Investigating the potential of stone reefs in reducing nutrient loads, as an input to the re-establishing of a stone reef in the Natura 2000-area “Løgstør Bredning, Vejlerne and Bulbjerg”

The geological study

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G E U S

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1. Introduction

GEUS is partner in a consortium under the leadership of the Limfjordsrådet to investigate the feasibility of re-establishing a stone reef at different locations in the Limfjord-Løgstør Bredning. A project under the name of "Stenrevprojektet" was initiated to fulfil this objective. GEUS's role is to do baseline study of the areas under investigation to locate sites that are geologically suitable for putting stones of certain weight and heights and establishing a cavernous stone reef. The established reef will serve a suite of purposes such as increasing the benthic vegetation cover for oxygen production, while at the same time enhancing the biodiversity of the region. Five areas were chosen for reef re-establishing and they are shown in Figure 1.

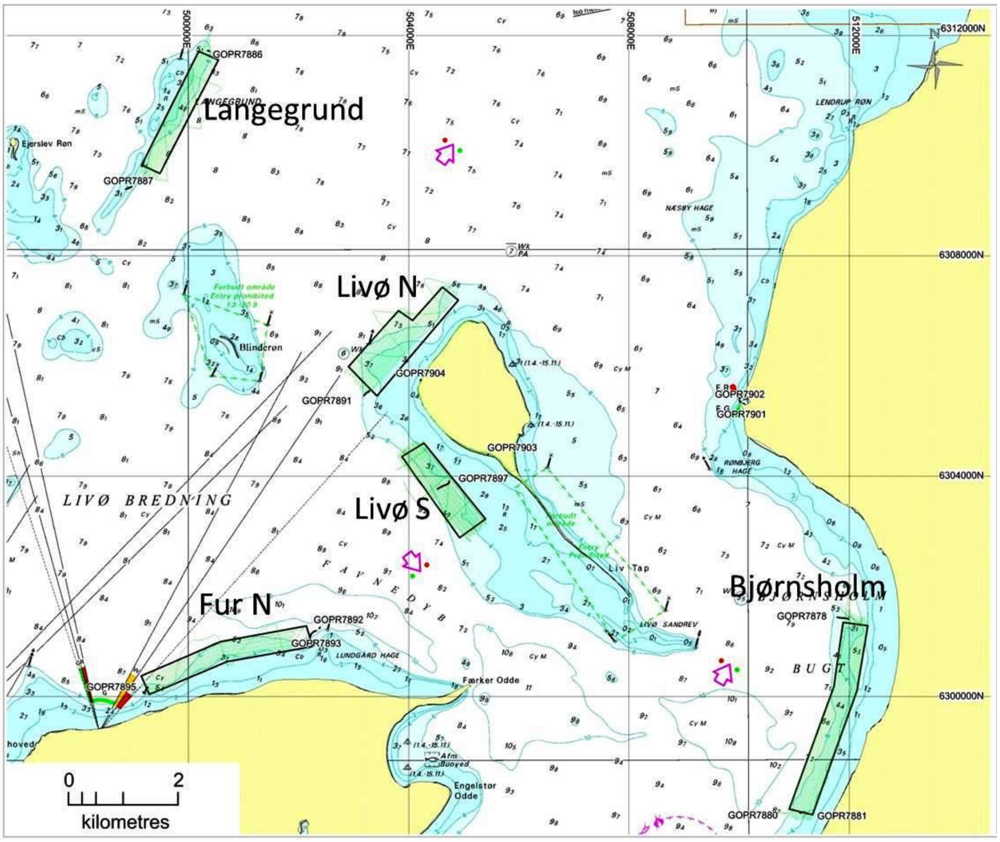


Figure 1. An overview of the surveyed areas in Løgstør Bredning (Limfjord).

The total area investigated is ~5.8 km² distributed over the five chosen areas for the geological study. The total number of survey lines is 89 with 25-40m spacing between lines, and that represent a total survey line-km of 184, as shown in Table 1.

Area name	Total size (km²)	No. survey lines	Surveyed line-km	Depth range m
Bjørnsholm Bugt	1.5 (150ha)	14+ 4cross	54	3.3-8.0
Livø Tap (syd)	1.2 (120ha)	14 + 4 cross	35	3.3-9.0
Livø Nord	0.94 (94ha)	15 + 3cross	30	3.0-8.0
Fur Nord	1.2 (120)	14 + 4cross	35	3.3-9.0
Langegrund	0.9 (90ha)	13 + 4cross	30	2.8-8.0

Table 1. statistcs of the surveyed areas.

1.1 Deliverables

Here is a list of the required deliverables and their status:

1. Multibeam survey in Løgstør Bredning – with detailed map in the potential reef areas, general map in the rest of the areas. Status: done in details for LivøN as well as for the rest of the areas.
2. Sidescan mosaic for Løgstør Bredning – Detailed for the potential area, and general for the rest. Status: done in details for Livø N, and for the rest of the areas.
3. Detailed quantification of stone distribution in the existing stone reefs that are relevant for the new reef re-establishment. Status: done for all areas , stone distribution is manifested as substrate 2,3, and 4 (See Appendix 1 for substrate definition).
4. 3D model in Løgstør Bredning, where detailed mapping took place. Status: 3D presentation of the bathymetry and the topglacial morphology were initiated on a Fledermaus software for viewing and presentation.
5. Thickness map of the soft sediment area. Status: done for all areas.
6. Morphology map for the moraine layer. Status: done for Livø N area as the most potential area for stone reef re-establishment.
7. Mapping the recent sedimentation in the optimum area. Status: the sedimentation map was not done as a standalone map but it is manifested within the topglacial layer thickness map, the erosional areas are shown where the moraine layer exposed to the seabed, and the sedimentation region at the coastal area and in basins.
8. Mapping the biogenic reef, macroalgae, and eelgrass distribution. Status: done within the produced substrate map where these features were marked whenever observed on the seabed sidescan images.
9. Mapping the geotechnical bearing capacity areas for stones in the potential areas. Status: done but the bearing capacity was deduced from the seismic interpretation of the seabed substrates. Physical geotechnical cores and tests should be performed by a specialised company. So we expect that the area is suitable for bearing the reef weight but we do not have the geotechnical data to support that.
10. All the above mentioned maps are produced on GIS platform and will be delivered to the project consortium for further use and planning.

2. Geological setting

The geological setting of the Limfjord was created by moulding glaciers and meltwater systems and as the last ice age came to an end, the area possibly developed into a lake and later the sea inundated the area, and created the cliff sections, islands and beach regions we know today. The Pre-quaternary deposits of the central Limfjord area is characterised by c. 55-60 million years old Eocene deposits of clay and diatomite with numerous volcanic ash layers (Pedersen et al. 2011). The Eocene deposits have been folded and thrusted up by ice cap advances during the Quaternary.

The deformation structures that can be observed in several coastal cliff sections in the central Limfjord area were created at about 25.000 years ago by a major ice advance during the last glacial maximum. When ice finally retreated from the region, the central part of the Limfjord may have been characterised by a late glacial lake in which clay and silt material from run-off systems connected to the quickly retreating ice margin were deposited on top of the glacial till units. As the region, during the late glacial to early Holocene period, were subjected to rapid glacio-isostatic uplift, the lake area probably dried more or less out.

At about 9000 years ago, rapid global eustatic sea level rise caused inundation of the area by the sea from the north (Petersen, 1998). This caused rapid erosion of the hilly landscape, and coastal cliffs, beaches, bars and Isthmus systems developed. At about 2700-2500 years B.P. the Limfjord area became partly isolated from the North Sea as the northern Isthmus system more or less closed and it became a more sluggish brackish water area (Christensen et al. 1998). A better sea connection was established at about 2000 years B.P. At about 1100 years B.P., the fjord area became more brackish again as the western Limfjord Isthmus systems closed. Several historical reports of repeated sea breakthroughs of the western Isthmus system have been reported for the period 1500-1700 A.D. At about 1825 A.D. a major breakthrough by Agger Tange in the west created the marine conditions which exist today in the Limfjord area.

3. Methodology

For investigating the geological setting (model) of the area and mapping the seabed substrate, bathymetry, and identifying the subsurface stratigraphy a suite of remote sensing geophysical systems supported by high accurate positioning and navigations systems were mobilised on GEUS's survey boat Maritina (Figure 2).

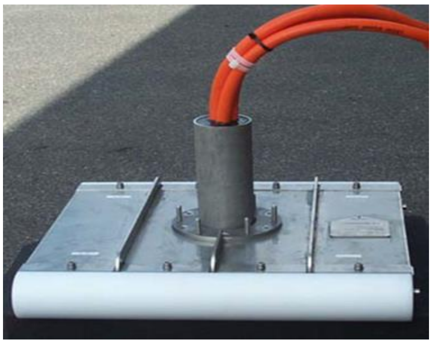
Figure 2. GEUS's survey boat Maritina in Rønbjerg harbour.

These systems were calibrated and a PatchTest was performed on the EdgeTech6205 Swath Bathymetry system to insure optimum depth data acquisition.

The survey started on Sunday 8/5/2016 with Maritina transit till Rønbjerg Harbour and the actual survey started Monday 9/5/2016. There were 3 GEUS employees on board (a surveyor, a technician, and a surveyor assistant) and a boat skipper. Surveys of some areas were repeated to insure best quality data acquisition. The data was QC'ed every day for correctness and quality.

The chosen areas are required to be surveyed with full coverage side scan sonar for the depth range of 3-7 m; therefore the survey lines were designed with variable spacing that ensures a side scan overlap of 150% and as much as possible bathymetry coverage. Cross lines were also made for stratigraphic interpretation and completion of the geological model.

The EdgeTech6205™ sidescan/swath bathymetry system with dual frequency of 250/550 kHz was used for mapping the seabed surface with high resolution acoustic imaging (Figure 3). The swath bathymetry part of the system provided swath coverage of depth data with full nadir (the area on the seabed normal to the acoustic axis of the system) coverage. Sound velocity profiles were taken at regular intervals in each area for bathymetry values calibration.

	
Figure 3. The EdgeTech 6205 SS/Swath bathymetry system.	Figure 4. The Innomar 2000 Sub Bottom Profiler.

The Innomar™ sub-bottom profiler provides detailed information about the sediment layers below seabed and shows their depositional and erosional history up to 20m depth below the seabed (Figure 4).

The supporting navigation and positioning systems are used to ensure all the acoustic data were acquired with high accuracy both vertically and spatially.

4. Data interpretation

The side scan data was processed with the SonarWiz v.6 software where the best filtered/water column corrected image of the seabed surface can be produced for interpretation.

For calibrating sidescan acoustic images, two transects per area were chosen and their positions were send to DSC (Dansk Skaldyrscenter) for ground truth data acquisition. Transects were chosen at areas with scattered or accumulated stone formations. Sites where the side scan shows a signature of algae growth on hard substrate were also identified on the acoustic image and positions were send to DSC for verification (Nielsen 2016) and testing the capability of the side scan image to detect algae on stones.

The bathymetry data were calibrated and corrected for outliers, tide, and sound velocity differences over the survey period of each area. The data was then displayed and the overlap variations were corrected. Sometimes the outer beam data were deleted to ensure maximum accuracy. Several processing software was used for this endeavour.

The seismic data acquired by Innomar sub bottom profiling system was converted to *.segy format to be read by GeoGraphix™ software for seismic interpretation and picking sub-seabed horizon that represent different stratigraphic layers. The data was also processed with Innomar's own software for high resolution seismic interpretation at near seabed horizons.

4.1 Side scan data interpretation

The resulting acoustic images of the side scan processing were used for the interpretation and classification of the seabed. The side scan data was interpreted using the SonarWiz v.6 software to ensure consistency. The results of the side scan image interpretation were converted to a projected (WGS84 UTM32N) GeoTiff raster for presentation on a GIS platform. The working unit area was defined to about 50x50m unless there is an obvious change in sediment type that requires delineation within this unit area. The results were polygons for each substrate types. The classification was based on SVANA Notat (Appendix 1) that classifies the substrate according to the stone percentage and size of stones at unit area.

For a quick reference: substrate 1b represents sand; substrate 2 is sand, gravel and <10% stones of >10cm size; substrate 3 is with 10-25% stones of >10cm; and substrate 4 is > 25% stones of >10cm size.

The ground truth data delivered to GEUS (acquired and interpreted by DSC) was used for validating the side scan interpretation endeavour.

4.2 Interpretation of the bathymetry data

The depth measurements acquired by the EdgeTech systems can cover up to 10times the water depth, but there is always a trade-off between the swath width and the bathymetry accuracy especially at the outer beams of the swath as shown in Figure 5 (orange ovals). The combination of the bathymetry swath measurements with the co-registered side scan imagery can improve the "cleaning" of the outliers rendering reliable bathymetry data.

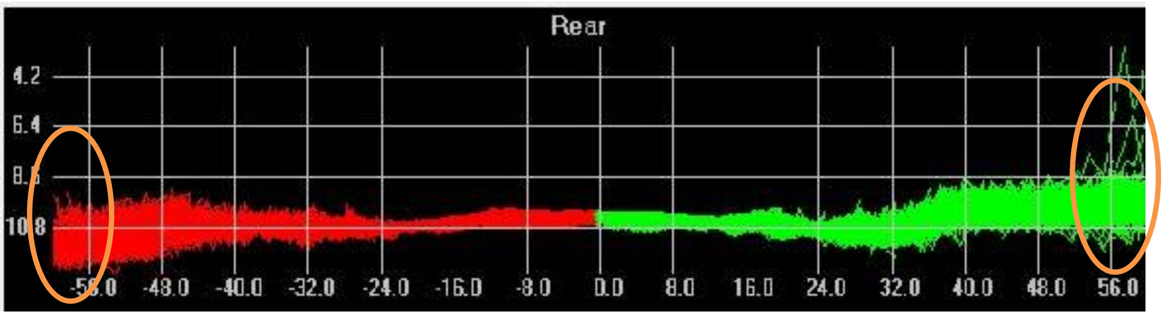


Figure 5. The EdgeTech 6205 bathymetry swath.

The depth data calibration and corrections with respect to boat motion is done automatically with input data from the high accuracy positioning system that was placed on the top of the acquisition system to minimise displacement error as shown in Figure 6.

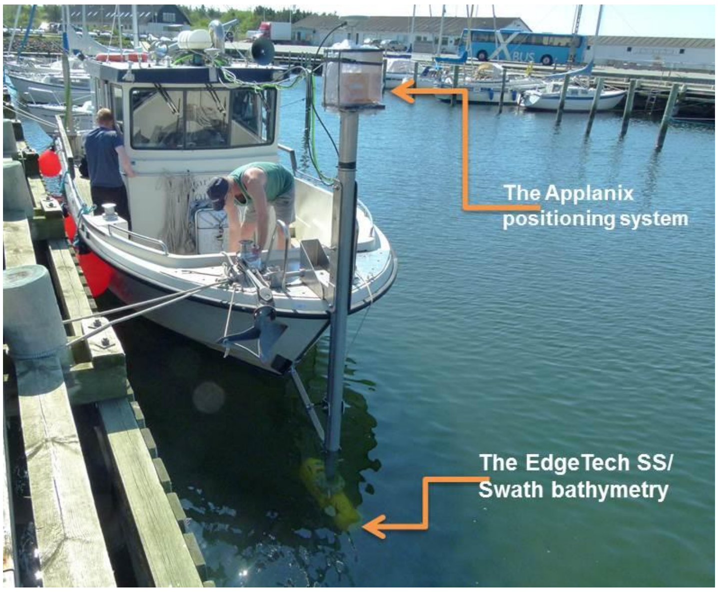


Figure 6. The Applanix positioning system configuration.

The final bathymetry data was converted to xyz format to be presented on a GIS platform.

4.3 Seismic data interpretation

The Innomar sub-bottom profiler producing information about the subsequent layers underneath the seabed, the depth of penetration, is a function of water depth, sediment type, and the presence of acoustic reflectors at the operating frequency such as gas.

The seismic data was processed first with the dedicated Innomar software (ISE V2.95) to verify the top-surface layer type and thickness. It was then converted, using the same software, to a different format (*.segy) that can be loaded into a more advanced seismic interpretation software (GeoGraphix Discovery™). This was done to all seismic lines of the area and an interpretation project/workspace was created in GeoGraphix. Each line was interpreted individually using knowledge of the geological history of the area including the general sea-level variations in the region. The horizons that represent the seabed, the Holocene deposits, the late glacial deposits, and the top glacial boundary were delineated, as shown in Figure 7. The figure shows a seismic profile striking SE-NW, i.e. perpendicular to the shore line in Livø N.

The glacial deposits are composed mainly of till (moraine) with abundance of stones and a mixture of gravel, sand and small stones in-between. The thickness of the post glacial deposit (younger deposits overlying the top glacial surface) shown in the figure is an important parameter for interpreting the surface layer with a side scan image as mentioned earlier. In some areas, the thickness of the layer becomes very thin or the glacial unit crops out at the seabed and is exposed to erosion or deposition. Erosion or re-deposition of finer material (clay, silt and sand) will concentrate gravel and stones at the seabed and these stone concentrations are visible on the side scan images.

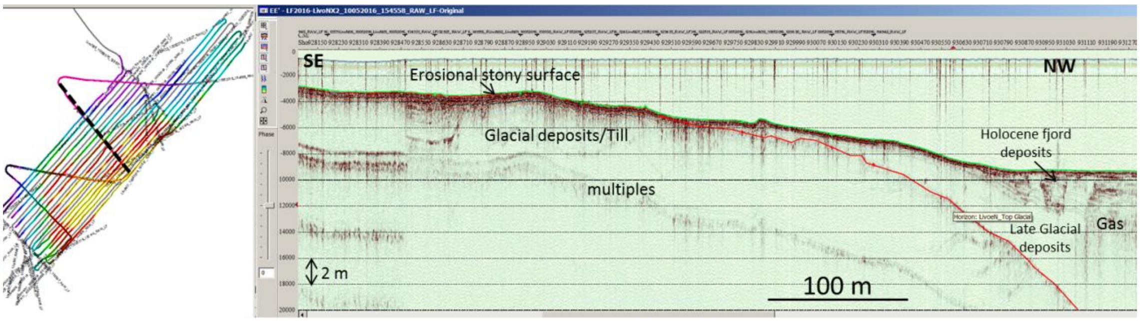


Figure 7. Seismic profile interpretation of a cross line shown in black on the left. Red line in the seismic profile is the top glacial surface.

The thickness of the post glacial layer deposits was measured for all survey lines and presented on a GIS platform.

5. Results

The results from the interpretation of the geophysical survey will be presented in the following order: the results from the Innomar-system (seismic), the side scan data and the bathymetry data. Results obtained from a previous investigations in the area (Jensen et. al. 2012) were also used in the final interpretation.

5.1 Livø North

The survey lines in Livø N have different spacing (25-40m) depending on the bathymetry of the area as shown in Figure 8. The seismic profiles of the Livø North area reveal a central near-coastal platform of glacial till deposits exposed at the sea bottom (Figure 9). Towards the north and west, the top glacial surface is covered by a thickening sequence (>10 m) of post-glacial, mainly fine-grained stratified deposits (Figure 10), which are blanked by gas in the deeper part of the profiles. The upper Holocene marine to brackish water unit is in places forming advancing, possible sandy to gravelly beach deposits.

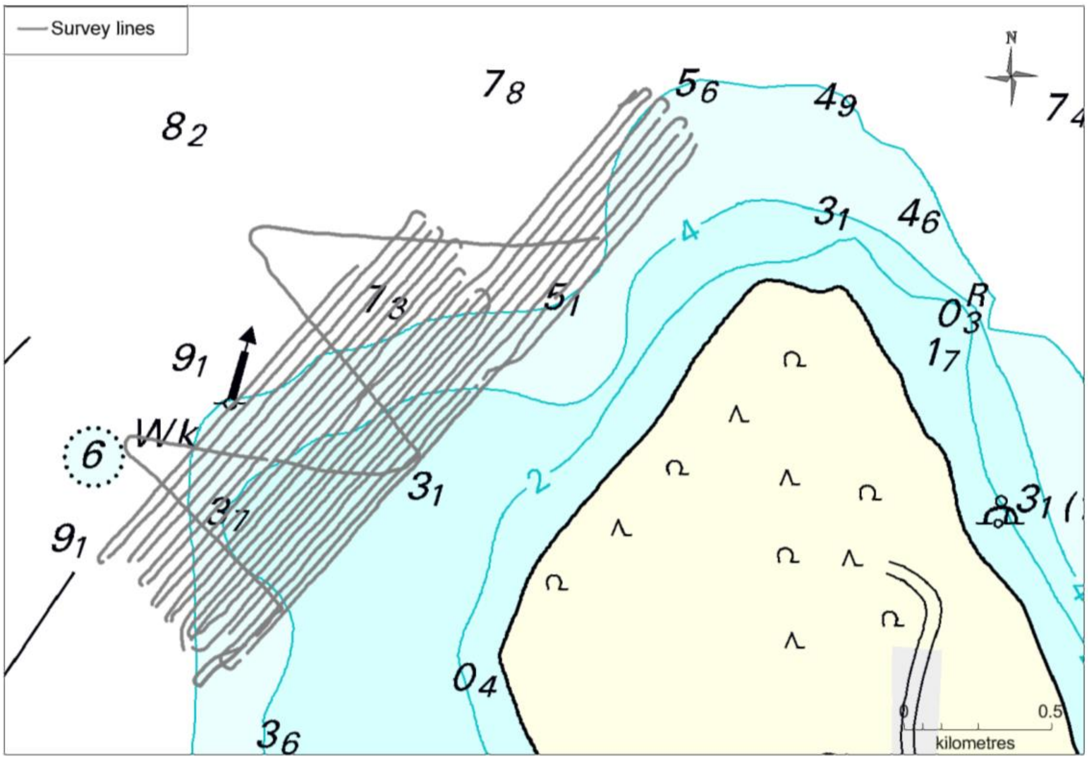


Figure 8. Livø N survey lines. The line spacing varies between 25-40m.

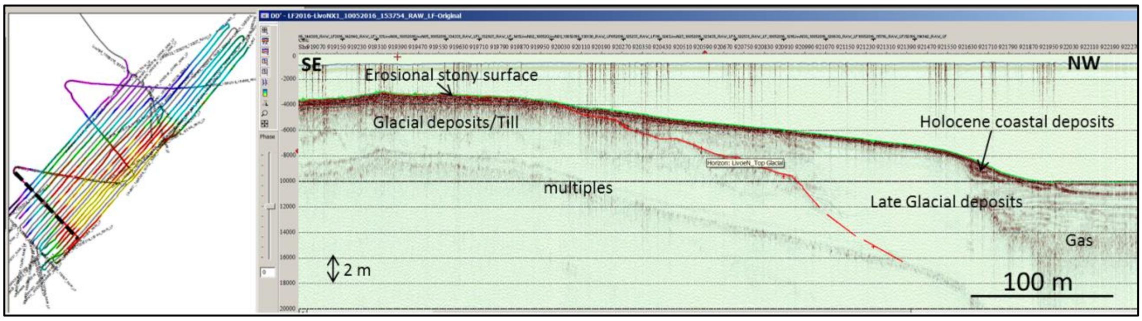


Figure 9. Innomar seismic section showing the Holocene coastal deposits, the late glacial deposits and the glacial deposits on a cross line.

Figure 10 shows that the thickness of the postglacial layer is very thin in the shallow parts and the glacial surface is mainly outcropping in the area designated with red in Figure 10. Towards NE and SW the thickness of the postglacial unit increases steadily to over 10 m.

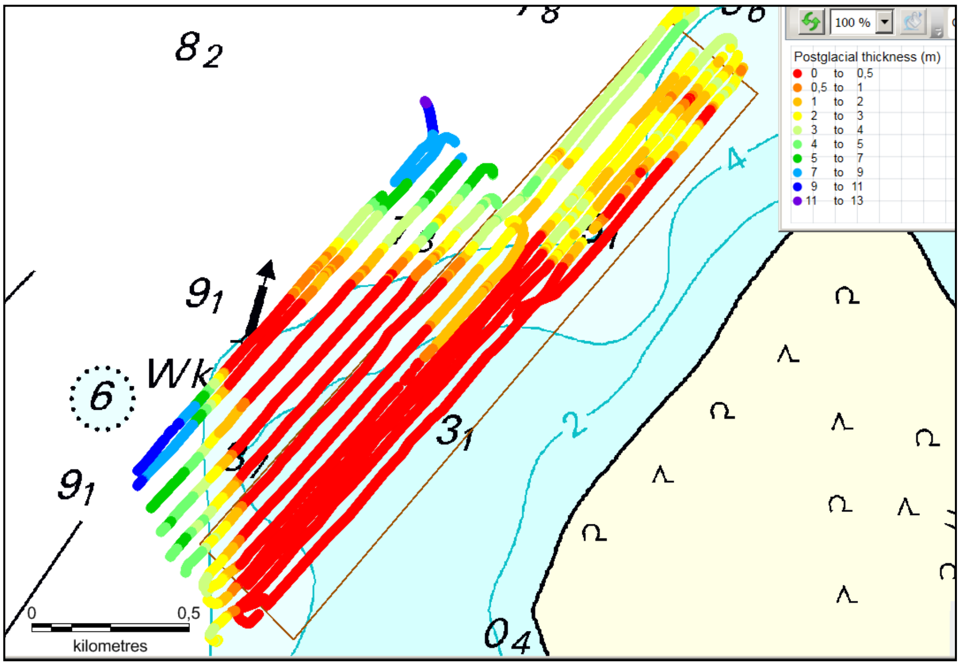


Figure 10. The thickness in m of the postglacial deposits or the depth below the sea bed to the glacial surface.

The ground truth data (acquired and interpreted by DSC) was used for validating the side scan interpretation endeavour. The result of this interpretation is shown in Figure 11. The results show that the shallow part of Livø North as well as the central part is dominated by stones, although sometimes in patchy formation. The deeper parts are mostly sandy and in between there is the transition zone of sand with scattered stones (Nielsen 2016) .

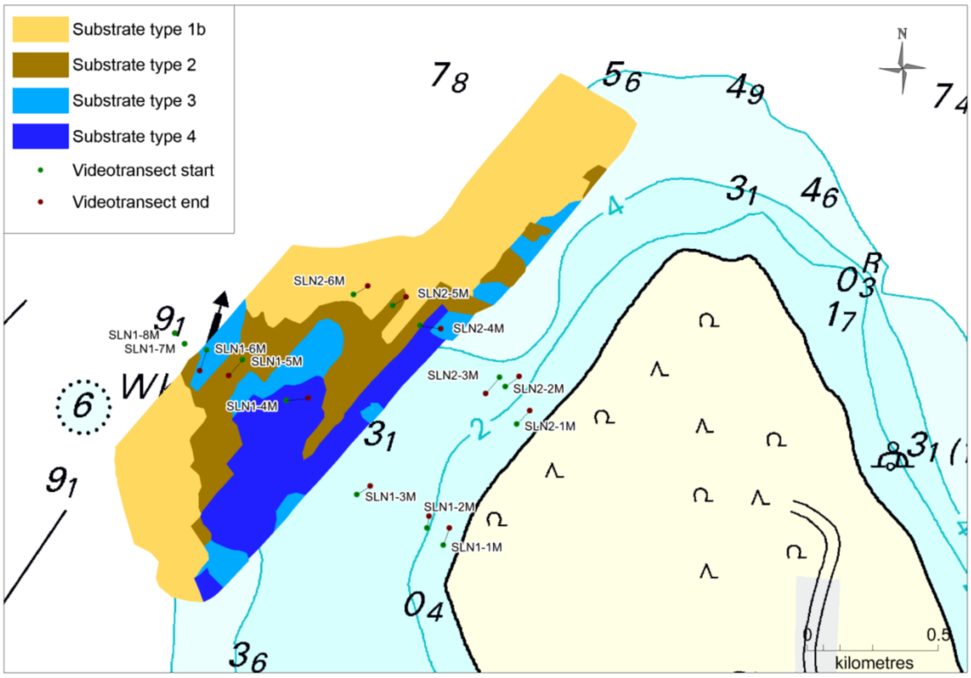


Figure 11. Sidescan interpretation results of Livø North showing the DSC ground truth transects proposed by GEUS.

The bathymetry interpretation shows the shallow part (brown colour) extends to central part of the surveyed area and slopping steadily towards the northern and the SW parts of the area. The depth ranges from 3 to 9 m. The final bathymetry data was converted to xyz format to be presented on a GIS platform as shown in Figure 12.

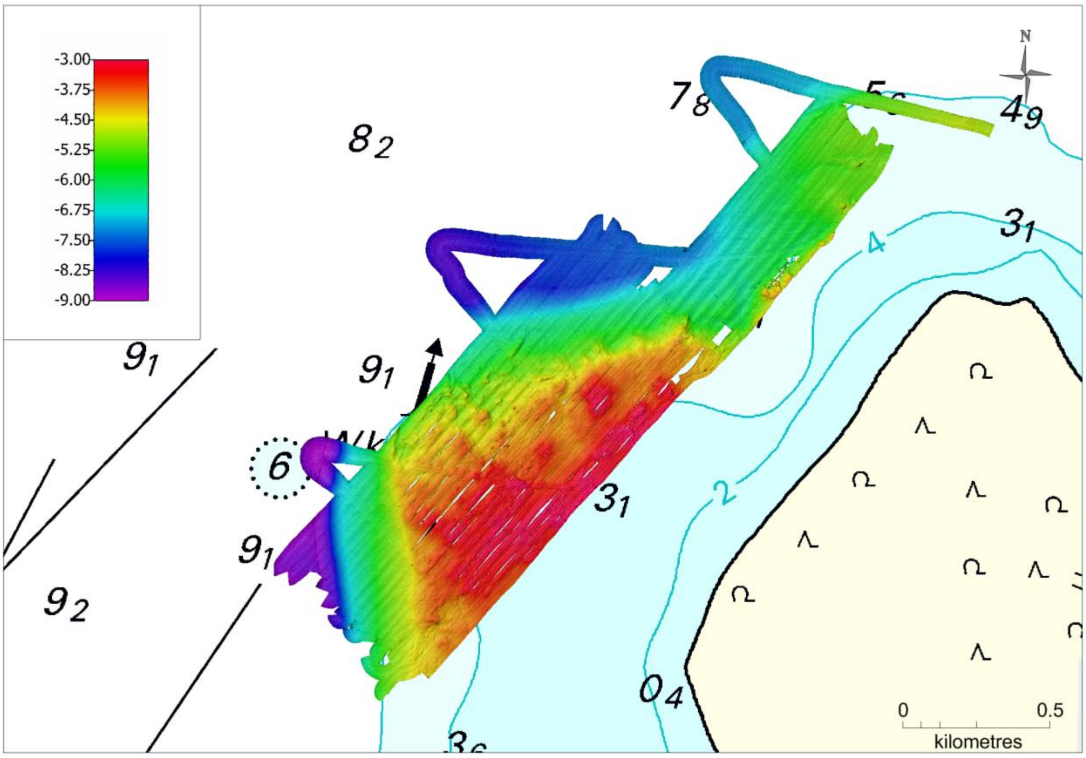


Figure 12. Livø North bathymetry. Legend represents depths in meters.

5.2 Fur North

The survey lines in Fur North have a variable line spacing of 25-40m as shown in Figure 13. The seismic profiles of the Fur North area reveal a coastal platform of glacial till deposits bulging out toward the north in the central part of the survey area (Figure 14). Toward the deeper north-eastern and south-western direction, the top glacial surface is covered by a thickening sequence (>10 m) of post-glacial, mainly fine-grained stratified deposits (Figure 16). The upper part of these consists of Holocene marine to brackish water deposits, which especially toward the northeast are forming advancing beach-platform deposits attached to the glacial till slope. ENE-WSW orientated seismic sections through the till deposits reveal prominent eastward inclined surfaces interpreted as glacio-tectonic thrust surfaces, that may incorporate large slices of Eocene deposits (Figure 15).

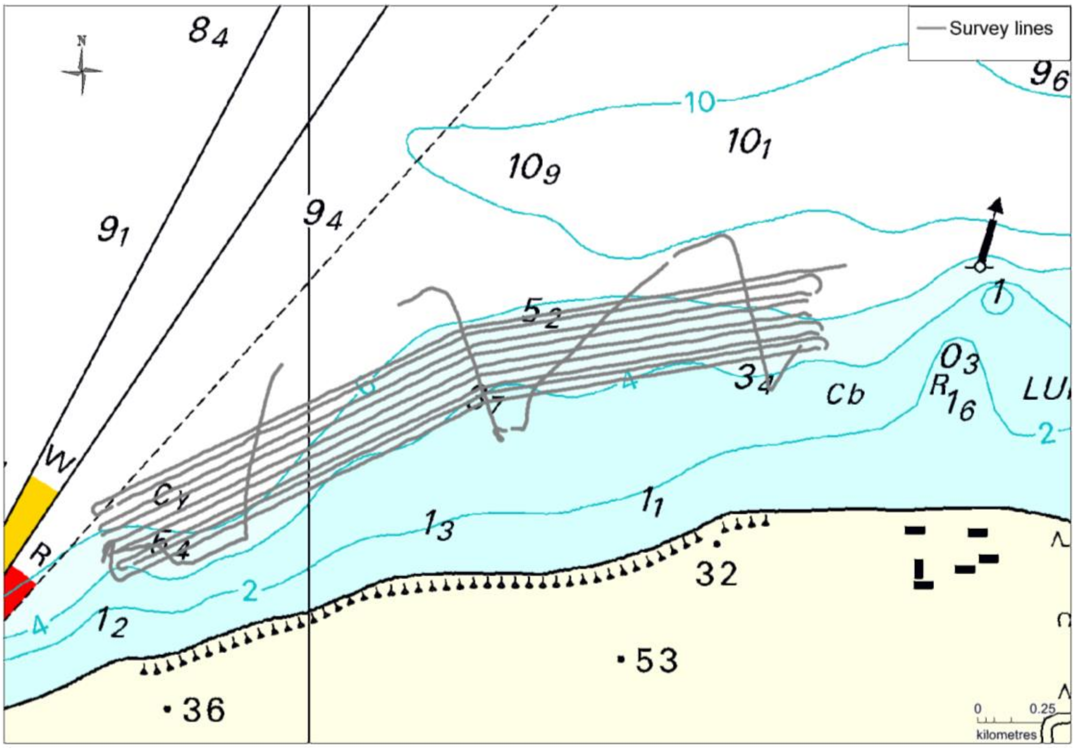


Figure 13. Fur North survey lines. The line spacing is 25-40m.

GEUS

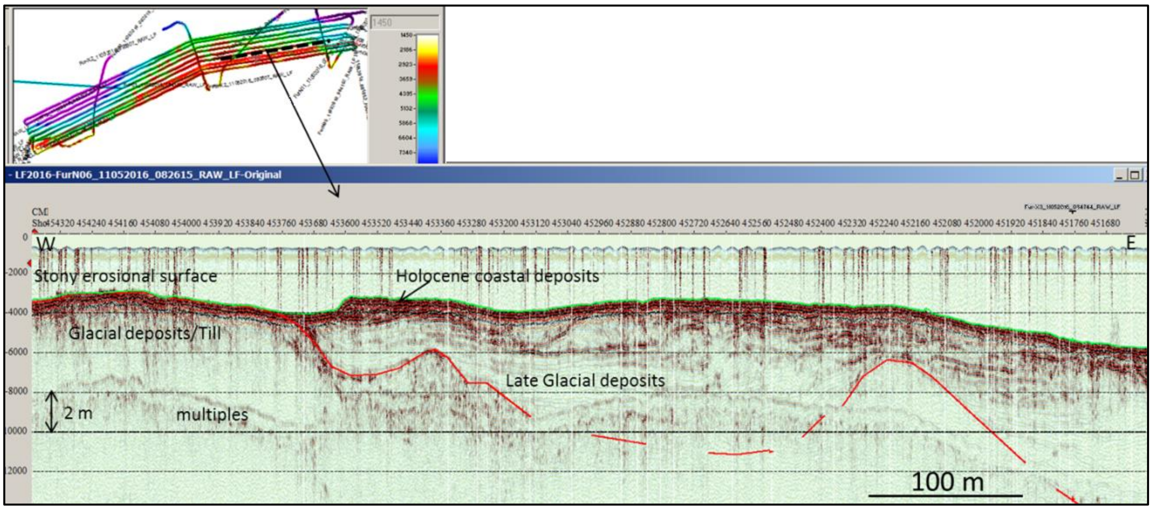


Figure 14. Innomar seismic section showing the Holocene coastal deposits, the late glacial deposits and the glacial deposits giving rise to the stony seabed surface.

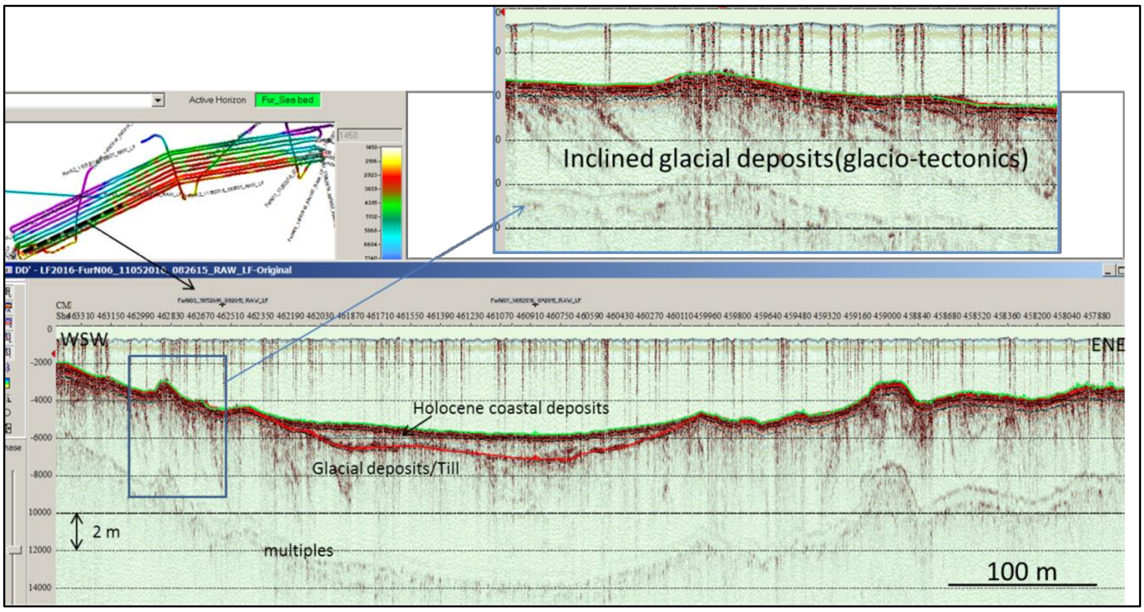


Figure 15. Innomar seismic section showing the Holocene coastal deposits and the glacial deposits revealing eastward inclined surfaces interpreted as glacio-tectonic thrust surfaces.

Figure 16 shows that the thickness of the postglacial layer is very thin in the shallow parts and the glacial surface is mainly outcropping in the area designated with red in Figure 16. Towards NE and SW the thickness of the postglacial unit increases steadily to over 5 m.

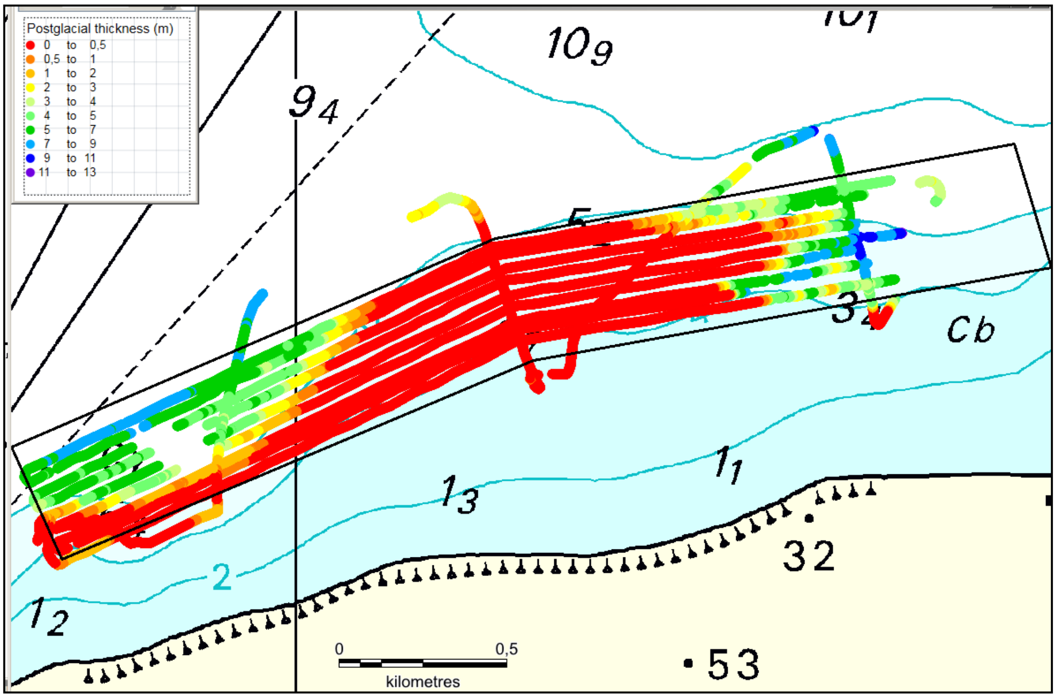


Figure 16. The thickness in m of the postglacial deposits or the depth below the sea bed to the glacial surface.

The ground truth data delivered to GEUS (Nielsen 2016) was used for validating the side scan interpretation endeavour. The result of this interpretation is shown in Figure 17 and the results show that the shallow part of Fur North is dominated by stones, although sometimes in patchy formation. The deeper parts are mostly sandy and in between there is the transition zone of sand with scattered stones.

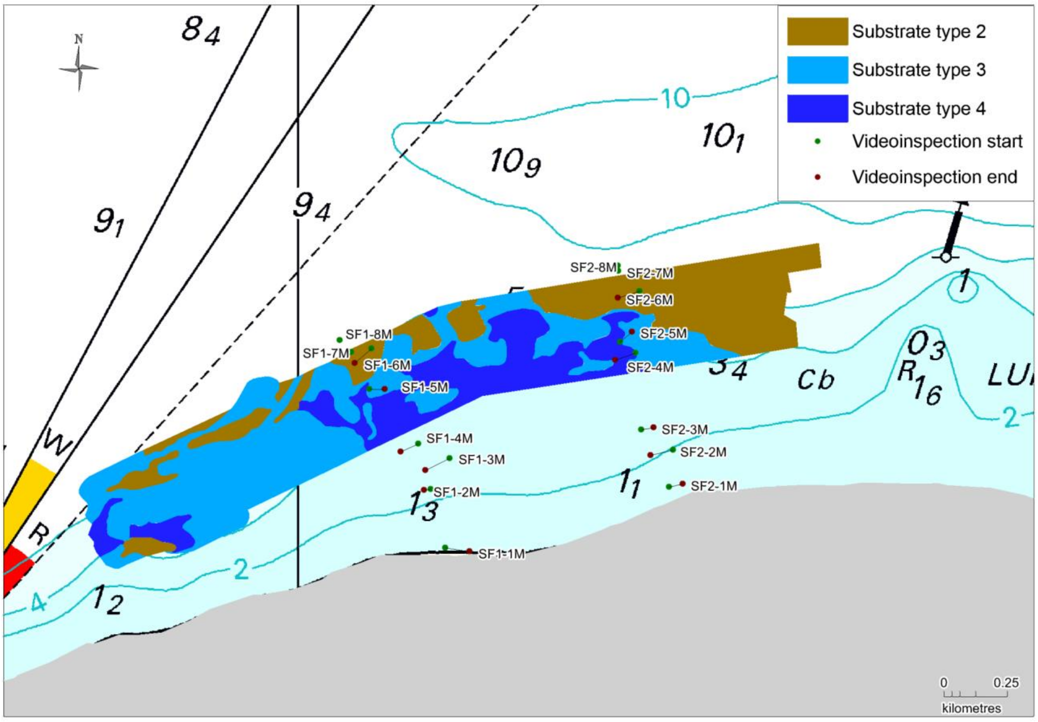


Figure 17. Sidescan interpretation results of Fur North showing the seabed substrates of the area and the DSC ground truth transects.

The shallow part (red/yellow colours) extends to central part of the surveyed area and slopping steadily steadily towards the eastern and the SW parts of the area (

Figure 18). The depth ranges from 3 to 10 m.

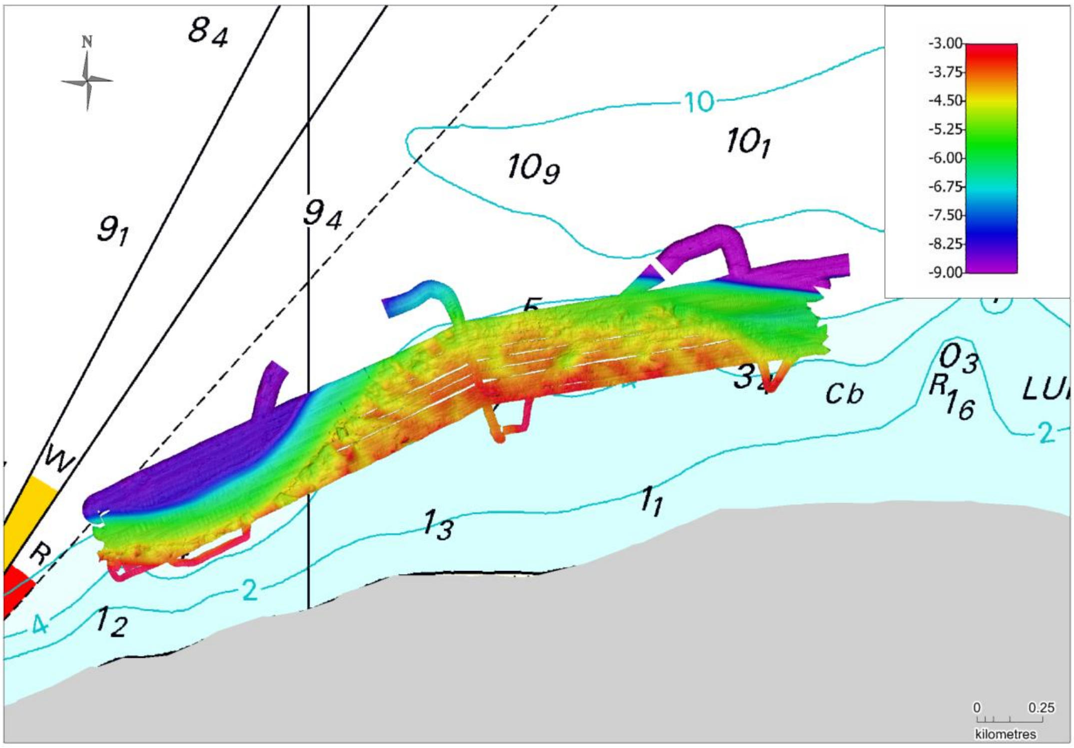


Figure 18. The bathymetry at Fur North shown in meters.

5.3 Langegrund

The survey lines in Langegrund have a variable line spacing of 25-40m as shown in Figure 19. The seismic profiles of the Langegrund area reveal two shallow platform areas of glacial till deposits exposed at the sea bottom at the eastern side of the shallowest parts of Langegrund (Figure 20). Toward the east and deeper part, the top glacial surface is covered by a thickening sequence (>12 m) of post-glacial, mainly fine-grained stratified deposits. The upper part of these consists of Holocene marine to brackish water deposits, forming advancing beach-platform deposits attached to the glacial till slope (Figure 20).

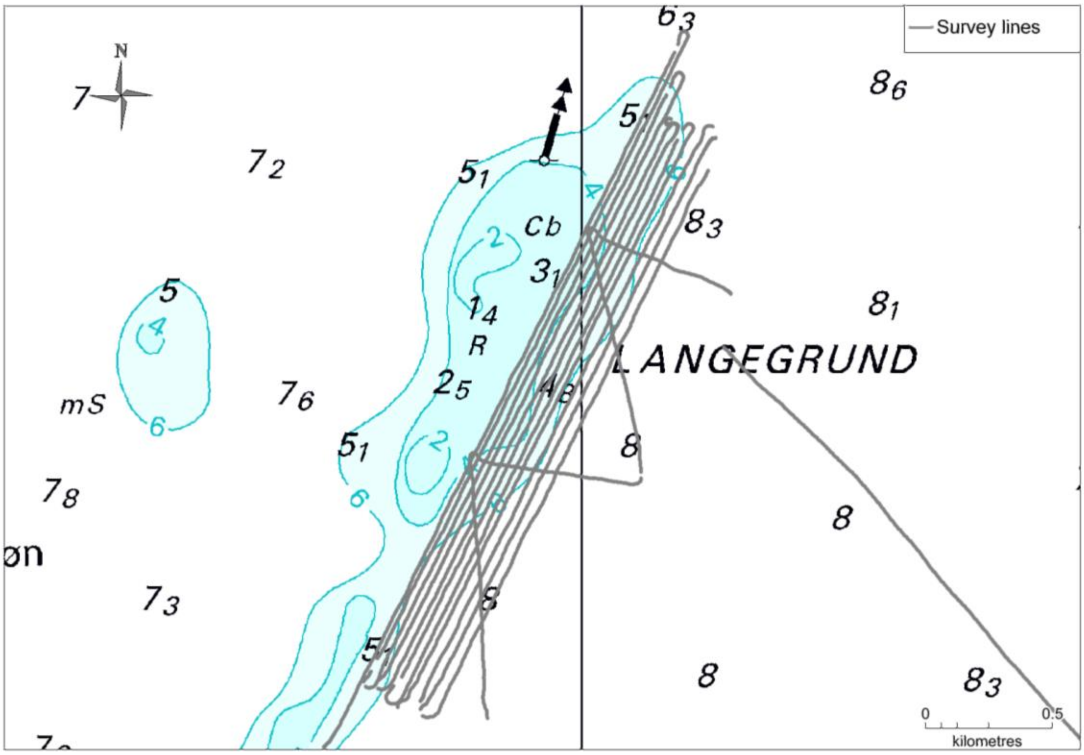


Figure 19. Langegrund survey lines. The line spacing is 25-40m.

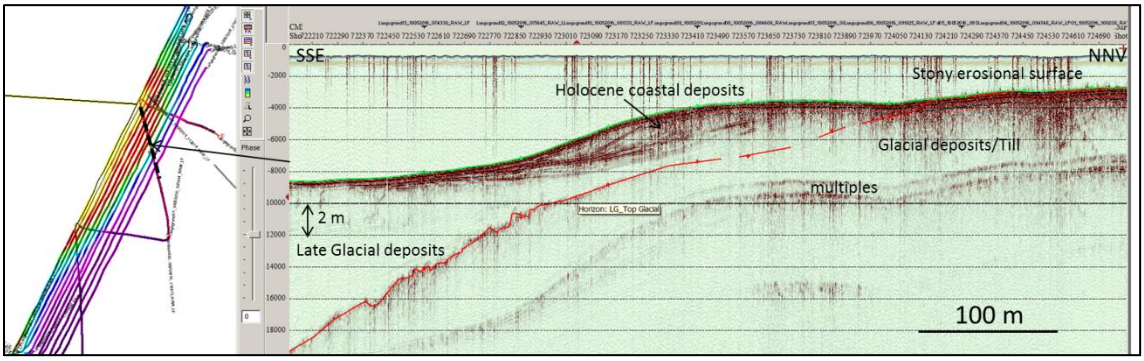


Figure 20. Innomar seismic section showing the Holocene coastal deposits, the late glacial deposits and the glacial deposits giving rise to the stony seabed surface.

Figure 21 shows that the thickness of the postglacial layer is very thin in the shallow parts and the glacial surface is mainly outcropping in the area designated with red in Figure 21. Towards the east the thickness of the postglacial unit increases steadily to over 10 m.

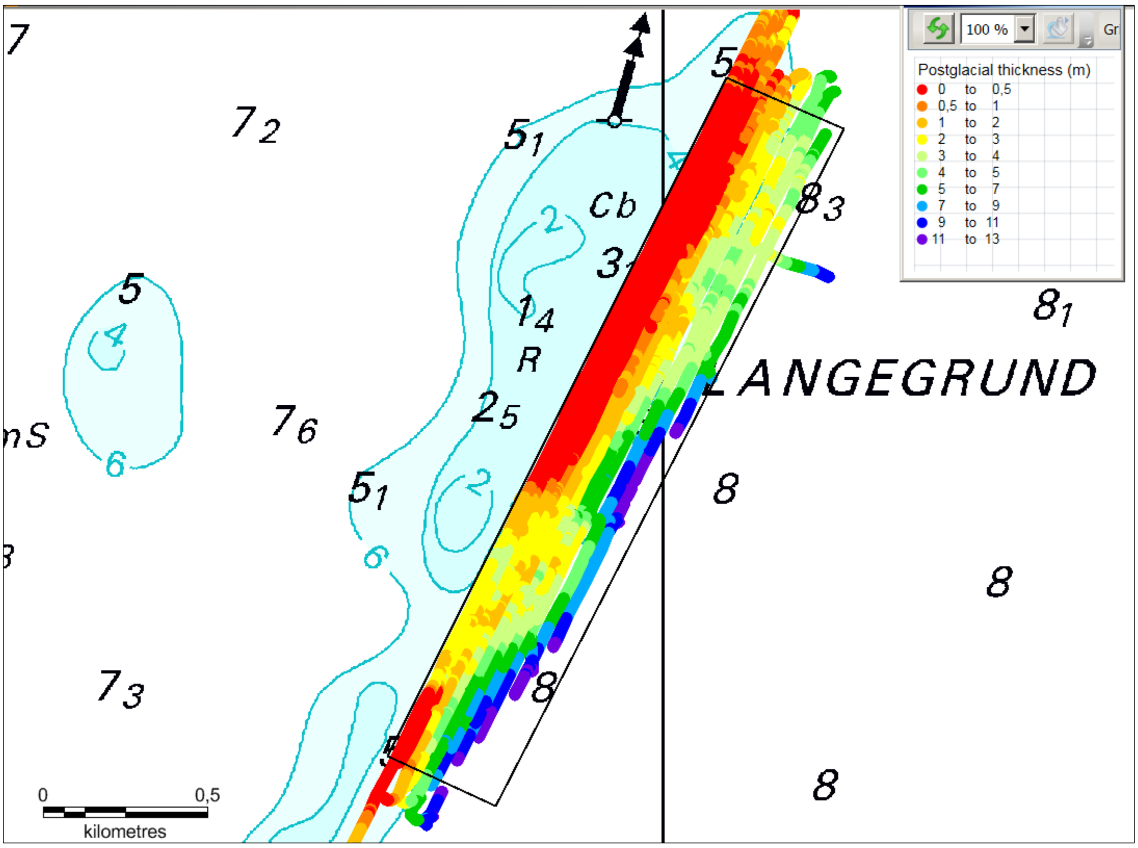


Figure 21. The thickness in m of the postglacial deposits or the depth below the sea bed to the glacial surface.

The ground truth data delivered to GEUS (Nielsen 2016) was used for validating the side scan interpretation endeavour. The result of this interpretation is shown in Figure 22. The results show that the shallow parts of Langegrund are dominated by stones. The deeper parts are mostly sandy and in between there is the transition zone of sand with scattered stones and shells.

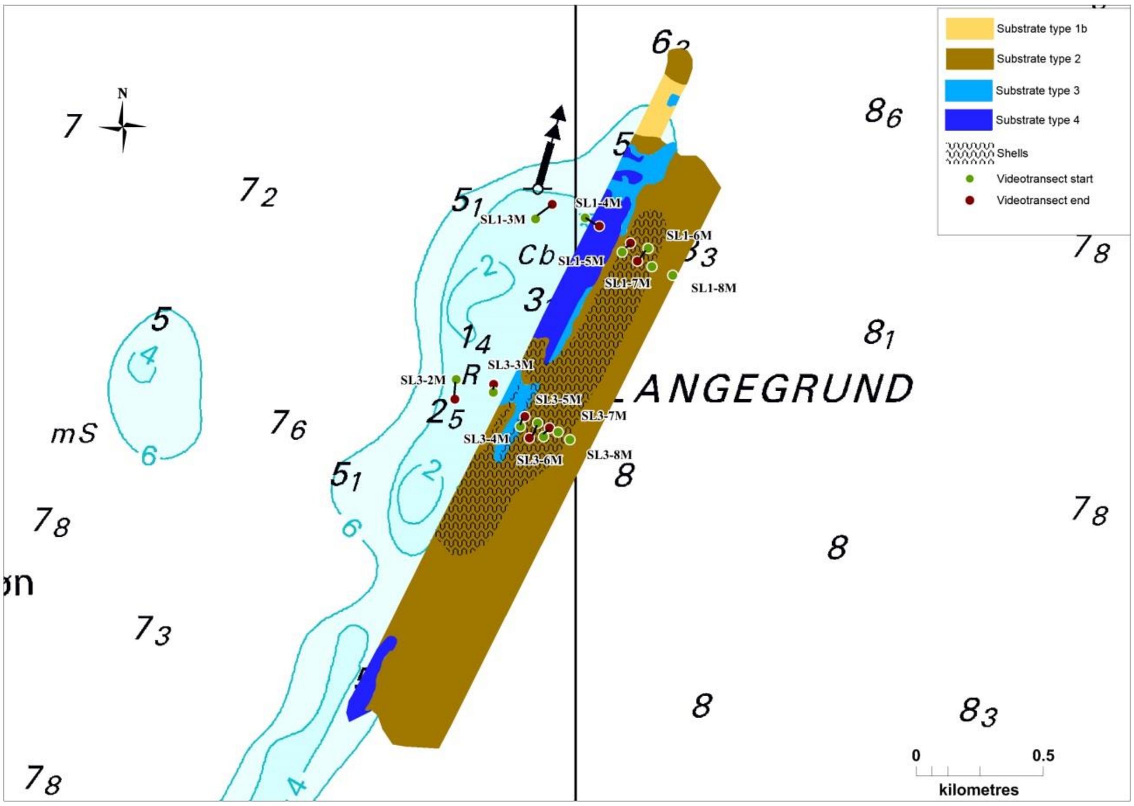


Figure 22. Sidescan interpretation results of Langegrund showing the DSC ground truth transects together with the substrates of the area.

The shallow part (red/yellow colours) is located near western part of the survey area and from there the there the bathymetry slopes steadily towards the SE (

Figure 23) with depths ranges from 3 to 8 m.

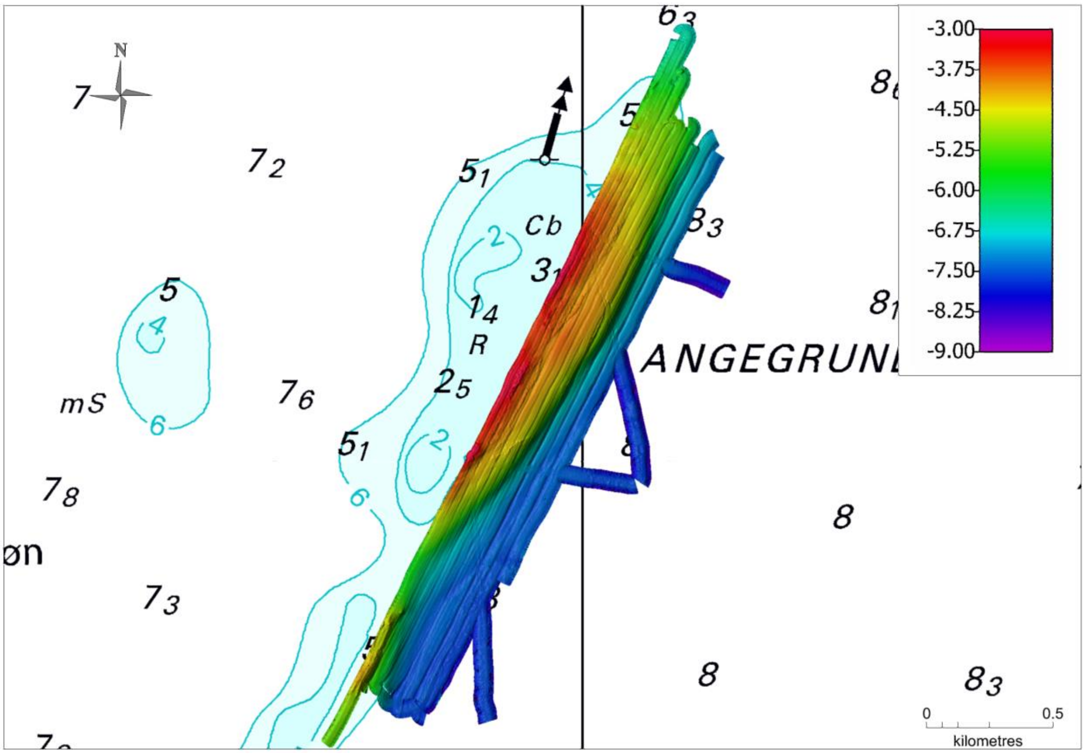


Figure 23. The bathymetry at Langegrund shown in meters.

5.4 Bjørnsholm Bugt

The survey lines in Bjørnsholm Bugt have a variable line spacing of 25-40m as shown in Figure 24. The seismic profiles of the Bjørnsholm area reveal a central and southern near-coastal platform of glacial till deposits exposed at the sea bottom (Figure 25). In the northwestern part of the survey area, the till platform extend outward to a spit-like feature (Figure 26). Between the coast and the spit an up to ca. 10 m thick sequence of postglacial deposits is found in a small basin and onlapping the glacial surface (Figure 27). The lower part of the basin-fill consists of well-stratified, possibly fine-grained deposits, which are interpreted as late-glacial silts and clays. These are topped by higher amplitude and possible sandy few metres thick Holocene bar systems. Towards the deeper western part of the central Bjørnsholm area, glacial deposits becomes buried by an up to 6 m thick sequence of late glacial stratified deposits topped by Holocene coastal deposits building out toward the west (Figure 27).

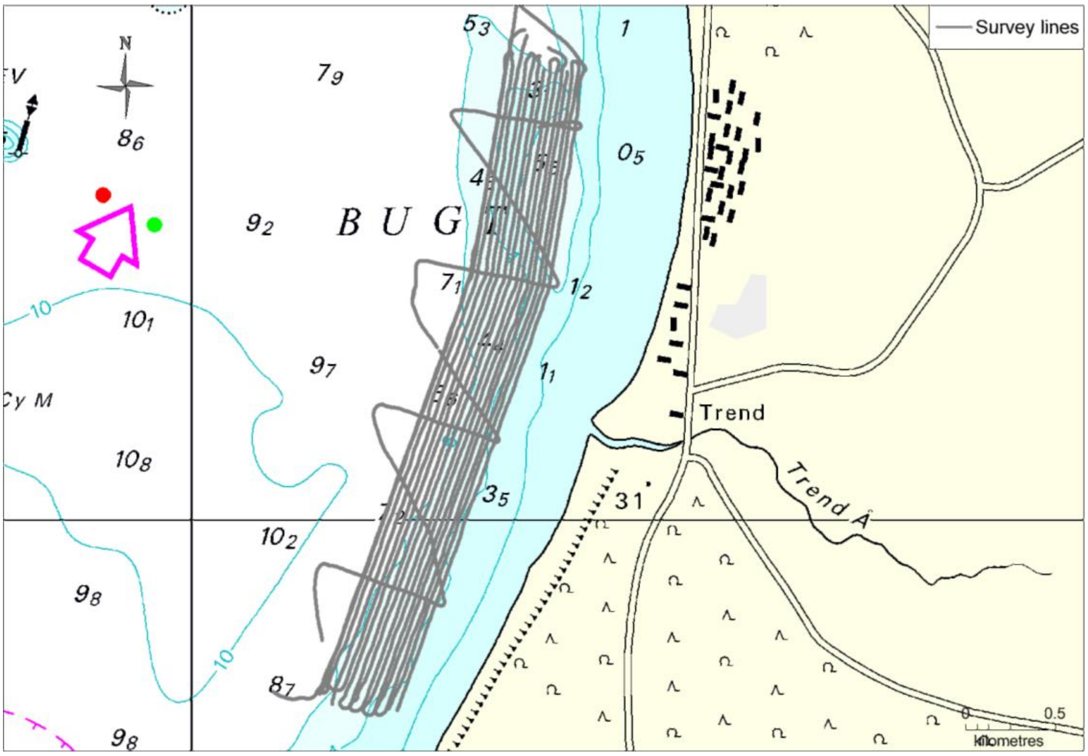


Figure 24. Bjørnsholm Bugt survey lines. The line spacing is 25-40m.

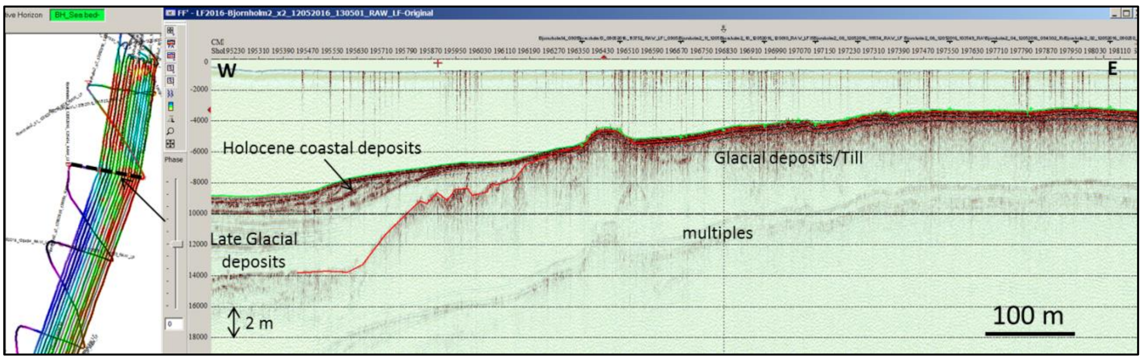


Figure 25. Innomar seismic section showing the Holocene coastal deposits, the late glacial deposits and the glacial deposits on a cross line.

GEUS

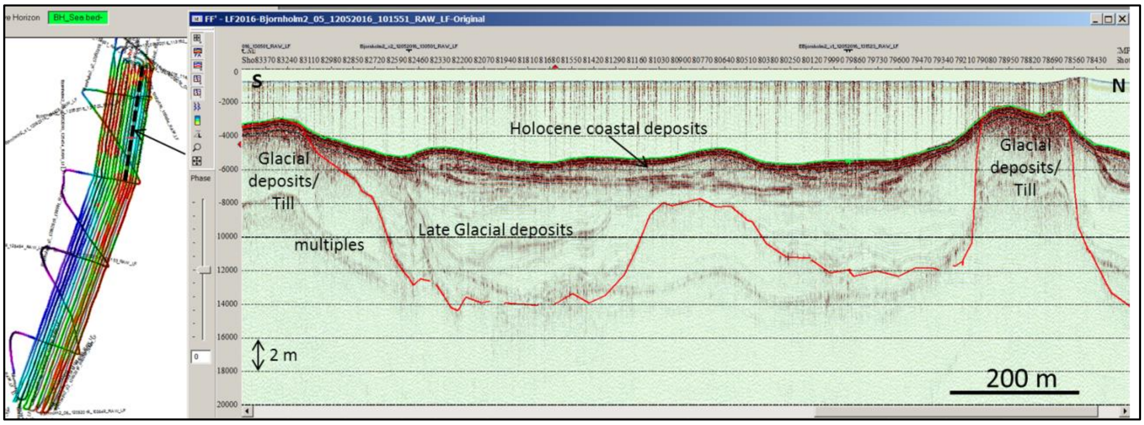


Figure 26. Innomar seismic section showing the Holocene coastal deposits, the late glacial deposits and the glacial deposits.

Figure 27 shows that the thickness of the postglacial layer is very thin in the shallow southern parts of the area and the glacial surface is mainly outcropping in the area designated with red in Figure 27. In the northern part the thickness of the postglacial unit increases to over 10 m.

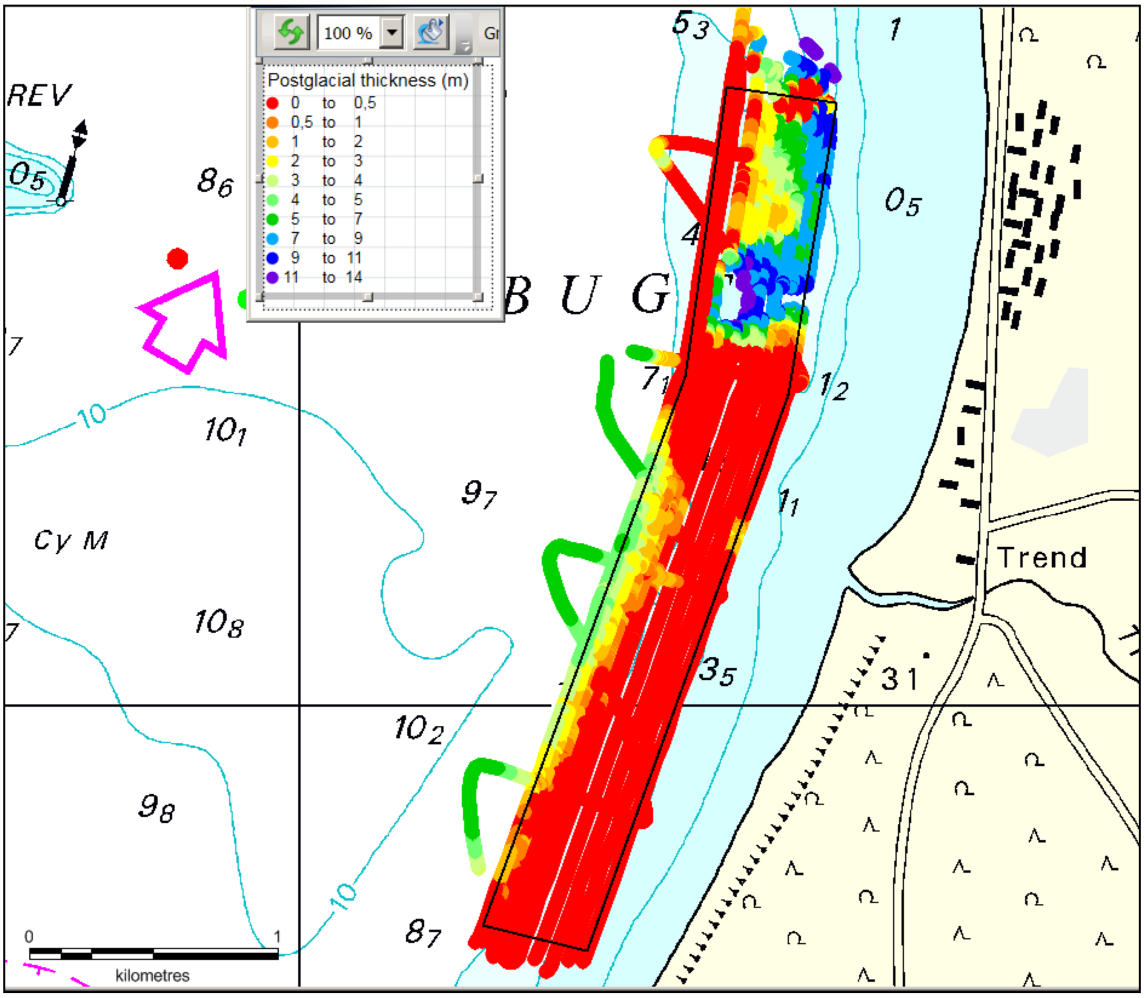


Figure 27. The thickness of the postglacial deposits or the depth below the sea bed to the glacial surface.

The ground truth data delivered to GEUS (Nielsen 2016) was used for validating the side scan interpretation endeavour. The result of this interpretation is shown in Figure 28. The results show that the shallow parts of Bjørnsholm are dominated by stones. The deeper parts are mostly covered with sand and gravel and in between there is the transition zone of sand with scattered stones. Relatively small areas of shells have been located in the southern part of the area on a substrate 3 and in the northern part on a substrate 2.

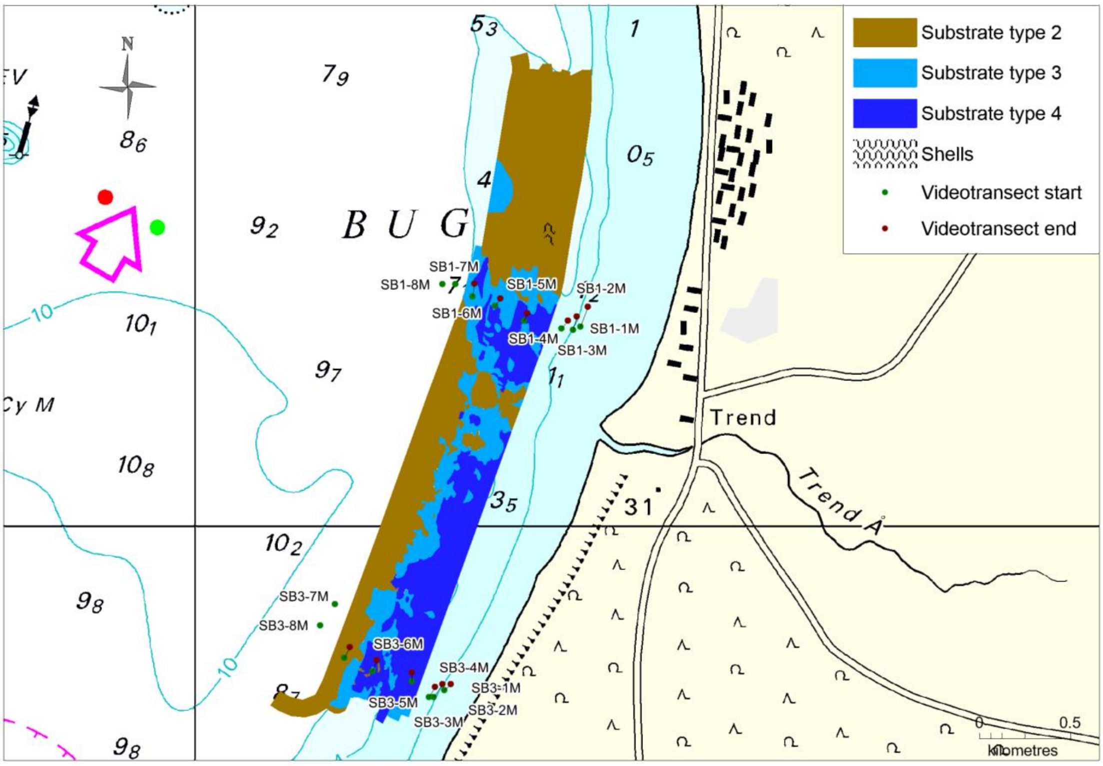


Figure 28. Sidescan interpretation results of Bjørnsholm showing the DSC ground truth transects together with the substrates of the area.

The shallow part (red/yellow colours) is mainly found near shore (Figure 29) with depths ranges from 3 to 5 m. Near the coast in the most northern part of the survey area the 10 m thick sequence of postglacial deposits is found in a small basin with water depth of about 5.4 m's. From the near coastal parts the bathymetry slopes steadily towards the W to about 7 m's.

GEUS

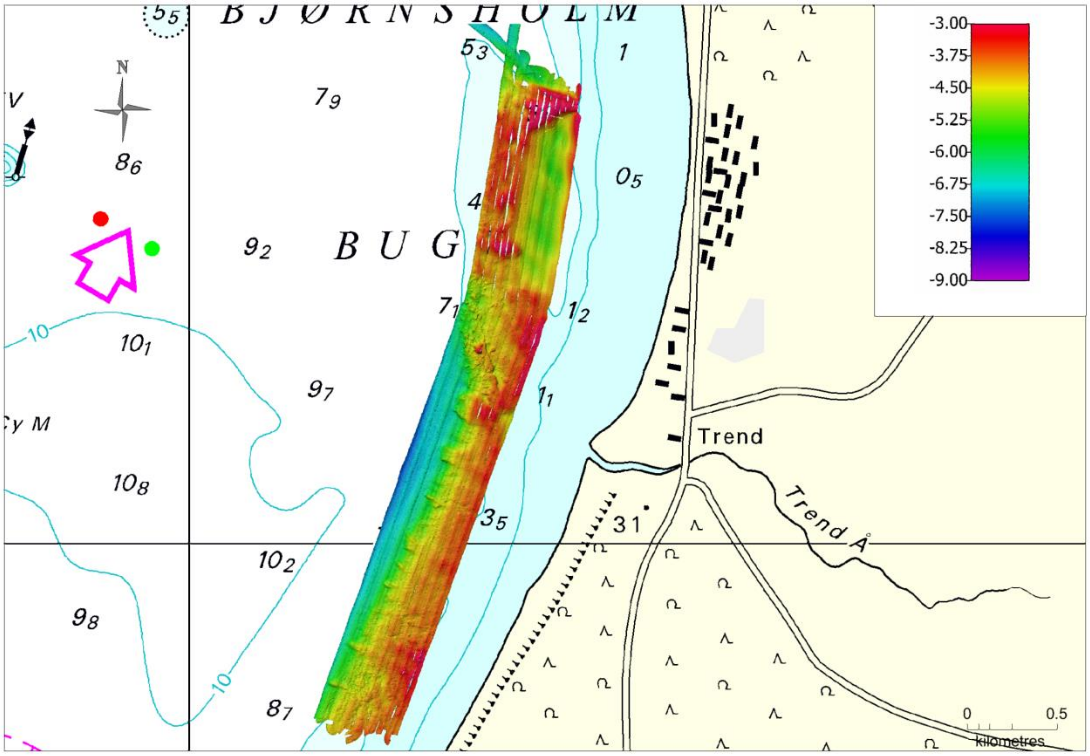


Figure 29. The bathymetry at Bjørnsholm shown in meters.

5.5 Livø Tap (South)

The survey lines in Livø Tap (South) have a variable line spacing of 25-40m as shown in (Figure 30). The seismic profiles of the Livø Tap area reveal a coastal platform of glacial till deposits exposed at the sea bottom (Figure 31; Figure 32). Toward the deeper southwestern direction, the top glacial surface is covered by a thickening sequence (>6 m) of post-glacial, mainly fine-grained stratified deposits. The upper part of these consists of Holocene marine to brackish water deposits, forming advancing beach-platform deposits attached to the glacial till slope (Figure 31; Figure 32).

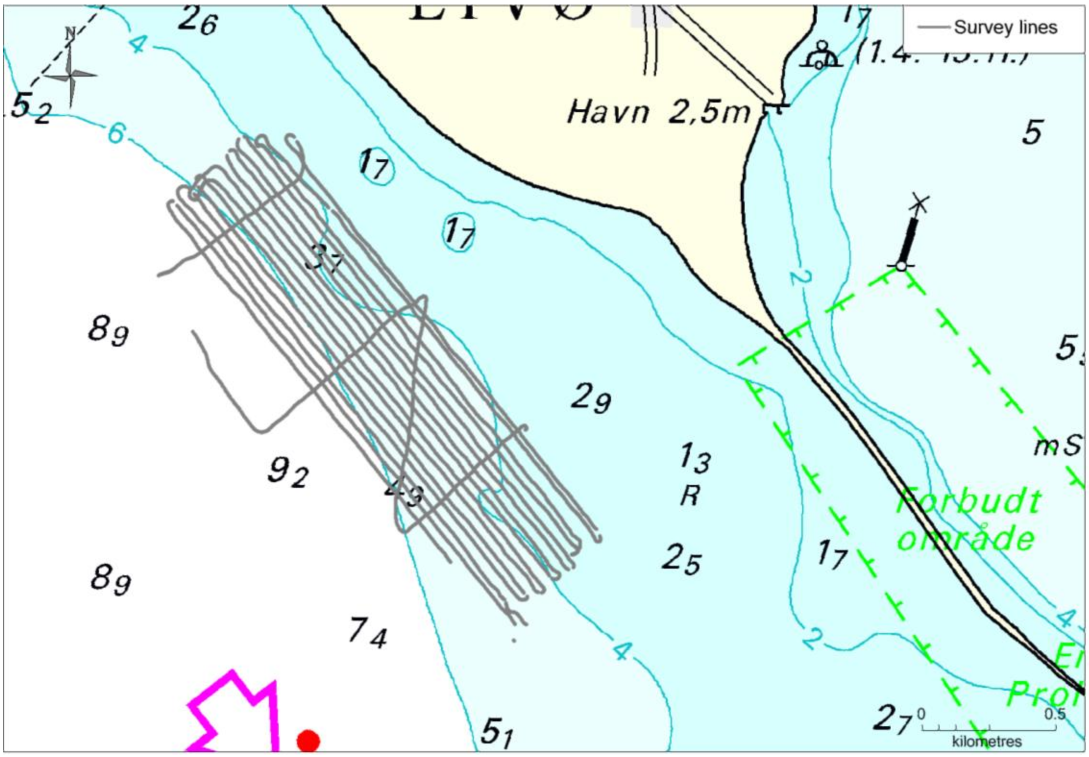


Figure 30 Livø Tap (South) survey lines. The line spacing is 25-40m.

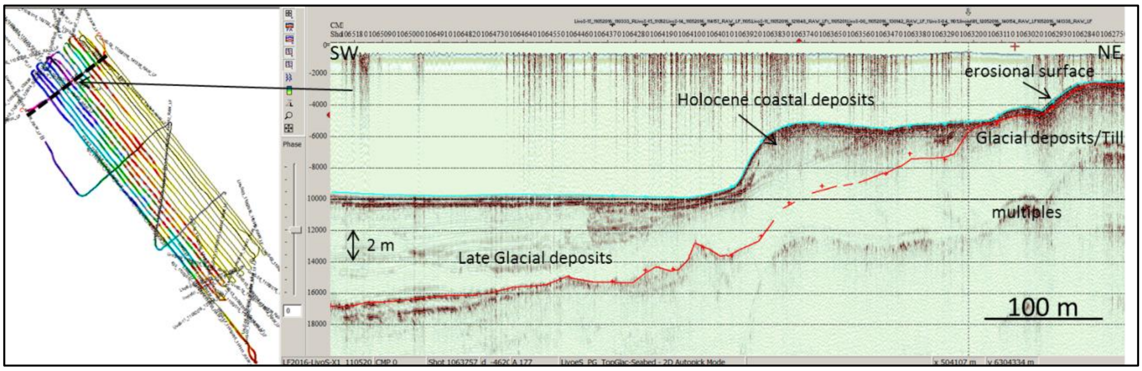


Figure 31. Innomar seismic section showing the Holocene coastal deposits, the late glacial deposits, the glacial deposits and the erosional surface in the northeastern end of the profile showed on a cross line.

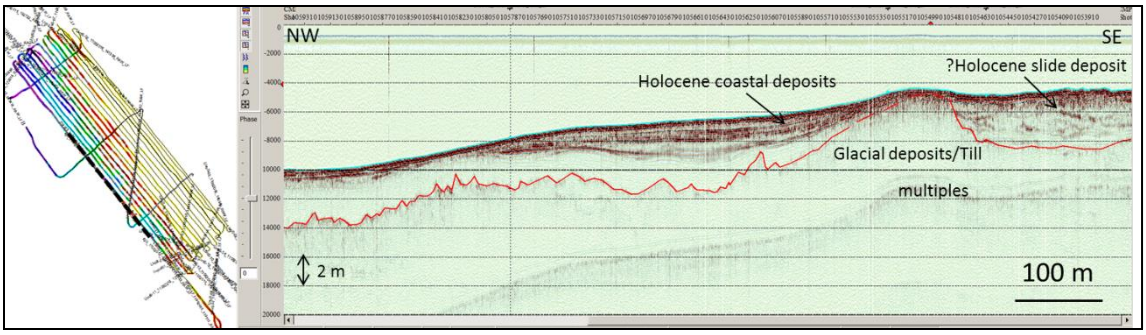


Figure 32. Innomar seismic section showing the Holocene coastal deposits, the glacial deposits and some possible Holocene slide deposits.

Figure 33 shows that the thickness of the postglacial layer is very thin in the shallow northeastern parts of the area and the glacial surface is mainly outcropping in the area designated with red in Figure 33. In the southwestern part of the area in deeper waters the thickness of the post-glacial unit increases to over 4 m.

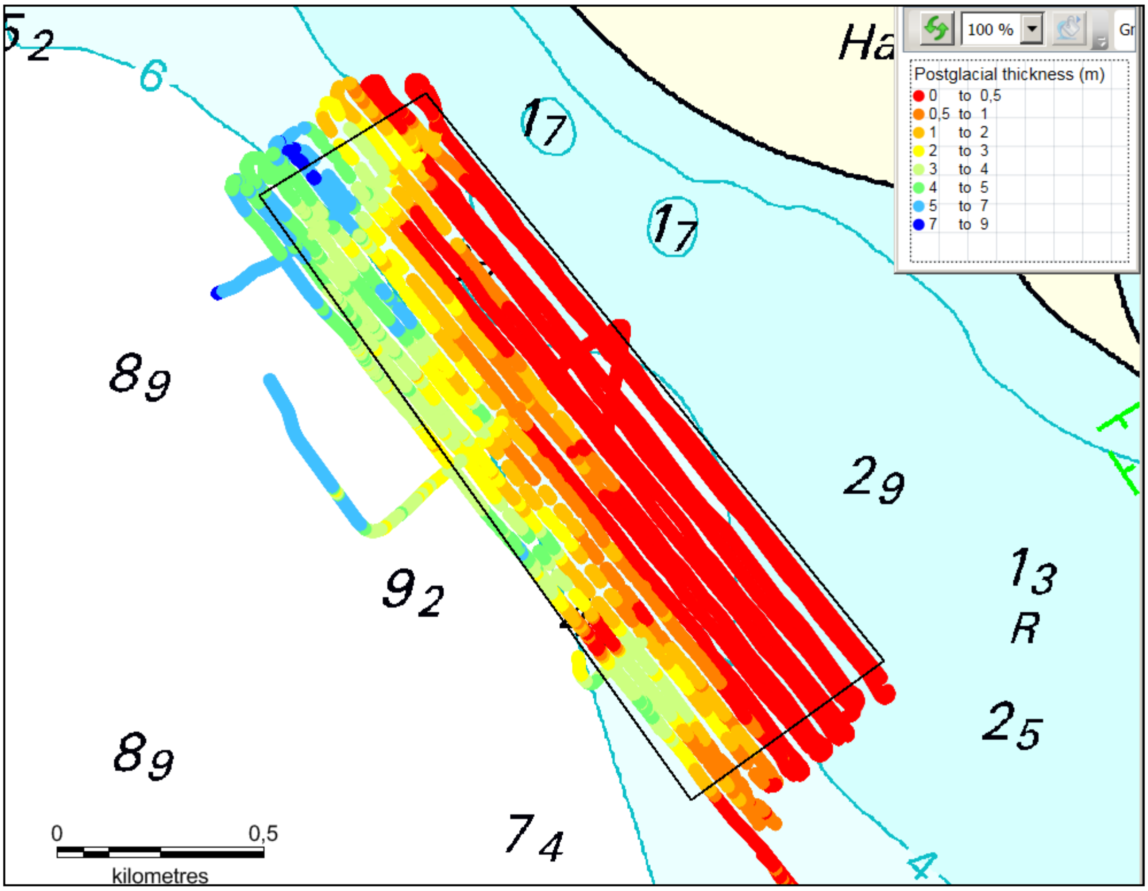


Figure 33. The thickness of the postglacial deposits or the depth below the sea bed to the glacial surface.

The ground truth data delivered to GEUS was used for validating the side scan interpretation endeavour. The result of this interpretation is shown in Figure 35. The results show that the largest parts of Livø Tap are dominated by sandy sediments with scattered stones. Relatively small areas of substrate type 3 have been located in the northern part of the area and in the central part. A single 4m long rectangular unidentified feature was observed on the side scan data located near video transect SLS1-5M (Figure 34).


Figure 34. A side scan image of the rectangular unidentified feature found near the video transect SLS1-5M at the location: 6.303.295 N 504.635 E WGS84, UTM zone 32 at a water depth of about 5 meters.

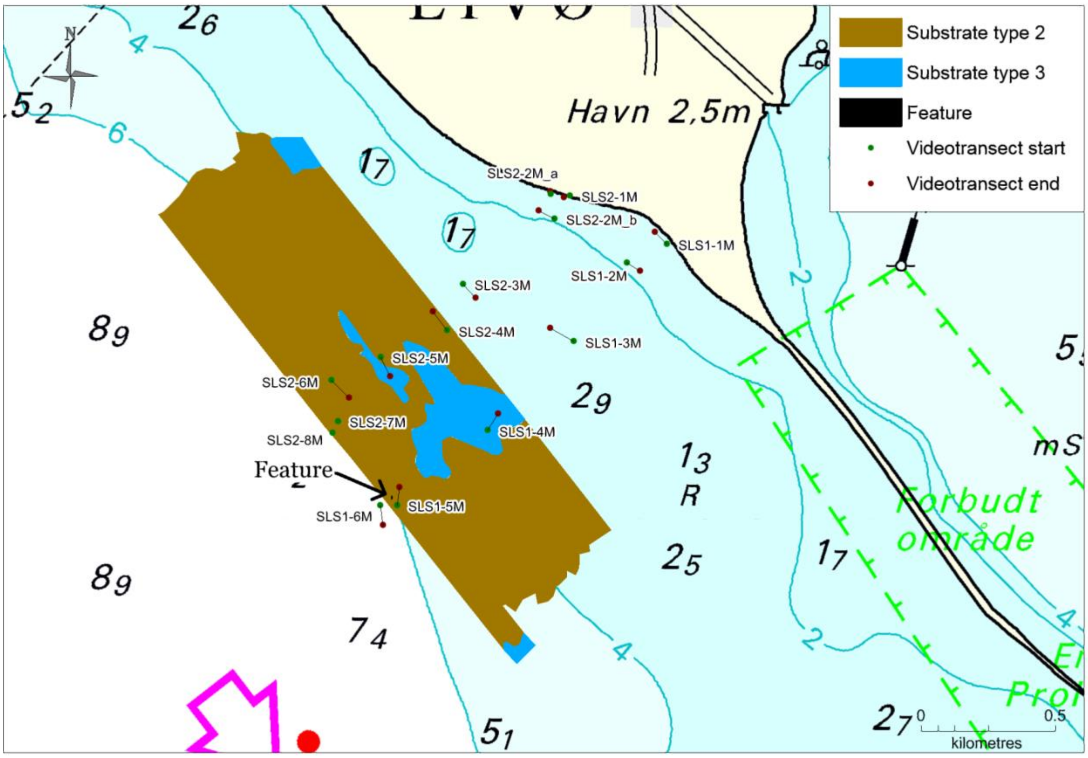


Figure 35. Sidescan interpretation results of Livø Tap showing the DSC ground truth transects together with the substrates of the area and a single feature found on the side scan data.

The shallow part (red/yellow colours) is found near shore (Figure 36) with depths ranges from 3 to 5 m. From the near coastal parts the bathymetry slopes steadily towards the W to about 9 m's.

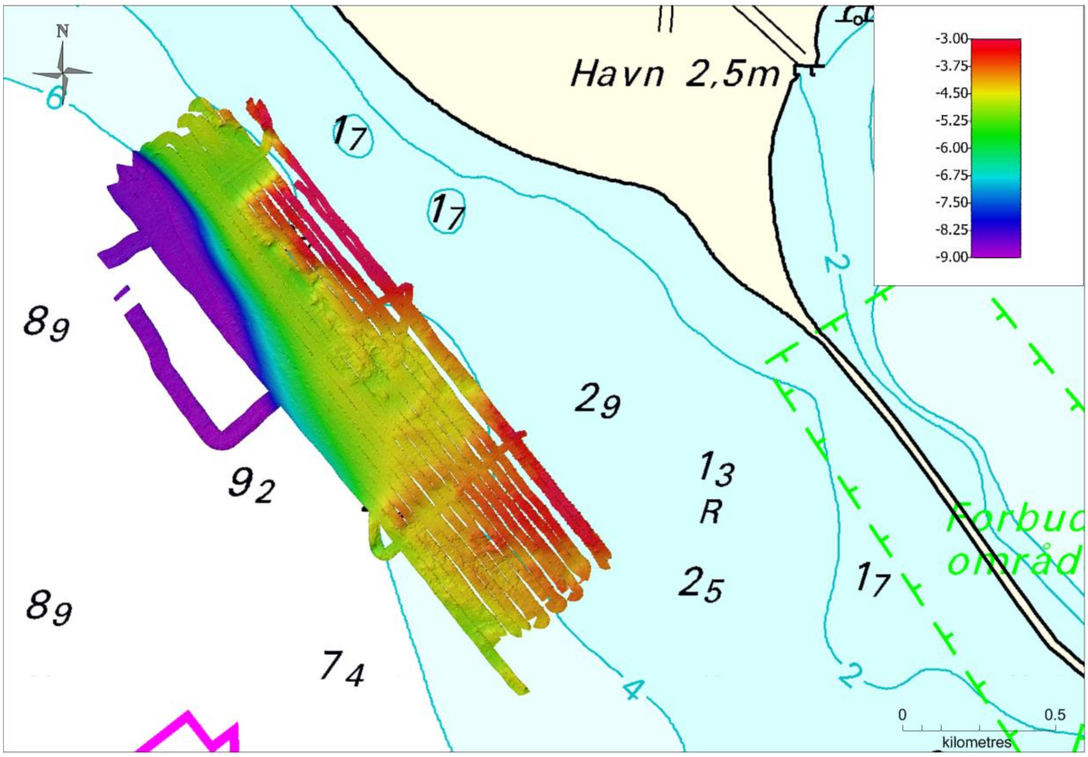


Figure 36. The bathymetry at Livø Tap shown in meters.

6. Discussion

6.1 Livø North

The survey could not continue to the very shallow parts of the area (i.e. below 3 m) due to the presence of large stones at shallow depths despite that we had an observer sitting on the bow of the boat watching the stones and guiding the skipper.

The survey areas were designed after the DHI (Danish Hydrographic Institute) model and the preference location they postulate in their report. But the very shallow areas and areas with known mud sedimentation were avoided.

The ground truth sampling campaign conducted by DSC has a high degree of consistency with the sidescan interpretation. Nevertheless, some areas show discrepancy between the two data sets and that can be related to the patchiness of the area and the scale of the sidescan data interpretation (50x50m).The transect could have been crossing these patches with different sediment type or the stones where stones were partially or totally covered by sand.

The algae growth on hard substrate could not be clearly identified with the sidescan imaging. When investigated closely with a GoPro™ Camera it shows that the algae growth is very limited and confined to the stones themselves (Figure 37), then it was difficult for the acoustic signal to distinguish between the substrate and the algae growth. In other surveys conducted by GEUS in the Danish waters algae as well as eelgrass was readily identified with sidescan imaging and verified by ground truth video. So the conclusion, we share with DSC (Nielsen 2016) , is that for small algae growth using acoustic sidescan imaging is not the best way for remotely identifying them.

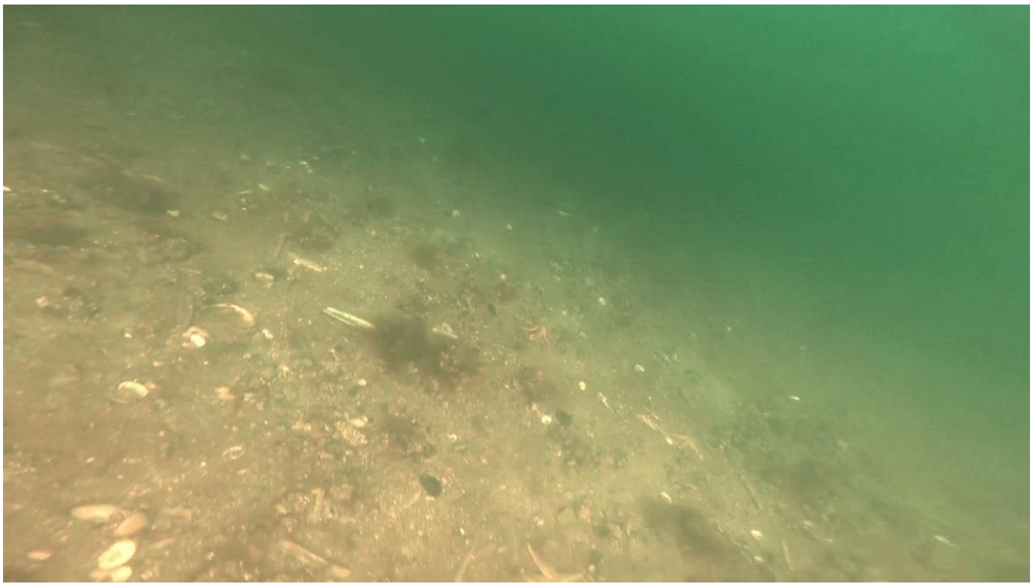


Figure 37. GoPro camera image of the seabed in the southern part of Livø North showing limited growth of algae.

The bathymetry data shows gentle slope morphology at shallow water down to 4-5m. Outside the shallow platform the seabed slopes sharply towards the SW and the NE to 10m. Some morphological features can be observed at shallow depths caused mainly by stone or combination of stones and sandy deposits. The gaps shown between the survey lines were caused by the outer beam uncertainty, so data were trimmed to maintain high bathymetric accuracy.

Figure 38 shows the 3D manifestation of the topglacial/till layer morphology. The figure shows the till surface crops to the seabed at the centre part of the area and gradually drops down towards the NE and SW parts of the area.

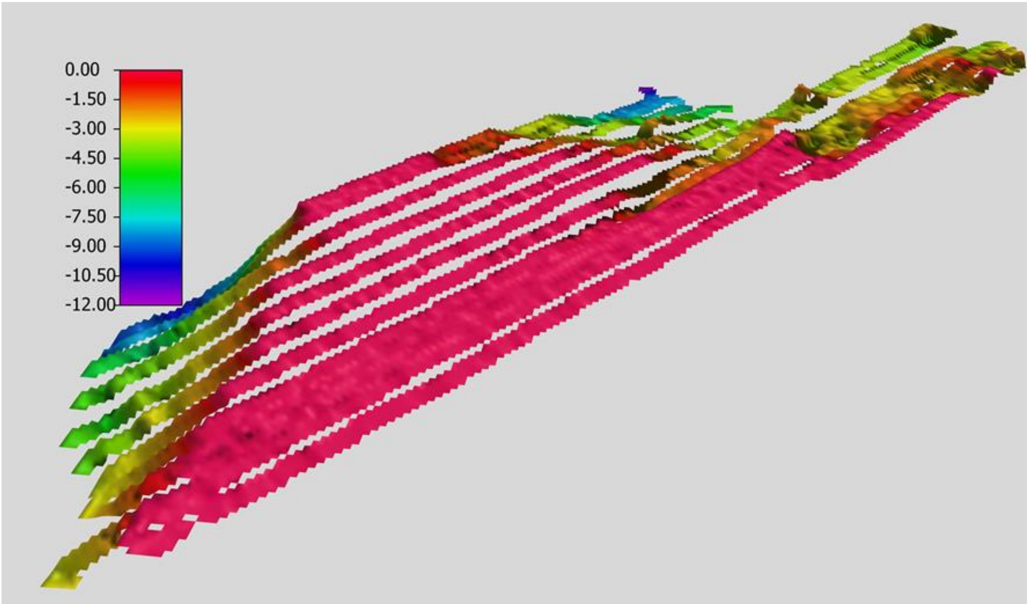


Figure 38. A 3D morphology of the topglacial (till) layer in Livø North. Legend values are depths below seabed in meters.

The seismic interpretation profiles are the key factor for identifying areas where the reef can be established and stones can be places without a risk of stone sinking or structure collapsing. If we look at a seismic profile that is parallel to the shore, i.e. striking NE-SW we can observe the top glacial layer (moraine) horizon rising steadily until it reaches the seabed (Figure 39). These areas with moraine exposed at the sea bed are ideal for establishing reefs.

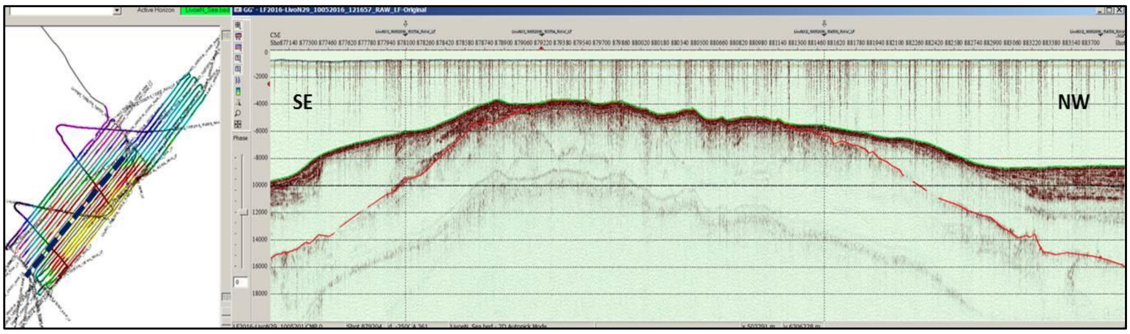


Figure 39. Seismic profile SE-NW showing the glacial layer (till) rising until it reaches the seabed in the centre of the profile.

If we overlap all these layers and quarry through them searching for the best possible combination that ensures type 2, 3 or 4 substrate, postglacial depth of 0-0.5m, and a seabed depth of a range 3-7m, then we will end up with the spatial extent where reefs can be re-established from the geological model perspective. Combining that with the biological observation and the DHI model will delineate the area and optimise the choice (the black hashed polygon in Figure 40 and Figure 41).

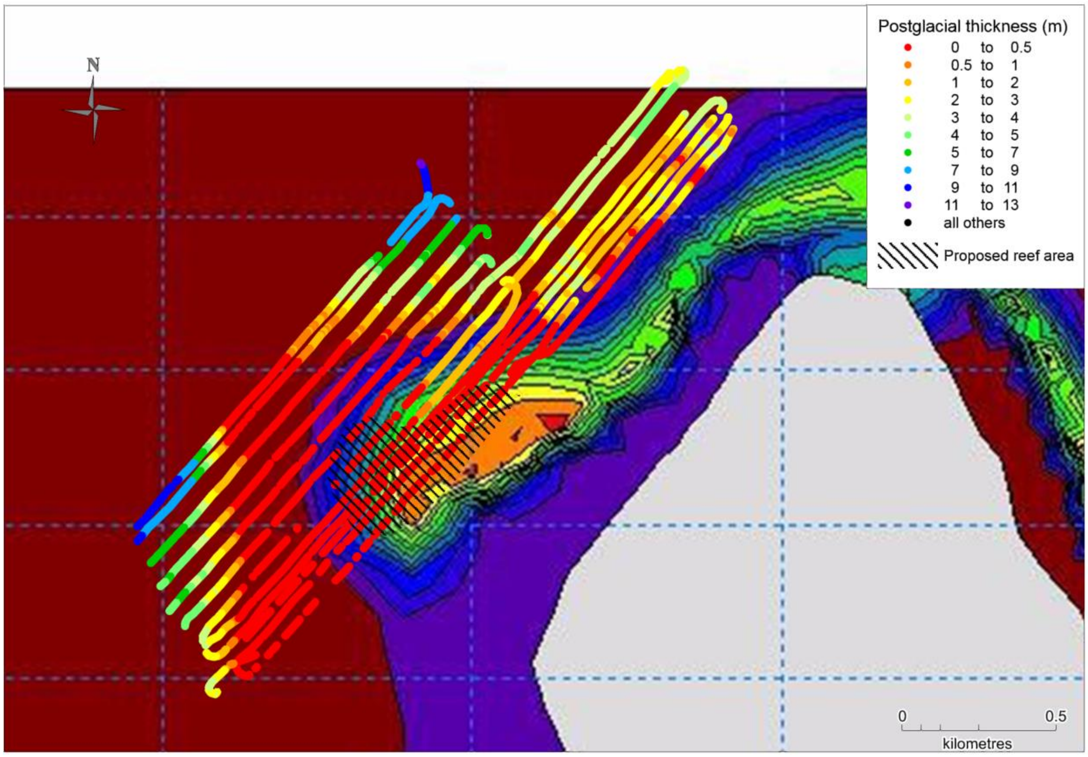


Figure 40. The chosen area for reef re-establishment in Livø North shown with the postglacial sediment thickness (black hashed area). The DHI modelling results is the background map.

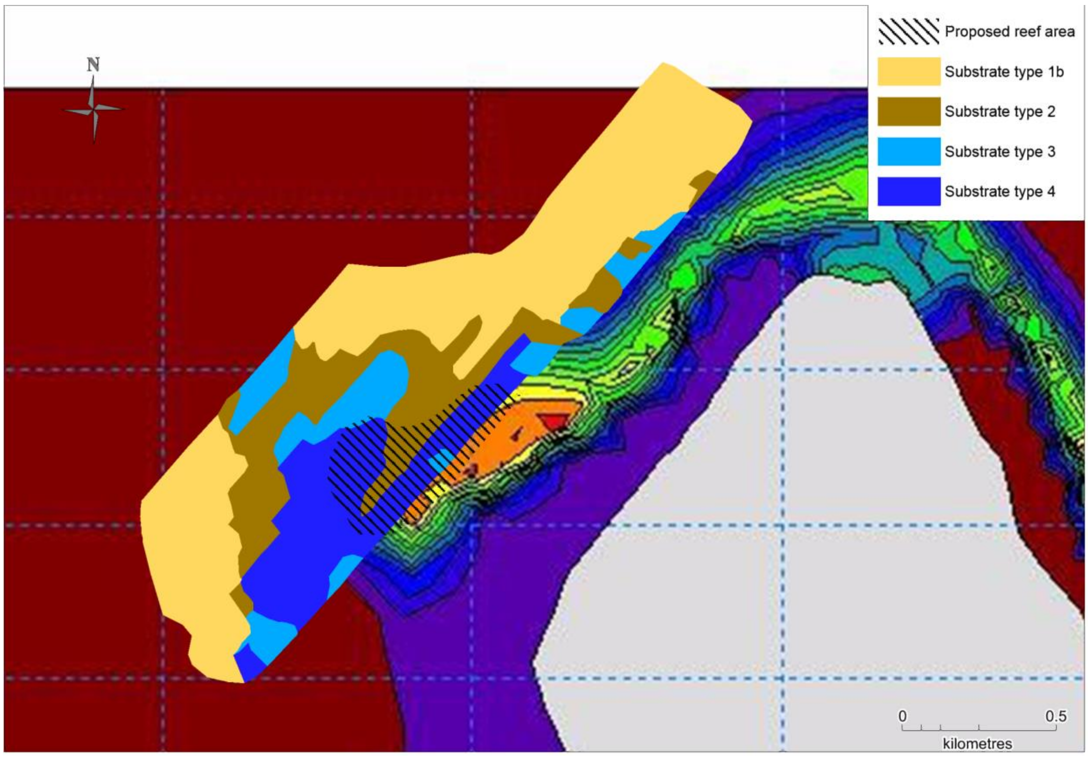


Figure 41. The chosen area for reef re-establishment in Livø North shown with the substrates for the area (black hashed area). The DHI modelling results is the background map.

It is highly recommended to conduct geotechnical investigations prior to the final decision on reef position. Grab sample analysis will give indications on the sediment type and the sorting/sediment transport. Vibrocores will provide data about strength and bearing capacity of the sediment giving rise to a highly accurate and reliable choice of seabed areas for reef re-establishment.

As Livø North was agreed upon to be the most potential area for establishing a stone reef on, it was considered as first priority for suggesting the actual polygons where these reefs are to be build.

After a thorough investigation, data analysis and interpretations the following reef positions were selected as they fulfil all requirements. GEUS suggested a geotechnical investigation in "Polygon1_GEUS" position (Figure 42) to be sure that the subsurface sediments are suitable for holding the weight of the laid down stones. There is up to 0.5 m sandy sediment on top of the glacial layer in the far northwestern part of polygon 1_GEUS which may not in theory be capable of bearing the weight of the new reef, so one expect some stone sinking in this area. However GEUS has no proof of that and geotechnical test can provide the required information on the sediment consolidation and the sinking probability and amount. There is also the possibility of up to half a meter erosion caused by the turbulence around the new reef.

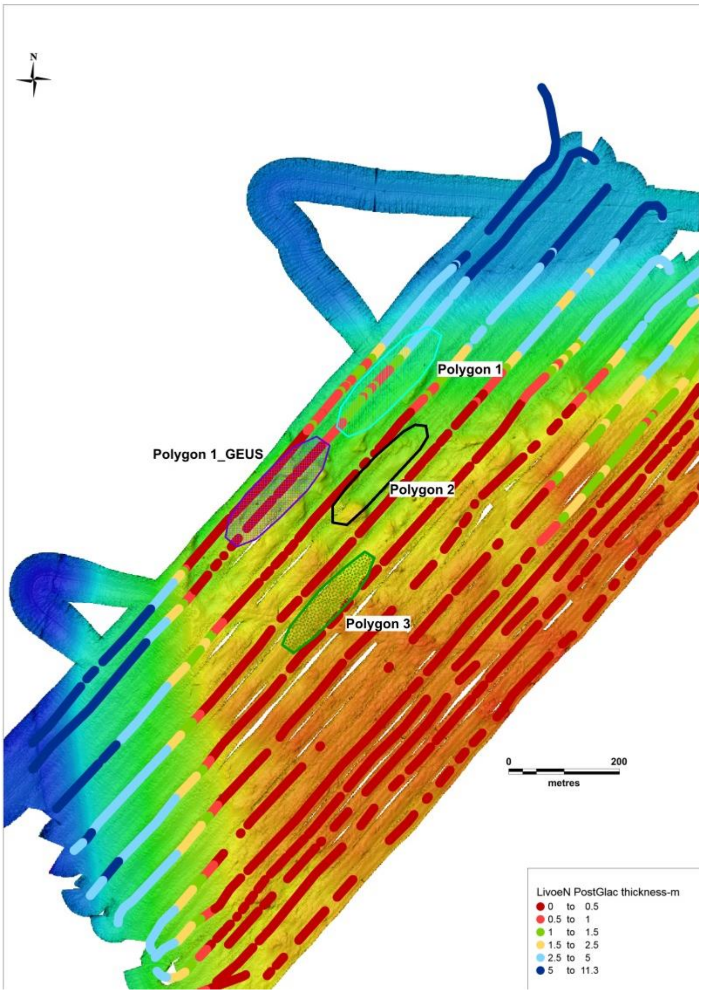


Figure 42. New stone reef positions in Livø North. Polygon named "Polygon 1_GEUS" is the new position that replaces the previously suggested "Polygon 1" position.

6.2 Fur North

Same procedure was followed in choosing the most suitable area for establishing a new stone reef in Fur North. The seismic profiles (Figure 43) were studied closely at the areas where it shows the crop out of top glacial layer (till) and matches the sidescan surface image where stones can be seen and their percentage can be delineated.
Fur North is outside the Natura-2000 designated area number 16 of Løgstør Bredning, Vejlerne og Bulbjerg.

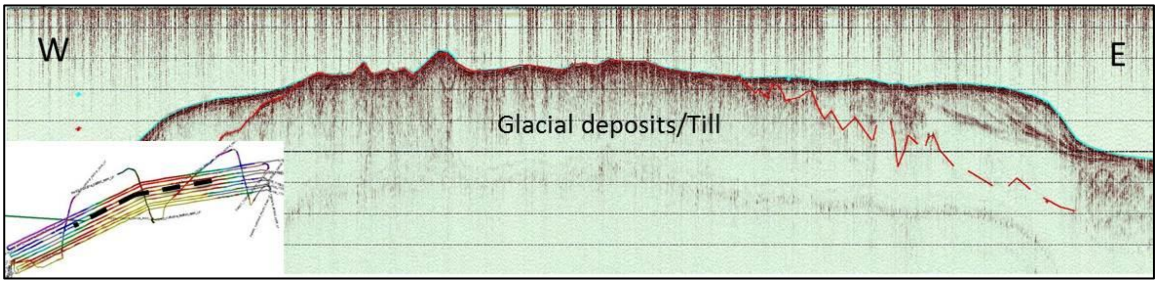


Figure 43. Seismic profile in Fur North showing the topglacial layer (till) exposed at the seabed.

The area chosen by DHI model was digitised and used together with the thickness of the post-glacial layer, the substrate, and the bathymetry to propose the best possible region where the new stone reef can be established, Figure 44 and Figure 45. Nevertheless, more investigation is needed to delineate the exact location of the new reef positions that includes sediment sampling, coring and geotechnical measurements.

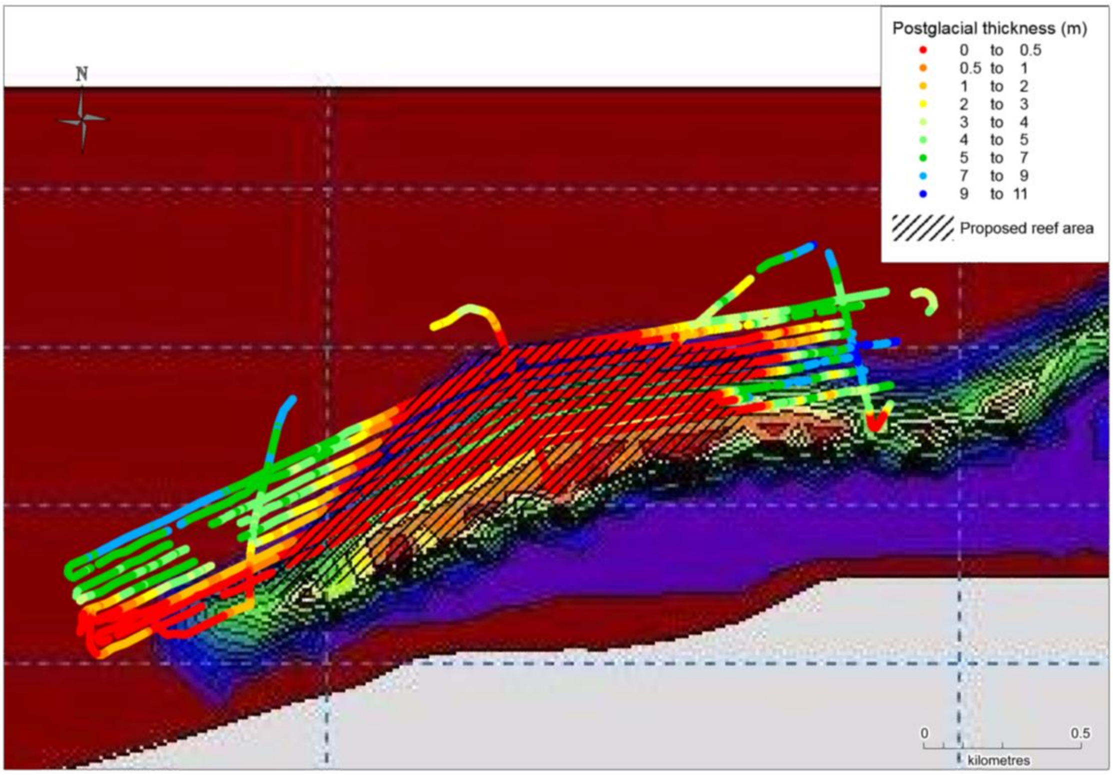


Figure 44. Fur North showing GEUS suggested new reef site (hashed area), also showing the postglacial thickness. The DHI modelling results is the background map.

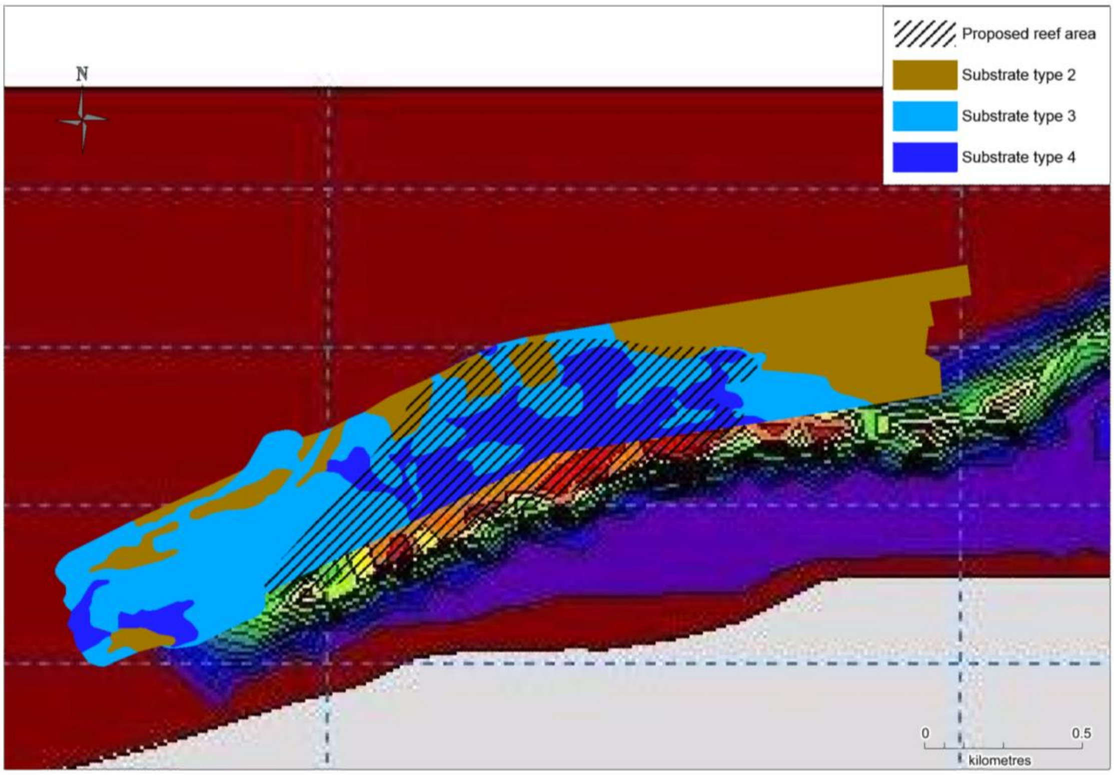


Figure 45. Fur North showing GEUS suggested new reef site (hashed area), also showing the substrates for the area. The DHI modelling results is the background map.

6.3 Langegrund

The exposed glacial deposits / till with large stone percentage is situated in the western part of the area while thick Holocene and postglacial sediments occupies the SW and NE as well as the eastern parts of the surveyed area (Figure 46). According to these information, obtained from the seismic profiles, the thickness of the postglacial deposits were measured. These data were used to support the interpretation of the seabed substrates and the stone distribution obtained from the side scan images and the ground truth transects.

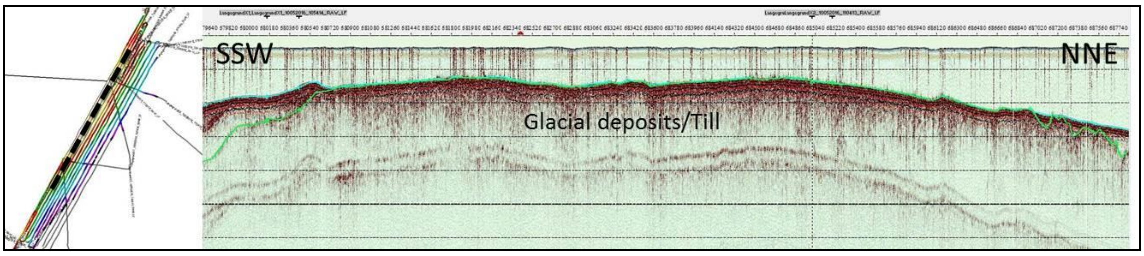


Figure 46. Seismic profile from Langegrund showing the glacial deposits (till) exposed at the seabed.

Having the DHI model of potential sites in the background, and together with the thickness of the postglacial layer, the substrate, and the bathymetry, the best possible site for establishing the new stone reef was chosen, Figure 47 and Figure 48. The chosen area extends beyond the DHI model as it is geologically suitable, but further investigations are required for the final decision to be properly made.

GEUS

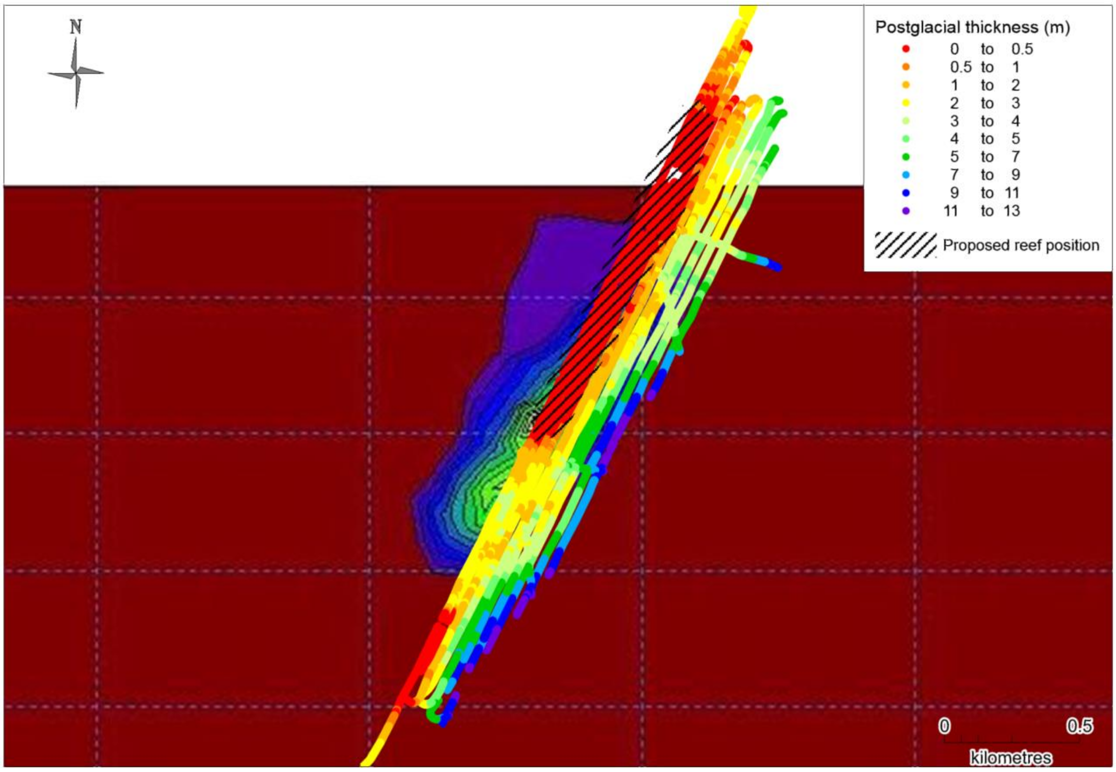


Figure 47. Langegrund showing GEUS suggested new reef site (hashed area), also showing the postglacial thickness map. The DHI modelling results is the background map.

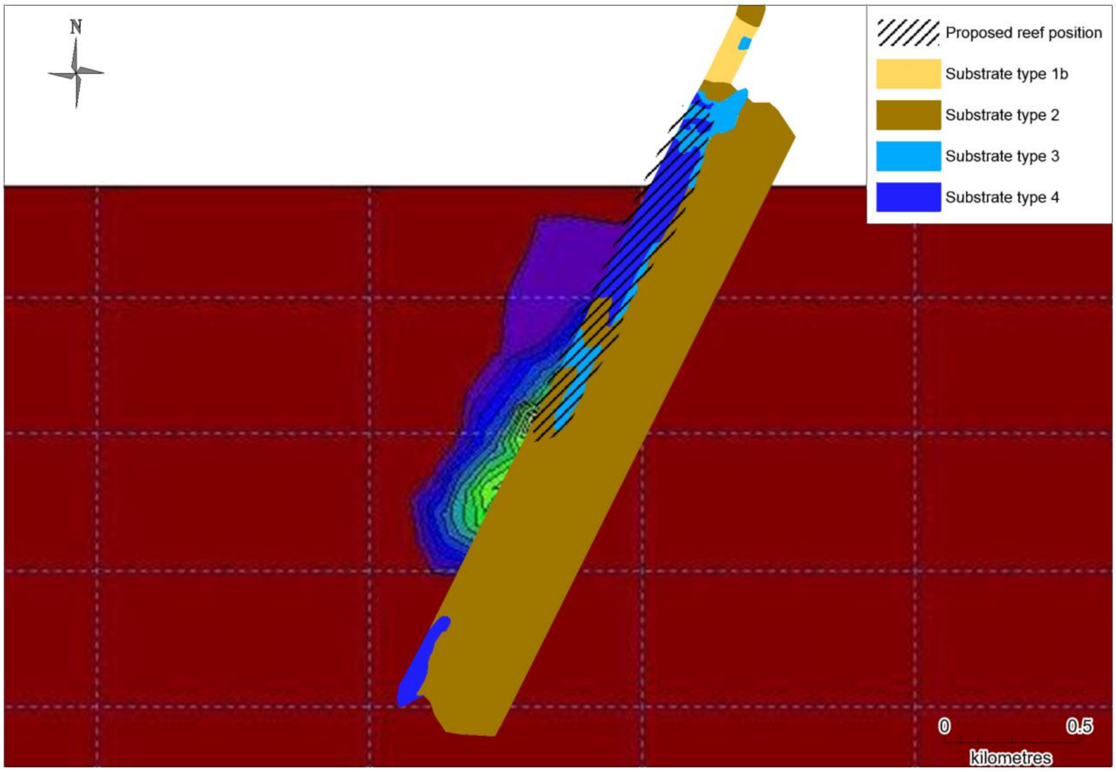


Figure 48. Langegrund showing GEUS suggested new reef site (hashed area), also showing the substrates for the area. The DHI modelling results is the background map.

6.4 Bjørnsholm Bugt

Similar approach was followed in Bjørnsholm area to choose a suitable site for establishing a new stone reef. Processing and interpretation of the sub-seabed sediment formation and stratigraphy using the results obtained from the shallow seismic sub-bottom profiler were done. The topglacial layers were mapped for all the seismic lines and their thickness below the seabed was calculated. The thickness becomes very small when the postglacial layer crops out on the seabed and get exposed due to erosion. A map showing these thicknesses is shown in Figure 49.

The substrate map was also produced from interpreting the side scan dataset which shows the seabed acoustic images and the interpretation was supported by ground truth data obtained by DCE transects. Combining these two interpretation results and knowing the geological setting of the area the most suitable site for stone reef establishment was proposed as shown in Figure 50.
It worth mentioning that these information and site proposal were based on remote sensing data, further geotechnical investigations and sediment analysis are required for pinpointing the final site of reef establishment.

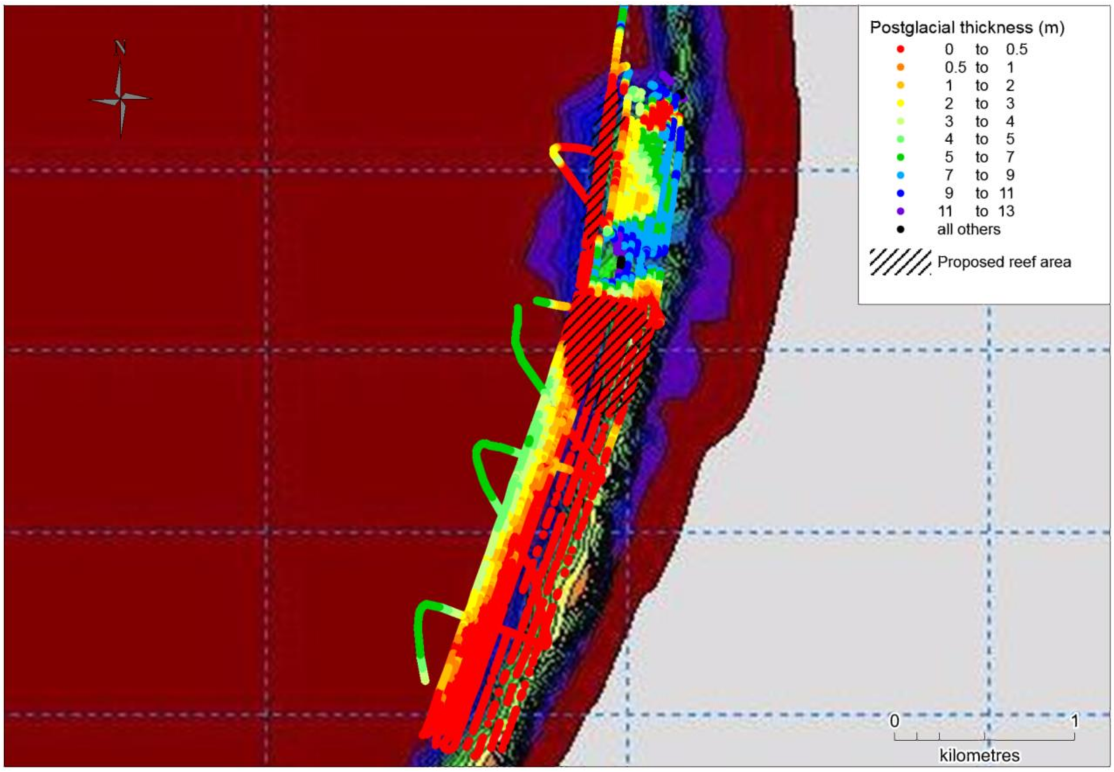


Figure 49. Bjørnsholm Bugt showing GEUS suggested new reef site (hashed area), also showing the postglacial thickness map. The DHI modelling results is the background map.

The major part of the area and the suggested reef positions are outside the Natura-2000 designated area number 16 of Løgstør Bredning, Vejlerne og Bulbjerg.

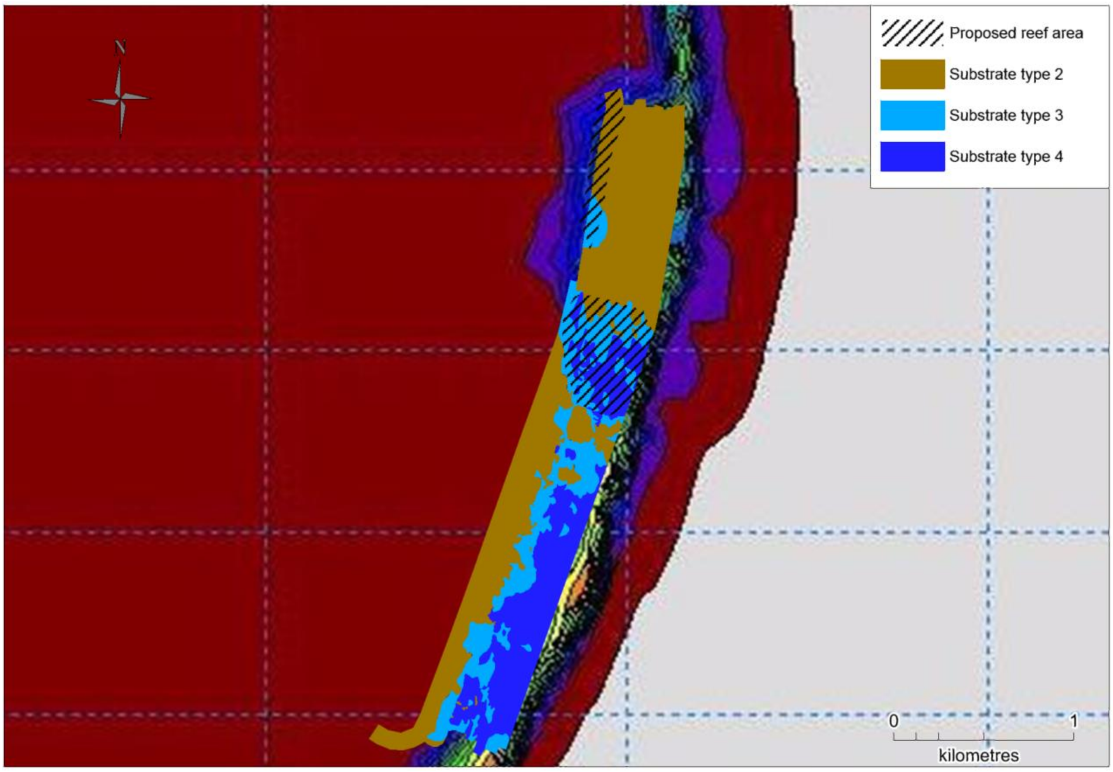


Figure 50. Bjørnsholm Bugt showing GEUS suggested new reef site (hashed area), also showing the substrates for the area. The DHI modelling results is the background map.

6.5 Livø Tap (South)

This area was surveyed to be a possible site for recreational purposes. The seismic section shows in Figure 51 the thickness of the postglacial soft sediments reduces towards the east, i.e. as we get closer to the shore of Livø Tap Island.

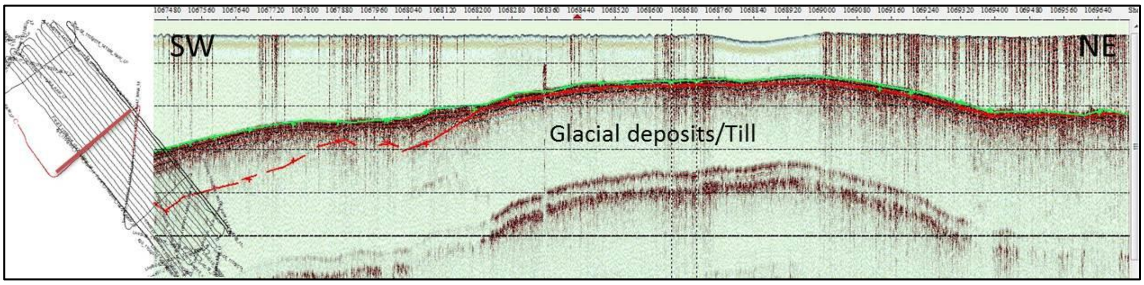


Figure 51. Livø Tap (South) seismic section perpendicular to the coast showing the postglacial layer thickness.

Processing and interpreting all the seismic lines of the area by marking the postglacial horizon as well as the seabed horizon yields the thickness of the postglacial layer as shown in Figure 52. As the area was not considered as a potential site for biodiversity enhancement or oxygen nourishment, it was not modelled by DHI for biomass distribution like the previous four areas.

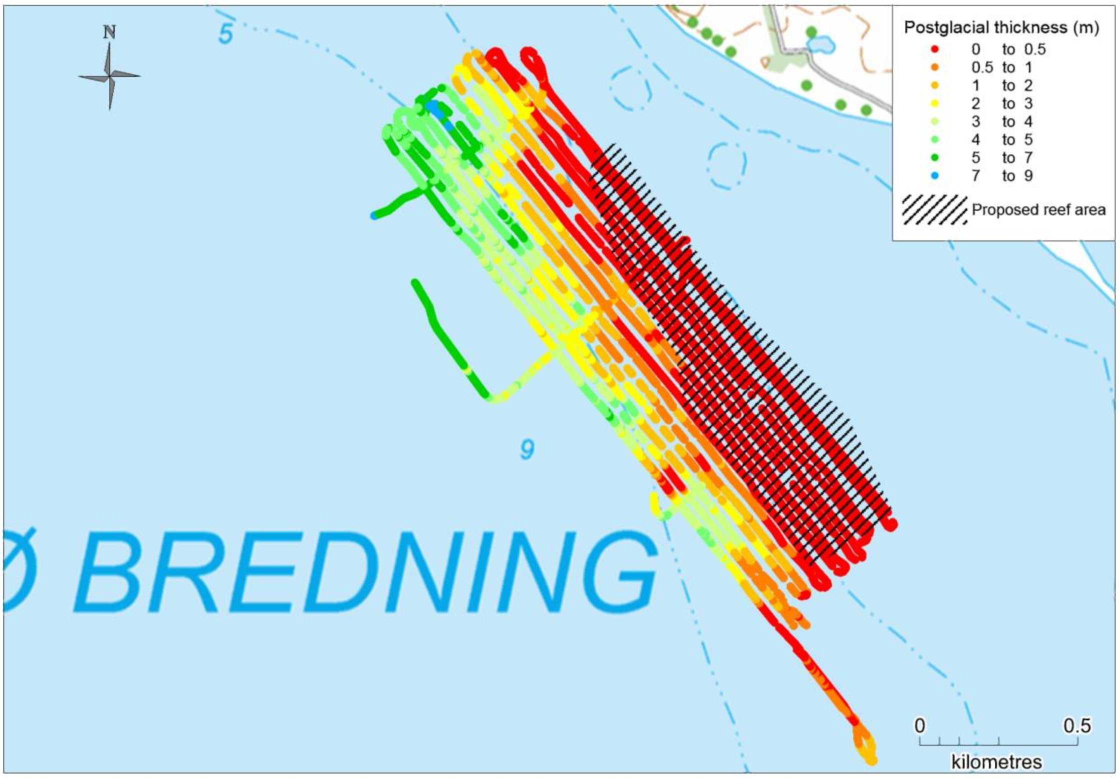


Figure 52. Livø Tap showing GEUS suggested new reef site (hashed area), also showing the postglacial thickness map.

The side scan mosaic of the area obtained from the survey was interpreted and together with the postglacial deposits thickness and the bathymetry a suitable site for reef establishment was proposed (Figure 53).

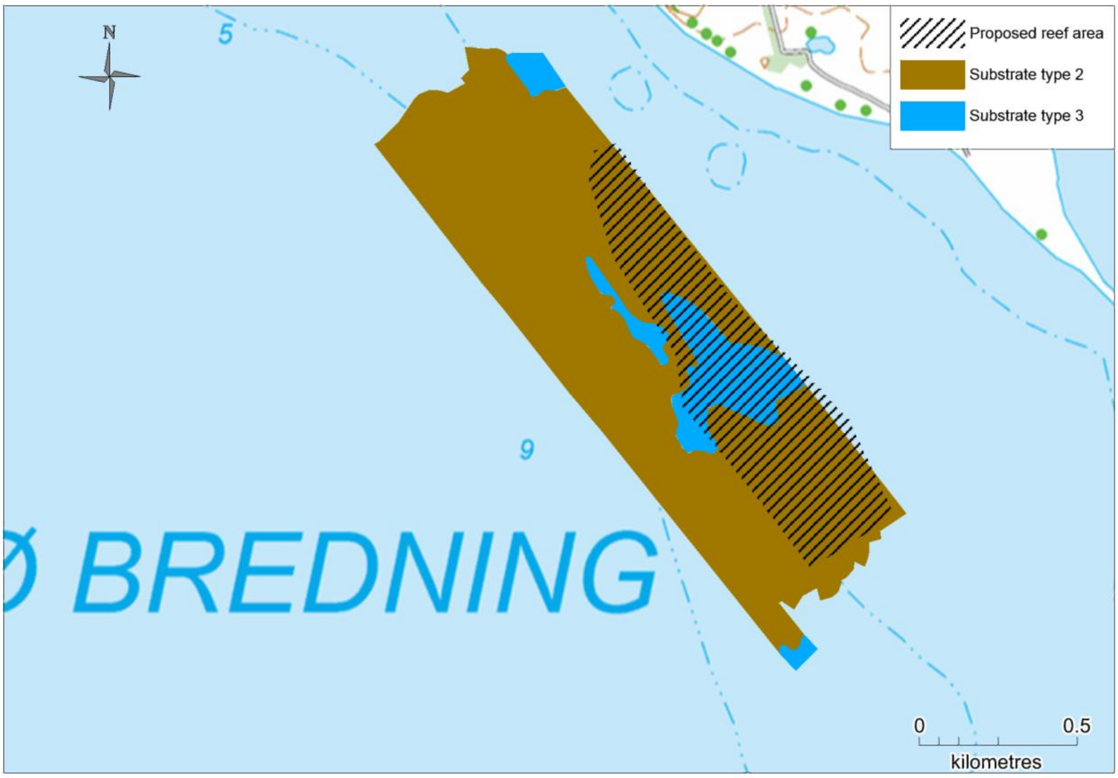


Figure 53. Livø Tap showing GEUS suggested new reef site (hashed area), also showing the substrates for the area.

The suggested stone reef site extends to areas of substrate 2 (sand and stones <10%) and there is no substrate 4 (stones >25%). This is actually due to the depositional nature of the area where a thin layer of sand covers most of the topglacial till deposits at shallow waters as shown in the high resolution seismic profile image in Figure 54.

Geotechnical analysis is also required in this area prior to the final decision on site location.

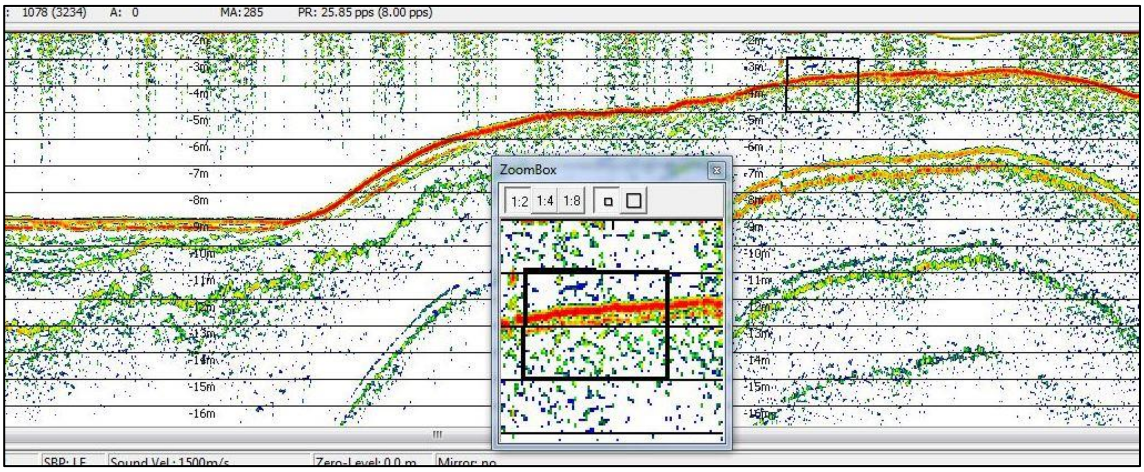


Figure 54. Livø Tap showing a zoom in high resolution image of the top section of the seismic profile (same as in Figure 51). It shows a thin second layer overlaying the glacial till.

7. Recommendations

Based on the background information of the area under investigation as well as the geophysical survey results and interpretation supported by the biological and hydrodynamic investigations, choosing an area for stone reef restoration requires the following:

1. Multi-disciplinary endeavour for analysing the different aspects and parameters affecting the stone reef re-establishment such as the geological setting, the hydrodynamic elements, and the biological status of the area under consideration.
2. A decision on the final goal of the reef, and the purpose it will serve is highly recommended. Will the restored reef function be to enhance benthic flora population for increasing oxygen production, or will it be cavernous reef that will also serve the pelagic animals such fish as well as the benthic fauna. The depth at which the reef will be established is a major parameter to consider in this work, because it will decide on the height of the reef and the stone size and distribution.
3. Upon that decision the design of the reef and its components can be suggested. Will it be cone shaped with many layers or almost flat with few layers of stones. The shape of the reef is very important for calculating the bearing capacity per unit area of the seabed and the size of stones required.
4. From the geological point of view, we have made the acoustic investigations of the area. And after interpreting the seismic, sidescan, and the bathymetry data we have recommended areas where stone reefs can be established with minimum risk of stone sinking. These areas where the topglacial moraine layer crops to the seabed surface or very near the seabed surface.
5. If for any other reason, such as depth restrains, the reef need to be established at other than these areas GEUS has delineated, a close study of the survey results need to be done for the suitability of the site can be deduced. In such areas geotechnical studies should be performed prior to the stone setting to determine the bearing capacity of the sites. To minimise the risk of sinking, the reef geometry and design requires the expertise of an offshore engineering company that have previously worked with off shore construction.
6. Considering the stone sizes, we believe that it should be of the same size of the currently existing stones in the area, what we are doing is reef restoration so the stone sizes should be similar to the surroundings. Again it depends on the purpose of the restoration and the depth it will be in. Cone shaped stone reef will require different design and stone sizes than the scattered one or two layers stones, and each will cause a different pressure on the substrate.
7. If the sediment transport and the dynamics in the reef re-establishing area is required, then we recommend to use a hydrodynamic model to quantitatively assess sediment deposition or erosion in the vicinity of the restored reef.

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9. Appendix 1 - substrate descriptions

The full coverage side scan mosaic of the surveyed area was classified into 4 substrate types, these are namely: 1a, 1b, 1c, 2, 3, and 4. The classification follows the Nature Agency (now SVANA) (Notate in 2012). The description of these classes is listed below:

1a. Soft seabed: These are homogeneous silty sand seabed or mud where there is no observed dynamic activity at the seabed and the sediment is composed mainly of silt, silty sand or mud.

1b. Sand: A homogeneous sandy seabed (sand is defined after the grain size of 0.06-2.0mm) with dynamic formations such as sand waves, ripple marks etc. In this class one can also find some shells or gravel.

1c. Patterned sandy seabed with clay: The seabed in this class is composed of clay or large relict clay blocks on silty or sandy surrounding where the clay high acoustic reflectivity gives a unique pattern of the seabed. This pattern can very possibly be caused by the high current at the seabed.

2. Sand, gravel, small stones with scattered (<10%) stones of >10cm: Highly variable substrate type dominated by sand and coarse sand with variable amount of gravel and small stones as well as few scattered large stones. The substrate is composed of a mixture of sand, coarse sand and gravel of ~0.06 – 20mm grain size, small stones of ~2-10cm grain size. The substrate may also contain larger stones of >10cm but only up to 10% of the coverage.

3. Sand, gravel, small stones with scattered (10-25%) stones of >10cm: The region classified as substrate 3 is a mixture of sand, gravel, small stones and scattered large stones of >10cm size. This substrate is similar to substrate 2, but it differs from substrate 2 in the percentage of the large stones content being 10-25% in substrate 3. The stones are often scattered in the area.

4. Stones >10cm with >25% coverage: The area classified as substrate 4 is dominated by large stones of >10cm in size, but sand, gravel, and small stones can also be observed in the area. Similar to substrate 3 the large stones can be found as a scattered layer, but substrate 4 may contain actual stone reef. Special type of substrate 4 is the pre-quaternary hard deposits such as granite and limestone. Substrate 4 includes also the bobbling reef and the biogenic reef.