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A 3D geological model of the Island of Gotland based on extensive airborne EM mapping, seismic data and log stratigraphy.

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SUMMARY

Due to heavy summer tourism activity, the island of Gotland experiences huge problems with seasonal groundwater scarcity, and to avoid transportation of water over long distances or expensive seawater desalinisation, it is imperative for the community that new groundwater resources are located and exploited. With this goal, an extensive AEM mapping plan was recently conducted over 37 % of the island. Interpretation of the acquired resistivity data is not trivial, because the aquifers do not relate to high resistivities like they typically do in areas with siliclastic sedimentary geology. The geology of the island is composed of carbonate-rich sediments with limited storage capacity and aquifers are typically located in fractured rocks. However, by using a cognitive interpretation approach of the AEM data supported by seismic reflection and borehole data, we are able to map stratigraphical and lithological units in the subsurface, and we show that it is possible to identify the aquifers as either resistive or conductive units relative to the surroundings. After having performed the conceptual interpretations, a geological 3D model was developed. This model serves as a repository for geological knowledge and as a tool for administrators to handle the problematic groundwater situation on the island.

Key words: AEM data, seismic data, 3D geological modelling, groundwater scarcity, water supply

INTRODUCTION

Recently, Airborne Electromagnetic (AEM) mapping has been widely utilized for groundwater exploration in areas with unlithified siliclastic sedimentary geology, for example in glacial terrains (e.g. Korus et al. 2017). In such areas, it is primarily the clay minerals within clay layers that contributes to the electrical conductivity measured. Aquifer mapping requires aquifers which are electrically resistive in contrast to the surrounding, more clay-rich conductive layers. Resistive aquifers, i.e. saturated with fresh water, are normally composed of sand and gravel. High resistivities will therefore often reveal the location and existence of groundwater reservoirs. This relationship is challenged in areas with lithified bedrock or in areas with carbonate-rich geology. In carbonate rocks, there is normally no such clay-mineral based relation between resistivity and the occurrence of aquifers, since the aquifers here normally exists in fractured rocks. If a contrast in clay content does not exist, the aquifer can, in some cases, still be resolved if there is a sufficient contrast in the resistivity of fractured versus the un-fractured parts of the rock. The un-fractured parts of the rock, can have a lower resistivity (if unlithified and containing residual saltwater) or higher resistivity (if lithified). Another challenge for aquifer mapping in areas with carbonate bedrock is that groundwater salinity typically varies considerably in carbonate bedrock settings.

In this study, we present a groundwater-targeted AEM survey from the island of Gotland. The bedrock here is dominated by consolidated limestone and marlstone. We have performed extensive interpretations of the data, combined these with a range of other data, and developed a 3D geological model with the aim of finding new fresh groundwater resources. The targets for the measurements have primarily been within fractured bedrock bodies but also within a thin glacial drift setting.

Gotland is a 3.184 km² large island located in the southern Baltic Sea and is a popular touristic site during summer times. This results in a shortage of groundwater resources for the island since the majority of resources are located in the bedrock aquifers with limited storage capacity. Thus, the island experiences huge periodic problems regarding groundwater supply. Saline groundwater and limited capacities of the aquifers represents a key problem the island's community has to solve.

To explore and search for new aquifers and to map the saline groundwater level two large helicopter-borne EM mapping campaigns have been undertaken. The AEM data supplements other ground-based geophysical and geological studies of the bedrock. This includes soil mapping, bedrock mapping, outcrop studies, Radio-Magnetotelluric measurements (RMT), Electrical Resistivity Tomography (ERT) and wire-line borehole logging. Oil exploration data (2D seismic reflection profiles) collected between the 1970's and 1990's by the Swedish state oil company (OPAB) have also been used to support the interpretation of the deeper part of the geology.

The bedrock of the island is composed of Silurian carbonates. The carbonate succession of reefal limestone, grainstone and marlstone was primarily formed in an inner carbonate shelf setting with frequent lateral and vertical shifts in lithology. The subsurface distribution of these various lithofacies, however, has until now been largely unknown. The 150-500 m thick Silurian succession overlies a 80-100 m thick Ordovician limestone sequence and nearly 200 m thick Cambrian siltstone, claystone and sandstone on top of the Precambrian basement. For a comprehensive description of the bedrock see Calner and Eriksson (2005) and Erlström et al. (2009). The bedrock is in most places covered by a thin Quaternary overburden of mainly glacial sediments. This cover varies in thickness from 0 m to about 25 m, but is mostly less than 3 m.

METHODS AND RESULTS

Data

The airborne data were acquired by SkyTEM Aps using a time-domain helicopter electromagnetic system carried as an external sling load independent of the helicopter (Sørensen and Auken, 2004). About 37 % (1.176 km^2) of the island was mapped with a line-spacing of 200 m in 8 survey blocks during 2013 and 2015 (Figure 1). The surveys were flown with a nominal terrain clearance of 30-50 m and a speed of approximately 80 km/h. The equipment setup was a dual moment configuration with peak moments of ~3,400 NIA for the low moment and ~150,000 NIA for the high moment. The Aarhus Workbench software was used for processing and to remove coupled and noisy data. The data were inverted using the spatially constraint inversion (SCI) developed by Viezzoli et al. (2009). Smooth inversion with 30-layers reaching a depth of 250 m was the most common parameterisation used to generate the models for the geological interpretation process. Data were interpolated into 3D resistivity grids in two different versions. The first with a 5 m vertical discretization down to 250 m below sea level, and the second with a 2 m vertical discretization down to 76 m below sea level. Both with 100 m cell size.

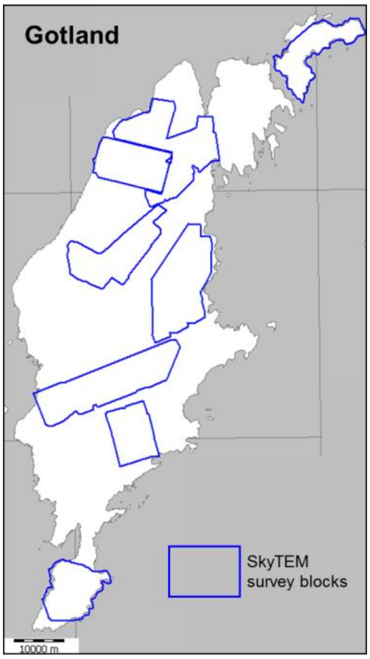

Figure 1 The island of Gotland with outlines of the 8 SkyTEM survey blocks. The island is 140 km long.

A total of 650 seismic reflection TIFF-files were available for the geological interpretation and modelling, but only sections with proper resolution in the uppermost 300 m were actually used (102 lines) and imported in the modelling software. An average seismic velocity of 3300 m/sec were used (simple depth conversion).

The OPAB database also contains a large number of investigation wells including various types of borehole log data. Those were used for stratigraphical correlation and 3D stratigraphic interpretation of the AEM data. Data from a very large number of water wells were also available, but generally, these have been of limited use, due to poor information regarding the drilled rock succession.

A wealth of detailed information about the surface geology were also utilized in the interpretation and modelling procedure. This encompasses for instance soil maps, bedrock maps, outcrop investigations and shallow geophysical 2D data.

3D modelling methodology

Prior to the actual 3D model building a conceptual geological model was developed for the area. This work was largely based on cognitive geological interpretation of the data (e.g. Dell'Aversana, 2017), and guided by existing stratigraphical knowledge. Second, the 3D model was constructed by using the modelling software package GeoScene 3D (https://www.geoscene3d.com/), where all data can be visually compiled and compared. Finally, the 3D model of the bedrock geology was merged with a model of the covering glacial sediments (see Gulbrandsen et al. 2018) thus resulting in a full geological model of the island.

The modelling principles follow the knowledge-driven, cognitive approach of Jørgensen, et al. (2013) which is based on a combination of manual layer and voxel modelling. With this approach it is possible to include background geological knowledge and account for the limitations introduced by the non-unique nature of the AEM data.

Two different 3D models were developed. A stratigraphical model reaching down to the Top Ordovician surface (app. 500 m below sea level), and a lithological model reaching down to 76 m below sea level.

Geological interpretation of data and conceptual model

Gamma log data originating from 31 OPAB boreholes across the island enabled a compilation of a log stratigraphy. 14 of these boreholes, situated close to each other in the southernmost part of the island are shown on a cross section in Figure 2. A good agreement is seen between the resistivity data and the stratigraphical units as defined in the log stratigraphy. Even the relatively thin layer of the Eke Formation is resolved – at least where it is not too deeply buried.

The seismic reflection sections were interpreted with support the from the SkyTEM-data and borehole information. In many cases, strong reflectors match with marked resistivity contrasts and they also match with the log stratigraphy in the OPAB boreholes. Together with the SkyTEM data, one of the sections is shown in Figure 3. Here, a good match is seen between a strong reflector and a clear resistivity contrast – interpreted to be the boundary between the Slite and the Visby Formations. Based on the conceptual geological understanding largely derived from the log stratigraphy and the seismic data, it was possible to extend the conceptual interpretations into 3D using the SkyTEM data. An example of the SkyTEM interpretation is shown in Figure 4. Here, it is seen that facies variations within the formations produces varying resistivity responses along the section (e.g. the Klinteberg Formation).

3D modelling results

A piece of the two resulting 3D models is shown in Figure 5. The stratigraphical model consists of 11 layers including the stratigraphical setting from the top of Ordovician until the

Hamra/Sundre Formation at the top. The entire section is gently dipping towards the SE. The final lithological model consists of four lithological and lithofacies units within the bedrock section (reefal limestone, limestone, marlstone, sandstone) and four units within the soil section (sand/gravel, clay/till, organic sediments, fillings). It is a voxel model composed of approximately 63 million voxels. Compared to the stratigraphical model the bedrock section is somewhat more varying caused by facies variations within each stratigraphical unit. The soil section, consisting of mainly glacial sediments, is much more complex.

Hydrogeological results

With the results from the 3D model, it has within each survey block been possible to point out areas with a high potential for groundwater abstraction. The results are of importance for the municipality of Gotland when planning and drilling new wells to increase the total volume of groundwater available for consumption. One of the designated areas has already been exploited and now supplies a local community with drinking water. This new location saves the municipality 100,000 EUR each year because they avoid transporting water by trucks from other parts of the island. Other potential areas will be investigated further over the coming years.

CONCLUSION

Our conclusion is that the SkyTEM-data significantly improved our understanding of the island's subsurface. Although we are dealing with carbonate geology, it has been possible to improve the stratigraphical knowledge and to map lithological key units like for instance marlstones and reefal limestones. It was essential to interpret the data with support from other data types, especially seismic data and borehole data. A very good match to these data is observed. With conceptual interpretations and by using a knowledge-driven interpretation approach, we were able to develop a 3D model comprising stratigraphy and lithology and other parameters. The 3D model will be used as a tool for future groundwater administration.

ACKNOWLEDGMENTS

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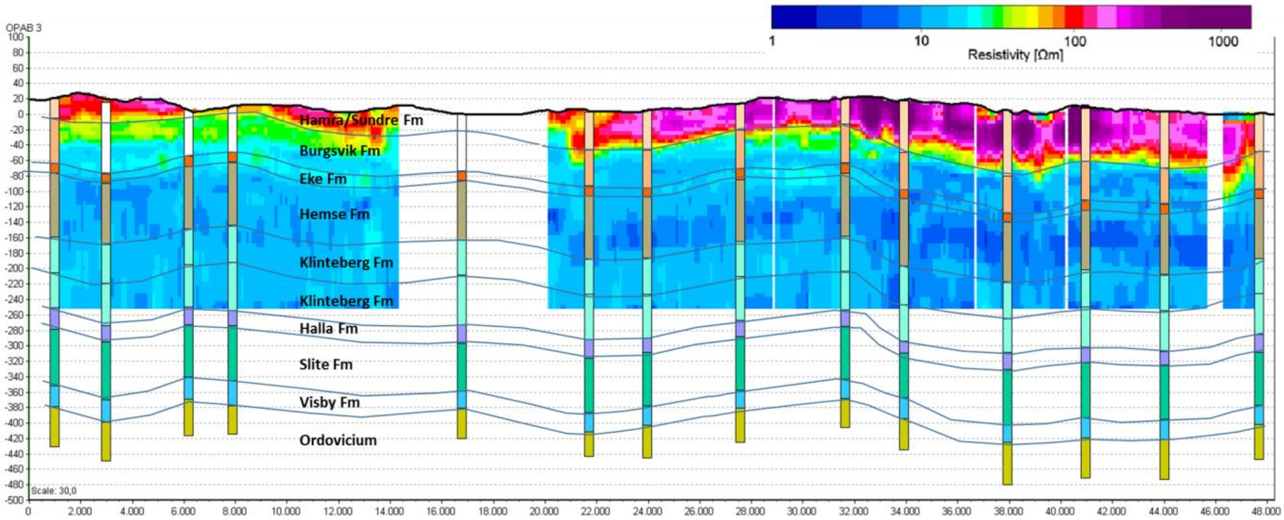

Figure 2 Cross section through 14 wells with log stratigraphy and compared with SkyTEM data.

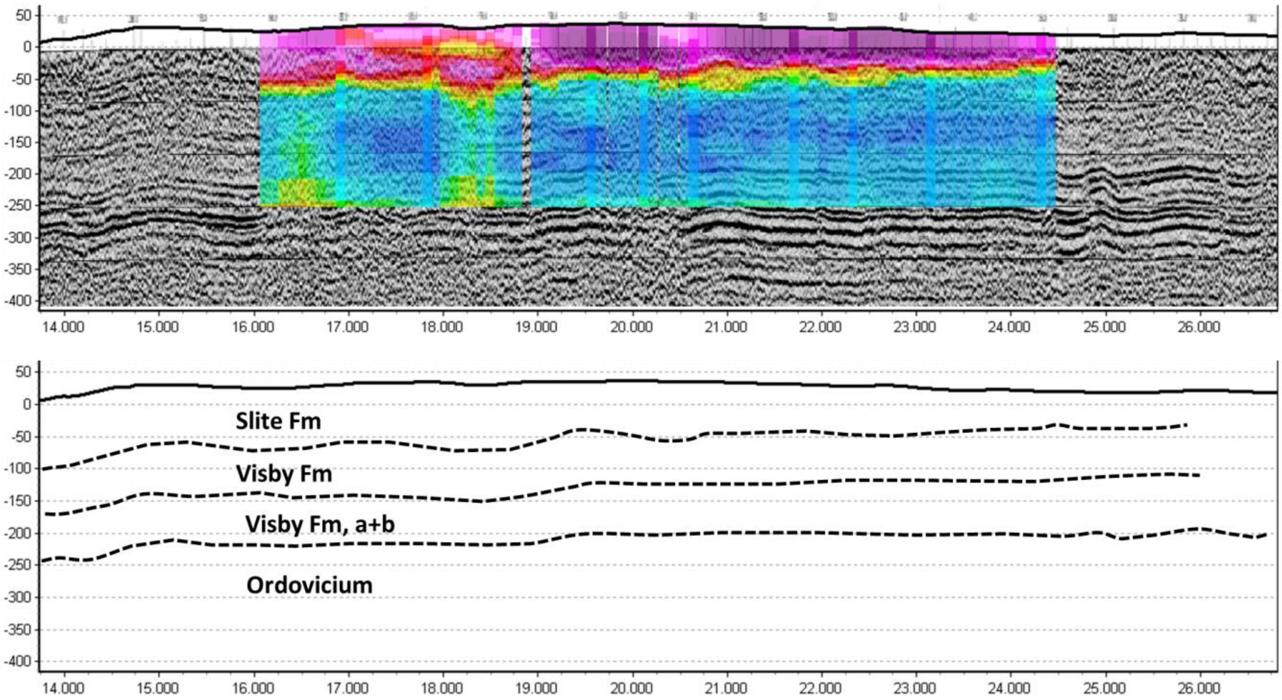

Figure 3 Example of co-interpretation of the seismic data and the SkyTEM-data. See resistivity scale in Figure 2

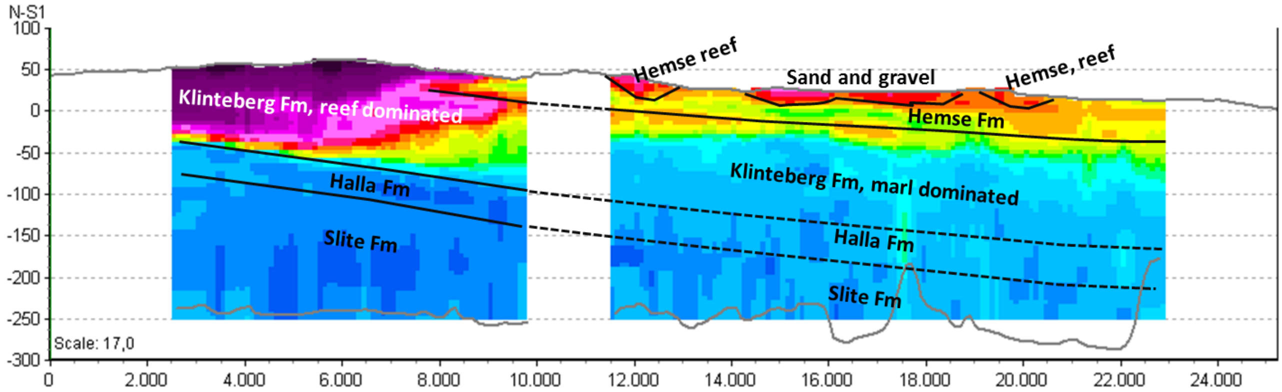

Figure 4 Conceptual stratigraphical interpretations of SkyTEM data (cross section through the 3D resistivity grid). See resistivity scale in Figure 2

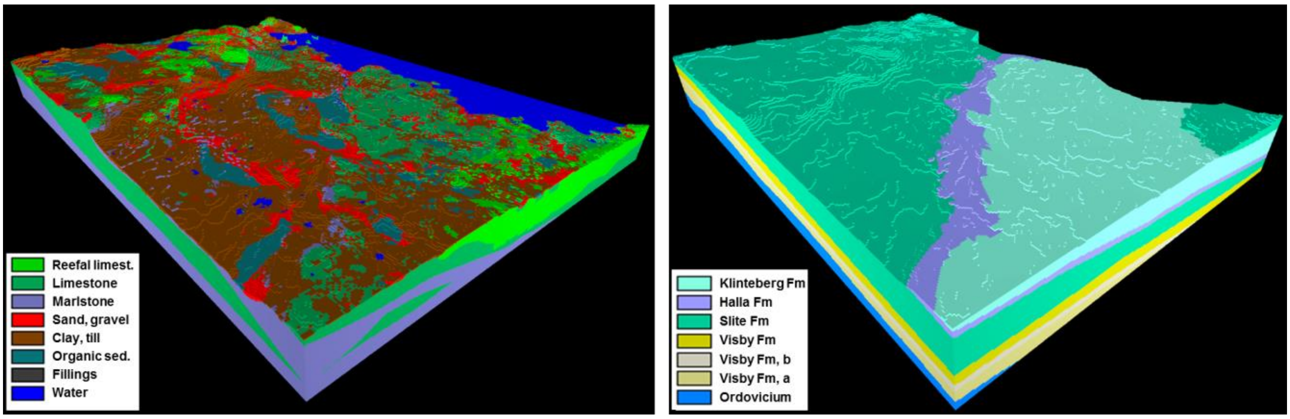

Figure 5 3D view of the lithological model to the left and the stratigraphical model to the right. The piece of the model area shown here is 26 x 37 km^2 in size. The depth of the models is 76 m b.s.l. for the lithological model and 250 m b.s.l. for the stratigraphical model.