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Improved geological information by modelling airborne TEM data over the island of Öland, Sweden

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SUMMARY

An airborne TEM survey was carried out over the Island of Öland in Sweden in 2016. The main objective was to improve the geoscientific database with the aim to assess the hydrogeological conditions and prerequisites for identifying potential new groundwater magazines. The nearly parallel-layered sedimentary succession facilitated the strong correlation between boundaries resolved in the resistivity models from the 1D inversion of airborne data and the geological variations observed in the boreholes and ground geological investigations.

The high resistive Mossberga dome is one example shown where a prominent residual Precambrian monadnock hill beneath the sedimentary cover is clearly resolved in the resistivity models. More interestingly, the lateral extent and depth to the top of crystalline bedrock coincide with bedrock information from existing boreholes. Moreover, a low resistivity zone in the central parts of the dome structure is clearly distinguished and could possibly be caused by a water-saturated fracture zone. This can play an important role in the flow of groundwater in that area.

The second example demonstrates use of resistivity maps at a wide range of elevations and depths for characterizing various geological formations and their extent in an area almost as large as the entire island.

The results show that the airborne TEM method is very applicable for characterizing geological settings as the one present on the island of Öland. The data and results from the survey can be utilized as a geoscientific basis that contributes to the assessment of groundwater resources, including planning for new wells, water protection areas, geo-energy drilling and other water management issues.

Key words: Characterization; Resistivity; Well data; Sedimentary rocks; Crystalline rock.

INTRODUCTION

The island of Öland, situated in the Baltic Sea 10 km east of the mainland of Sweden (Figure 1), faces problem with the ground water resources every summer during the tourist peak period. There are two main reasons for the periodic shortage of groundwater in Öland. One is the limited storage capacity in the Quaternary deposits, bedrock and surface waters. The second one is that there is a very limited retaining time for the precipitation because it is in most parts quickly transported to the Baltic sea in an extensive system of drainage ditches. The drainage is also facilitated by a combination of thin Quaternary cover and a relatively compact bedrock surface, especially in the limestone areas. This in turn reduces the possibilities for groundwater formation by infiltration to the Quaternary deposits and bedrock.

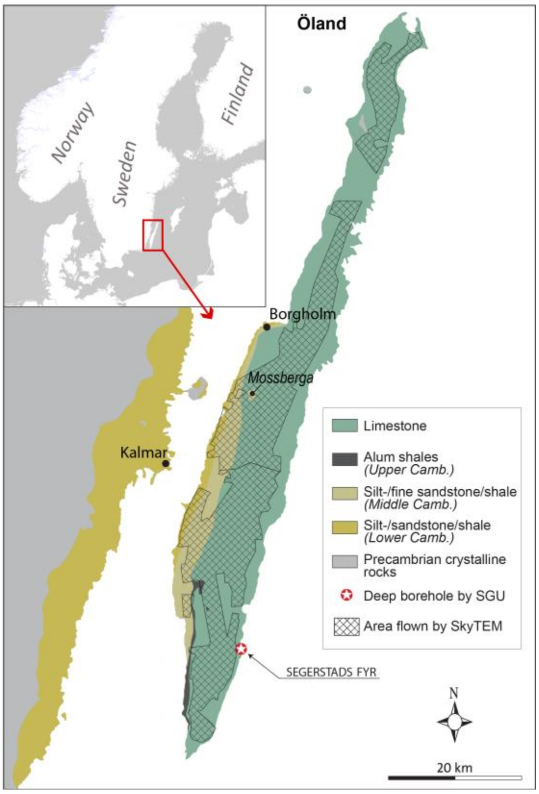

Figure 1. Simplified bedrock geological map of Öland after Erlström (2016). Location of the island is shown in the inset map at the upper left corner. The white star shows the location of the 254 m deep Segerstads Fyr, drilled by SGU in 1968.

Until now there has been insufficient basis for characterizing the overall geological and hydrogeological conditions in the quest of identifying potential new groundwater magazines for new and complementary groundwater wells. In 2016 extremely low groundwater levels occurred, which led to several alternative solutions to improve redundancy in the drinking water supply.

In this context, the SkyTEM Surveys ApS conducted in the autumn of 2016 an airborne transient electromagnetic survey. This survey with a coverage area of 800 km^2 was coordinated by the Geological Survey of Sweden (SGU). The aim of the survey was to improve the overall knowledge about the geology of Öland, which could be coupled to the hydrogeologic conditions and localization of potential new groundwater resources on Öland.

The extensive acquired data set of good quality made it possible to image the resistivity of the ground down to a depth of 250 m. The data furthermore offered an excellent opportunity to study the extent of key geological formations in a semi-3D manner. We utilized the Aarhus Workbench (AWB) software package for processing and inversion of the acquired data. Auken et al. (2009) present a detailed account on the data processing techniques implemented in the software. The data were inverted in 1D using the Spatially Constrained Inversion (SCI) developed by Vizzoli et al. (2009).

Borehole information, geological maps, and the inversion results were incorporated in the 3D geological modelling software, Geoscene3D from I•GIS. This was the basis for constructing the 3D hydrogeological and geological models over almost the entire island of Öland.

The validity of the results from the airborne TEM measurements were evaluated against ground geophysical data and borehole information. This evaluation process is exemplified by two examples, using the resistivity models from the 1D inversion of the airborne TEM data together with borehole information to characterize the geological structures in 3D.

GEOLOGICAL SETTINGS

The up to c. 250 m thick Palaeozoic sedimentary succession (Figure 1) consists of Lower Cambrian sandstone, Middle Cambrian siltstone, and claystone followed by the Alum Shales of Upper Cambrian (Furongian) and Lower Ordovician age, and the topmost bedrock consists of an up to 40 m thick Lower Ordovician limestone succession. The latter forms the bedrock surface on most parts of the island. The entire sedimentary sequence rests on the Precambrian crystalline bedrock (Erlström 2016). In the western parts of the island a sharp bedrock cliff consisting of limestone formations overlaying Alum Shale, siltstone, and claystone appears in the island’s landscape. Further to the northwest the cliff is less distinct since it is draped by quaternary deposition and coincides with a marked coastline (Flodén 1980, Tuuling & Flodén 2016). The whole sedimentary succession has a general dip of 0.2–0.3 degrees to the east and south east. However, in the Mossberga area (see Figure 1 for location), the crystalline Precambrian bedrock is already found at about 50 m depth.

RESULTS

Example 1: The Mossberga dome

The crystalline basement rock on Öland shows generally a rather flat surface with a slight dip towards the east and south east. However, in some areas topographical prominent residual mountain are preserved. One of the most striking is the Mossberga dome, located about ten kilometres south of the city of Borgholm (Figure 1). The center of the dome was studied by core drilling (Mossberga-1) already in 1933 by ABEM. The drilling encountered already at 47 m depth Precambrian quartzite (Westergård 1936). The overlying bedrock in these drillings consists of a Middle Cambrian succession of conglomeratic sandstones followed by shales and siltstones. The structure is also outlined as a depression in the landscape.

The average resistivity map over the area, representing the uppermost five meters of the ground shows a circular, low resistive structure which is almost two kilometer in diameter (Figure 2). The lower resistivity seen in the centre of the structure is caused by the fact that the high resistive Lower Ordovician limestone is eroded away and the more conductive clay- and siltstone constitute the bedrock surface.

The resistivity model along a few profiles crossing the dome are studied in detail. In the resistivity sections, the Mossberga dome appears as a very distinct high resistive structure. One SW-NE running cross section (see Figure 2 for the location) is illustrated in Figure 3. In the model, the dome has a width of two km and a height of at least 80 m (Figure 3). The available borehole information verifies the resistivity models. The high resistive upper limestone layer is missing over the central part of the dome. The low resistive layers in the central parts are consequently related to the Middle Cambrian silt-, clay- and sandstone dominated strata. The resistivity section also indicates that the Lower Cambrian succession, found elsewhere in boreholes on Öland, decreases significantly in thickness towards the crest of the dome. This is also verified by a corresponding decreasing thickness of the Lower Cambrian in the boreholes.

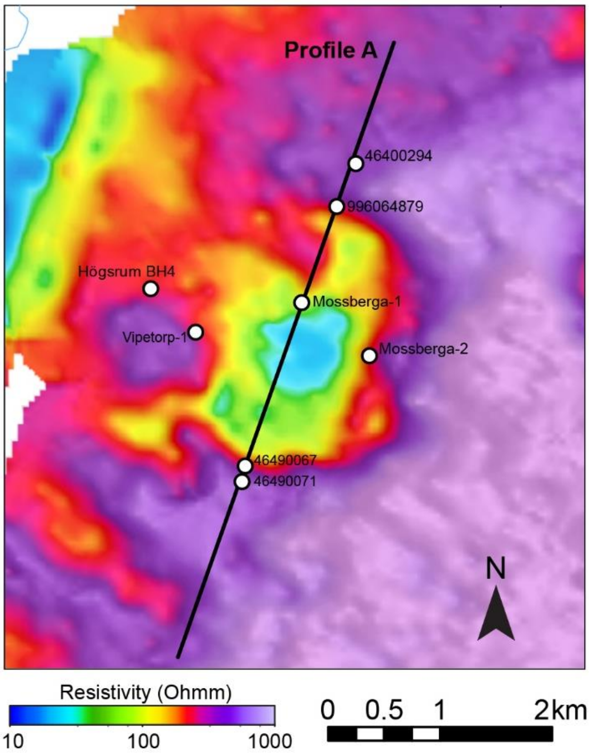

Figure 2. Average resistivity map from the upper 5 m of the ground. Drillings in the area and the location of Profile A are also shown on the map.

The presence of conglomerates and a significantly condensed Lower Cambrian succession on top of the quartzite in the Mossberga-1 borehole indicate that the dome has been a submarine high or even an island during the Early Cambrian.

In Figure 3 a low resistive zone appears at the central part of the dome that is observed in several profiles. One interpretation of this can be that it represents a water-saturated fracture zone in the quartzite that could be of interest for groundwater extraction.

Example 2: Geological characterization by resistivity slices at different depths

Resistivity maps made from two-meter-thick horizontal slices representing six different depths are shown in Figure 4., The digital elevation model is presented in the upper left corner of Figure 4 as the height reference. The resistivity maps representing the shallower elevations (depths) (+20 m to -20 m a.s.l) show an abrupt resistivity increase towards the eastern parts of the island with an exception in the northern parts where the overlying sediments are thicker. A very sharp SW-NE boundary marked by the black line indicates the contact between the high-resistivity Ordovician limestone (to the east) and the low-resistivity Cambrian clay/siltstone. We would like to point out that along almost all the resistivity models no clear boundary between the Alum Shales and the overlying limestone could be distinguished. Based on the evidences observed in core boreholes, the best explanation could be that there is within the Alum Shale succession several limestone layers which in turn reduces the resistivity contrast with the overlying Ordovician limestone. At depths between 40 to 120 m the resistivity model is dominated by resistivities <150 Ohmm which characterizes Lower and Middle siltstone/claystone as well as Lower Cambrian sandstone units. The resistivity map at 120 m depth reveals presence of the more resistive (>300 Ohmm) Precambrian crystalline rock that underlies the sandstone. The dashed black line marks the approximate contact between the two units. The deep borehole (Segerstads Fyr), shown by the white star on the -120 m.a.s.l map (and also in Figure 1) met the crystalline bedrock at 252 m depth. One should note that the resistive dome structure at Mossberga area (discussed in the first example above) is clearly observed on the maps below -20 m elevation.

We would like to mention that using the near surface "*resistivity depth slices"* a considerable number of low resistivity fracture zones within the resistive limestone could be identified and mapped (not shown in this abstract). These fracture zones are considered important conductive hydraulic pathways for groundwater.

CONCLUSIONS

The study presents results from an extensive airborne TEM survey over the island of Öland. The data are of high quality and the inversion models contain valuable information about the geometry of geological formations and structures. Comparison of the resistivity models from the 1D inversion of the airborne TEM data with borehole information, ground geological and geophysical data validates a reliable interpretation. The Mossberga dome example demonstrates an excellent correlation between the vertical and lateral extents of the dome resolved by the resistivity models and those observed in the boreholes. Observation of a low resistivity zone in the central parts of the dome is judged to be a potential groundwater bearing zone. Use of the resistivity slices at different elevations and depths enabled us to characterize and map the key structures such as fracture zones and contact between various formations from the surface down to depth of about 250 m.

ACKNOWLEDGMENTS

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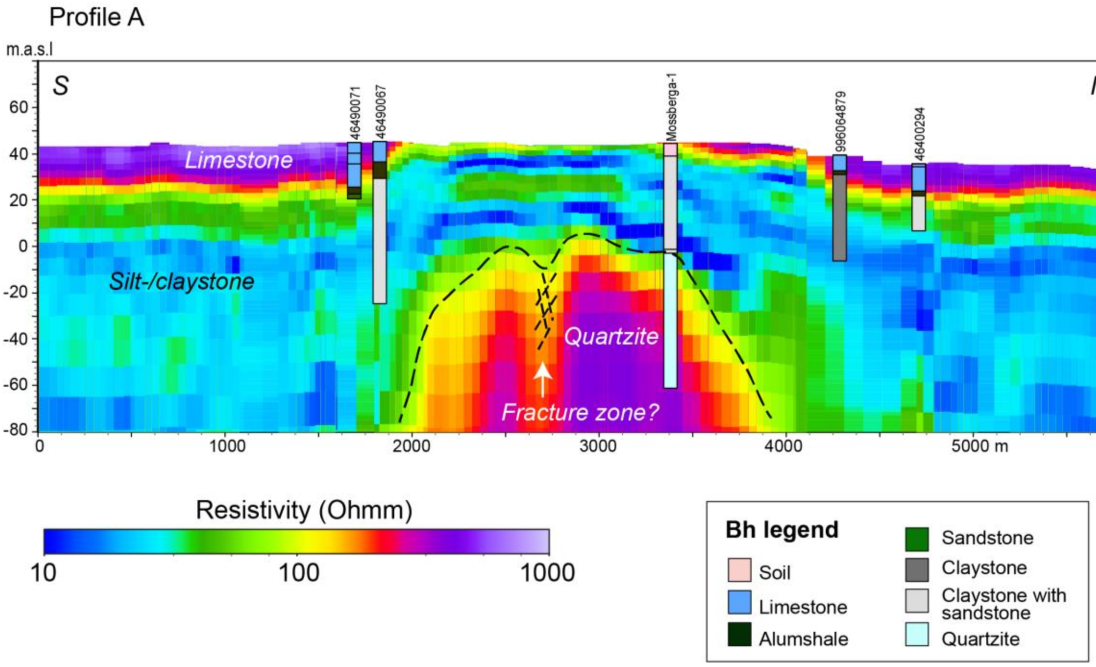

Figure 3. Resistivity section along profile A. The location of drillings, with lithological information are also shown in the section. The location of the profile is shown in figure 2. Note that the vertical scale is exaggerated compared with the horizontal scale.

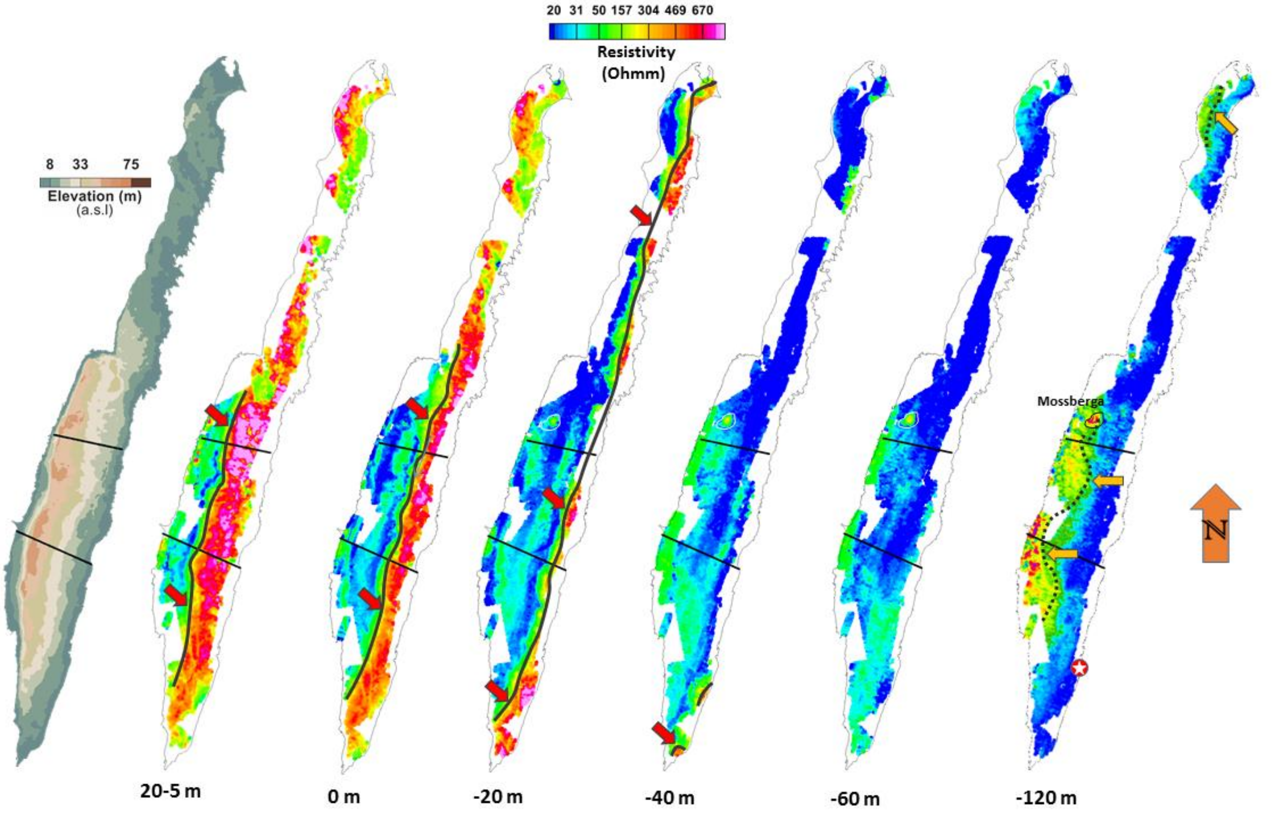

Figure 4. Resistivity maps for six slices take at various elevations. The maps are produced from the 3D grid of the SCI models. The SW−NE striking solid black lines marked by red arrows show the contact between the resistive Ordovician limestone and underlying clay/siltstone. Between -40 m to -120 m.a.s.l the maps are dominated by low-resistivity sedimentary rocks of Precambrian age. Below -120 m more resistive areas, probably caused by the crystalline bedrock, appear in the western parts of the survey area. The dashed back line marks the possible contact between Lower Precambrian sandstone and underlying crystalline rock. The white star shows the location of the deep borehole drilled by SGU in 1968.