Stockholm University

Bachelor Thesis

Degree Project in
Marine Geology 15 hp

Sediment classification from backscatter analysis of multibeam data from Lake Vättern

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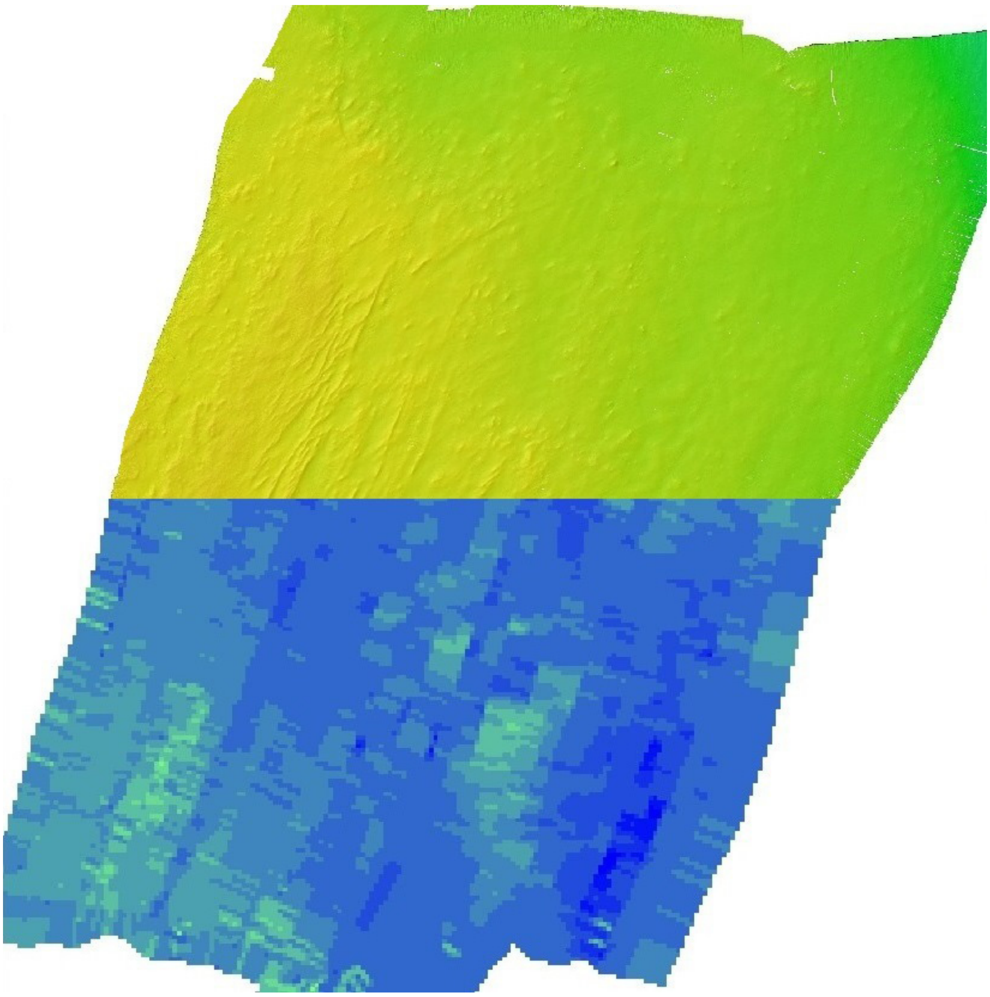

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SAMMANFATTNING

Under 2008, 2012, 2013 och 2014 karterades områden i södra Vättern med ett multistråligt ekolod. En del av dessa data användes i detta examensarbete där ett utvalt område norr om Visingsö har analyserats avseende de ytliga bottensedimenten. En djupkarta skapades efter databearbetning, och analys av backscatter samt Angular Range Analysis (ARA) genomfördes för att karaktärisera sjöbottnen. Resultaten visar flera småskaliga undervattens-ryggar, med olika former, storlekar och orientering. Dessa kan hänföras till processer som ägde rum då den senaste inlandsisen drog sig tillbaka från området. För att veta säkert när ryggarna skapades, och hur de är relaterade till isens uppbrott och tillbakadragande, måste mer forskning göras, och prover av bottensedimenten måste tas.

ABSTRACT

In 2008, 2012, 2013 and 2014 areas of southern Vättern were mapped with a multibeam echosounder. Some of these data were used in this thesis where a selected area north of Visingsö was analyzed for the superficial sediments. A depth map was created by data processing, and analysis of backscatter and Angular Range Analysis (ARA) was conducted to characterize the seabed. The results show several small-scale submarine ridges, with different shapes, sizes and orientation. These can be attributed to processes that took place since the last ice sheet retreated from the area. To know for sure when the ridges were created, and how they are related to ice breakup and withdrawal, more research must be done, and samples of the bottom sediments must be taken.

ACKNOWLEDGEMENTS

I would like to thank Martin Jakobsson, my supervisor, for getting me interested in the field of Marine Geology to begin with, and the chance to work with the Lake Vättern data. I have learned far more than I could imagine, and realized the sheer amount of work that is necessary to get good results. Another thank you goes to Sara Greenwood, who provided the raw data. Also a big thank you to everyone else who has helped me through this thesis, it is much appreciated.

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1. INTRODUCTION

In marine geology different methods have been used to map the ocean floor. The multibeam echosounder (ME) is one, used to gather bathymetric information. It may provide a high-resolution map of an area, but no direct information is received about the lithology. Cores will have to be drilled to acquire ground truth information about the lithology. There are however now methods, such as Angular Range Analysis, where data from MEs can be used to get additional information to the standard bathymetry, which may be used to interpret the geological composition of lake- and seafloors.

1.1 THESIS OBJECTIVES

The task of this 15 ECTS thesis, written at the Department of Geological Sciences, Stockholm University, was to analyze a given mapped area north of Visingsö in Lake Vättern and get an idea of the nature of the lake floor. To accomplish this, a backscatter mosaic was created, which showed how rough the bottom is; and ARA (Angular Range Analysis) was performed, which developed an estimate of the bottom sediments' grain size. The mapping took place during field work in 2013 by Martin Jakobsson among others.

The goal of the thesis was to develop skills in the processing of bathymetric data collected with multibeam sonar, and to answer the question: "What bottom morphological shapes are identified in the backscatter?"

1.2 GEOLOGICAL BACKGROUND

Lake Vättern is located in the south-central of Sweden, and is the country's second largest lake (1912 km^2). Its shape is similar to a convex lens, 135 km long and 31 km wide (at most), and has a maximum depth of 128 m (Forsman and Edlund, 2014). It lies within the Transcandinavian Igneous Belt (TIB), which intruded the Paleoproterozoic Svecofennian crust around 1.86-1.66 Ga (Bingen et al., 2008). After continent-continent collision the Sveconorwegian orogeny was formed, and rifting occurred along the Sveconorwegian Frontal Deformation Zone (SFDZ). As a result, a graben occurred, possibly around 700-800 Ma, which now hosts Lake Vättern (Andréasson and Rodhe, 1990).

At the start of the last deglaciation, Sweden was covered by the Scandinavian Ice Sheet (SIS). As the climate became warmer, the ice sheet retreated and melt water created the Baltic Ice Lake (BIL) around 16.0 ka, as Öresund became dammed due to isostatic uplift (Andrén et al., 2011). As the SIS continued retreating the area of Lake Vättern began to uncover, and it's current state started to form. At about 11.7 ka the BIL was drained for the last time, through a passage north of Mt. Billingen, and formed the Yoldia Sea (Andrén et al., 2011). During this stage the SIS continued retreating and fully exposed the Lake Vättern area (Fig. 1a). Figure 1 shows how the coastlines change between the Yoldia Sea and the Ancylus Lake. Somewhere in this transition between 11.1-10.5 ka Lake Vättern was at last fully formed (Andrén et al., 2011).

1.3 SURVEY AREA

The surveyed area that this work focuses on is 15 km^2 and is situated close to the center of Lake Vättern at 58°13' N, 14°30' E (Fig. 2). The depth varies between 15 and 82 meters, but the average depth is ~33 meters. Lake Vättern has two affluents, Huskvarna River and Forsvik River, who together with the effluent Motala ström attribute to the residence time of 60 years for the water in Lake Vättern (Forsman and Edlund, 2014). The land areas surrounding the lake contains mostly of granitoid rocks and granites.

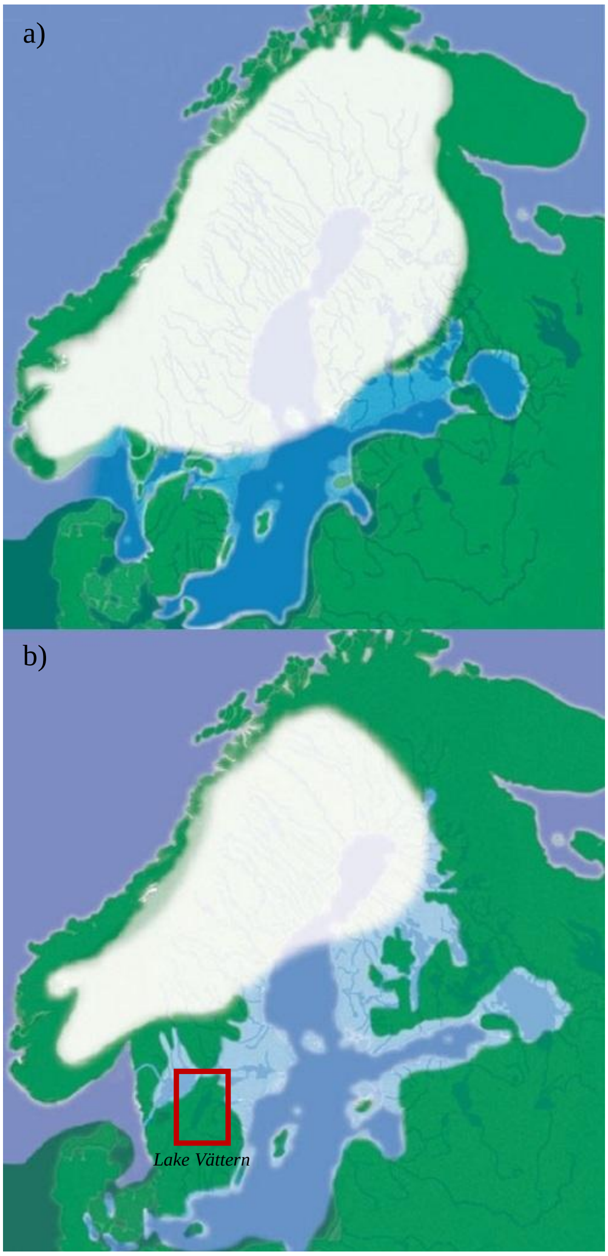

Figure 1 - Paleogeographic maps showing a) the Yoldia Sea at ca. 11.1 ka and b) the Ancylus Lake at ca. 10.5 ka – modified from Andrén et al. (2011).

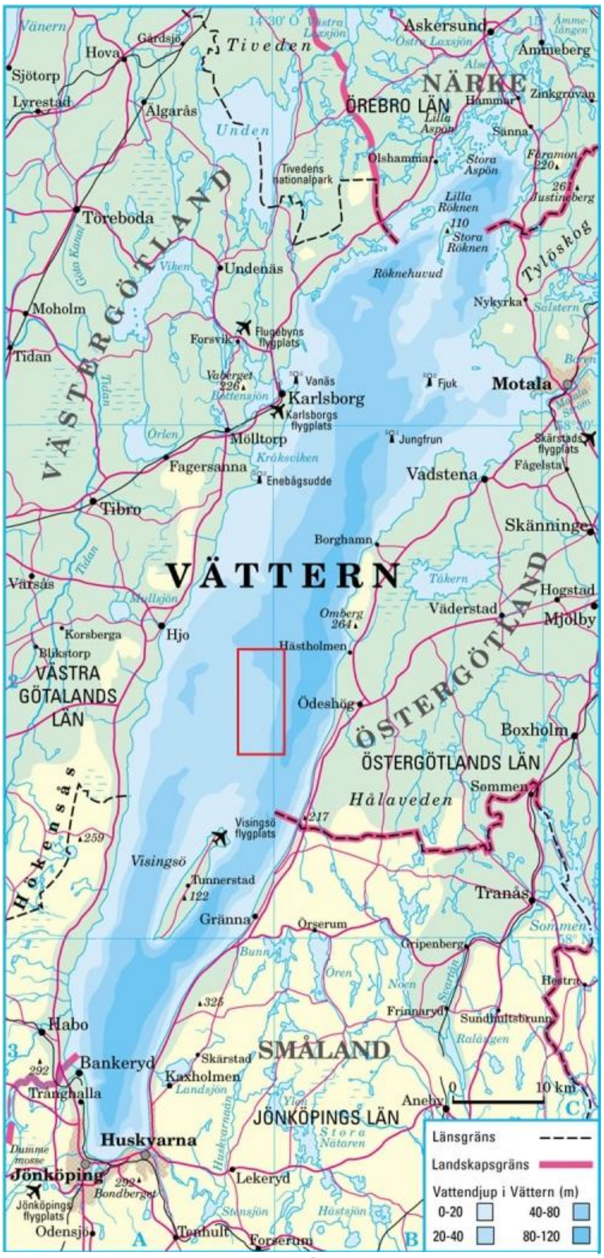

Figure 2 – Bathymetric map of Lake Vättern with the survey area marked with a red rectangle - modified from Forsman and Edlund (2014).

2. METHODS

2.1 MULTIBEAM ECHOSOUNDER

An echosounder uses sound pulses that travel through water to measure the depth to the lake- or seafloor. The sound is created by the use of a transducer, which converts electric energy to sound, by the help of piezoelectric components (Jakobsson, 2012, oral communication). If the geographical position of the depth is known, a 3D point reference is created. A bathymetric map can be constructed using many points, which means many beams of sound are needed. Through the use of several transducers connected, an array that is capable of producing narrow sound beams can be created, which can be transmitted to cover a wide area (transmit footprint), which is illustrated in Figure 3. While sound is being transmitted, specific areas are listened to (receive footprint). Where these two footprints intersect is called a beam. Along the transmit footprint multiple beams can be formed due to phase shifts in the receiver array, hence the name multibeam echosounder (Hell, 2011).

When using a ME there are things needed to take into account to be able to retrieve good data: sound velocity in the water column, heading, roll, pitch, yaw, heave, tide, time, and precise position. All of this is important to be able to know where the lake- or seafloor has been ensonified by a beam in 3D space. In a liquid the speed of sound is a function of the density and the bulk modulus (Hell, 2011). Salinity, temperature and pressure control these properties, so they need to be measured in the water column. These are not constant, therefore the sound velocity is not constant, and so the beam bends due to refraction. In order to convert the time delay (Δt) and the beam angle (α) to a sounding (x_S, y_S, x_S) you need to ray trace the beam from and back to the transducer's positions (x_T, y_T, z_T) while taking the transducer orientations (φ_T, θ_T, ψ_T) and the sound velocity profile into consideration (Hell, 2011).

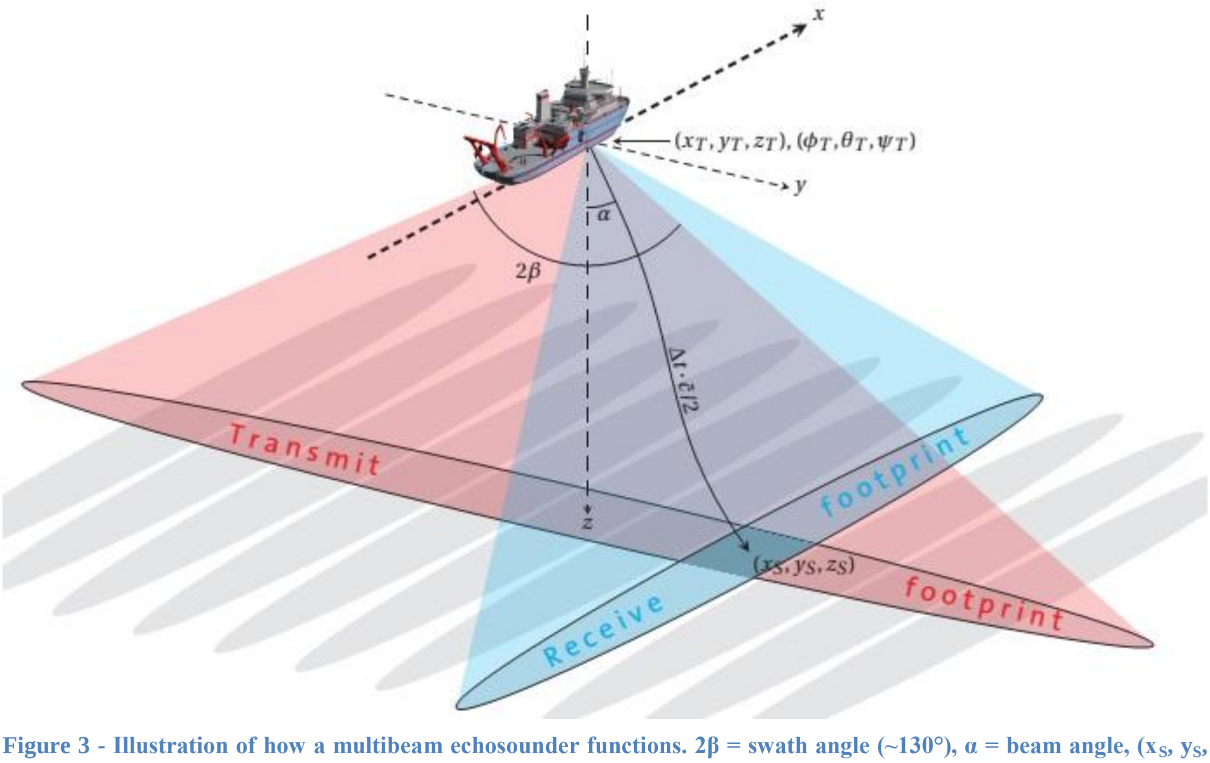

Figure 3 - Illustration of how a multibeam echosounder functions. 2β = swath angle (~130°), α = beam angle, (x_S, y_S, x_S) = sounding, (x_T, y_T, z_T) = transducer position, (φ_T, θ_T, ψ_T) = transducer orientation (roll, pitch and yaw angles), (Δt = t/2) = time delay (Hell, 2011).

2.2 BACKSCATTER AND ARA

When a swath intersects the lake- or seafloor it will do so at an angle, creating a dispersion of the individual beams (Fonseca and Mayer, 2007). Backscatter measures the intensity of the returned sound beam and is useful to assess the sediment type and roughness of the seafloor (rougher means more dispersion). The backscatter intensity varies with power of source, interaction with the seafloor (depends on angle) and absorption in water (depends on range) (Le Bas and Huvenne, 2009). In the result, a mosaic, the difference in backscatter intensity can be presented with various colors. For example, a lighter color can represent higher backscatter intensity, which means coarser sediments.

Angular Range Analysis (ARA) is a process used to characterize the seafloor by correlating the actual backscatter angular response to a curve of expected acoustic response (grazing angle vs. returned backscatter intensity) based on the Jackson model (IVS3D Fledermaus, 2011). The result is a classification of the seafloor in terms of different backscatter response curves, which may be displayed using different colors. Information that can be extracted from this method is the acoustic impedance, acoustic attenuation, the roughness and the grain size of the seafloor sediments (Fonseca and Mayer, 2007).

2.3 DATA ACQUISITION

Data used for this Bachelor Thesis was acquired from Lake Vättern in 2013 using a ME (Kongsberg EM2040, 300 kHz 1°×1°), mounted on the RV Skidbladner, a survey boat 6.4 meters long. Along with the ME equipment a Seatex MRU5+ motion sensor was used. In order to correct the ME system for variations of sound velocity in the water column, a sound velocity probe by Applied Microsystems was used. In addition, sound velocity at transducer face was continously logged using an installed probe. Positions were acquired with a Hemisphere R320 GPS, RTK corrected using the SWEPOS system (Jakobsson et al., 2014). The raw ME data collected were stored in *.all-files format, with positions referenced to the horizontal datum WGS84. To know the depth of Lake Vättern the vertical distance between the ellipsoid WGS84 and geoid model SWEN08_RH2000 (which is comparable to Mean Sea Level (MSL)) was used. The average water level of Lake Vättern is 88.5 meters above RH2000. This is what the depth data is referenced to.

2.4 DATA PROCESSING

The raw data was processed and handled using a suite of software from IVS3D including: DMagic, Fledermaus, and FM Geocoder Toolbox (FMGT) (Version 7.3.1a, Build 205, 64bit edition). Maps were created using ESRI ArcMap (Version 10.3).

The raw data was loaded into DMagic. There was a problem with the .all-file 0226_20130607_190705_Skidbladner, who failed to load properly, and was thus excluded completely. To choose a grid size, the average depth of Lake Vättern of 39 meters was used (Forsman and Edlund, 2014) and an adequate footprint of the beam was calculated using the formula:

$$F = 2 * d * \tan\left(\frac{\alpha}{2}\right) \quad \text{(Equation 1)}$$

F = footprint, d = depth, and α = sonar opening angle. This gave a footprint of ~0.7 meter, so a grid size of 1 meter was chosen and the data was gridded using the algorithm Weighted Moving Average with a weight diameter of 3. The average depth of the survey area is ~33 meters, which gives a footprint of ~0.5 meter. This could have been used as a basis for the grid size, but a larger grid size was used because the artefacts would be easier to process, at no cost of relevant data. The auto-processing function CUBE was used to create PFMs, which are files with editable surfaces that can be processed. Chosen was a bin size of 1 meter and WGS84, UTM zone 33N as the output coordinate system. No other changes to the settings were made. The data was then cleaned from artefacts and unimportant soundings (Fig. 4) in order create a bathymetric map of the area. This was done completely by manual editing, since automatic functions, such as “Select outliers”, did not help at all. The EM2040 data were in general rather clean. Most artifacts are found in the outer portions of noisier beams. The cleaned data was saved as a new, clean PFM-file.

To create a backscatter mosaic and the ARA, the FMGT software was used. The raw data from Lake Vättern was added, and created using the “Automatic Processing” option. The clean PFM-file was imported to clear the raw data from unwanted parts. To get an even better result some changes were made to the Processing Parameters. The Sonar Default values were changed to “Custom Override All”, and the Sonar Type chosen was “Simrad EM2040 MBES”. Also the “Along Track Beam Width” was changed from 2 to 1 degree , “Cross Track Beam Width from 1.5 to 1 degree, and the “Surface Sound Speed” was changed from 1500 to 1450 m/s (the sound speed from the raw data was used). The Beam Angle Cutoffs were also changed, where the “Starting Beam Angle” was changed from 0 to 1 degree, in an attempt to reduce the nadir. Also the mosaicking style “No nadir if possible 2” was applied. The AVG (Angle Varying Gain) Correction Algorithm was changed from “Flat” to “Trend”, in order to improve the noise reduction (IVS3D Fledermaus, 2011). For greater interpretability the histogram was also edited for the mosaic.

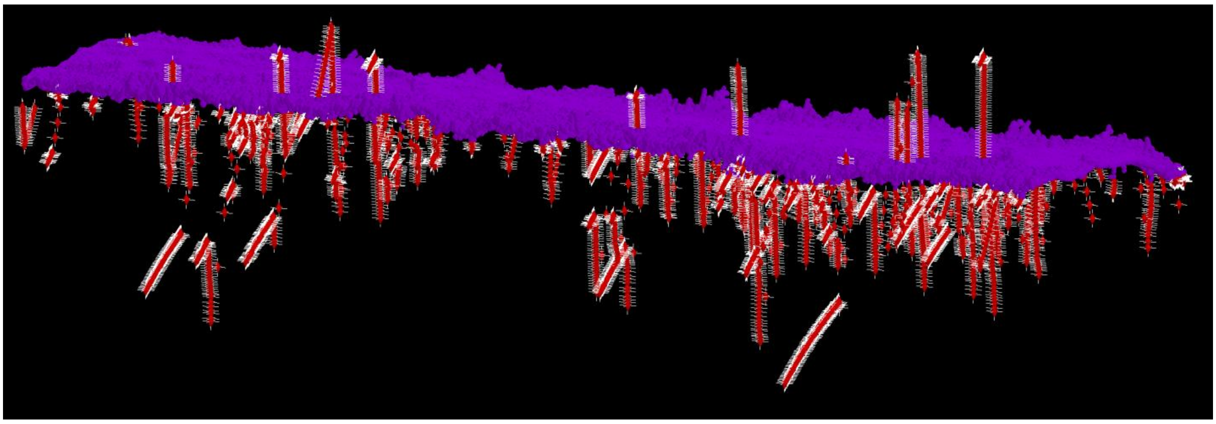

Figure 4 - Part of the data set showing the artefacts (red spheres). Screenshot is from the 3DEditor in the Fledermaus software.

3. RESULTS

The bathymetric map that was the result of the data from the survey area gives a high resolution image of the lake floor (Appendix, Fig. A). The focus here is on the central part and the area which was subjected to systematic surveying (Fig. 5), and gives a good opportunity to interpret the bathymetry and backscatter/ARA results.

3.1 BATHYMETRIC FEATURES

The lake floor is generally quite flat, with mostly only gradual depth differences. The lake floor is rugged and rather heterogeneous with respect to types of bathymetric features and their distribution (Greenwood and Jakobsson, in press). There are small scaled features, which are marked in Figure 5a, and will be further discussed.

Figure 6a shows ridges that are a couple of hundred meters long, are narrow and have amplitudes of about 1 meter. They have a slight downward slope towards the north, a NNE-SSW orientation, are straight, parallel and are close to each other. Also visible west of the straight ridges are ridges that connect to each other in a wavy pattern, with the same orientation. These ridges were also described by Greenwood and Jakobsson (in press). In Figure 6b the ridges are not easily visible, no matter which color map in the FMGT you choose to present the backscatter in. This means no apparent difference in acoustic characteristics that affect the backscatter is present, which is also shown in the ARA (Fig. 6c).

More wavy ridges are present in Figure 7a, although these are not interconnected. They have a different orientation (ENE-WSW) and smaller amplitudes (ridge height) (Greenwood and Jakobsson, in press). These ridges are not at all visible in the backscatter (Fig. 7b) or the ARA (Fig. 7c).

Figure 8a displays more ridges similar to the straight ones in Figure 6a, but these have a non-parallel orientation. Their northern end-members are quite distinct, like “noses”, and give the ridges shapes resembling matchsticks according to Greenwood & Jakobsson (in press). Other than that they are quite similar to the before mentioned ridges, including the sharp cross-profile shown in Figure 9. It also shows that the eastern side of the ridges can be steeper and deeper than its western counterpart. The ridges are again barely visible here in the backscatter (Fig. 8b) and not at all in the ARA (Fig. 8c).

In Figure 10a we have a rough area of the lake floor. In the center we have a shallower area, with ridges of varying shapes, but a unifying orientation of NNE-SSW. Their cross-profile is not as sharp or as high as in other areas. In the center- and upper-left part of Figure 10a we have more wavy ridges as seen in other areas. These have an orientation of NE-SW. The results from the backscatter mosaic and the ARA are a bit more interesting in this area. There is a clear difference in backscatter response in Figure 10b; and in grain size in Figure 10c.

3.2 BACKSCATTER FEATURES

Figure 10b shows the resulting backscatter mosaic of the survey area. In Figure 11 there is a close-up of the area of interest, and the features that have been mentioned above. The mosaic of the area seems to be quite uniform, with not many abrupt color differences. In the north-east and south-east corners a slight gradual change from a light to a darker grey can be seen. Only in south-west corner can we see a more abrupt difference, which is shown in Figure 10b. A darker color corresponds with weaker backscattered signal, which represents a smoother surface.

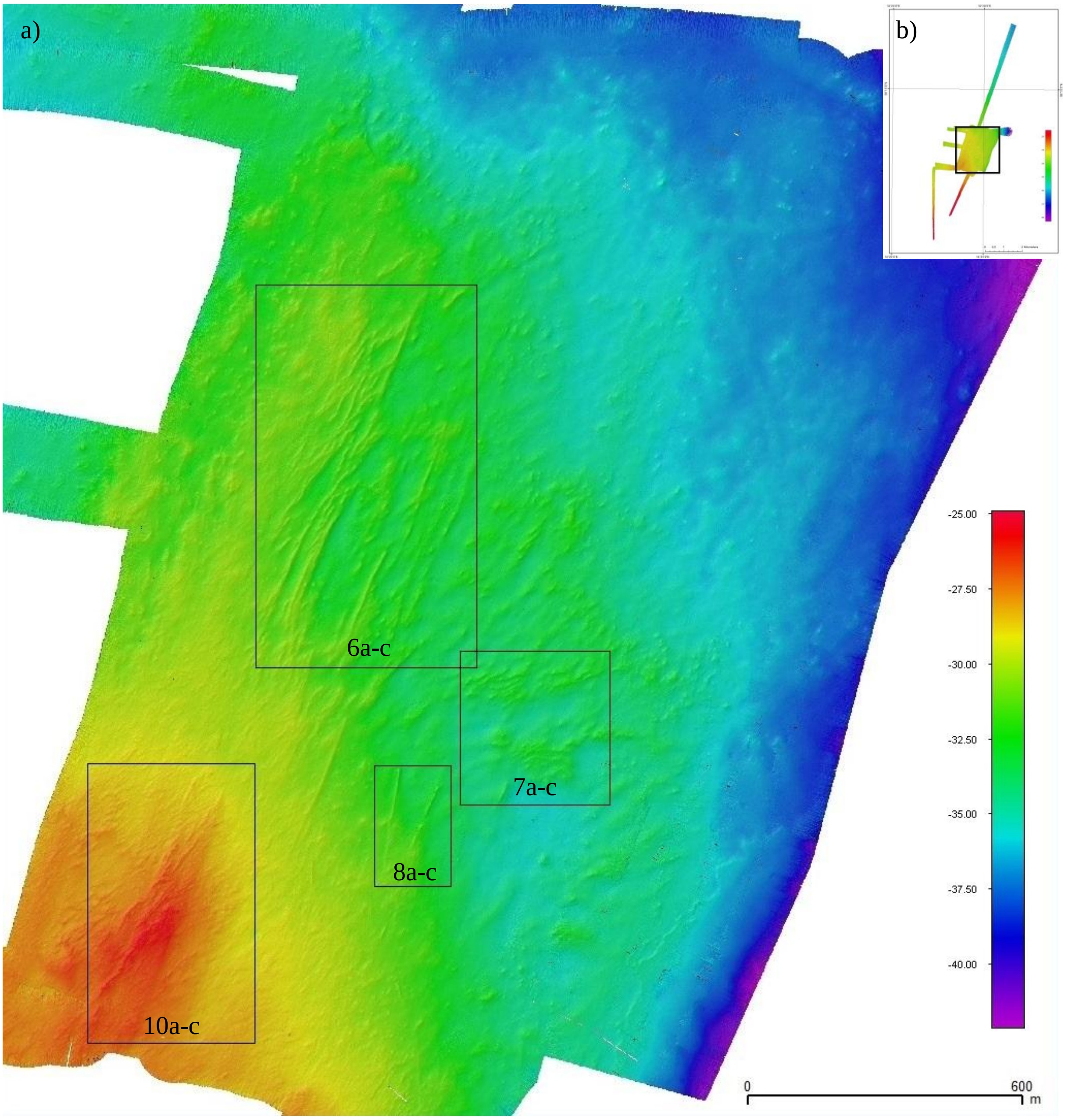

Figure 5 – Bathymetry map a) the part of the survey area that is of interest. Discussed features are marked with rectangles, with matching figure numbers. The depth legend is in meters b) the entire survey area; attained using a Kongsberg EM2040 ME. The Fledermaus software was used for processing, cleaning and visualizing. (See Appendix, Fig. A for a full-sized version). The inset rectangle shows the area in panel a).

3.3 Angular range analysis

The result from the Angular Range Analysis can be seen in Figure C, and the area of interest in Figure 12. Since the ARA is made from the backscatter, they match each other quite well. Larger differences are due to the ARA's lower resolution and its inclusion of grain size. The distribution of the sediments is somewhat uniform. The finest sediments are in the flattest and deepest areas, besides the ones in the southwest. The most abundant sediments are medium and gravelly muddy sand. The coarsest sediments are the scarcest, along with the very finest, which encompasses coarse sand and sandy gravel, and very fine and muddy sand. The coarsest sediments are concentrated to only a small area in the southeast corner of the survey area, when the finest sediments are more distributed. Besides the central ridges in the area of Figure 9 the bathymetric features in this survey are not at all visible in the ARA.

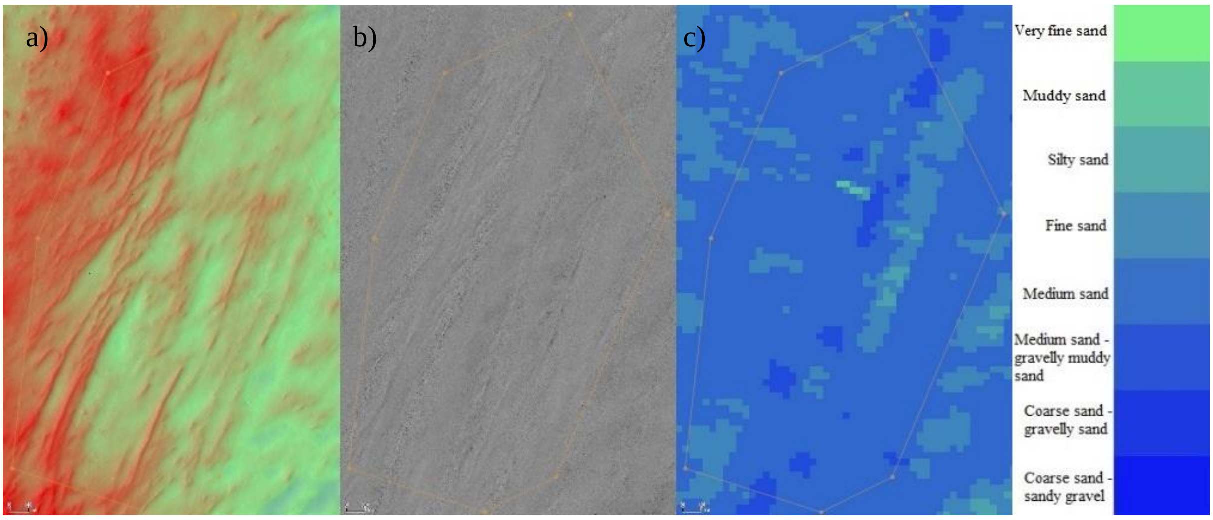

Figure 6 - Ridges oriented NNE-SSW a) Bathymetry b) Backscatter response c) ARA.

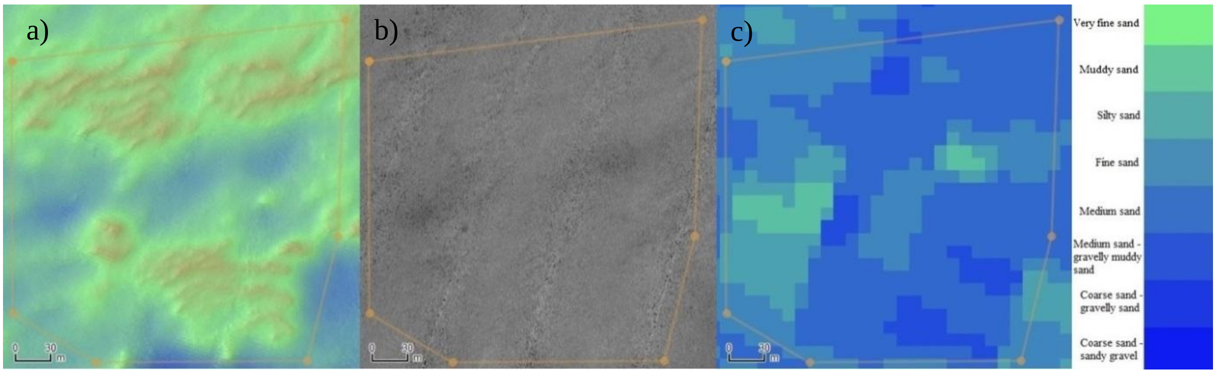

Figure 7 - Wavy ridges oriented ENE-WSW a) Bathymetry b) Backscatter response c) ARA

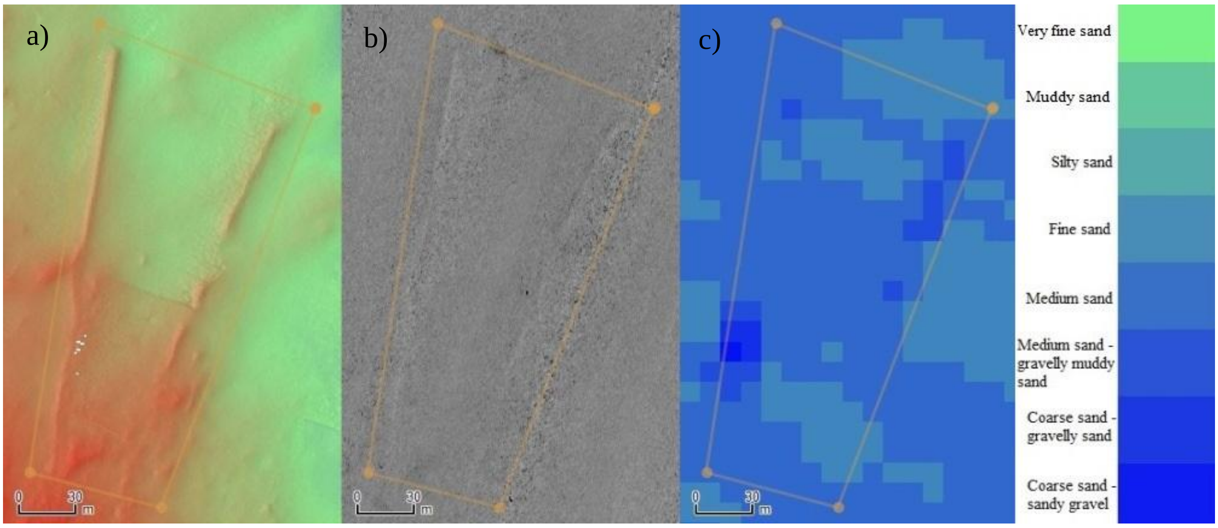

Figure 8 – Ridges with varying orientation, with distinct northern tips, or "noses" (Greenwood and Jakobsson, in press) a) Bathymetry b) Backscatter response c) ARA

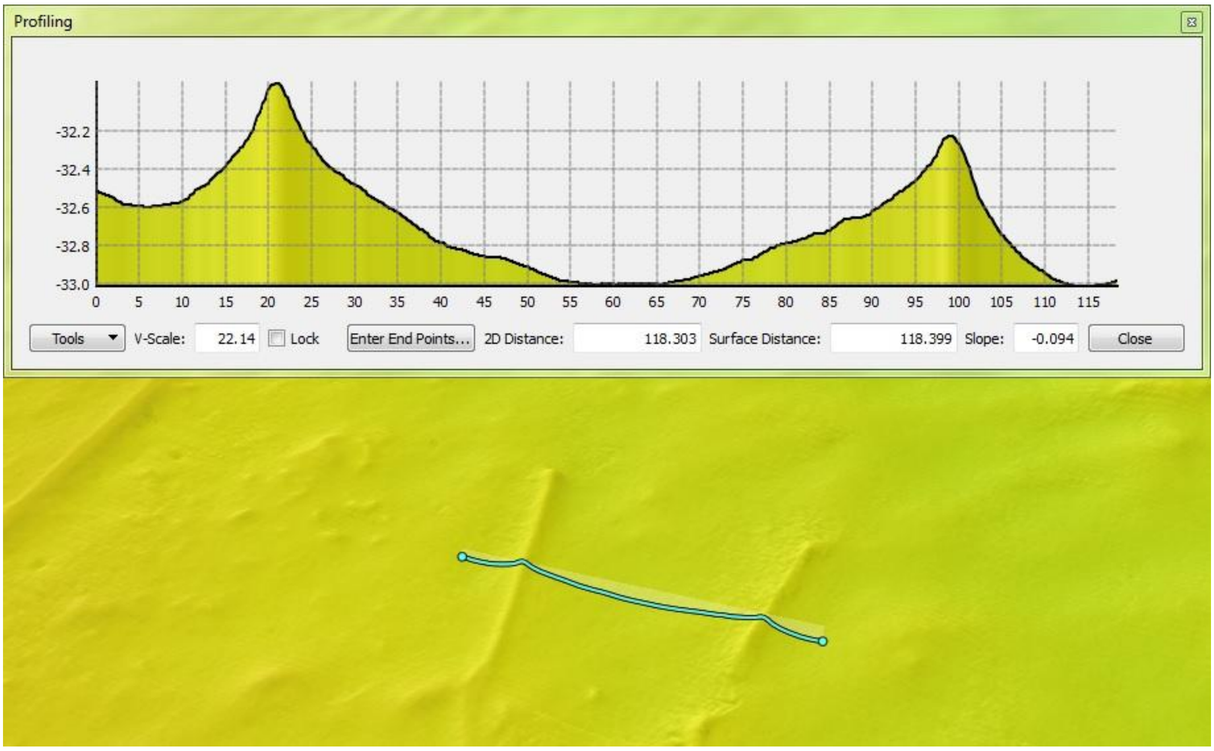

Figure 9 - Cross-profile of ridges in Fig. 8.

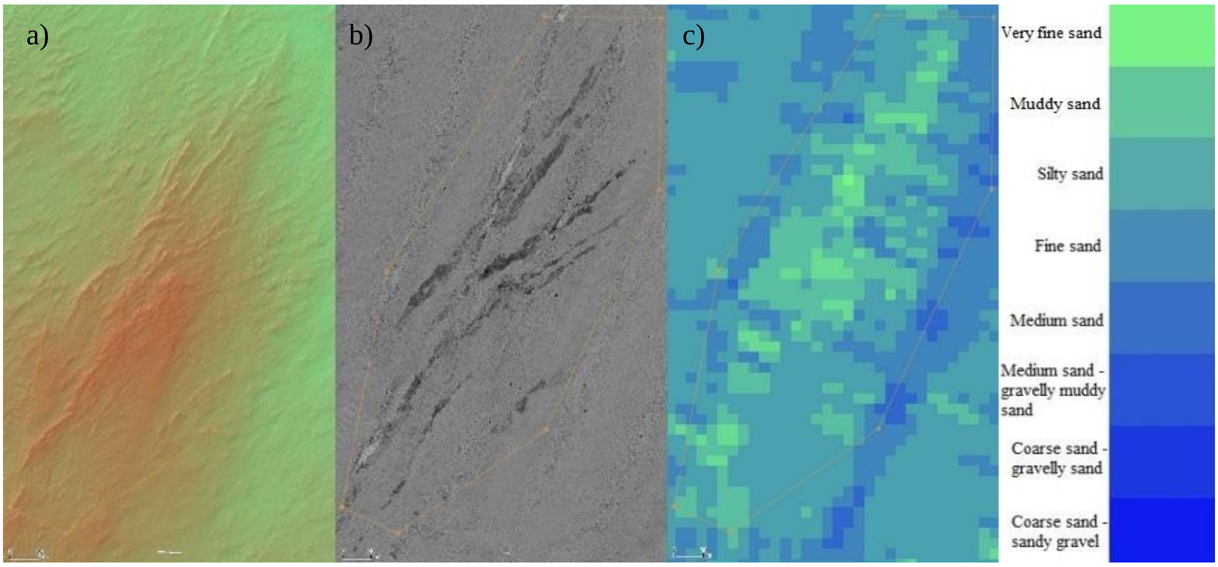

Figure 10 - Wavy ridges oriented NE-SW in the top left corner, and ridges oriented NNE-SSW in the center a) Bathymetry b) Backscatter response c) ARA

Figure 11 - Backscatter mosaic, displaying the backscatter response a) The part of the survey area that is of interest b) The entire survey area, processed and visualized using the Fledermaus software (See Appendix, Fig. B for a full-sized version). The inset rectangle shows the area in panel a).

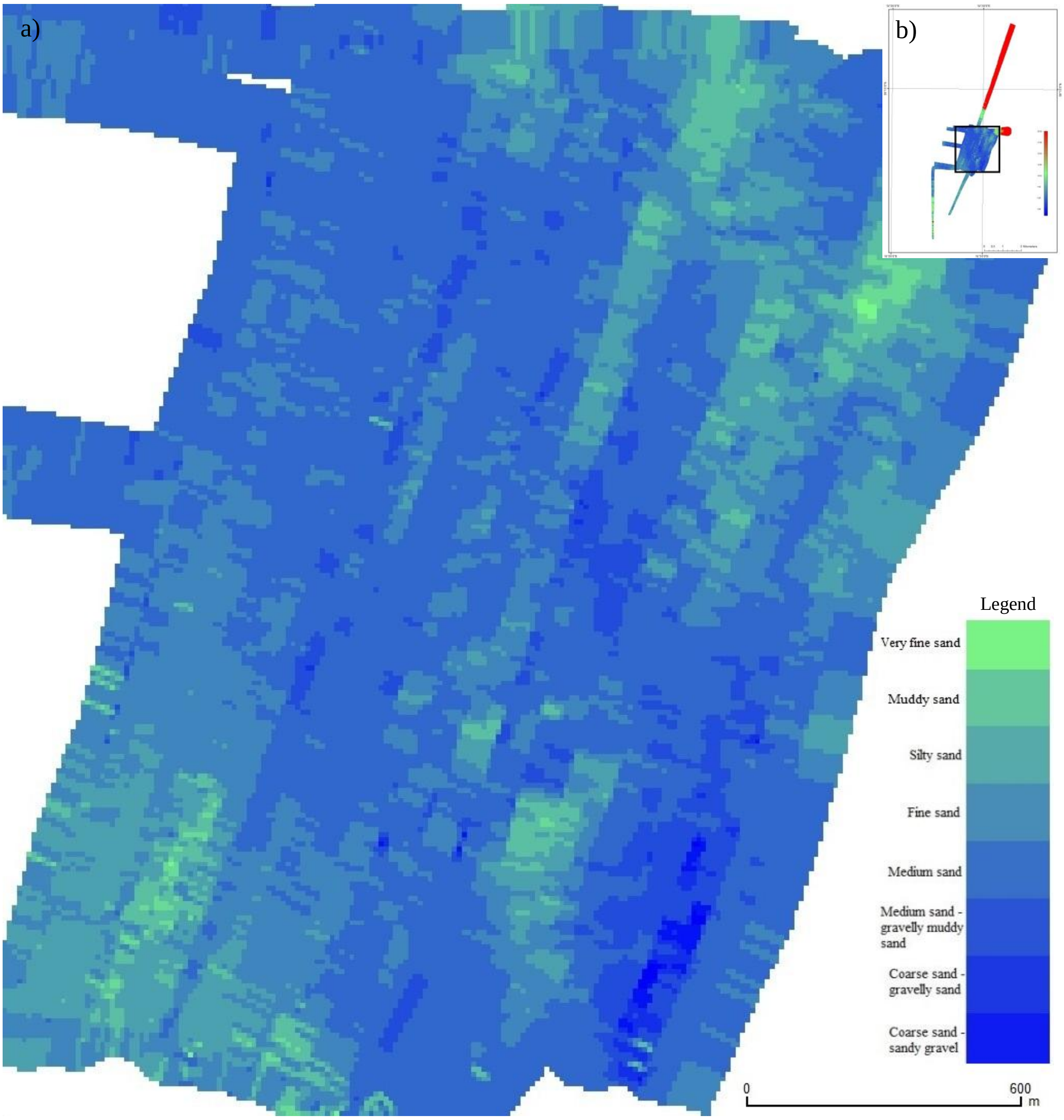

Figure 12 - Results from the Angular Range Analysis (ARA), where the surface sediment type is estimated using the backscatter strength a) The survey area of interest. A color on the map represents a certain sediment type b) The entire survey area. Processed and visualized using the Fledermaus software (See Appendix, Fig. C for a full-sized version). The inset rectangle shows the area of panel a).

4. DISCUSSION

The main objective of this thesis was to get experience in dealing with data from a ME by using different methods and software. The result was three maps that give different information of the lake floor, which will be discussed below.

4.1 GLACIAL HISTORY

20 ka Sweden was completely covered in ice. As time progressed, the ice retreated, exposing more land. Around 12.5 ka the survey area in Lake Vättern began to uncover, and during the next 300 years the process continued, fully exposing the area. At 11.4 ka Lake Vättern was no longer covered in ice (Björck et al., 2001). During this time, ca. 11.5 ka, due to isostatic unloading, Lake Vättern experienced an earthquake with a seismic moment magnitude of 7.5 (Jakobsson et al., 2014).

These events shaped Lake Vättern, so the features present in the survey area could originate from this. How much or if the earthquake has affected these features is however not clear.

4.2 BATHYMETRY

The bathymetry map shows ridges of different shapes, sizes and orientation. How these ridges were created, and how they are related to each other, i.e. if they were created at the same time or/and in the same environment, is something worth investigating Greenwood and Jakobsson (in press) suggested that these features are records of a glacial near-marginal environment. They considered three various origins for different features:

a) The wavy ridges could have been formed as small moraine segments at/near the grounding line. Similar moraines of subaqueous origin have been found in other parts of Sweden (Strömberg, 1965). This suggests an ice margin with a SW-NE orientation and an ice flow coming from the northwest. However, Björck et al. (2001) suggest that the ice margin had an WNW-ESE orientation.

b) The ridges in Figure 6 and 8 can have formed from filling of crevasses at the base of the ice sheet. These crevasses may have had a complicated connection to each other, explaining the varying shapes and orientations of the ridges.

c) The sharp top of the edges and shape of the sides of them can be because floating ice laterally being pushed by the marginal ice sheet.

The resulting bathymetry map is nowhere near perfect. There are remaining artefacts (Fig. 13a), though mostly along the edges due to noisy outer beams (Fig. 13b). One possible explanation for the partly noisy data and problematic outer beams could be that the wind speeds increased during the survey and that few sound velocity profiles from this area were collected (Jakobsson, M., 2015, oral communication).

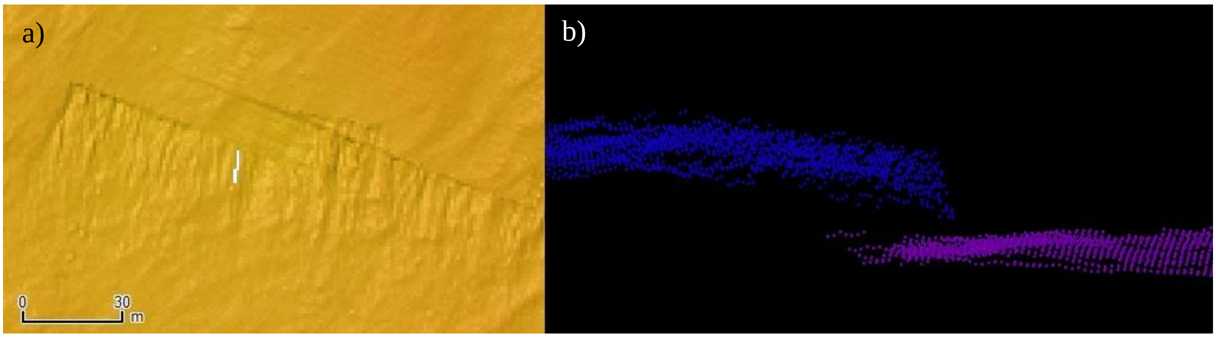

Figure 13 - Artefacts in the bathymetry a) Part of the map where the artefacts could not be removed b) Two lines of the data that do not align

4.3 BACKSCATTER

In Figure B it is visible that the survey lines that extend from the center differ greatly. It looks like the northern survey lines are darker, due to calibration difficulties, most likely the ME changing its mode. Similar problems are clear in the southwest. This is why they were not included in the results, and not considered important.

In the resulting backscatter mosaic, in the area I have deemed important, there are not many features to observe. The backscatter response is only very clearly different in the southwest corner (Fig. 10b). The bathymetry is illuminated from the NW, casting the eastern flank of the ridges in shadow. Coincidentally, the shadowy eastern flanks in the bathymetry and the dark patches in the backscatter mosaic match extremely well. In a cross-profile you can see that the western flanks are quite steep, while the eastern flanks are flatter. The angle at which a beam hits the lake floor makes a big difference when it comes to backscatter.

A reason for the difference in backscatter response could be that underwater currents or waves cause erosion and that finer sediments settle on the eastern flank, and thus a difference in the backscatter is created. To which depth waves creates enough motion to induce erosion is something that must be taken into consideration. Greenwood and Jakobsson (in press) wrote that at 35-40 meters below lake level features are beneath the modern wave-base , even considering a post-glacial low-stand of 20 m below present lake level. These features are at ~25 meters below lake level, so the area may have been affected by wave action since the deglaciation.

4.4 ARA

Since the ARA is based on the backscatter, some of the artefacts present in the backscatter mosaic are present in the ARA. In Figure C the difference between the extruding survey lines and the center is clear. The northern survey lines present the bottom as red, which means clay. Again these survey lines are ignored due to the difficulties of proper calibration. The sediment characterization is based on how well the response curve fit a modelled curve, implying that many parameters affect it. The grazing angle is a major component, and sometimes the depth is too great for it to work. The results seem reasonable, except the ones from the extruding survey lines of course.

Although we have estimated the sediment grain sizes, we still do not know their origin, or the types of sediments present. Coring is necessary in order to ascertain origin, composition and age. The distributions of the grain sizes are quite patchy, and the reasons for this could be a problem with the software. Finer sediments often prefer calm areas, and coarser sediments occur in more energetic environments.

Angular Range Analysis is still quite a new method and needs more time to be able to become more reliable. One good result does not guarantee more, and precise calibrations will continue to be paramount.

5. CONCLUSIONS

The goals of this thesis have been accomplished to a satisfying degree. A lot has been learned about the processing of data from a ME, and what kind of information that can be extracted. An area of Lake Vättern has been analyzed using backscatter and ARA, creating a mosaic and an ARA map of the area. The question: "What bottom morphological shapes are identified in the backscatter?" has been answered, which is "not many". This area is mostly flat and featureless, apart from the visible ridges. The bathymetry can be visible, but not very well. Patches of varying backscatter response are reflected, but the cause of these is not crystal clear.

In order to make more sense of the features in this area more research has to be done. Coring will be a requirement, to be able to ascertain the origin and composition of these sediments. ARA is a very helpful tool, but it needs to be further developed.

APPENDIX

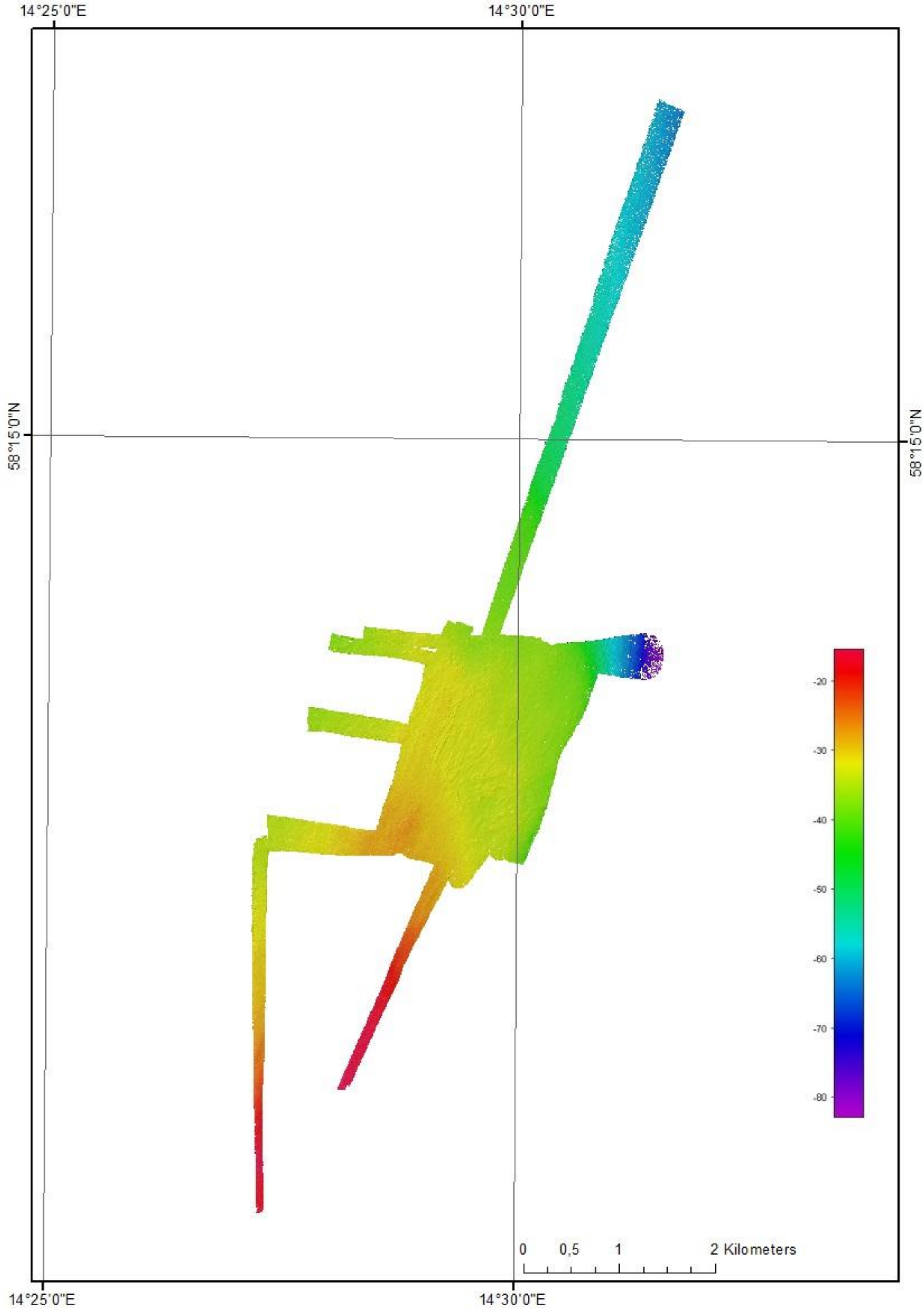

Figure A - Bathymetry of survey area

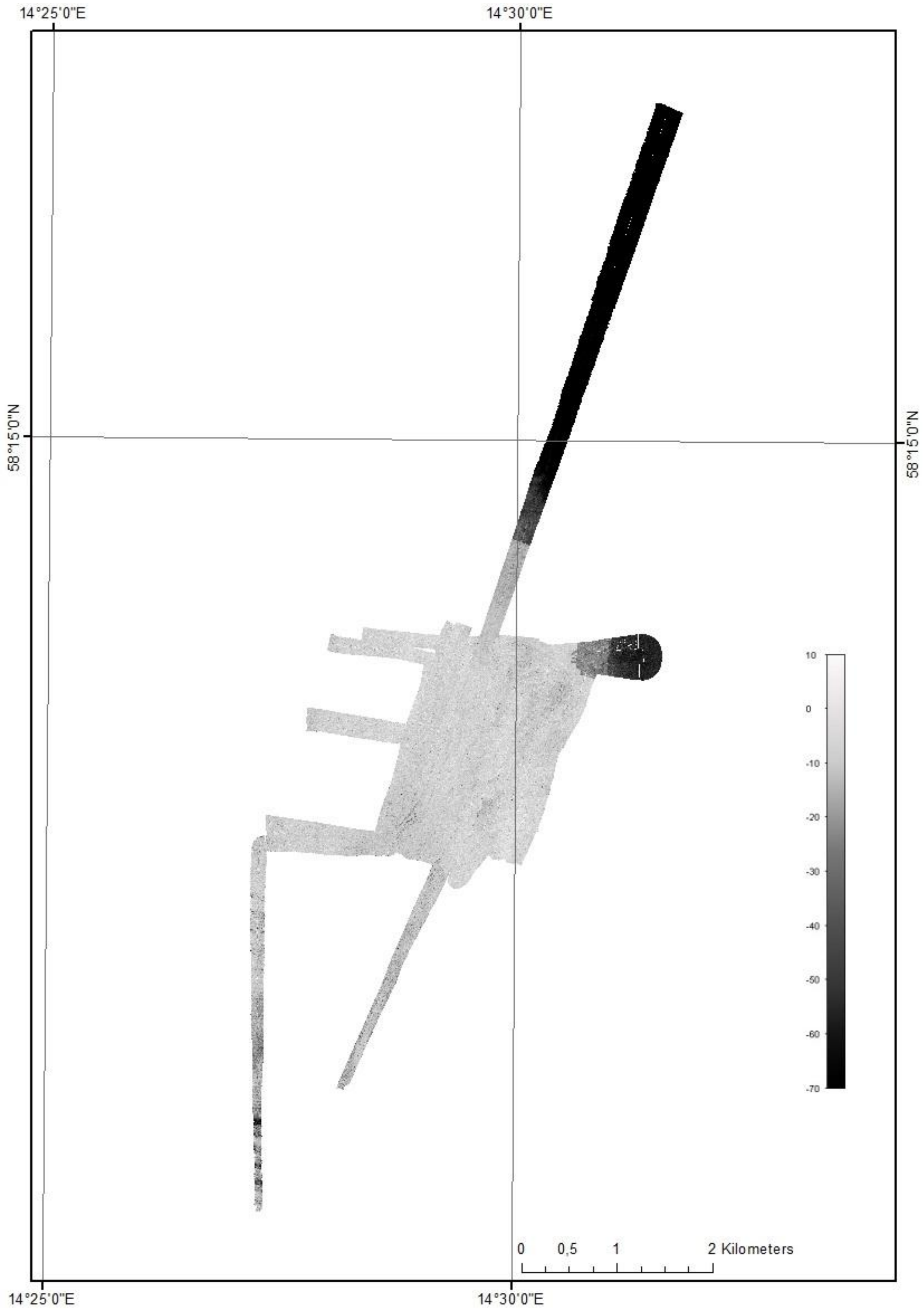

Figure B – Backscatter mosaic of survey area displaying the backscatter response

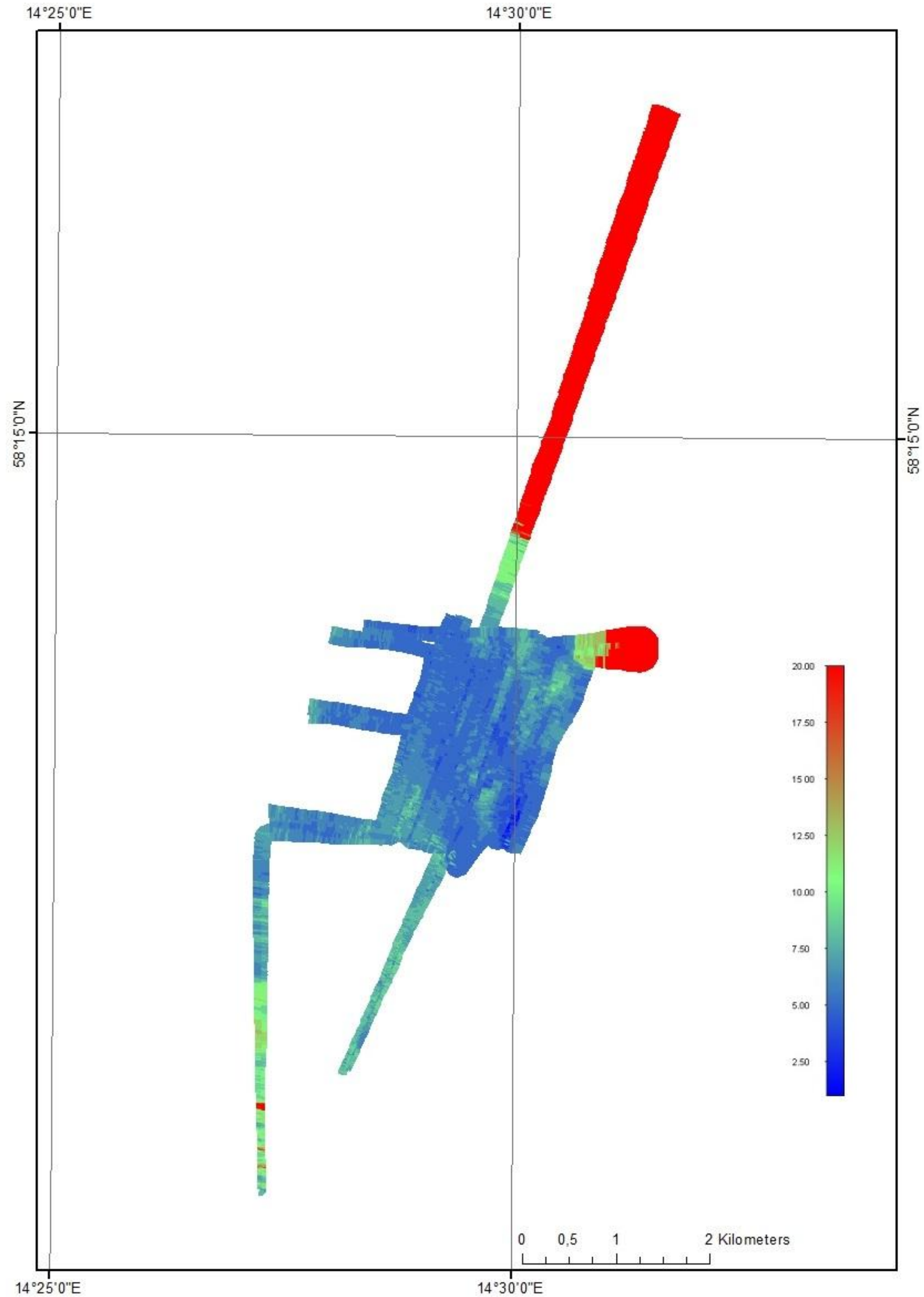

Figure C - Survey area with ARA characterization results.

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