3D Geological models from combined interpretation of airborne-TEM and geological data- Two examples from Sweden

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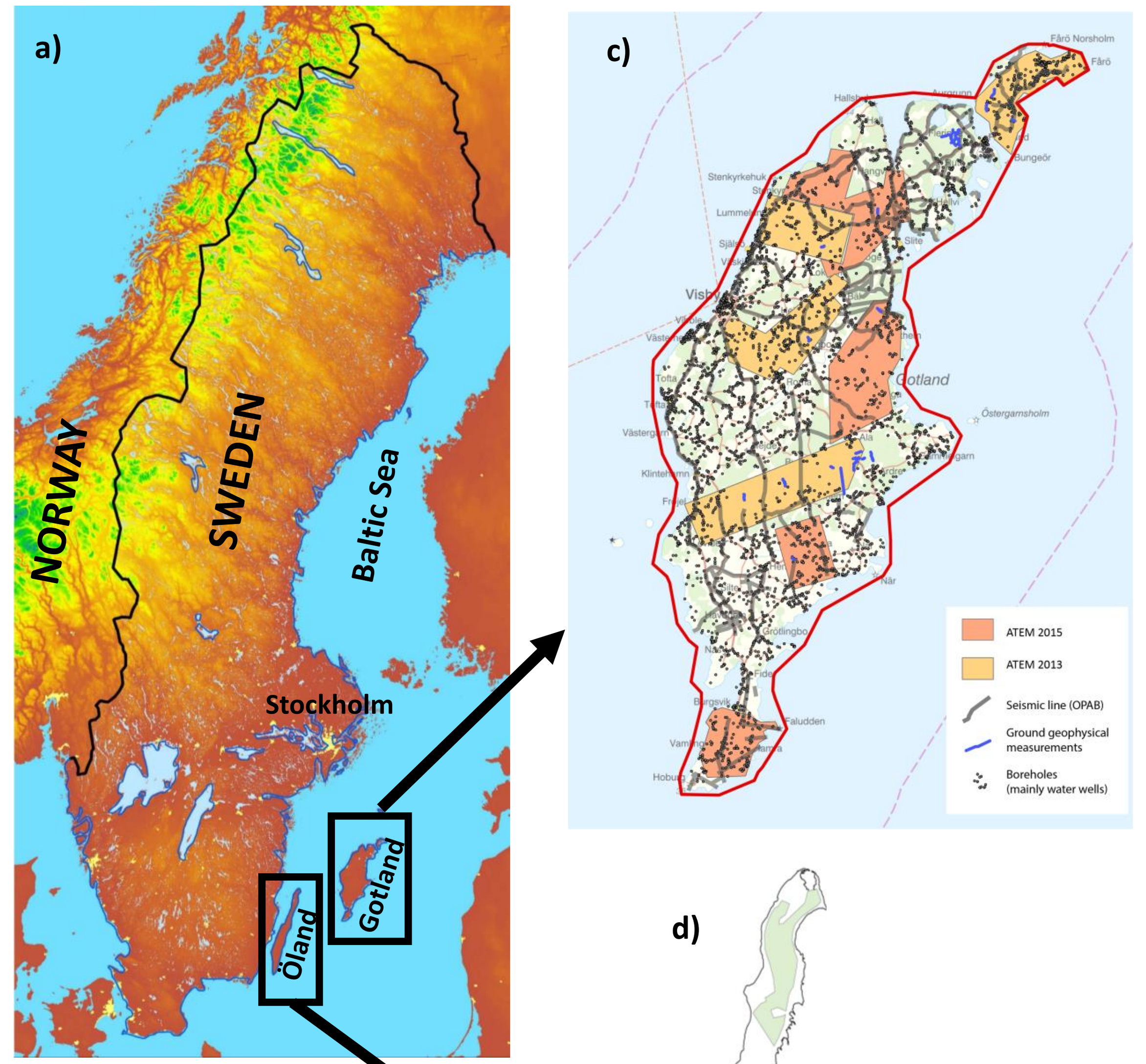
Background

The airborne TEM (ATEM) data presented in this study were collected by the SkyTEM Surveys ApS between 2013 and 2016, covering large areas of the islands of Öland and Gotland, in Sweden (Fig.1). Both islands face problems with water supply due to limited groundwater resources. The aim of the surveys was to identify new groundwater resources, specify the depth to saline groundwater and to improve the understanding of the geology of the islands.

The geological survey of Sweden (SGU) has processed and inverted the data to provide resistivity models of the subsurface, down to a few hundred meters depth. These models together with data from existing boreholes and ground observations were interpreted to construct geological 3D models that can be used as an excellent tool to study the structures controlling groundwater processes.



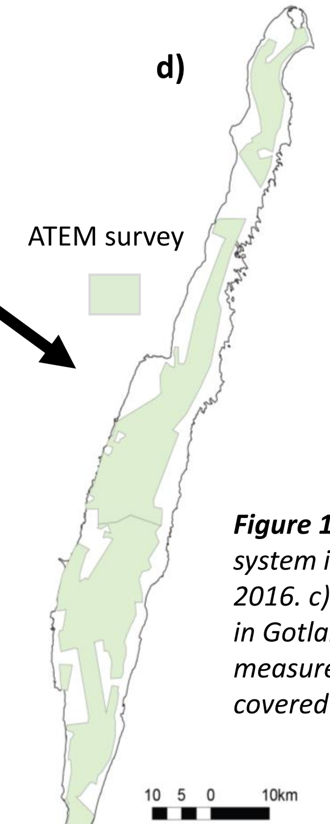


Figure 1: a) Location of the islands in Sweden. b) SkyTEM system in operation over an area in the Isaland of Öland, 2016. c) Locations of areas covered by ATEM measurements in Gotland. Yellow and orange polygons show measurements in 2013 and 2015, respectively. d) Areas covered by ATEM data in Öland shown as green polygons.

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Methodology

The extensive acquired airborne ATEM data has a good quality that made it possible to image the resistivity of the ground down to a depth of 250 m. In order to incorporate the results from the airborne measurements in modelling the geology in 3D we have taken the following steps (Fig. 2):

1- Aarhus Workbench (AWB) software is used to process and invert of the acquired data (Auken et al., 2009; Vizzoli et al. 2009).

2- Resistivity model, available ground geophysical data, borehole information, geological maps, etc. are incorporated in the 3D geological modelling software (in our case we used, Geoscene3D from I•GIS.).

3- All the data are used to construct a lithostratigraphic model (LM) along each flight line.

4- A 3D resistivity grid is built up from resistivity models and together with LM model a 3D lithological voxel model (LVM) is formed.

5- In areas with no airborne ATEM data coverage the existing geological data, ground geophysical data and borehole information are used to form the LVM that has lower resolution at depth.

At a few areas the validity of the results from the airborne TEM measurements were evaluated against ground geophysical data and borehole information. We have also used all existing ground geophysical data such as electrical resistivity tomography (ERT) radio magnetotelluric (RMT) and reflection seismic data (mainly in Gotland). Figure 2 shows the steps for making the models in an area in the Island of Öland.

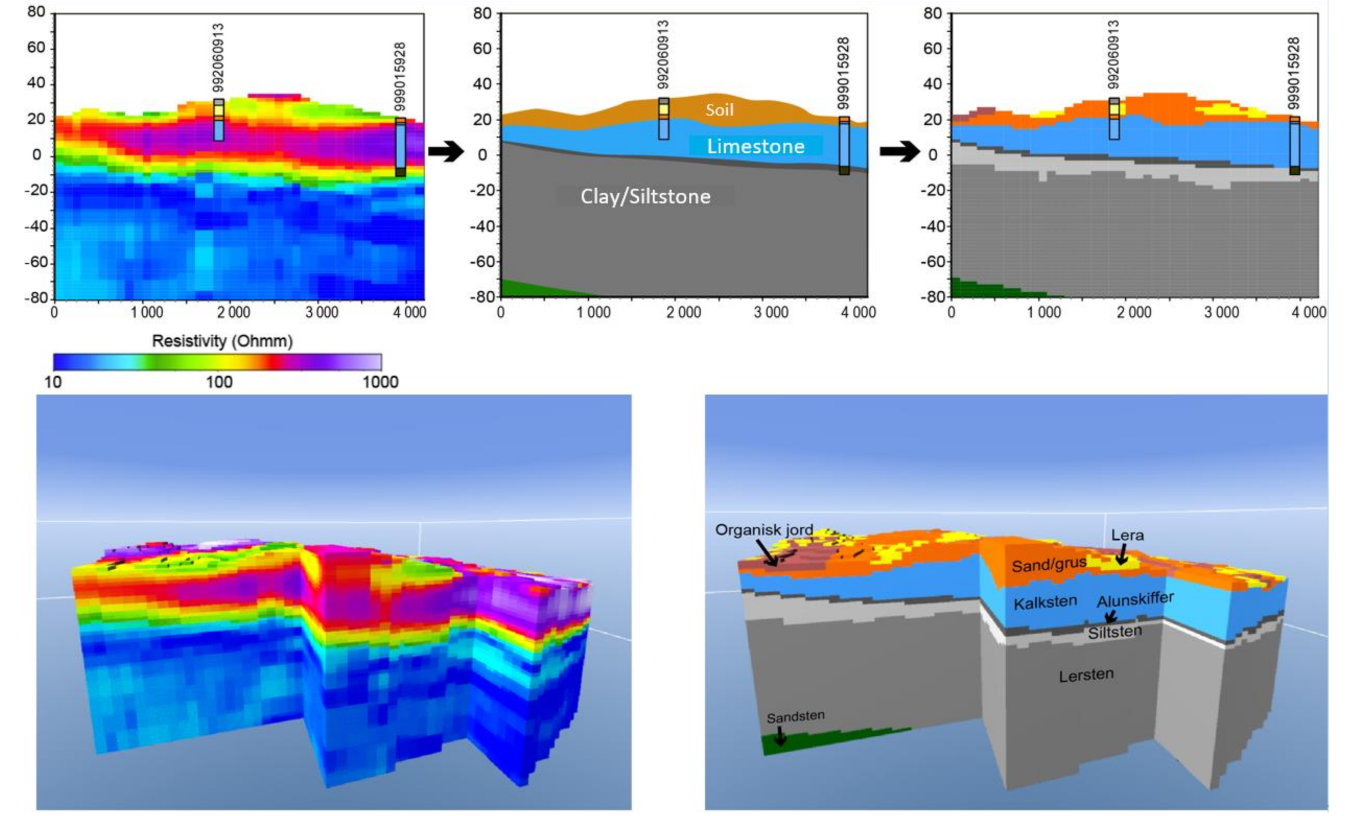
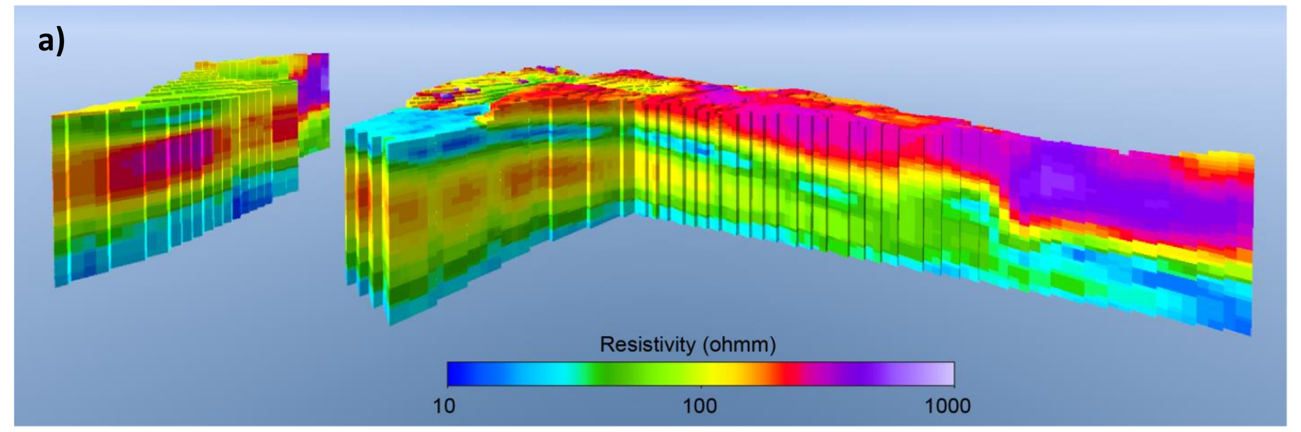


Figure 2: The steps taken to make a 3D geological model. a) The resistivity models along flightlines are constructed. b) The resistivity models together with all geological data are interpreted into a layered model along flight lines. c) The layered model is trasnformed into a lithological voxel model. d) Example of resistivity model gridded in 3D. e) Lithological voxel model in 3D of the same area shown in (d).

3D geological models over Gotland

ATEM measurements were carried out over the island of Gotland in 2013 and 2015. The main objective with the surveys was to identify new groundwater recourses and to locate the depth to saline groundwater on the island (Dahlqvist et al., 2015 & 2017). The resistivity models from the ATEM survey, together with other existing data have been used to develop three types of 3D models over the island; a litostratigraphical bedrock model, a lithological soil and bedrock model and a groundwater salinity model. The 3D voxel models shown above are located on the eastern part of Gotland in the Åminne area. The viewpoint is located in the southwest and the vertical scale is exaggerated 25 times relative to the horizontal.



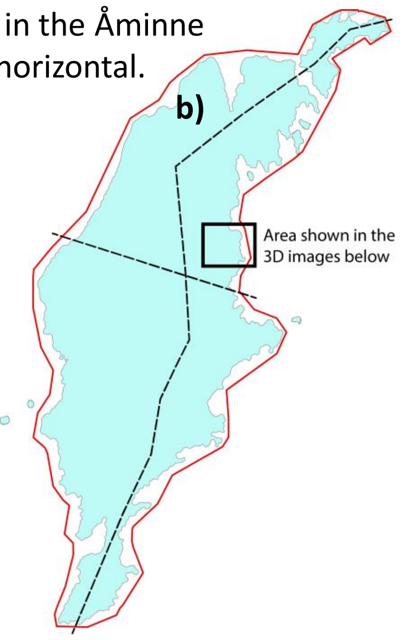


Figure 3: a) Resistivity model in the area shown in (b) with a black box. b) Location of the selected area for the example models shown in Figures 5 & 6. The black lines show the selected profiles to show the lithostratigraphic model in Figure 4.

The lithostratigraphical bedrock model (Fig. 2) contains 11 layer from Ordivician up to Silurian Hamra formation (Erlström et al. 2009). The layers zone A and B are only geophysically defined from borehole logs and probably belong to the lower part of the Visby formation.

The litostratigraphic model is available both as layer and voxel model (cell size 100x100x5 m and reach down to 250 m.b.s.l.)

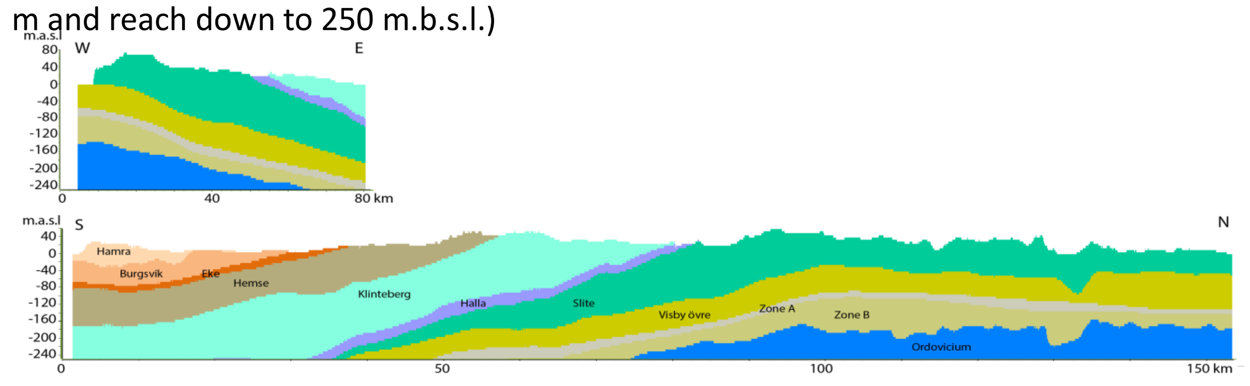


Figure 4: Lithostratigraphic model in Gotland along the lines shown in Figure 3b.

The lithological model consists of the bedrock and soil layers merged into a common voxel model. The soil layer is divided into three classes with similar hydrogeological properties; permeable soils - sand and gravel, less permeable - clay, silt and clayey till and organic soils. The lithostratigraphical model has been used as the basis for the lithological modeling since some lithological boundaries also coincide with the stratigraphic. In areas with ATEM measurements, the resistivity models have been used to distinguish marl, limestone and reef limestone. The lithological soil and bedrock model have a cell size of 100x100x2 m^3 and reach down to 80 m.b.s.l.

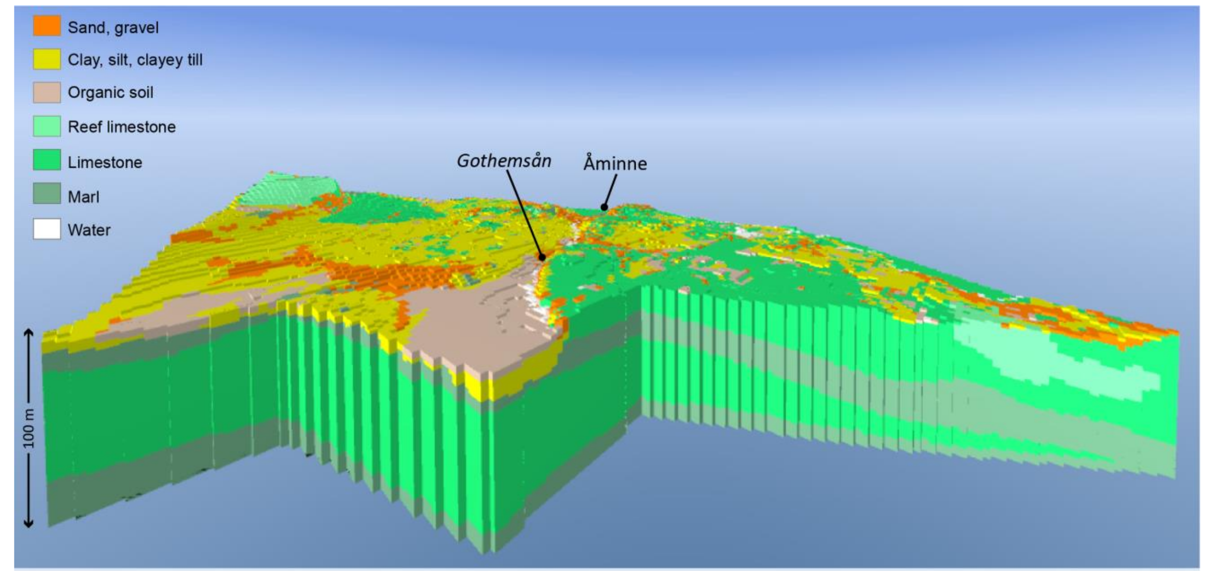


Figure 5: Lithological model in Gotland in the area marked by a black box in Fig. 3b.

The groundwater salinity model contains two categories only – saline groundwater and fresh water. The surface of the saline groundwater has been mapped primarily based on the resistivity models from the ATEM data. Then, a voxel model has been produced by populating all voxels below the constructed surface to be "saline". After that, additional information from water wells has been added to the model.

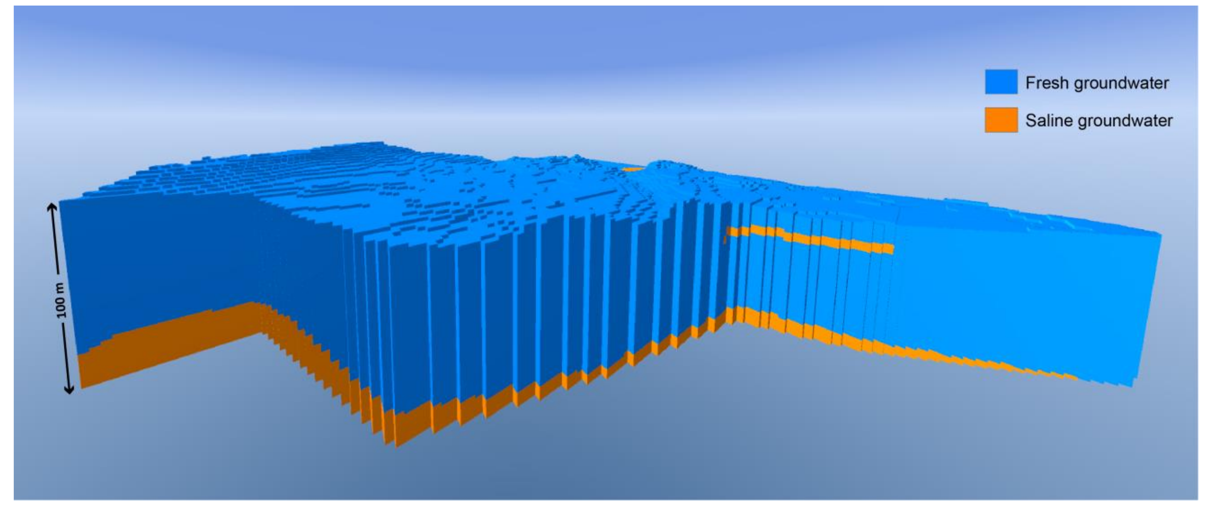


Figure 6: Salinity model in Gotland in the area marked by a black box in Fig. 3b.

Acknowledgments

The 3D modelling was done in collaboration with Flemming Jørgensen (formerly GEUS now Region Midtjylland) and Mats Lundh Gulbrandsen (I · GIS A / S) according to a methodology based on a combination layer and voxel modeling (Jørgensen et al. 2013, 2018 & Gulbrandsen et al. 2018). All geological modeling was done in Geoscene 3D (I · GIS) software.

3D geological models over Öland

The island of Öland 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. 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.

The up to c. 250 m thick Palaeozoic sedimentary succession (Figure 7) 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

In Figure 8 we show the resistivity model down to a depth corresponding to -80 m elevation in Öland. Similar to the modelling work done in Gotland the resistivity model, borehole data and other geological information are used to make a lithostratigraphic layered model over the entire island. An example of LM along a nearly S-N profile is shown in Figure 9. The resistive limestone overlays the more conductive silt/claystone that is underlain by more resistive sandstone of File Heider formation. The Precambrian crystalline bedrock (see Fig. 7) has the highest resistivity and is resolved at a few locations in the area covered by the airborne measurement. At one very distinct location in Mossberga (distance 75 km in the profile shown in Figure 9) the crystalline bedrock is as shallow as 50 m below the surface and is clearly resolved in the resistivity models and matches the borehole information nearly perfectly (Bastani et al., 2018).

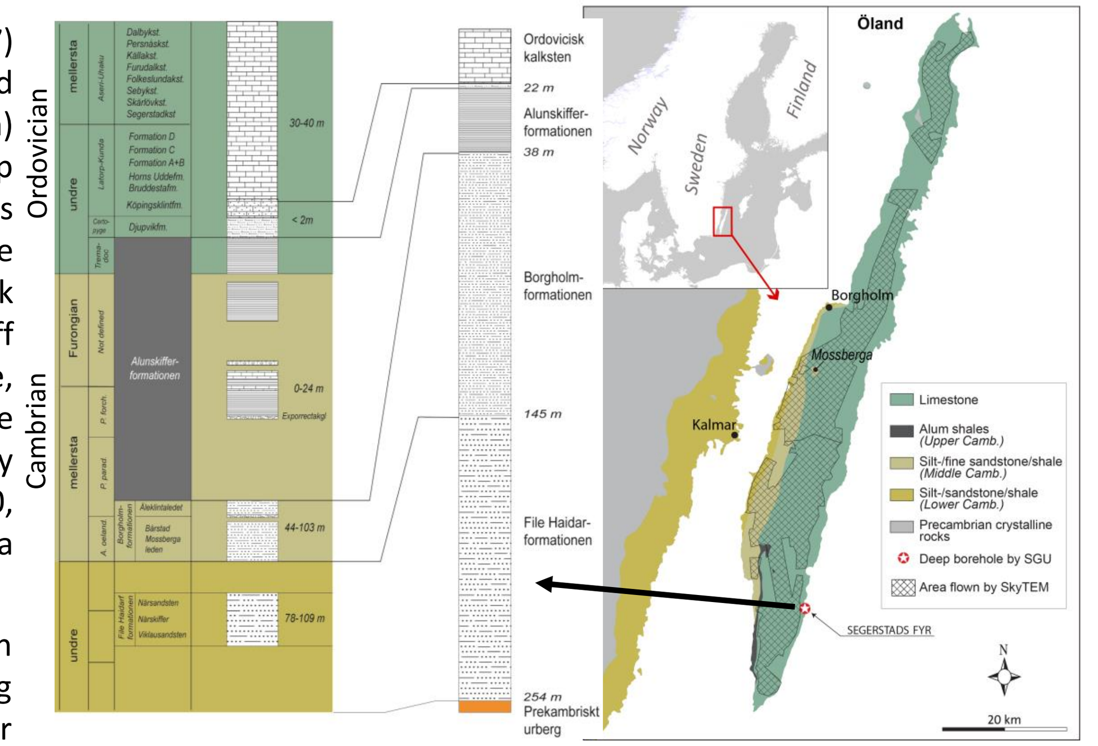


Figure 7: Simplified geological map of Öland (right) and detailed geological interpretation of borehole cores in one of SGU's deep boreholes in Segerstads Fyr (left).

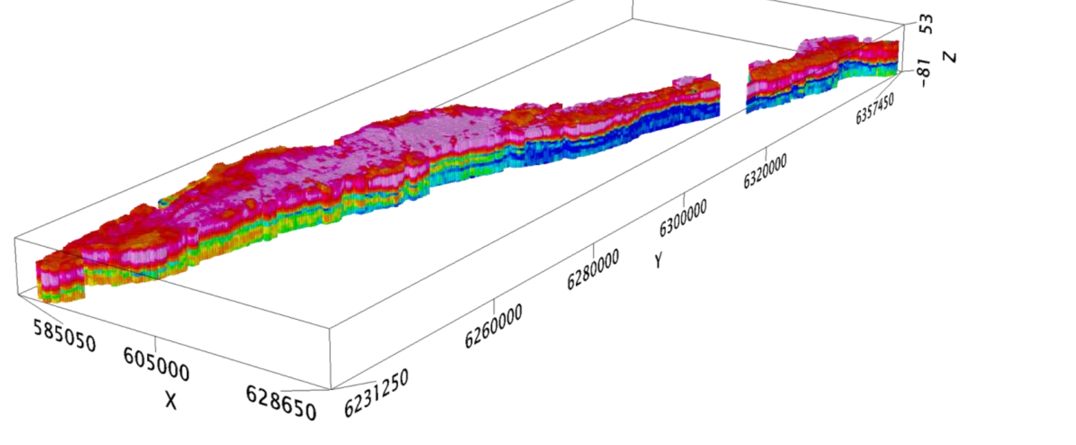


Figure 8: Resistivity model from the 1D inversion of airborne TEM data in Öland gridded in 3D.

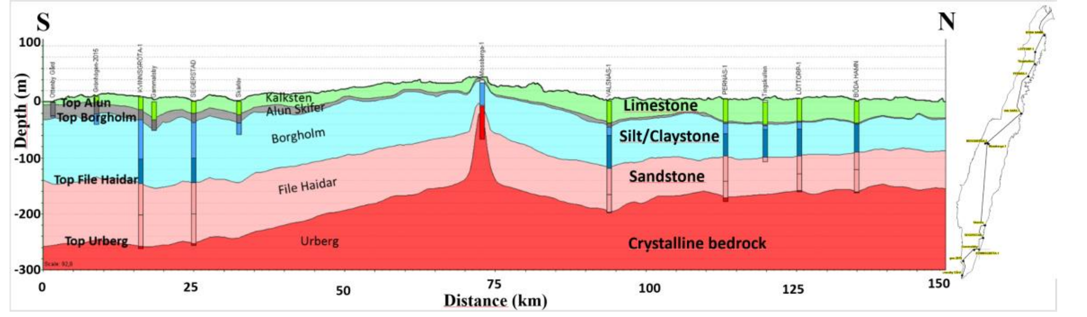


Figure 9: Lithostratigraphic model in Öland along the S-N profile shown in the inset map.

Concluding remarks

In this study we present the 3D geological models over the islands of Öland and Gotland which were constructed from the integrated interpretation of all the available data. The models are composed of voxels, each representing a certain lithology classified using a statistical approach. The classification is based on the resistivity range, distance to the neighboring wells/boreholes and the geological observations at the surface. The 3D voxel models will be/have been utilized in hydrological modelling, societal planning, and groundwater management.

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