

Results from Marine geological investigations outside Forsmark

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Geological Survey of Sweden

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

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Summary

A detailed marine geological survey was conducted in a 10 km² large area outside Forsmark comprising hydroacoustic, 100 m spacing between survey lines, and groundtruthing. These data, together with reanalyzed survey data retrieved in 2002 from the same area, were used to produce maps of seabed and underlying bedrock surface morphology as well as horizontal and vertical extension of sediments.

An esker is discovered running approximately in a north northwesterly-south southeasterly direction in the area, which may be causing submarine groundwater discharge. Pockmarks, which are caused by sediment gas of thermogenic and/or microbial origin, are detected in the area.

In addition to the original commissioned survey, bedrock surface and seabed morphology as well as horizontal and vertical extension of sediments in a larger adjacent area were reanalyzed and produced from survey lines retrieved during a commission by SKB in 2002 and during SGUs regular mapping program in 2002, 2008 and 2009.

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1 Introduction

This report presents the results from the investigation “An extended detailed Marine Geological Survey outside Forsmark” of the sea bed adjacent to the nuclear power plant site at Forsmark. The survey was commissioned by the Swedish Nuclear Fuel and Waste Management Co (SKB) and carried out by the Geological Survey of Sweden (SGU). The survey comprised detailed hydroacoustic mapping and ground truthing. The work was performed in accordance to ”Metodbeskrivning för maringeologisk undersökning” (SKB MD 260.001) and following the activity plan “Utökad maringeologisk undersökning av havsbotten utanför Forsmark” (AP SFR 10-002) during the period August 2010 to May 2011. The fieldwork was carried out in August 2010.

In addition to the data collected in 2010, hydroacoustic and groundtruthing data, collected in 2002 (Elhammer and Sandkvist 2005), during a survey commissioned by SKB, are reanalyzed and used in the production of the deliverables in the 2010 survey area. Survey lines retrieved in 2002, 2008 and 2009 during SGUs regular mapping programme are also reanalyzed and used together with the 2002 SKB lines in the production of deliverables in a larger, adjacent area including Öregrundgrepen, see Figure 1-1.

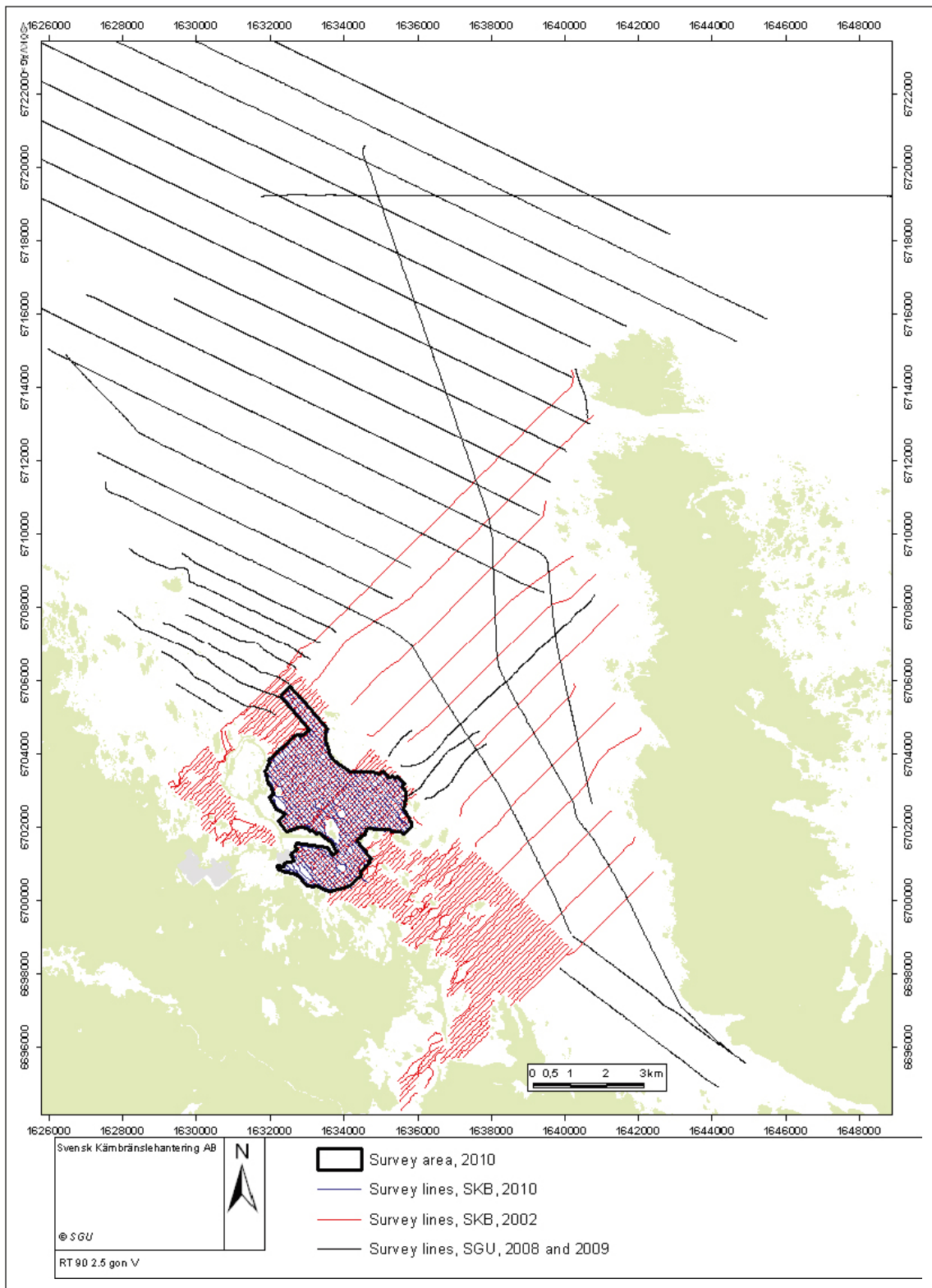


Figure 1-1. The primary survey area (in black) above SFR with the survey lines retrieved in 2010, in blue, and the survey lines retrieved in 2002, in red, commissioned by SKB. The survey lines retrieved in 2002, 2008 and 2009 during SGU's regular mapping program, shown in black, mark the extended, adjacent area, which also is included in the deliverables.

2 Objective and scope

The aims of the present marine geological survey were to map (in the primary survey area shown in Figure 1-1):

- The morphology of the sea bed.
- The morphology of the underlying bedrock surface.
- The horizontal and vertical extension of sediments.

During the course of the work the area was extended to a larger, adjacent area, including the Öregrundgrepen region as shown in Figure 1-1.

3 Background

SGU performed, in 2002, a detailed marine geological survey, which covered the same area as the survey in 2010, as well as a larger area of the seabed outside Forsmark. The survey lines, measured in 2002, had 100 m spacing in the 2010 investigated area. The results and deliverables of that survey consisted of maps showing the morphology of the seabed and underlying bedrock surface as well as seabed sediments and the horizontal and vertical extensions of the sediments. The data was used to model future sea barriers and lakes. The aim of the present survey is to increase the resolution of the data in that area and to do targeted investigations on identified future sea barriers. The survey lines, for the present survey, are placed with 100 m spacing perpendicular to the lines surveyed in 2002, see Figure 1-1.

The area outside Forsmark was mapped in 2002, 2008 and 2009 within SGUs regular mapping program using hydroacoustics, approximately 1,000 m between survey lines, and associated groundtruthing. These data are also used in the production of the deliverables; water depth and vertical extensions of sediments in the larger area as shown in Figure 1-1.

4 Equipment

4.1 Description of equipment

The field survey equipment used is:

- Survey vessel: A water jet powered 7.7 metres survey launch.
- Positioning, survey monitoring and depth logging: LEICA DGPS receiver, Hemisphere differential GPS receiver, EPOS RDS corrections, Navipac survey computer system.
- Echo sounding: Foruno / Reson 200 kHz.
- Sub bottom profiler: Geopulse digital Profiler 1–15 kHz / Triton SB-logger.
- Reflection seismics: Benthos Bubble Pulser one channel / Delphseismic.
- Swathsonar: Geoswath, swaths for depth measurements and conventional side-scan sonar measurements at 250 kHz / GS+.
- CTD probe, Valeport.
- Sediment samplers: Small grab sampler and gravity corer.
- Under water digital camera.

The equipment for analyses and interpretation consists, in short, of:

- Software for survey planning, data interpretation, geometric correction, production and delivery of spatial databases (mainly Meridata, Micro Station, IRAS-C 8.0, ESRI ArcMap 9.3 and software specially developed by and for SGU).
- Software for handling and storing sediment sample descriptions (mainly Microsoft Access 97).

5 Effectuation of survey

The assignment was performed according to the specification "Metodbeskrivning för maringeologisk undersökning" (SKB MD 260.001) in the area shown in Figure 1-1. The survey lines were placed perpendicular to the lines surveyed in 2002 with 100 m spacing.

Surveying was performed along the preplanned survey lines. The survey included echo sounding, sediment profiling, reflection seismic, side scanning sonar and swaths for depth measurements.

In areas where the actual water depth was much shallower than according to the nautical charts, the survey area and line planning was adjusted according to the physical conditions. During surveying, the systems were all used simultaneously with digital recording of all data, and positioning of each system. Information about the surveying of each line was noted in a protocol as well as any changes or problems. After quality control of each survey line, the data were processed, preliminary interpreted and ground truthing stations were chosen.

Ground truthing is done to verify the geological interpretation of the hydroacoustic image. It is also used to solve interpretation problems. Two different types of samplers were used: a 1 m gravity corer for soft sediments and a grab sampler for coarser sediments. Before sampling, the sampling site was photographed with an under-water digital camera and descriptions of the seabed were noted in a protocol. The camera position aboard the survey launch is approximately (± 2 m) the same as the sampling station. Each sample is described and the description is stored in a database. The database contains a main table for technical data, positions, water depth, time and sampling method etc. This table is then linked to tables that contain sediment description data, sub sample data including sub sample weight etc. Normally the samples are photographed.

5.1 Preparations

Function testing of the equipment.

With the exception of the positioning and water depth measurements, the data is used qualitatively rather than quantitatively. Calibration is thus not used.

Positioning is controlled against a fixed point on land.

Echo sounding measurement was controlled against known water depths. Sound velocity in water is measured with a specially designed CTD-probe. Information from an automatic water level gauge situated within the survey area, supplied by SMHI (Swedish meteorological and hydrological institute), were used to measure changes in sea water level in the area during the survey.

5.2 Retrieval of data

5.2.1 Positioning and coordinate system

Positioning during the field work was performed using LEICA and Hemisphere differential GPS receivers. The navigational data were recalculated from the receivers NMEA-strings in longitude/latitude to the Swedish SWEREF TM projection and also adjusted for the location of the sensors. The differential corrections were based on the EPOS system and the precision of positioning for the present survey is regarded as accurate as to less than the meter level.

5.2.2 Survey principles and instrumentation

Instrumentation for reflection profiling in the range above c. 10 kHz are mostly referred to as echo sounders, whereas those in the range 3–10 kHz are called sediment profilers. Technically they are very similar, using ceramic transmitters which usually also serve as receivers. Below c. 3 kHz it becomes necessary to use other types of transmitters; air guns, water guns and various types of high voltage transmitters. These low frequency instruments, referred to as seismic profilers, also require separate receivers in the form of hydrophone arrays. The till and bedrock surfaces are usually derived from these seismic soundings.

Sediment profiling. The sediment sounders are capable, under favorable conditions, of penetrating mud, clay and sand, down to more than 50 m below the seabed. However, they rarely penetrate till. In the present case the sediment profiling provided clear records of the uppermost mud sediments and the glacial varved clays. Exceptions were those areas where the sediments were gas-charged and where sand had a rather accumulated thickness.

5.2.3 Environmental parameters

Velocity determinations. The sound velocity in the water at the time of the survey is essential for the evaluation of the echo sounding and swath records. The required data – depth, salinity and temperature may either be determined by measurements performed exclusively for the purpose or achieved from hydrographical observations. For the evaluation of the present recordings, four to seven CTD and sound velocity profilings were performed each day.

5.2.4 The data acquisition system

The digital depth data from the instruments were stored in separate computer files, and GPS positional data in a separate file. Before storage, the positional data strings (NMEA – GPGGA) were converted to X/Y-coordinates in the SWEREF TM map system. Furthermore, the 3-dimensional layout of the instruments during the survey was recorded on file in order to facilitate coordinate calculation of positions and instrument depth for each shotpoint.

Table 5-1. Data acquisition parameters, such as record length, frequency, pulse length, trigger and sampling rate, for the different hydroacoustic instruments used during the surveying.

Channel/Instrument	Data	Record length (ms)	Frequency range (kHz)	Pulse length (ms)	Trigger rate (ms)	Sampling rate (kHz)
Bubblepulse, Benthos.	Low-resolution stratigraphy, till and bedrock surfaces.	240	0.1–1	10	250	5
Sediment profiler, Geopulse digital profiler.	High-resolution stratigraphy of uppermost sediments.	240	3–12	3	250	30
Side-scan sonar, Geoswath.	Seabed-morphology and geology.		250		100	
Depth, Geoswath.	High-resolution terrain models.		250		100	

5.3 Data handling, Analyses and interpretation

5.3.1 Depth measurements

Depths across and along the survey lines were measured using the swathsonar and at the sampling stations using the echo sounder. Data were stored in ASCII-format with x, y, z, time and date. Information from an automatic water level gauge situated within the survey area, supplied by SMHI (Swedish meteorological and hydrological institute), was used to correct the measured data from changes in sea water level in the area during the survey. The depth measurements were filtered and used to produce a digital terrain model over the area.

5.3.2 Seismic and sediment echo sounding data

Seabed penetrating data are primarily stored in SEG-Y format. After conversion to image raster format, each file is quality controlled and accepted or, if rejected, data is collected again at this survey line. After quality control, the resulting position file is filtered. The survey data are transformed to image format and the seismic and sediment echo sounding data are interpreted simultaneously, see examples of sediment echo soundings and seismic profiles in Figures 5-1 and 5-2. The acoustic stratigraphy was, by SGU in Uppsala during 2010 and 2011, interpreted to geological lithology.

The information from the sediment sampling is used in the interpretation. Knowledge of the local geology and sedimentology are important. The interpreted sections are transformed to ASCII files with x, y, z values and a geological code.

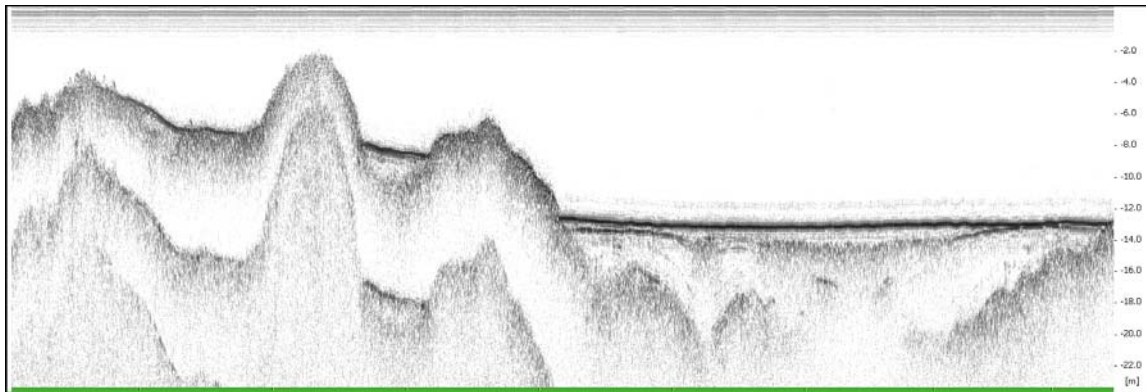


Figure 5-1. Sediment echo sounding profile from one of the survey lines in 2010.

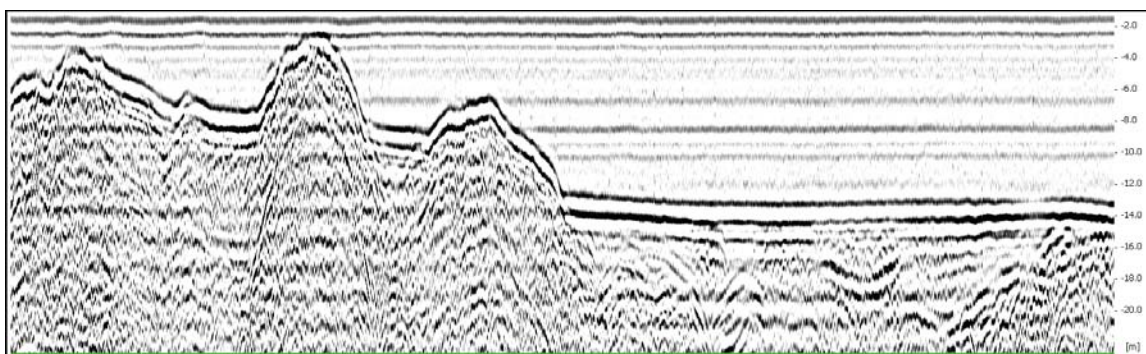


Figure 5-2. Seismic profile from the same survey line as above.

These time based files are recalculated to meter based sections in the same format. Information about the sound velocity in different materials is based on literature studies. From these sections a graphical data set is produced, showing the geological material at the seabed along the survey lines. The following Tables 5-2 to 5-4 show examples of how positions, transformed from SWEREF 99TM to RT90 2.5V, stratigraphical data and associated geological codes for each shotpoint are illustrated and delivered to SICADA.

Table 5-2. Examples of position and positional errors for shot numbers in survey lines.

Line nr.	ShotPOINT_id nr.	Easting coord. (RT90 2.5V)	Northing coord. (RT90 2.5V)	Elevation	Coord. system	North. error	East. error	CoMm
LFR000077	166	6704644.67	1633501.58	0	RT90-RHB70	1	1.00	0.50
LFR000077	167	6704645.09	1633501.21	0	RT90-RHB70	1	1.00	0.50
LFR000077	168	6704645.51	1633500.86	0	RT90-RHB70	1	1.00	0.50
LFR000077	169	6704645.95	1633500.49	0	RT90-RHB70	1	1.00	0.50
LFR000077	170	6704646.38	1633500.13	0	RT90-RHB70	1	1.00	0.50
LFR000077	171	6704646.82	1633499.77	0	RT90-RHB70	1	1.00	0.50

Table 5-3. Examples of data from an interpreted section.

Line nr.	ShotPOINT_id nr.	Depth from (m)	Depth to (m)	Layer nr.	Soil_C (Code)	Marine_seis (Code)	Soil_c_genes code
LFR000077	166	000.00	000.53	1	20	41	9
LFR000077	166	000.53	004.51	2	7	76	3
LFR000077	166	004.51	004.51	3	-1	99	-1
LFR000077	167	000.00	000.46	1	20	41	9
LFR000077	167	000.46	004.40	2	7	76	3
LFR000077	167	004.40	004.40	3	-1	99	-1

Table 5-4. Codes used for the seismic units.

Soil_c code	Marin_seis code	Soil_c_genes code	Text_swe	Text_eng
-1	2	-1	Gaslock.	Gaslid.
-1	3	-1	Osäker tolkning under markering.	Uncertain interpretation below selection.
29	10	24	Postglacial lera, gyttjelera.	Postglacial clay/gyttja clay.
29	16	8	Övergångsleror.	Transition clays.
29	19	8	Glacial lera.	Glacial clay.
23	27	8	Glacial silt.	Glacial silt.
21	31	9	Postglacial finsand.	Postglacial fine sand.
20	41	9	Postglacial mellansand-grovsand.	Postglacial medium sand/ coarse sand.
33	57	7	Glaciofluvial avlagring.	Glaciofluvial deposit.
7	76	3	Lerfattig morän, finkornig.	Till, finegrained.
-1	99	-1	Kristallin berggrund.	Crystalline bedrock.

5.3.3 Sonar

Sonar data are primarily stored in XTF- format. After conversion to image raster format, each file is quality controlled and accepted or, if rejected, data is collected again along this survey line. After quality control, the resulting position file is filtered. Acoustic data is corrected for slant range and geographically positioned in registered raster strip files. The resulting strip files are mosaiced together and transferred to geo referred tiff images with 25 cm pixel size for the primary survey area, see Figure 5-3. The mosaics are interpreted to produce a geological map of the seabed sediments. To help in the interpretation, data from the seismic and sediment echo sounding, sediment sampling, water depths and other background data are used. The interpretation is based on the different signal returns different geological materials give, rock shown as dark and rough areas while unconsolidated sediments give a pale and “soft” impression. Important factors for an accurate geological mapping are the understanding of how the sonar signal interacts with the morphology and geology of the sea bed, the effect of “shadowing”, and an overall knowledge about the geology in the area.



Figure 5-3. Part of the side-scan sonar mosaic produced from the survey above SFR in 2010.

6 Results

The fieldwork in 2010 resulted in approximately 110 km survey lines. The locations of the survey-lines are shown in Figure 1-1. In addition, 23 seabed inspections with camera were performed, and, where possible, sediment samples were retrieved. Thirteen small grab samples and one gravity core sample were taken.

The morphology of the sea bed in the present area is based on depth measurements from the swath-sonar along the survey lines measured in 2010. The seabed map and the horizontal and vertical extension of sediments in the present area of investigation are based from hydroacoustic and seabed data collected both in 2010 and 2002. See Figure 1-1.

The area of investigation is ~ 10 km² large where the seabed surface consist of ~ 3% crystalline bedrock, 17 % glacial clay, 0.1 % postglacial clay, 11 % postglacial fine sand, 23 % postglacial sand/gravel, 45 % till, and 0.9 % glaciofluvial deposits. Postglacial fine sand and postglacial sand/gravel is almost entirely underlain by glacial clay. Also, the glacial clay is almost entirely covered by thin layers of residual material consisting of sand and gravel. The till in the southern part, close to land and the esker, may be partly boulder clay, and is covered by thin layers of glacial clay and/or sand/gravel. The esker seems to generally be underlain by bedrock. The surface sediments indicate that most of the area is of an erosional and transportable character. A minor area of fine sediment accumulation (postglacial clay) is found in the eastern part.

An esker is discovered running approximately in a north northwesterly-south southeasterly direction in the area. The esker is covered by younger sediments in the northern part of the area and is a predominant feature on the seabed in the southern part of the area. The esker is probably an extension of the “Börstils” esker seen on land.

Interesting features detected on the esker are smaller depressions, which coincide with disturbances in the water column in recorded sediment echo sounding profiles, see Figures 6-1 and 6-2. These depressions may be a result from submarine groundwater discharge.

Pockmarks of sizes up to 40 meters in diameter are found in the area. Pockmarks are craters in the seabed caused by fluids (gas and liquids) erupting and streaming through the sediments (Judd and Hovland 2007), see Figure 6-3. Here, most probably gas of thermogenic and/or microbial origin is the cause for the pockmarks, see the sediment echo sounding profile in Figure 6-4. Thermogenic gas may be of crustal origin or come from organic material in subducted continental sediments. Microbial gas is generated within postglacial fine-grained sediments. The gas may be partly of thermogenic origin since the thickness of postglacial fine-grained sediment in the area is small, which indicate initial low organic content and thus minor amounts of biogenic material.

Gas seeps and large fields of pockmarks have been found along deep-seated tectonic lineaments along parts of the Furusundsleden and Stockholm archipelago (Flodén and Söderberg 1994, Söderberg and Flodén 1991). It should be noted that (Söderberg and Flodén 1992) reported that the gas found there is of thermogenic origin.

Water depths and sediment stratigraphy collected from 53 hydroacoustic survey lines retrieved in 2002, 2008 and 2009 outside the 2010 survey area of investigation and in the Öregrundgrepen area are analyzed and delivered, see Figure 1-1. Here eskers, both on the seabed and below younger sediments are mapped in seismic and sediment echo sounding profiler data, which were not detected in the analyses in 2002. The seismic data also indicate that the bedrock is, in places, of sedimentary (possibly sandstone) origin.

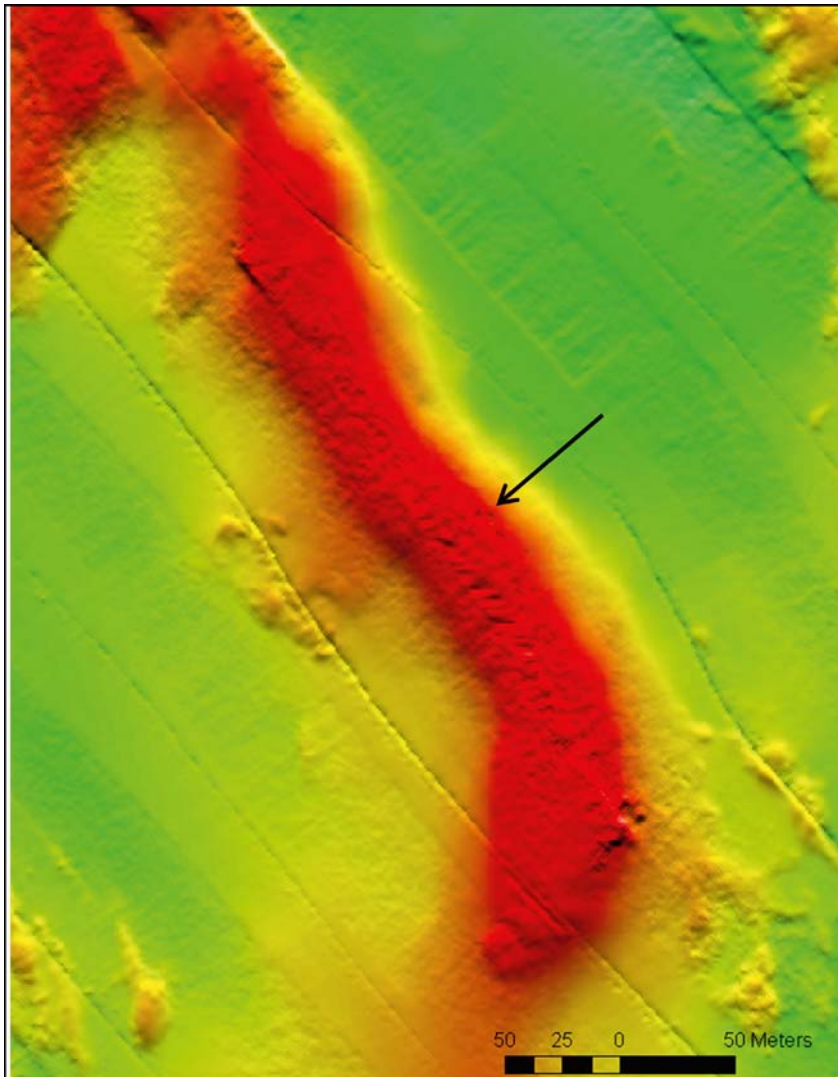


Figure 6-1. Terrain model of the seabed in the southern part of the area revealing the esker. The arrow shows the locations of depressions on top of the esker. These depressions could be due to submarine groundwater discharge. See also Figure 6-2.

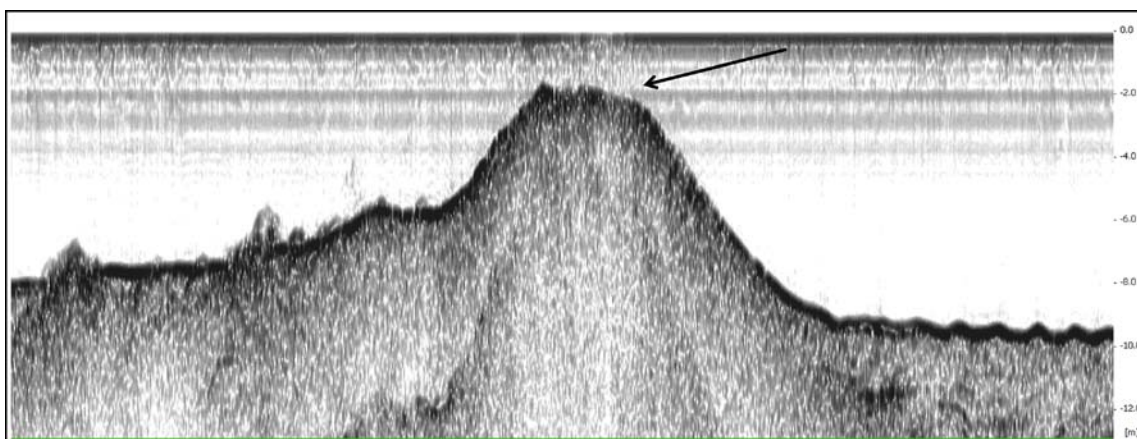


Figure 6-2. Sediment echo sounding profile crossing the esker at the location of the depressions. Disturbances in the water column are detected, see arrow, which could be caused by submarine groundwater discharge.

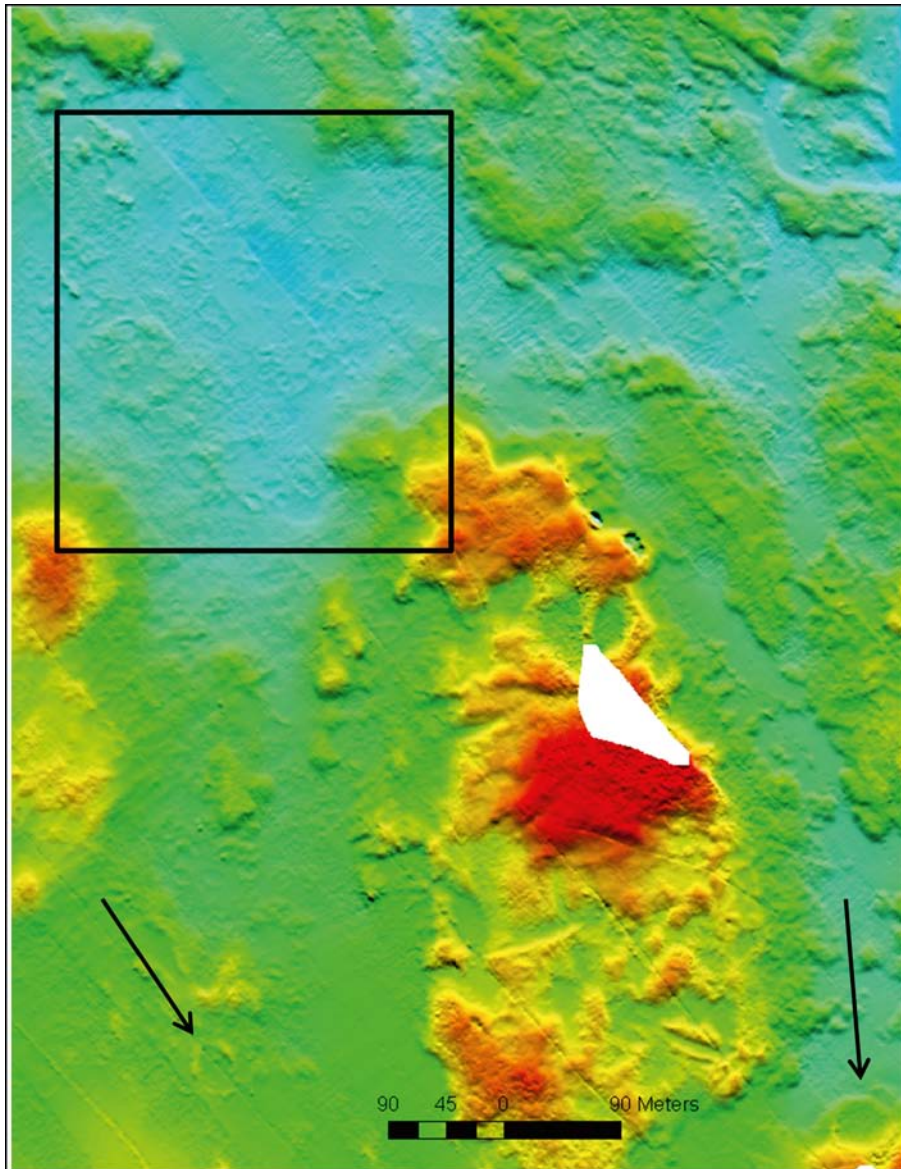


Figure 6-3. Terrain model of the seabed showing two larger pockmarks, location of the arrows, and an area where pockmarks are frequent features, inside the box.

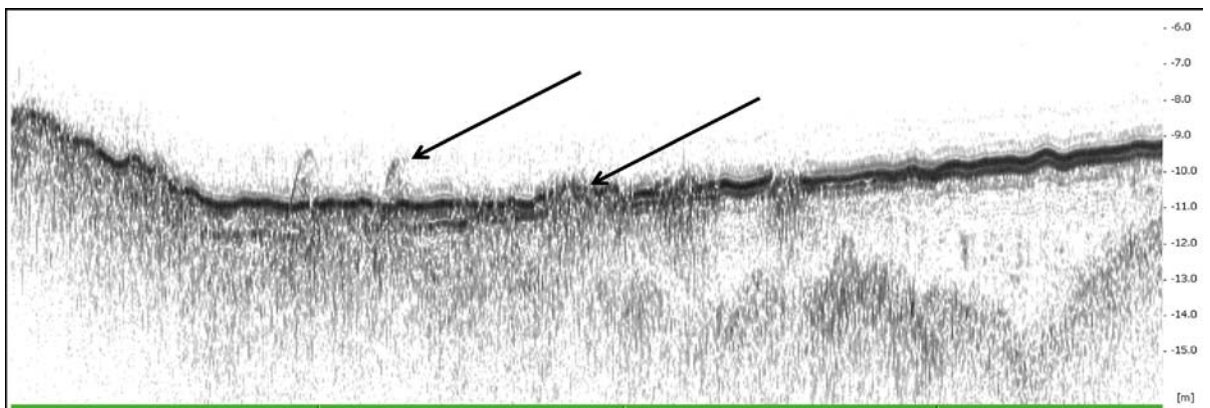


Figure 6-4. Sediment echo sounding profile from the area within the box in Figure 6-3 indicating gas in the uppermost sediments and in the water column close to the seabed. The gas hinders the soundings to penetrate the sediment. The profile also indicates that the thickness of postglacial sediments is minor.

7 Conclusion

The 2010 area of investigation is of an erosional and transportable character. A smaller area where fine sediments accumulate is found in the eastern part. An esker, running approximately in a north northwesterly-south southeasterly direction, as well as pockmarks are detected.

In the Öregrundgrepen area, eskers, both on the seabed and below younger sediments are mapped.

Further investigations, such as, resistivity and electromagnetic measurements as well as detections of ^{222}Rn activities and/or Uranium-Thorium series geochemical tracers are proposed to be conducted in order to study submarine groundwater discharge from the esker. To determine the origin of the gas, which cause the pockmarks, sampling and chemical analyses should be conducted. A number of longer boreholes should be retrieved to confirm the indications of eskers and sedimentary bedrock in the seismic data from the Öregrundgrepen area.

8 Deliverables

- A side scan sonar mosaic in Geotiff format with 25 cm pixelsize covering the area surveyed in 2010. RT 90 2.5V.
- Seabed maps in ESRI shape where (“matl”) is thin layers (sw. “tunna lager”, < 50 cm) of sediments and (“matr”) is the dominating sediment (sw. huvudjordart) in the upper meter of the seabed. The area surveyed in 2010. RT 90 2.5V.
- Seabed topography (bathymetry) in Geotiff format with 1 m pixelsize and in ASCII format (x, y, z) with 0.2 m grid size. The area surveyed in 2010. RT 90 2.5V.
- Sections with interpreted geological stratigraphy and associated positional information according to SICADA in ASCII format. The lines surveyed both in 2010 and 2002 for the area above SFR surveyed in 2010. RT 90 2.5V.
- Data from twenty-three seabed inspections performed in 2010 in excel-format according to SICADA and as word-documents. Underwater and sediment sample photographs. RT 90 2.5V.
- Water depths from 53 survey lines, in the extended area outside Forsmark and in the Öregrund-grepen area, see Figure 1-1, according to SICADA in ASCII-format. RT 90 2.5V.
- Sections with interpreted geological stratigraphy and associated positional information according to SICADA in ASCII format from survey lines in the extended area outside Forsmark and in the Öregrundgrepen area. RT 90 2.5V.

9 References

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