- Verify sediment classes: similar backscatter/phi signatures overlying different bathymetric and morphological features
- Example: bedrock shows high backscatter intensities, similar to boulders, cobbles and gravel, thus requires additional validation with slope/rugosity (Bellec et al., 2017)
- Classify backscatter/phi mosaic according to sediment classes



**Figure 15.** Sediment map based on classified Phi mosaic.



**Figure 16.** Sediment map based on classified backscatter mosaic.

- Backscatter may underperform in hard bottom areas, compared to soft bottom areas (Mohammadloo et al., 2017), thus it is recommended to validate classified sediment types with ground-truthing again (expert interpretation)
- The more sediment classes the more accurate validation, e.g. 'mixed' classes can be created and if ground-truthing validation is not straightforward, they can be merged with other classes in next steps

## 5b Geophysical classes

- Gather all physical layers in GIS formats (.asc, .tif., .txt, etc):
  - Bathymetry
  - Sediments
  - Slope, rugosity
  - Broad-scale and fine-scale bathymetric position index (BPI)
  - Morphology
  - Ground-truthing: sediment type info
- Inspect each layer using their known physical properties as reference, e.g. classified morphology, classified sediments, bathymetry can be divided

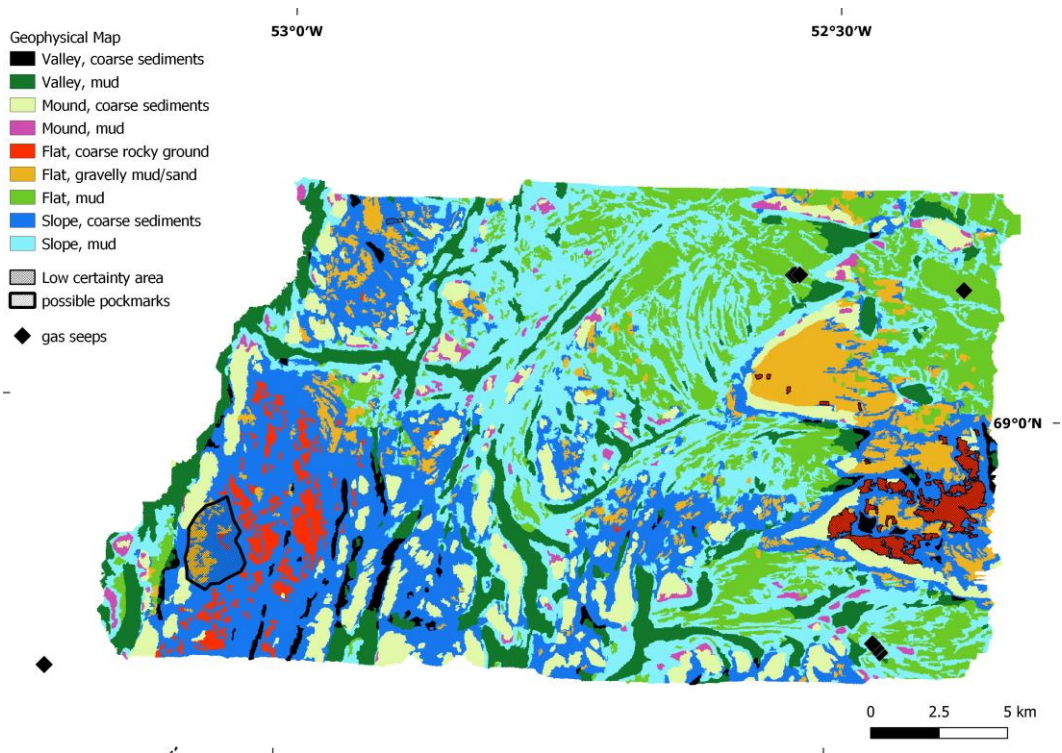
into classes based on water mass types in the area or vertical zones, slope can be divided based on slope steepness index, etc.

- Produce geophysical map; steps:
  - Compare all layers
  - Cumulate layers
  - Define geophysical classes
  - Classify cumulated layers according to geophysical classes
  - Validate classes with ground-truthing (expert interpretation)

Geoform	Class description	Morphology (BPI class)	Sediment type
Valley, coarse seds	depression, coarse seds	Depression	B
	depression, coarse seds	Depression	CRG
	depression, coarse seds	Depression	GM/S
Valley, mud	depression, mud	Depression	M
Mound (IHO hill), coarse seds	crest, coarse & soft seds	Crest	B
	crest, coarse & soft seds	Crest	CRG
	crest, coarse & soft seds	Crest	GM/S
Mound (IHO hill), mud	crest, coarse & soft seds	Crest	M
Flat, coarse ground	flat, bedrock	Flat	B
	flat, coarse rocky ground	Flat	CRG
Flat, gravelly mud/sand	flat, gravelly mud/sand	Flat	GM/S
Flat, mud	flat, mud	Flat	M
Slope, coarse seds	slope, coarse seds	Slope	B
	slope, coarse seds	Slope	CRG
	slope, gravelly mud/sand	Slope	GM/S
Slope, mud	slope, mud	Slope	M
			bedrock (B)
			coarse rocky ground (CRG)
			gravelly mud/sand (GMS)
			mud (M)

**Table 4.** Example of geophysical classification using information on morphology and sediments from Disko Bay pilot area. Some classes are merged based on the distribution of dominant sediment type/morphological feature.

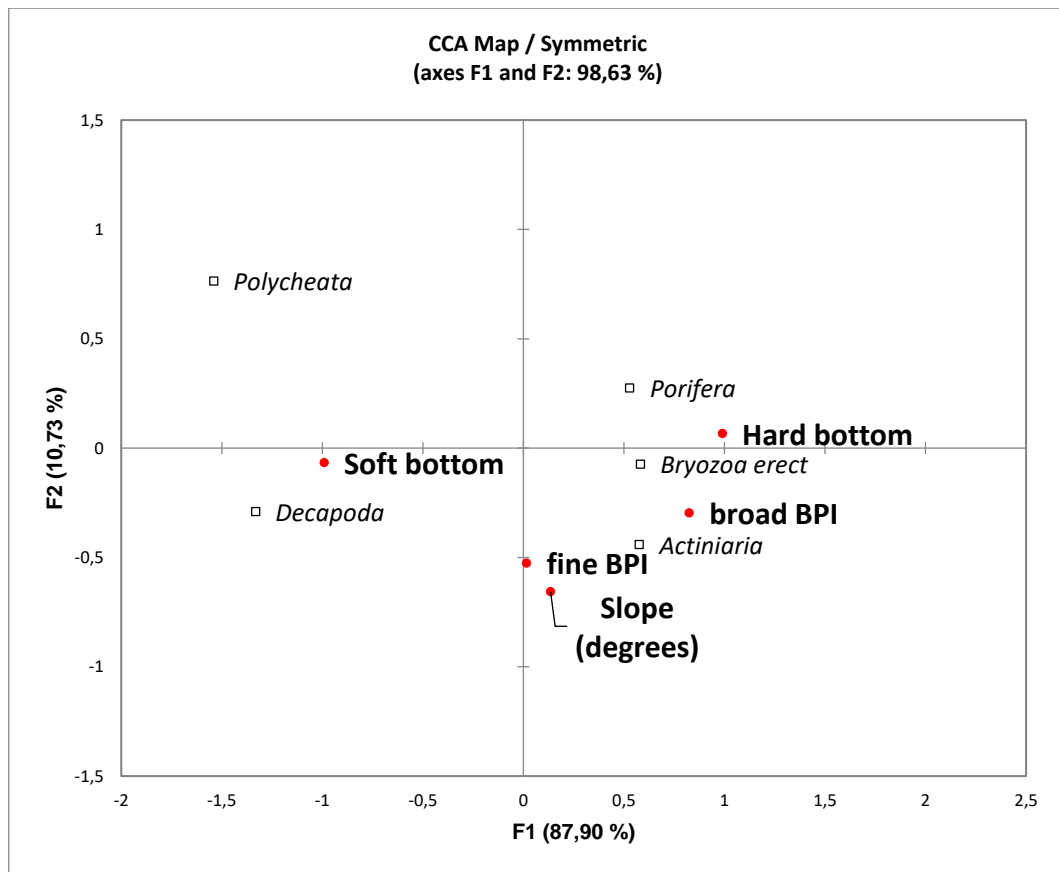




**Figure 17.** Classified geophysical map from Disko Bay pilot area, validated with ground-truthing data.

## 5c Habitat map

- Define the relationship between benthic communities and physical environment (i.e. independent, statistically significant variables) via data modelling (e.g. linear regression) and multivariate statistical analysis (e.g. Canonical Correspondence Analysis); input data:
  - Ground-truthing: benthic taxa/communities
  - Bathymetry
  - Sediments
  - Slope, BPI, rugosity
  - Geophysical classes (reference)



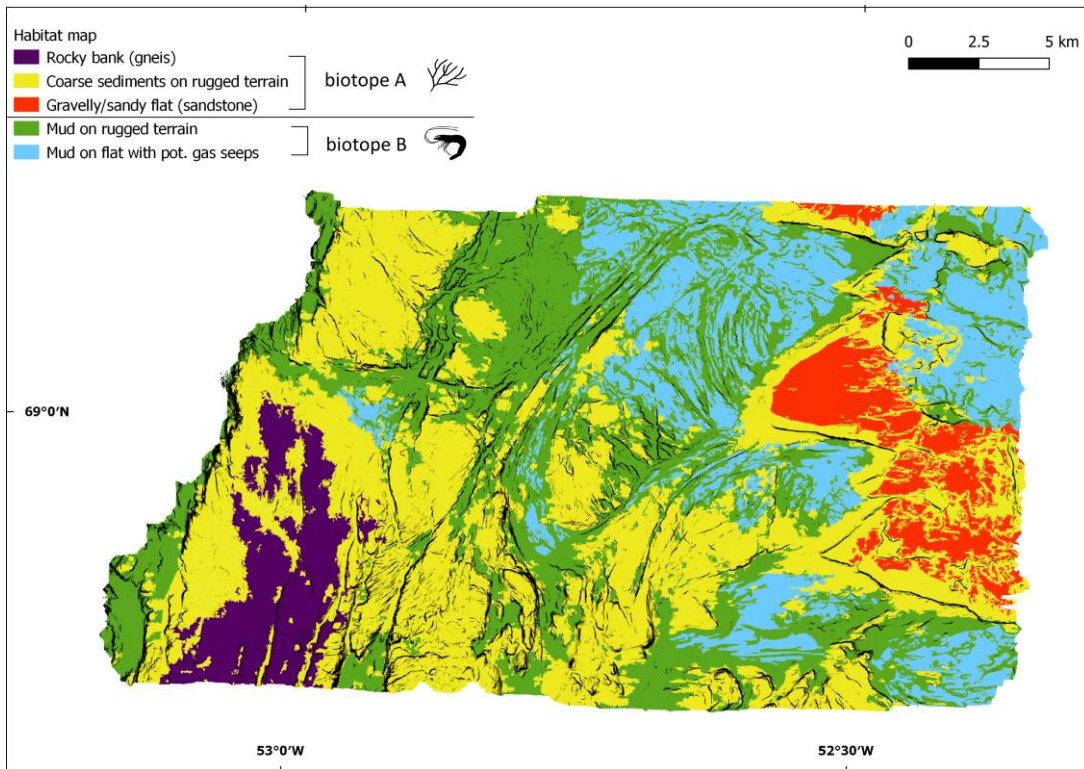
**Figure 18.** Ordination diagram (Canonical Correspondence Analysis) showing relationship between dominant benthic taxa and significant and independent environmental variables, i.e. (grouped) sediment classes, slope and broad and fine BPI. Example from Disko Bay pilot area. Taxa plotting to the left are associated with soft bottom and taxa plotting to the right are associated with hard bottom. Slopes and BPI have only minor influence on distribution of taxa.

- Inspect each physical layer using their correlation with benthic communities, e.g. bathymetry can be divided into classes based on distinct benthic communities occurring in shallow vs deep waters etc.
- Produce habitat map -> steps:
  - Compare all layers
  - Cumulate layers
  - Define habitat classes
  - Classify cumulated layers according to habitat classes
  - Validate habitat classes with distribution of benthic taxa/communities (expert interpretation)

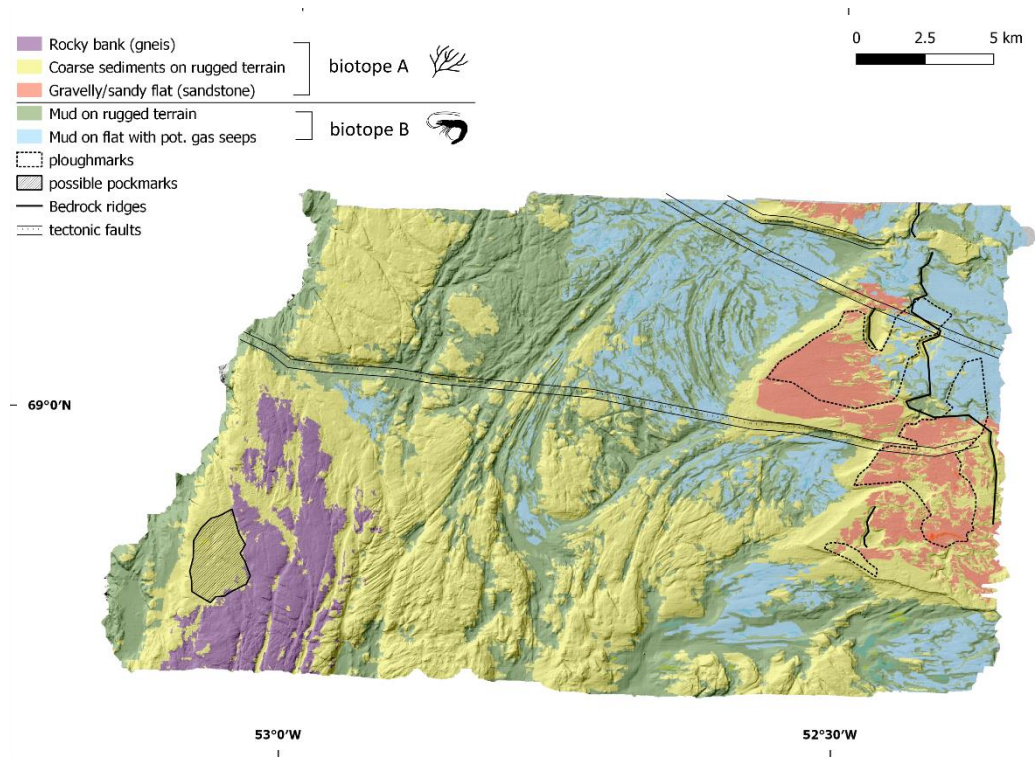


Habitat (MapHab)	Biotope	Habitat	Geoforms (adapted from CMES/Mareano/EU)	Sediments (generalized Gougeon et al. 2017)	Biotope/Taxa (IOZ, INAMoN)
A1 - rugged terrain, rocky seds	Sessile fauna (>300m)	flat, rocky ground	Flat/Floor	coarse rocky ground	A (Ascidians, Porifera, Bryozoa)
		rugged terrain, rocky seds	Flat/Floor	bedrock	A (Ascidians, Porifera, Bryozoa)
		rugged terrain, rocky seds	Ridge/Slope	bedrock, coarse rocky ground	A (Ascidians, Porifera, Bryozoa)
A2 - rugged terrain, coarse seds		rugged terrain, coarse seds	Mound	bedrock*, coarse rocky ground*, gravelly mud/sand	A (Ascidians, Porifera, Bryozoa)
		rugged terrain, coarse seds	Ridge/Slope	gravelly mud/sand	A (Ascidians, Porifera, Bryozoa)
		rugged terrain, coarse seds	Valley	bedrock*, coarse rocky ground*, gravelly mud/sand	A (Ascidians, Porifera, Bryozoa)
A3 - flat, gravelly mud/sand	flat, gravelly mud/sand	Flat/Floor	gravelly mud/sand	A (Ascidians, Porifera, Bryozoa)	
B1 - rugged terrain, mud	Shrimp (250-450m)	rugged terrain, mud	Valley/Trough	mud	B (Decapoda, Polychaeta)
		rugged terrain, mud	Mound	mud*	B (Decapoda, Polychaeta)
		rugged terrain, mud	Ridge/Slope	mud	B (Decapoda, Polychaeta)
B2 - flat, mud, pot. gas seep		flat, mud, pot. gas seep	Flat/Floor	mud	B (Decapoda, Polychaeta)
					* lack of ground-truthing/small fraction

**Table 5.** Habitat classification from Disko Bay pilot area based on geophysical classes (i.e. morphology and sediments) and dominant benthic communities with their respective water depth ranges. Five main physical habitat types were identified and two main biotopes in the area.

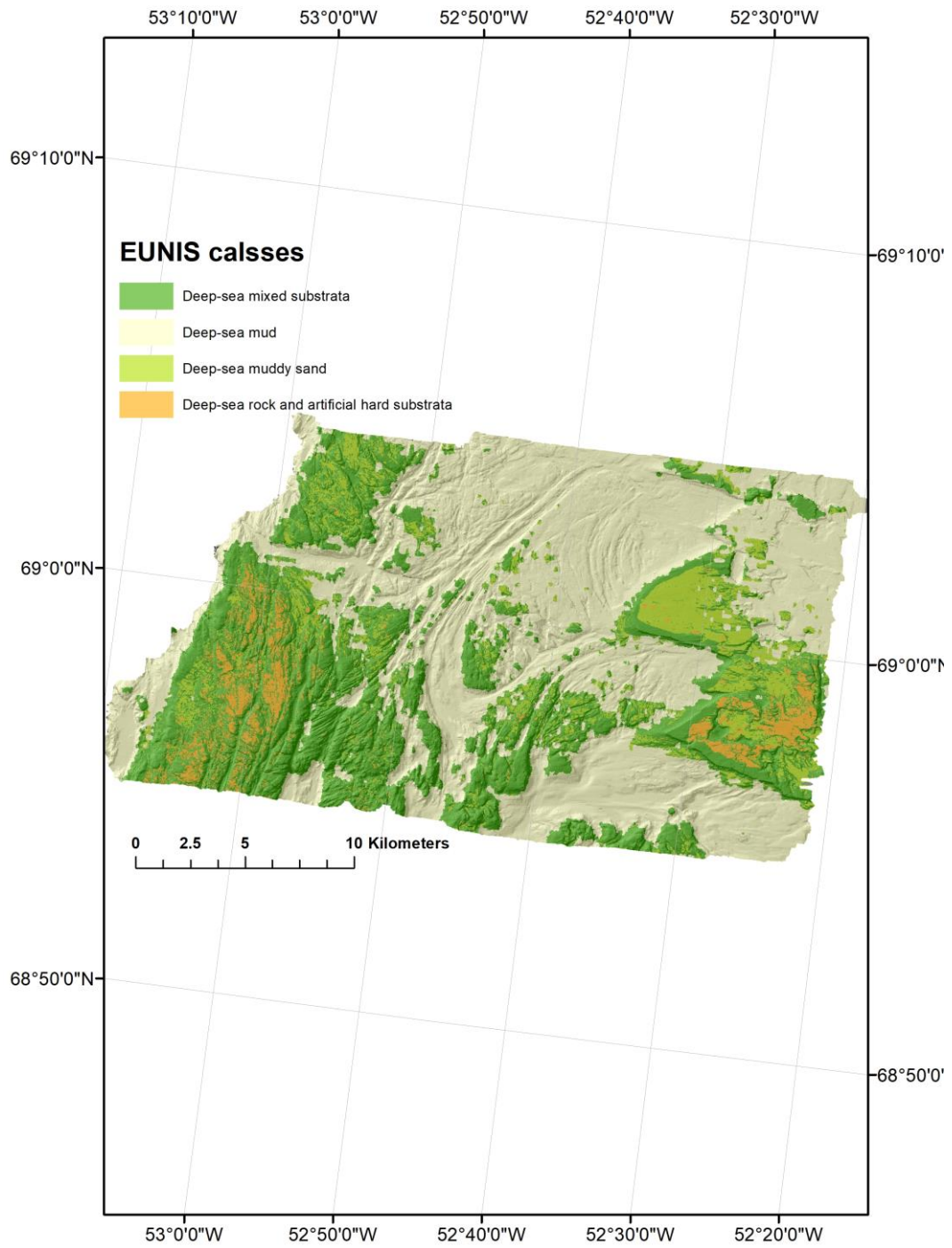


**Figure 19.** Habitat map of Disko Bay pilot area.



**Figure 20.** 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).

- Habitat map – example of application of the EUNIS seabed classification scheme to the Disko Bay pilot area



**Figure 21.** Habitat map of the Disko Bay pilot area classified after the EUNIS classes.

- EUNIS classification scheme has insufficient amount of classes for the deep sea habitats, thus is not recommended for the Greenland shelf characterized by highly complex topography and varying water depths; it is however a useful reference for classifying sediments after some modifications

## 5d Standardized habitat classification for Greenland

Using adaptations of the existing standardized seabed (habitat) classifications, such as EUNIS (Davies et al., 2014), 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 planned surveys. GOCH is 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 with geological interpretation of the features (=geomorphology) whenever possible.

(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 strongly linked to bathymetry data and is based on the 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 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 classification: CMECS, EMODnet, BGS
			Flat/Floor				
			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 classification: EUNIS-modified	
			coarse rocky ground	Course rocky ground	R		
				Course rock ground with thin layer of mud	Rm		
			gravelly sand	Gravelly sand	gS		
			gravelly mud	Gravelly mud	gM		
				Mud with dropstones	Md		
	Genesis		mud	Mud	M		
			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	
CHEMISTRY		Shelf	Gas seeps	cold seeps?			
BIOTA	Taxa	Shelf	bryozoan				GINR & ZSL database
			brittle star				
			kelp				
			mollusks				

**Table 6.** Preliminary GOCH classification scheme based on Disko Bay pilot area.

Following the GOCH classification, five different (physical) habitats were identified in the **MapHab** pilot area (see also figures 19-20):

Factor 1		Factor 2		Factor 3		Factor 4	Factor 5	Habitat
morphology	geomorphology	Sediment type	Genesis	Bathymetry	Water mass	Chemistry	Biota	
flat (small-scale slopes)	bank	bedrock	Gneiss	<200 m	Polar Water		ascidians, sponges, soft corals, sea cucumbers, bryozoans	<b>Rocky bank</b>
		coarse rocky ground						
mound		coarse rocky ground	Gneiss (mostly)	150-300 m	Polar Water		ascidians, sponges, soft corals, sea cucumbers, bryozoans	<b>Coarse rugged</b>
slope		gravelly mud						
valley		gravelly sand						
Flat	Iceberg ploughmarks	gravelly sand	Sandstone	150-300 m	Polar Water		ascidians, sponges, soft corals, sea cucumbers, bryozoans	<b>Sandy floor</b>
		gravelly mud						
Mound		mud		300-500 m	Subpolar Mode Water		shrimp, ptychaet worms	<b>Muddy rugged</b>
Slope								
Valley								
Flat		mud		300-500 m	Subpolar Mode Water	gas seeps	shrimp, ptychaet worms	<b>Muddy floor/gas</b>

**Table 7.** Habitats identified in Disko Bay pilot area with associated GOCH factors.



## 6 Future data improvements

Our 'best practice' protocol for mapping benthic habitats in Greenland will be subject to continuous improvements and methodological advancements. New GINR offshore vessel will provide an opportunity for habitat mapping surveys in deeper waters (max. depth 3 km) supporting deep-water fishing and benthic monitoring. Thus, next version of the 'best practice' protocol will include recommendations for use of new multi-beam model, projected for the offshore vessel (i.e. Teledyne Reson SeaBat 7160) and deep-water habitat mapping.

Improvement plans also involve sub-bottom profiler collecting high-resolution seismic data in order to complement multi-beam data, permit characterization of sediment stratigraphy and sediment types and for studies of geological processes on the seabed and in the upper sediment column. Lines with high-resolution seismic data should ideally cover a wide range of geological settings, in order to provide information on geological processes, which have formed the seabed. This would give additional information for optimal location of visual and physical sampling. The high-resolution seismic data are thus, used in combination with other seabed data for mapping seabed sediment distribution and linking geological and biological processes. To better represent the physical environment in future mapping of marine benthic habitats, it is also recommended that hydrodynamic and biogeochemical models are developed to reflect the expected variability on hydrodynamic and biogeochemical variables at fine horizontal scales.

- **Sub-bottom profiler highlights** - the example of Innomar SES-2000 medium-100 (projected for new GINR vessel):
  - Parametric interference between primary waves to produce a narrow, focused beam with a frequency range of 0.5–5 kHz.
  - The profiler records are generally of high quality with a resolution of 30–40 cm
  - Maximum penetration of 150 m ( $120\text{ m} \pm 3.6\text{ m}$ ) into soft, fine-grained sediments. The penetration is less in sand, coarse-grained sediments, and hard bottom (i.e. till)
  - The resolution increases towards shallower water due to the decreasing area of the signal footprint. In areas with irregular sea-floor topography or steep slopes the resolution decreases because of larger footprint
  - Reasonably good data are obtained with up to 4-5 meters wave height when the survey vessel runs in the direction of the weather

- The primary frequency pulses around 20 kHz; its' harmonics can interfere with other acoustic systems onboard and the systems should be synchronized so that high quality data can be acquired both during transit and planned surveys; this will reduce the ping rate, but high resolution does not need to be measured on every line. Every fourth line should be adequate in order to meet the objectives of providing relevant information to support the interpretation of seabed substrates
  - High spatial resolution in water depths between 2 and 2,000 meters
  - This model incorporates a parametric narrow-beam sub-bottom profiler (frequency 4–15kHz) with echo-sounder functionality (frequency ~100kHz). During rough sea conditions, the results will be improved by heave compensation and electronic beam stabilization
  - Format: .sgy files are loaded in a seismic interpretation program, e.g. Kingdom Suite and a number of seabed types are defined on basis of visual scanning of the profiles and sediment sample information
  - Example: sub-bottom profiles can identify seabed depressions interpreted as pockmarks, which are formed as a result of gas or pore fluid seepage. Acoustic masking on the sub-bottom profiler data supports the gas seep-age theory; in some cases mixed with iceberg ploughmarks, both natural disturbance of seabed integrity.
  - Sub-bottom profile data will supplement the geomorphology factor in the GOCH scheme (see previous chapter) in the future work with more in-depth information about geological features and sediment genesis
- Recommendations for **hydrodynamic modelling**:
    - The use of 3D hydrostatic models with algorithms mimicking internal wave propagation and reflection with rising topography and with a horizontal spatial resolution down to approximately 200-1000 m
    - The use of 3D biogeochemical models with primary focus on phytoplankton production and grazing (zooplankton), the flux and decomposition of organic carbon and oxygen concentration
    - The use of satellite-derived data including temporal and spatial propagation of surface chlorophyll and sea surface temperature



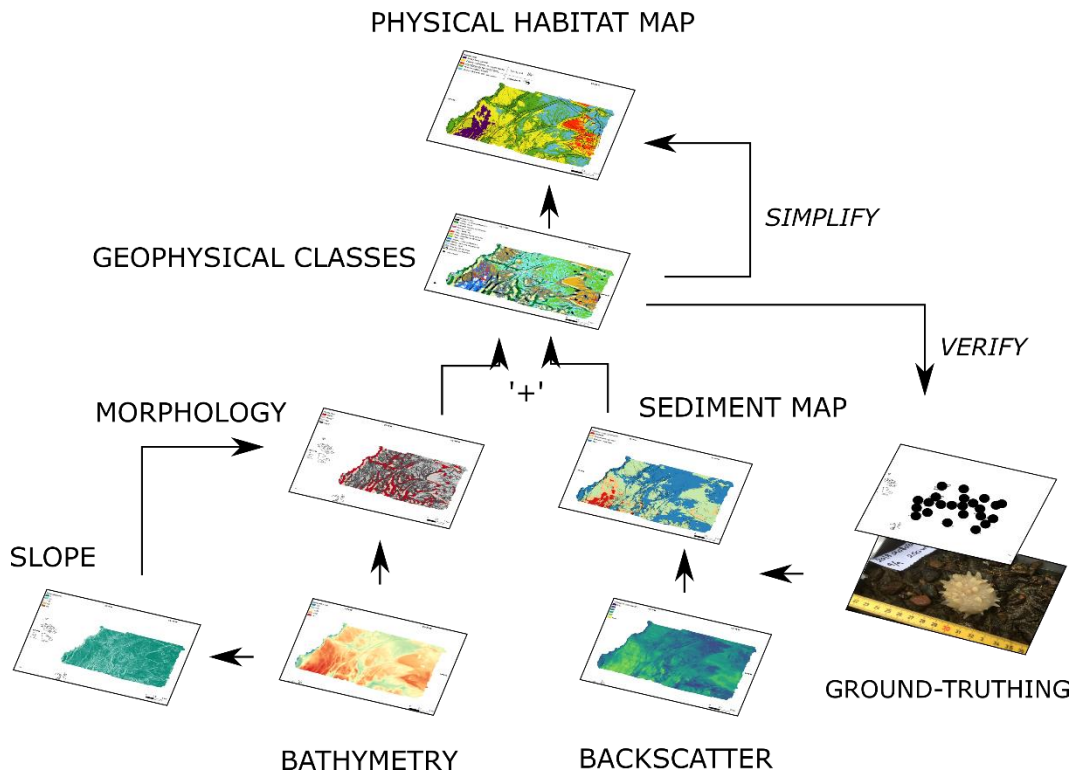
- The use of predictive habitat models to link explanatory variables extrapolated from hydrodynamic and biogeochemical models, multi-beam surveys and satellites to species and habitat presence/absence and/or abundance data, and subsequently predict their distribution outside the observed locations
- Future focus on data collection that can be used to improve the calibration and validation of hydrodynamic and biogeochemical models, such as data loggers mounted fishing trawls and trawlers, other ships of opportunity and/or mounted together with GPS trackers on marine mammals. Principally, high temporal resolution of data, such as temperature, salinity, oxygen and/or turbidity covering extensive periods are important for validation of dynamic models, contrary to occasional and infrequent monitoring during surveys

## 7 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 a successful data collection using multi-beam and ground-truthing gear in a single step, processing and map production with guidelines and recommendations, all described in detail in this protocol. The single step mapping survey approach together with the annual GINR surveys providing an opportunity to collect additional ground-truthing samples whenever needed are the highlights of this cost-effective and time-efficient mapping guide. As a result 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 (**MapHab** technical report; Krawczyk et al., 2019). 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 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 #Modelling #Greenland #Seafloor program.

- **Summary workflow scheme for benthic habitat mapping:**



- **End-use of the mapping products**

- Natural resource extraction – fisheries assessments/management
- Nature management - protected areas
- Environmental assessment
- Certification of fisheries (e.g. Marine Stewardship Council)
- Commercial fisheries (e.g. Royal Greenland, Polar Seafood, Sustainable Fisheries Greenland)
- Marine Spatial Planning
- Commercial mining – raw materials and minerals
- Oil and gas exploration

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