3D MODELLING AND RESISTIVITY MEASUREMENTS FOR HYDROGEOLOGICAL ASSESSMENTS IN THE NORTHERN PART OF VOMBSÄNKAN

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Dissertations in Geology at Lund University,
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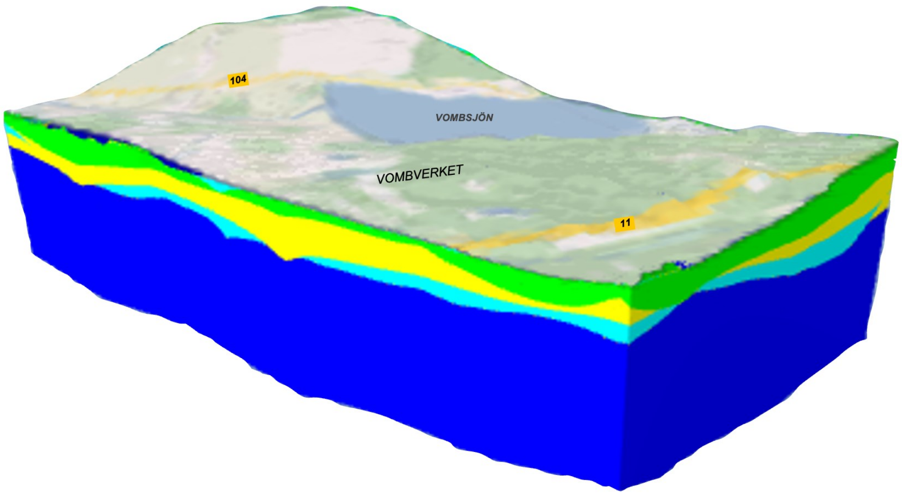

Department of Geology
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2023

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Contents

Cover Picture: 3D geological model of Vombverket created by Geoscene 3D (view toward the North).

3D MODELLING AND RESISTIVITY MEASUREMENTS FOR HYDROGEOLOGICAL ASSESSMENTS IN THE NORTHERN PART OF VOMBSÄNKAN

FARID KHORSHIDIAN

Khorshidian, F., 2023: 3D modelling and resistivity measurements for hydrogeological assessments in the northern part of Vombsänkan. *Dissertations in Geology at Lund University*, No. 670, 57 pp. 45 hp (45 ECTS credits) .

Abstract: The geology of Vombsänkan is characterized by a complex sequence of Quaternary deposits overlying the Paleozoic sedimentary bedrock. The area is 759 km^2 and has recorded several ice advances followed by glacial retreats and ice melting. The glacial history of Vombsänkan, which is controlled by sequential geological events such as active ice-margin and stagnant ice, formation of dead ice as well as damming and subsequent drainage of glacial lakes and melting, has resulted in a diverse stratigraphy that is difficult to correlate across the entire basin. Abundant borehole data convey a recurring depositional pattern of the Quaternary deposits, which consist generally of till beds covered by glaciolacustrine and glaciofluvial deposits. The basin hosts several large aquifers with favourable hydrogeological properties. However, no detailed information in three dimensions exists on the hydrostratigraphic units and their properties. Lack of a 3D visualization of the northern part of Vombsänkan and an instruction for the application of Geoscene 3D in modelling of a complex geological setting such as Vombsänkan, emphasizes the importance of this thesis work. This study introduces a new 3D model of the northern part of Vombsänkan using Geoscene 3D. A simple hydrostratigraphic model is presented for the Vombverket water treatment plant, which demonstrates the presence of a thick glacial clay unit on top of the sedimentary bedrock. Locally, a till unit occurs between the sedimentary bedrock and the clay unit and the uppermost unit consists of 5–10 m of sand and gravel. Using Geoscene 3D, the approximate volume of the aquifer is estimated to 9.1–18.2 km^3 for the confined aquifer within the sedimentary bedrock, and 1.3–2.6 km^3 for the open aquifer within the overlying sand and gravel unit. The major flow directions are from the adjacent areas of higher elevation such as the Romeleåsen Horst in the Southwest and the Linderödsåsen Horst in the Northeast.

Keywords: Conceptual 3D modelling, Resistivity, Hydrogeology; Blue Transition, Vombsänkan, Vombverket

Supervisors: Dan Hammarlund (Department of geology), Alfredo Mendoza (LTH), Torleif Dahlin (LTH)

Examiner: Charlotte Sparrenbom

Subject: Bedrock Geology

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3D-MODELLERING OCH RESISTIVITETSMÄTNINGAR FÖR HYDROGEOLOGISKA UTVÄRDERINGAR I NORRA DELEN AV VOMBSÄNKAN

FARID KHORSHIDIAN

Khorshidian, F., 2023: 3D-modellering och resistivitetsmätningar för hydrogeologiska utvärderingar i norra delen av Vombsänkan. *Examensarbeten i geologi vid Lunds universitet*, Nr. 670, 57 sid. 45 hp.

Sammanfattning: Vombsänkans geologi kännetecknas av komplexa kvartära avlagringar som täcker den paleozoiska sedimentära berggrunden. Området är drygt 750 km^2 stort och har påverkats av flera isframstötar och avsmältningsskeden under slutfasen av den senaste istiden. Olika processer under Vombsänkans historia, som glacial erosion och deposition, dödisavsmältning och isdämda sjöar, har därmed resulterat i en varierad stratigrafi som är svår att korrelera över hela bassängen. En stor mängd borrningsdata vittnar dock om ett generellt mönster i de kvartära avlagringarna, i huvudsak bestående av moränlager täckta av glaciolakustrina och glaciofluviala avlagringar. Bassängen hyser flera omfattande enheter av vattenförande lager med gynnsamma hydrogeologiska egenskaper. Dock har hittills ingen detaljerad information i tre dimensioner sammanställts beträffande de hydrostratigrafiska enheterna och deras egenskaper. Detta arbete fokuserar därför på 3D-visualisering av den norra delen av Vombsänkan och en handledning för tillämpning av programvaran Geoscene 3D för modellering av Vombsänkans komplexa geologisk miljö. En enkel hydrostratigrafisk modell presenteras för området kring Vombverkets vattenreningsanläggning, vilken visar förekomsten av ett mäktigt lager av glacial lera ovanpå den sedimentära berggrunden. Lokalt förekommer ett moränlager mellan den sedimentära berggrunden och leran, som i sin tur överlagras av glacifluviala avlagringar bestående av 5–10 m sand och grus. Baserat på Geoscene 3D uppskattas den ungefärliga volymen av de vattenförande lagren i den sedimentära berggrunden till 9.1–18.2 km^3 medan motsvarande volym hos den ytligt förekommande sand och grusenheten är 1.3–2.6 km^3. Grundvattnets huvudsakliga flödesriktningar är från närbelägna områden med högre topografi, främst Romeleåsen i sydväst och Linderödsåsen i nordost.

Nyckelord: Conceptuell 3D-modellering, Resistivitet, Hydrogeologi; Blue Transition, Vombsänkan, Vombverket

Handledare: Dan Hammarlund (Geologiska institutionen), Alfredo Mendoza (LTH), Torleif Dahlin (LTH).

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1. Introduction

Water is essential for life on Earth, and it is the world's most important natural resource. In Sweden, 50% of the drinking water supply comes from groundwater and 50 % is provided by surface water (Sydvatten 2009). However, it has been very challenging to ensure a reliable water supply with good quality.

The human activity and the air pollution are constantly increasing. Because of the global warming, protection of the groundwater recourses is demanding. Therefore, it is crucial to systematically increase the hydrogeological information for a better understanding of the groundwater systems (Blue Transition 2023). For instance, the geological conditions, structure and dimension of the hydrostratigraphic units, water level as well as possible contaminants and risk assessments to protect the water resources for the future.

Conceptual 3D modelling provides a useful visualization and interpretation of data sets such as borehole data, hydrogeological properties, field observations, structural geology as well as tectonic structures and geophysics. The measured geophysical data of a region and the geological setting are strongly related to each other because the measured geophysical data are depended on the physical properties of glacial deposits and rock units such as lithology, mineralogy and structure of the geological setting. A conceptual model that is based on borehole information together with geophysical data, leads to a better understanding of the regional geology.

3D modelling is a common approach to hydrogeological assessments such as water permit processes, evaluation of the groundwater drawdown and radius of influence. A 3D conceptual hydrogeological model consists of different hydrostratigraphic units, where each unit has similar hydraulic properties such as transmissivity (T), hydraulic conductivity (K) and permeability.

The demand for detailed knowledge about the subsurface features in hydrogeological applications is increasing (Dahlin and Zhou 2006; Dahlin et al. 2002). The resistivity method is an efficient approach in geophysical investigations for definition of the geological units and the internal structure of the groundwater systems. The method is considered as an emerging and favourable technique for mapping of groundwater and underground structures (Sparrenbom et al. 2016; Dahlin et al. 2017). The resistivity data can be imported to software such as RES2DINV to create 2D and 3D geophysical models. Combinations of geological and geophysical data are often used in hydrogeological evaluations of groundwater systems.

In a recent scientific report published by SGU, Dahlqvist et al. (2021) described the geology of Vombsänkan, an elongated sediment-filled depression located between the Romeleåsen Horst and the Linderödsåsen Horst in southern Skåne (Fig. 1) using borehole data and helicopter-borne geophysical survey (SkyTEM). The report explains the geological and tectonic evolution of the area and provides a detailed classification of the bedrock and Quaternary deposits of Vombsänkan. The northern part of Vombsänkan contains significant amounts of groundwater with considerable uptake capacities including several large groundwater systems.

Ising (2020) created a geological 3D model from the middle and southern part of Vombsänkan but there is no research that provides 3D visualization of the northern part of Vombsänkan. The department of Engineering geology at Lund university (LTH) is aiming to increase the hydrogeological information by creating conceptual models using Geoscene 3D. Being able to process and combine several types of data and providing an excellent visualization, Geoscene 3D is a powerful software for creating profiles, 2D and 3D models. Yet, there is no previous research available that describes the 3D modelling procedures with Geoscene 3D using the borehole data. Lack of an instruction for the application of the software in modelling of a complex geological setting such as Vombsänkan, emphasizes the importance of this thesis work. This study suggests a 3D interpretation of the hydrogeological processes in the northern part of Vombsänkan. In addition, a description of the 3D modelling procedure is provided within this thesis work.

Moreover, a conceptual 3D model will be introduced, illustrating the geology of the northern part of Vombsänkan using Geoscene 3D. The software is a useful tool for comparing several data types in the form of 2D and 3D models. It is considered as a powerful modelling software specifically for hydrogeological studies and conceptual 3D modeling, providing simultaneous interpretations of different data sets.

The result of this thesis work is a combination of conceptual 3D modelling and geophysical investigations in the form of field-based resistivity. The field measurements data will be visualized and interpreted in Geoscene 3D to validate the results of the conceptual modeling. The combination of conceptual 3D models and geophysical models enables a more coherent and reliable interpretation with reduced uncertainty. This study aims at providing a better understanding of groundwater resources in the northern part of Vombsänkan.

1.1 Blue transition

Groundwater quality is significantly influenced by human activities such as land use, natural gas extraction and pollutant inputs. Within a hydrogeological setting the groundwater characteristics are strongly controlled by the quality of the surface water and the soil.

The water flows on the surface and joins the groundwater recourses through the uppermost geological units. Therefore, it is necessary to control the quality of the soil to ensure a safe and sustainable supply of drinking water. The important balance between land and water is unfortunately, disintegrated by the climate change and human activities in the North Sea Region. Nowadays, the quality and quantity of these resources are severely endangered, and the dimensions of this environmental concern are dramatically increasing each year. Indeed, regional climate and the water cycle are closely connected, both being influenced by ongoing decreases in precipitation, runoff, groundwater level and soil moisture as well as increasing evaporation (Whitehead et al. 2009). In fact, the surface water level balance has significantly altered because of the global warming. The chemical inputs from the surrounding elements such as the air and the adjacent landscape, have a direct impact on the quality of surface and groundwater. When these resources are polluted due to human activity, altered water chemistry leads to challenges for drinking water production (Whitehead et al. 2009).

The Blue Transition project is a collaboration between seven European countries as a part of the program 'A climate resilient, North Sea Region'. The project targets a systematic change by an integrated water and soil management to ensure good-quality water (Blue Transition 2023). The goal is:

1. Fundamental changes within the land use, forests, agriculture, wetlands, peatlands and protected areas in both short and long term to improve groundwater resources. 2. Integrating, connecting and balancing the activities in agricultural, natural and urban areas. 3. Ensure the future availability of good quality water while helping to renew the natural habitats and

reduce carbon emissions (Blue Transition 2023).

The Blue Transition project has two research areas in southern Sweden, at Lake Bolmen and around Vomb. Engineering Geology at Lund University (LTH) is conducting hydrogeological and geophysical investigations at these sites (Engineering geology, LTH 2023). Some of the main strategies defined by the project include sustainable salinity solutions, effective freshwater conservation, cooperation with farmers, trials and investigations as well as soil and water management plans (Blue Transition 2023).

A major part of this study is geological and hydrogeological evaluation of Vombverket water treatment plant, located at South of Vombsjön.

1.2 Vombverket

Vombverket is driven by Sydvatten and it is located at South of Lake Vombsjön. The water treatment plant is one of the main suppliers of drinking water through artificial infiltration in southern Sweden.

Water pumps from Lake Vombsjön to the infiltration basins for the groundwater recharge, where it infiltrates and joins the shallow unconfined aquifers. From several wells, groundwater is pumped to the waterwork for purifying that is producing 1100 l/s drinking water (Sydvatten 2009).

1.3 Aims

The general aim of this thesis is to create three different conceptual 3D models with Geoscene 3D using existing data such as borehole lithology. The primary model is based on borehole data from the northern part of Vombsänkan.

A similar procedure is applied to create a hydrogeological conceptual model which is defined based on the hydrogeological properties of the units such as hydraulic conductivity (K). In addition, a refined conceptual model focused on the Vomb area (Vombverket), South of Lake Vombsjön is created.

The more specific aim of the study is to use the geological and hydrogeological conceptual 3D modelling together with resistivity geophysical investigation as a tool to evaluate the hydrogeological properties of the northern part of Vombsänkan. This study will provide increased understanding of the hydrogeological conditions, such as the structure of the hydrostratigraphic units, aquifer geometry and flow processes. The demand for groundwater is rapidly increasing. Therefore, the results of this study are important for Sydvatten in their efforts to develop the regional drinking water supply.

1.4 Limitations

- The reliability of the imported borehole data cannot be evaluated in detail which leads to uncertainties. The classification of the borehole data into five lithology groups results in a simplified model of the otherwise heterogenous geology.
- During the modelling process and the correlation, units that are thinner than 5 m such as small lenses are ignored. Since, the study area is relatively large (759 km^2), including all these features, such as thin till beds is time consuming. However, in hydrogeological systems a very thin unit such as a thin till unit may have a significant impact on the hydrogeological properties such as groundwater flow and leakage. Consequently, an exact hydrogeological evaluation in the northern part of Vombsänkan is difficult and requires more detailed investigations.
- The borehole data contain many general terms that imply large uncertainty. For instance, soil, rock, filling, well, and glaciofluvial sediments. Within this thesis work, based on previous studies as well as the adjacent boreholes, a new category is defined for the generic terms.

However, the classification of these lithology groups is problematic. Therefore, further investigations such as field observations and core logging are required.

- In addition, to facilitate the modelling process, some of the units are merged into one group. For example, clay-till and sand-till that have different hydraulic conductivities (K) are classified into the group till. Classification of clay and fine-grained sand/silt into the group of clay/silt is another limitation that influences the hydrogeological evaluations. Moreover, the hydraulic conductivity (K) varies between different rock types within the sedimentary bedrock and the Precambrian bedrock. For instance, gneiss, diabase, amphibolite and granite with different K values are categorized in a new group. A similar approach is applied for the classification of the sedimentary bedrock which consists of several units with different lithologies. Since, the lithology of the sedimentary bedrock varies significantly within the study area. Most notably, the variation in K and porosity within the sedimentary bedrock is more prominent. Considering the diverse bedrock geology of Vombsänkan, an accurate estimation of the hydraulic conductivity of each unit is difficult.
- Since the modelling is done for the northern part of Vombsänkan, it does not suggest an accurate stratigraphy for a small section. Performing the modelling process when zoomed in is time consuming.
- There are a lot of boreholes that are drilled only a few m into the ground, and they do not provide information on the deeper parts. The correlation of the units for the areas without any deep boreholes is therefore inaccurate and based on the stratigraphy of the nearest wells.

2.Background

2.1 Study area

The study area is the northern part of Vombsänkan in central and southeastern Skåne (Fig. 1). Vombsänkan is 759 km^2 in size and has a NW-SE-directed extension from Gårdstånga in the Northwest to Kåsberga in the southeast. The area is located between two tectonic lineations associated with the Tornquist Zone. The northwestern part of Vombsänkan is defined by Romeleåsen Horst and the southeastern part extends towards the Fyledalen Valley (Dahlqvist et al. 2021). The Romeleåsen Horst consists of elevated Precambrian bedrock while the northern part of Vombsänkan is mostly flat.

Vombsänkan is characterized by several lakes and rivers such as the most important ones Kävlingeån and Nybroån. In the southern part of the area there are two rivers, Kabusaån located East of Ystad and Svartån in the West.

A part of this thesis work is focused on hydrogeological evaluation of the area South of Lake Vombsjön, at Vombverket (Fig 1).

2.2 Geology

2.2.1 Bedrock

The Precambrian igneous metamorphic bedrock is mainly composed of gneiss and granite, and it is exposed in several areas in Romeleåsen as well as East of Lake Vombsjön at the border of the Colonus Trough (Fig. 2). Diabase (dolerite) dikes are abundant with a major trend parallel to Vombsänkan found both on Romeleåsen and in the Colonus shale trough. Other common rocks are amphibolite and quartzite. Most of the information about the igneous metamorphic bedrock is based on seismic investigations and the borehole data. However, some of the wells do not reach the depth of the bedrock, which limits the information about the depth of the unit. At the Herrestad Ridge and South of Sövde, the Precambrian bedrock exposes where thin units of Jurassic and Cretaceous strata coexist together with the bedrock at both locations (Dahlqvist et al. 2021). The sedimentary bedrock in Vombsänkan consists of Mesozoic units that overlie the Precambrian igneous metamorphic bedrock (Appendix 1). Based on borehole data and seismic investigations, Paleozoic strata have not been found in Vombsänkan.

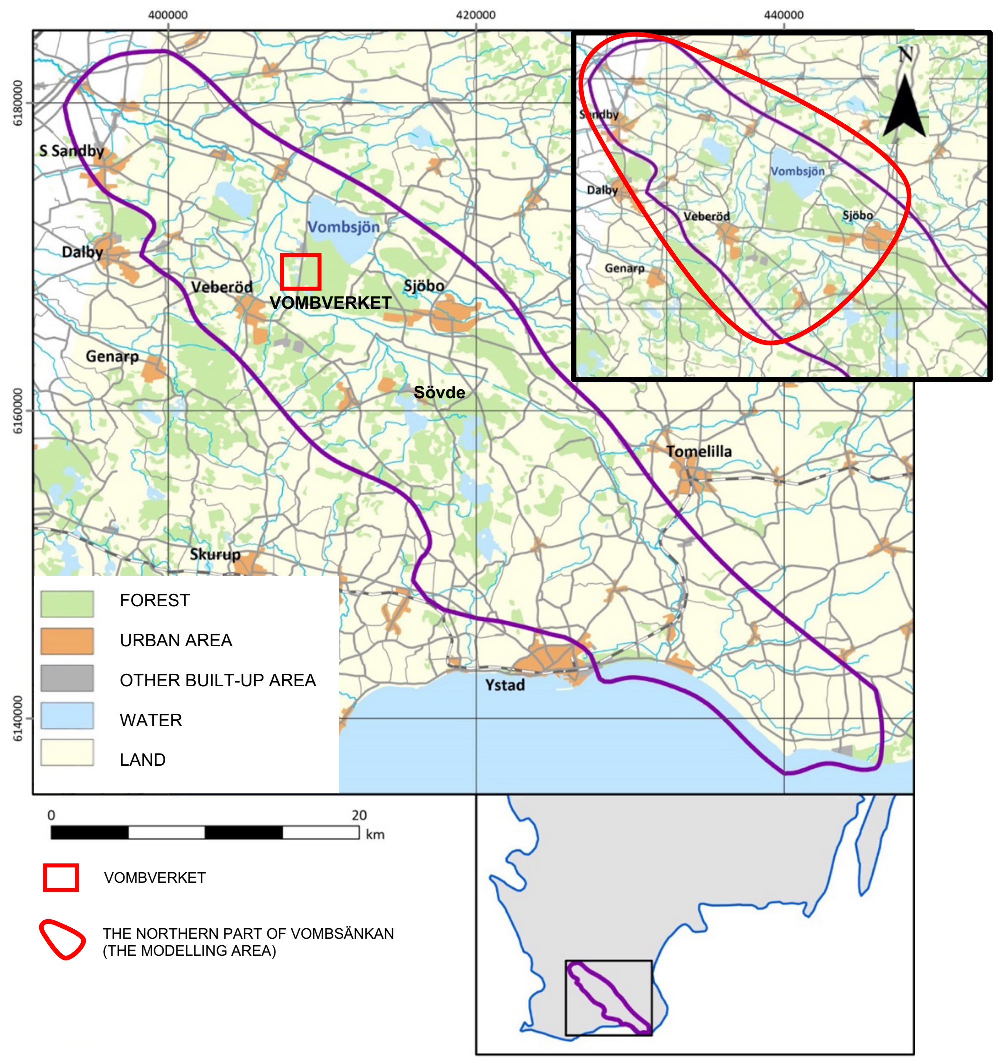


Fig. 1. Vombsänkan, southern Sweden. The area is 5 to 11 km wide and continues towards Östersjön and Bornholm (Dahlqvist et al. 2021). The location of Vombverket and the modelling area is marked on the map.

The Triassic and Jurassic units of the sedimentary bedrock belong mainly to the Kågeröd formation, consisting of red to yellowish brown clay and fine-grained sands and sandstones. The thickness of the Kågeröd clay reaches a maximum of 18 m around Herrestad Ridge (Dahlqvist et al. 2021). The lower Jurassic bedrock is characterized by the Höganäs formation, which consists mainly of silt, sand and clay. The lower and middle Jurassic Fuglunda Formation consists mainly of glass sand. These carbonate-rich silt and clay units are mostly found on top of the Precambrian bedrock, but it does not mean that these units are always present, and this sequence can vary through different part of Vombsänkan. The most important units of upper Jurassic age are the Fyledalen clay, the Vitabäck clay and the Nytorp sand. The Vitabäck unit consists of fine-grained rocks composed of silt, fine-grained sand and organic-rich clay. The middle to upper Jurassic of Vombsänkan is characterized by clay and fine-grained sand up to the lower Cretaceous.

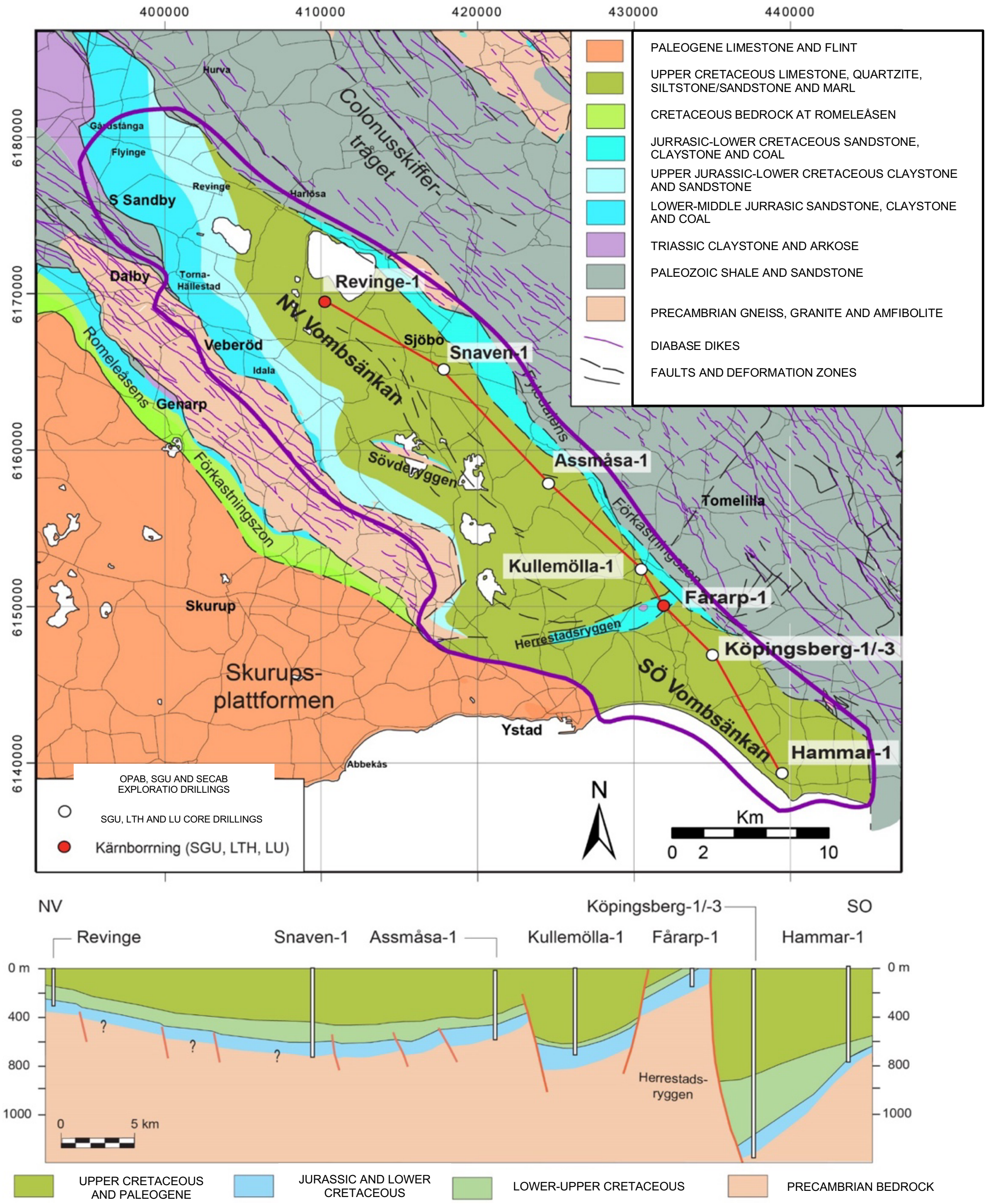


Fig. 2. Bedrock map and a geological cross section based on borehole data from Vombsänkan (Erlström 2004; Dahlqvist et al. 2021).

The lower Cretaceous units are composed of sandstones, claystones, siltstones and carbonates. These units are relatively homogeneous and may contain coal. The lower Cretaceous units are described as sandy and glauconitic sediments, carbonate rocks and phosphate-bearing conglomerates. This suggests a near shoreline shallow marine depositional environment. This sequence is known as the Vomb Formation, which has a higher carbonate content Southeast of Vombsänkan where sandy carbonate rocks and marls are abundant (Dahlqvist et al. 2021).

2.2.2 Quaternary deposits

The geological history of Vombsänkan has recorded several glacial advances, dead ice, melting and the intermediate stages between each glaciation. The geology of Vombsänkan is therefore considered as a diverse stratigraphy which is characterized by the formation of glacial deposits such as till beds, glaciolacustrine and glaciofluvial deposits. The southern part of Vombsänkan, is predominantly covered by till whereas glaciofluvial and glaciolacustrine deposits are generally the dominant sediments of the northern part (Dahlqvist et al. 2021) (Fig. 3).

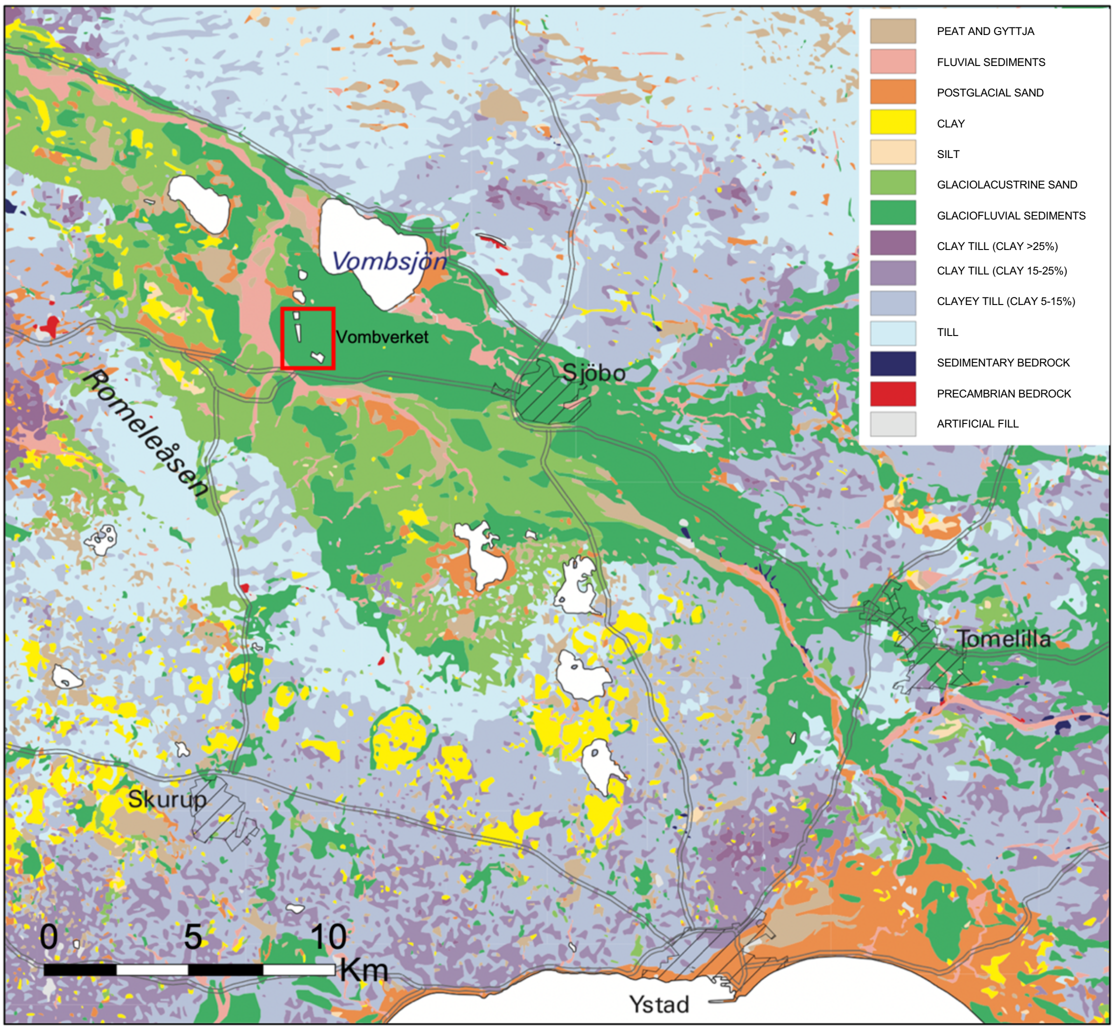


Fig. 3. Map of the Quaternary deposits of Vombsänkan and adjacent areas (1:250000) (Daniel 1992).

Glaciolacustrine sediments

The Late Weichselian ice margin is estimated to have been located generally parallel to Vomsänkan from northwest to southeast. The last glacial advance was from Northeast and the ice melted around 16000 to 17000 years ago (Hughes et al. 2016: Stroeven et al. 2016; Houmark-Nielsen and Kjaer 2003). In the northern part of the area, remaining bodies of stagnant ice resulted in the formation of kettle lakes surrounded by glaciofluvial deposits dominated by sand, commonly underlain by clay. Moreover, the melting of stagnant ice, led to formation of the typical topography of southern Skåne, which is characterized by hummocky moraine as well as several ridges and shallow valleys. Lake Vombsjön and lake Krankesjön are the largest lakes in the area, both formed as the result of melting of large bodies of stagnant ice.

Till

The most common type of till in Vombsänkan is clay-till. The associated landform system and topography are relatively flatter towards Romeleåsen, the Colonus Trough and Southeast of Vombsänkan (Dahlqvist et al. 2021). Around Vombverket where the boreholes do not reach the depth of the till unit the dimensions of the till units are unknown. The Quaternary deposits map shows that the ground surface around the Romeleåsen Horst and the Linderödsåsen Horst is mainly covered by till (Fig. 3)

Glaciofluvial sediments

The glaciofluvial deposits of Vombsänkan are typically formed as outwash and delta sediments that are more common in the northern part of Vombsänkan. The southern part consists of several shallow valleys, which creates a specific topography. Eskers in form of long ridges of sand and gravel are only observed near the edges of Vombsänkan, for example Hällestads åsar, Ramsåsaåsen and Bilarpsåsen. However, the origin of the ridges in the southeastern part is controversial and unclear since the area is mostly covered by moraine and fine-grained sediments (Dahlqvist et al. 2021).

Postglacial deposits

Postglacial sand and gravel, in places covered by sand dunes are locally reported from near the coast up to 15 m above the sea level (Daniel 1992). Postglacial sand is observed around Lake Vombsjön and Lake Sövdesjön, reaching a maximum thickness of around 5 m. Along the major rivers such as Kävlingeån, Klingavälsån, Björkaån and at the bottom of Fyledalen, overbank sediments are deposited in the form of sand, silt and clay, usually less than 1 m in thickness. Peat, gyttja and clay-gyttja are also abundant, reaching a thickness of 1-5 m. A geological cross section from the southern part of Vombsänkan is illustrated by Ising (2020) and Dahlqvist et al. (2021) (Fig. 4).

2.3 Hydrogeology

Vombsänkan consists of several large aquifers with a substantial uptake capacity. The groundwater is generally stored both within the sedimentary bedrock and the Quaternary deposits, emphasizing the hydrogeological importance of the area.

Seventeen major groundwater resources are documented in Vombsänkan. Eleven resources are associated with sand and gravel aquifers, such as Holmbyåsen, Revingehed, Hultan, Åsumsfältet, Ilstorp, Fyledalen, Snogeholm, Krageholm, Köpingsberg, Glemmingebro, and Kåsebergåsen. Six major aquifers are linked to the sedimentary rock aquifers including, Vombsänkan, Kågeröd, Eslöv-Flyinge, Stora Herrestad-Fårarp, eastern slope of Romeleåsen, and Eriksdal (Dahlqvist et al. 2021).

Generally, the aquifers within the sand and gravel units are open aquifers. In addition, substantial amounts of groundwater are stored in confined aquifers within the sedimentary bedrock typically formed by near surface sandstone with high porosity. Considering their dimension and volume, the pore aquifers are the most important groundwater resources in Vombsänkan. Some of the major groundwater resources, such as Vombverket South of Lake Vombsjön and Revinge North of Lake Krankesjön, are located in the northern part of Vombsänkan. South of Lake Vombsjön is characterized by relatievely thick permeable units with a substantial groundwater uptake capacity. For instance, at Hultan East of Lake Vombsjön, the groundwater uptake capacity is estimated to 25–125 l/s (Gustafsson et al. 2005). These geological conditions emphasize the hydrogeological importance of the northern part of Vombsänkan.

In the southern part, for example at Ystad and Tomelilla, the groundwater is used for drinking water and agriculture.

The groundwater geochemistry is generally characterized by high concentrations of sulfate, chloride, as well as elevated hardness and pH (Dahlqvist et al. 2021).

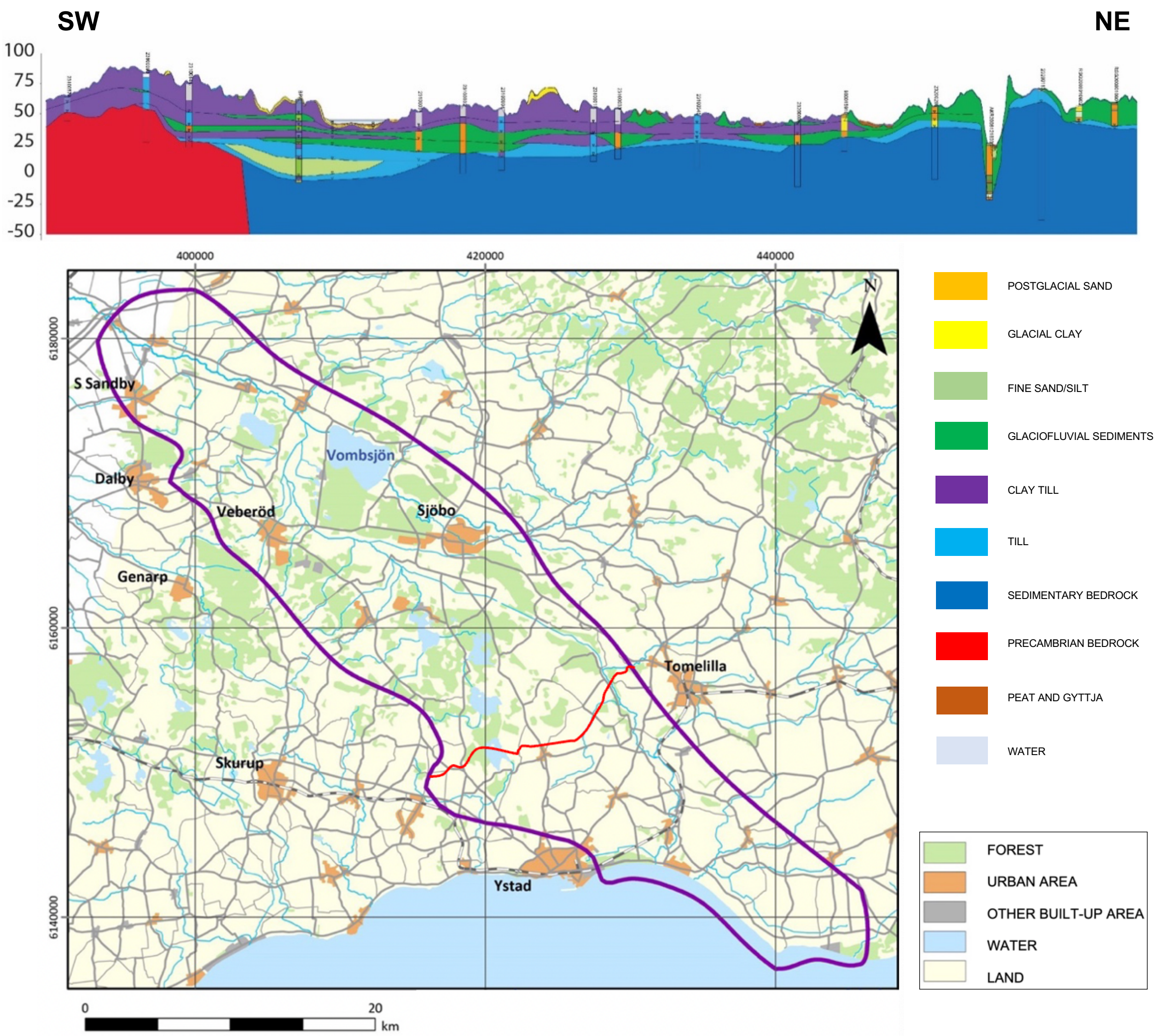


Fig. 4. A geological cross section of the southern part of Vombsänkan (illustrated with red) (Ising 2020; Dahlqvist et al. 2021).

3. Material and methods

3.1 Geoscene 3D

A major part of this thesis work has been carried out with the software Geoscene 3D to create conceptual 3D models of the northern part of Vombsänkan and with a focus on Vombverket. The borehole data, currently existing resistivity and SkyTEM data are imported and visualized as 3D models. In this thesis work the SkyTEM models are imported in Geoscene 3D (Appendix 2). However, the results of the field-based resistivity measurements are used as the main geophysical approach of the interpretation. The result can be investigated within the software providing a simultaneous visualization and comparison of geological and geophysical 3D models. Based on the borehole data, a 3D model is created for the northern part of Vombsänkan. The model is evaluated and verified by resistivity surveys in the field followed by hydrogeological interpretation of the model based on the hydraulic conductivity of the lithological units. The result is a conceptual hydrogeological model with defined hydrostratigraphic units, which can be used for a better understanding of the hydrogeological properties. Some of the major features and functions of the 3D modelling process with Geoscene 3D will be discussed further.

3.1.1 Background

Geoscene 3D is designed by the Danish corporation I-GIS for creating 3D geological models. The software is designed to use an extent range of geological data including borehole data, geophysical data, GIS data, geochemical contamination data and specifically hydrogeological information (Geoscene 3D 2020). Geoscene 3D can be used for many other similar programs such as urban designing, civil engineering, constructions and geotechnical engineering (Geoscene 3D 2020).

3.1.2 User interface

After starting the program there are a few main parts available for the user, such as the camera windows in the center, the object bar to the left and the map window. The tools and functions can be seen on top of the camera window (Fig. 5).

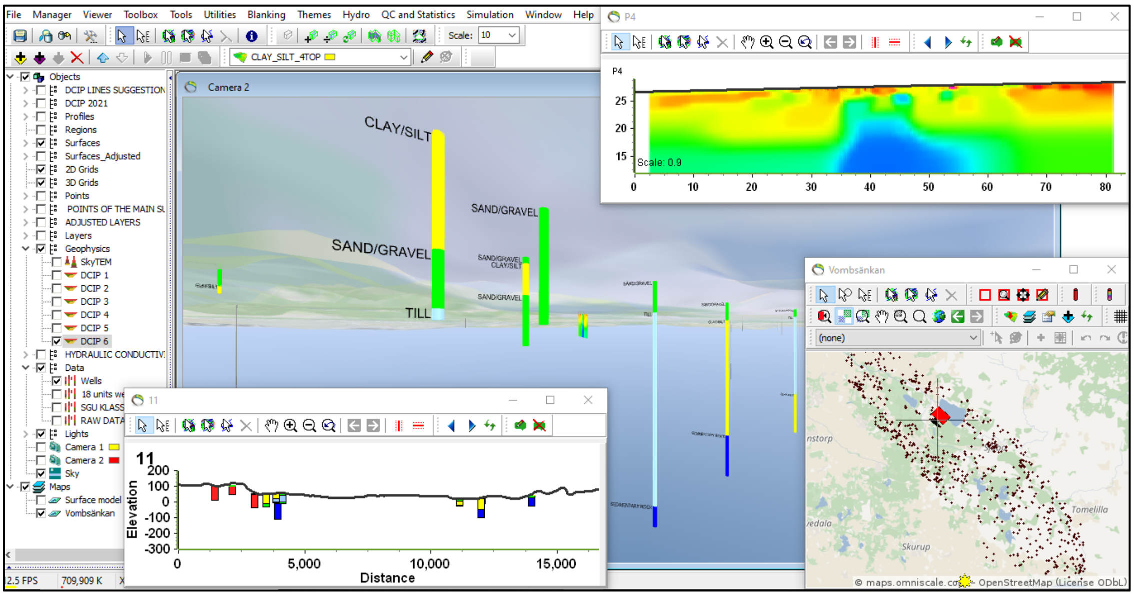


Fig. 5. The user interface and the position of the main windows at Geoscene 3D, illustrating the location and stratigraphy of the wells, the map window, a 2D resistivity section and a profile at Vombverket.

The user can choose to make the map, cameras and the profile windows visible, adjust the size and the position of the windows or close them at any time during the working process. The two camera windows make it easy for the user to navigate and/or have a fixed view of the area as well as for creating animations in form of visualized videos. The object bar to the left illustrates a list of the imported data, active layers and objects. Similar objects are categorized into the main branches, such as 3D grids, surfaces, layers, points and profiles that are very useful for projects with many objects added. Any object can be disabled or enabled at any time during the modelling work. The map window can contain useful information like topography of the terrain, geographical location and the seen extent. Seen extent is the area of interest within the project that can be defined and changed at any time by the user. Furthermore, the objects such as position of wells, profiles, terrain, surfaces and geophysical data can also be added to the map for a better overview during the process. The map window provides an extra environment with a different scale helping the user to get a better view and control of the project, specifically during the parts of the modelling that require smaller scales or switching back and forth to different areas and views, such as marking a specific area, creating and editing profiles, regions and surfaces. An important function of the map window is to create a surface model based on the defined position of the lithological units at the surface that can be compared with the Quaternary deposits map to evaluate the modelling results.

There are several types of data that can be imported and processed in Geoscene 3D including borehole data, digital terrain model, hydrogeology, geochemical contaminations, seismic data, imagery and raster layers, vector map layers, geophysical wireline logs, TEM, DC, ERT and tabular data such as database and csv (Geoscene 3D products 2020).

Geoscene 3D supports a variety of data formats such as csv, txt, xyz, shp, grd, as well as SEGY, CAD, vector theme, SQL server and image files (Geoscene 3D 2020).

3.1.3 Borehole data classification

The borehole data are the base of the 3D modelling within this thesis work. The pre-processing and the classification of the borehole data are essential steps for most parts of the project. Preparation of the borehole data is strongly affecting the results of 3D modeling. Some of the fundamental stages of the modelling are based on the borehole data, such as creating the interpretation points and profiles, surfaces and the geological units (layers in 3D modelling). Therefore, it is important that the borehole data classification is done correctly, and this part will be described further for a better understanding of the 3D modelling process. The raw version of the borehole data commonly contains information about the physical properties of the rocks and sediments at specific depths together with an estimation of the lithology of the unit. The borehole data are usually categorized in various groups of lithology that are too large for data import and 3D modelling in Geoscene 3D. Moreover, sometimes the data contain unclear descriptions without any specification of the lithology. For example, the unit could not be observed due to the presence of the well filter, the lithology could not be recognized by the borehole operator, or it contains traditional names of a unit without any specific geological meaning and even possibly an incorrect estimation of the lithology. Therefore, the data must be interpreted and classified into new groups related to the project before importing to Geoscene 3D. The generalization concept of the new groups can vary depending on the purpose of the project.

Within this study, classification of the borehole data is done considering the hydrogeological properties of the units, such as hydraulic conductivity or permeability. The original file contains around 1000 boreholes. A new lithology column is added to the borehole data containing the interpreted lithology. Without the generalization of the borehole data 3D modelling is difficult. Indeed, the model cannot be comprised of too many categories as the model architecture becomes complicated that is very time-consuming. For instance, the borehole data may contain up to 200 different lithologies that are immensely difficult to correlate.

In this study, similar lithological units are generalized into new representative groups. For example, granite, amphibolite, gneiss and diorite are classified into an igneous/metamorphic rock group that represents the local crystalline bedrock. A unit that includes sand, silt, clay and gravel in the description field is assumed to be a till. Coappearances of sand and clay, sand and silt, clay and silt should be classified to new groups. Another principle is to classify all different groups of a specific lithology with different grain sizes into separate units, for example by classifying all groups of fine-grained gravel, gravel and coarse-grained gravel into the group gravel. The classification must result in a realistic stratigraphy. It is very important that all adjacent wells are considered and investigated before replacing the units with new groups of lithologies. Within this thesis work, classification of a group into a new lithology unit is done based on the investigation of the adjacent wells as well as by correlating the units with previous studies and geological maps. The geological maps of Vombsänkan provided by SGU (Daniel 1992) are used. For instance, it is inferred from the Quaternary deposit map that there are no outcrops of Precambrian bedrock around Vombverket, South of Lake Vombsjön. All these types of observations within the borehole data are therefore corrected and replaced with relevant lithological categories that match with previous studies, lithologies of adjacent wells and available geological maps. Consequently, the new lithology column is a corrected version of the borehole data that are suitable for 3D geological modelling for hydrogeological purposes. The lithology groups are generalized into five major groups including igneous/metamorphic rock, sedimentary rock, till, clay/silt and sand/gravel.

3.1.4 Data import

The initial steps of the data import involve a wizard that gives the options of adding some basic settings including the coordinate system, the related terrain (ground surface) of the project area, the scene extent and the map window. Wizards are a series of adjustments and settings that aid the user toward the end of a specific process.

The borehole data can be imported using *add data wizard*, and after choosing the proper setting the wells can be visualized in the program (Fig. 6). The related symbols for the wells can be added by the user and it is possible to export and save the symbol file. If another project needs to be created by the user, it is possible to quickly import the created symbol to use for other projects and avoiding creating the symbol table again. In addition, it is possible to set the elevation of wells adjusted to the terrain surface for a more realistic simulation of geological environments. This option is useful when the borehole does not contain elevation data. The wells can be investigated by creating 2D profiles as well as within the 3D view and the map window. Fig. 7 shows two boreholes that illustrate the lithology of the wells before and after the classification.

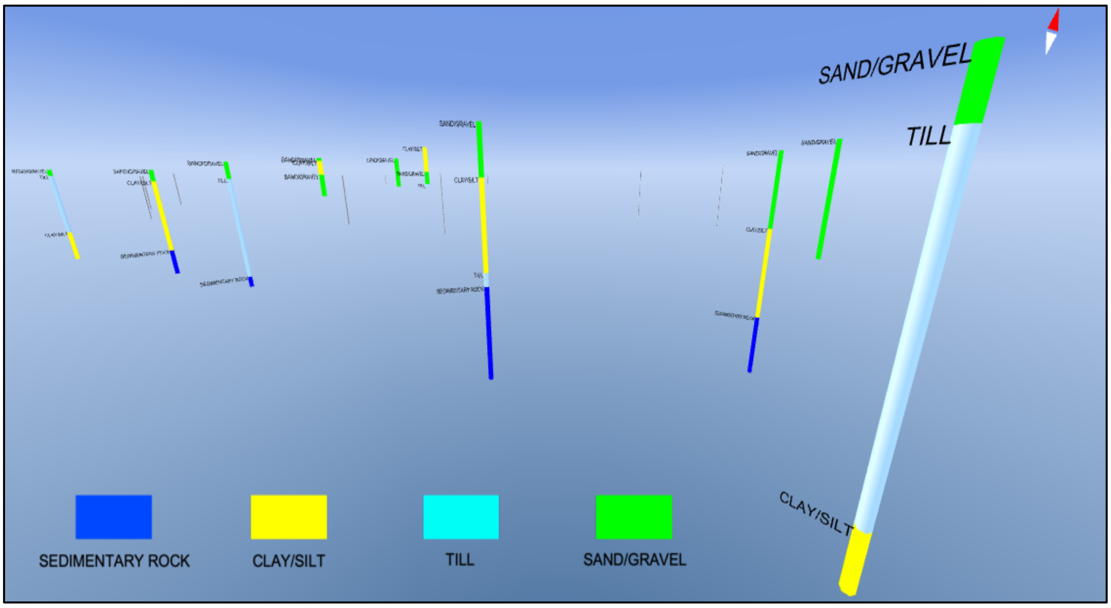


Fig. 6. 3D visualization of the borehole data, South of Lake Vombsjön. After importing the borehole data in Geoscene 3D, the wells can be investigated in the 3D window.

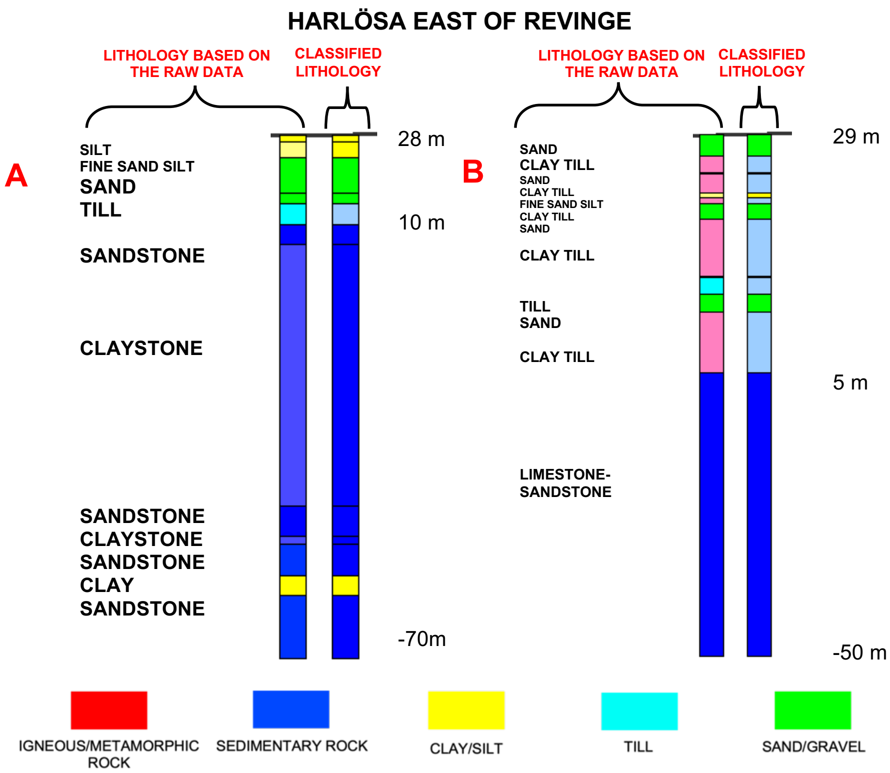


Fig. 7. Two boreholes before the classification (Raw data) and after the classification (Classified). The units are classified into five units (symbol). Borehole A has documented the vertical variation of the stratigraphy within the sedimentary bedrock. Borehole B illustrates a diverse stratigraphy. A recurring pattern including at least four glacial advances resulted in deposition of four different till beds. Each till unit is covered by glaciolacustrine and glaciofluvial deposits.

3.1.5 Layered base 3D modelling

To create a layered base model from the lithology of wells, an interpretation point database needs to be created. This can be done via the *setup model data wizard* function. Then, the project is ready for layered base 3D modelling and the interpretation points can be placed in the 3D window, map window or at the profiles. Interpretation points are a series of points that the user creates to define boundaries of the lithological units (Fig. 8). Geoscene 3D provides a tool called *locate layer wizard* that allows the user to insert the interpretation points based on the boundaries associated with the borehole data that are imported as the well object. The interpretation points can be edited and adjusted further if necessary.

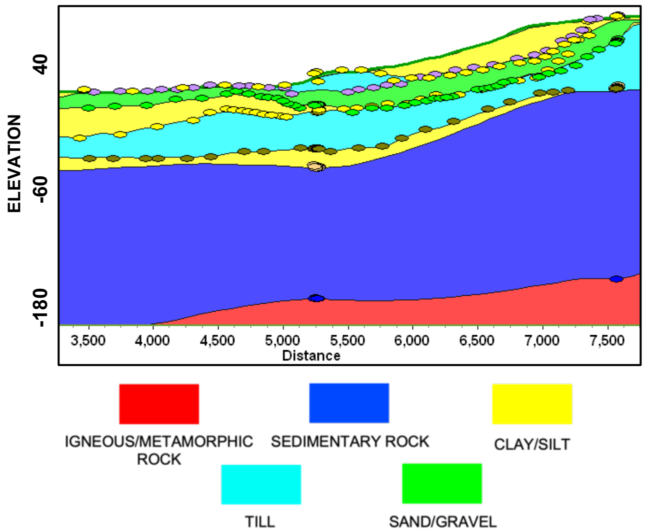


Fig. 8. Creating the interpretation points in Geoscene 3D.

Within this thesis work, a major part of the modelling is carried out by manual interpretation. The points that are placed based on the geological correlation principles, can be interpolated as a surface. This can be done via the interpolation wizard function. The interpolation settings are important for the position and extension of the units. For instance, the search radius indicates the maximum distance that the interpretation points can be connected to form a surface. A higher interpolation search radius results in a wider extension of the surface. In this study, the interpolation search radius is set to 2000 m, and the interpolation type is set to inversed distance weighting. That means if the distance between two points is less than 2000 m, the points interpolate to a surface. It is also possible to edit a surface within the 3D camera window, profiles and the map window. The surfaces are the boundaries of the geological units and can be used to create layers by importing the top and bottom surfaces of units through the layer object settings (Fig. 9). The result is a layer-based 3D model.

3.1.6 Profiles and grid adjustment

A major part of the 3D modelling of Vombsänkan with Geoscene 3D was carried out by creating and interpreting profile groups. Two separate profile groups were created with an approximate distance of 2 km between each profile (Fig. 10). The profile window is one of the most suitable ways to create the interpretation points and in this thesis work, the profile window is preferred for the modelling progress. However, it can also be done through the map window and the 3D window. After adding the surfaces and layers, the profiles still need to be adjusted since the layers are often pinched out into each other (Fig. 11).

The layers and boundaries cannot cross each other or appear above the terrain. This is unfortunately a very common issue during the modelling process with Geoscene 3D that requires further adjustments. The grid adjustment tool allows the user to define the geological order of the study area as well as removing pinch out effects and adjusting the surfaces (Appendix 3). However, the grid adjustment is a complicated function. By starting the process, a window illustrates the situation of the adjusted layer related to the reference layer that can be edited by the user. The user has the possibility to add several grids in a single adjustment.

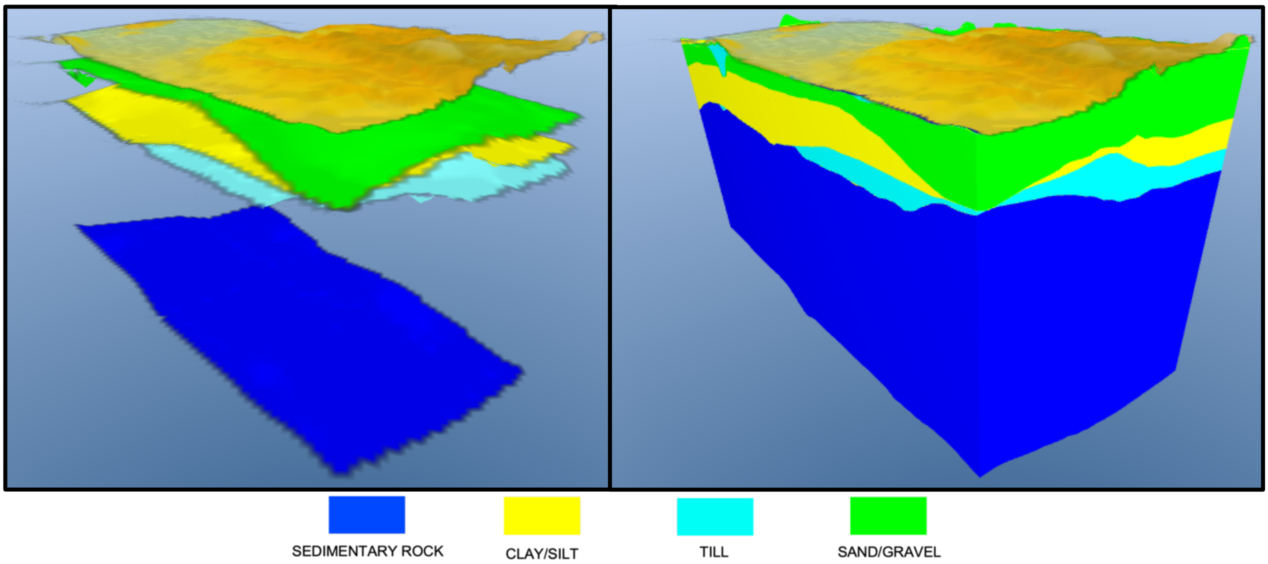


Fig. 9. Layered 3D model illustrating the stratigraphy at Vomb, South of Lake Vombsjön, which consists of four major units. The surfaces interpolated from the interpretation points and the layers created from the same surfaces are also shown.

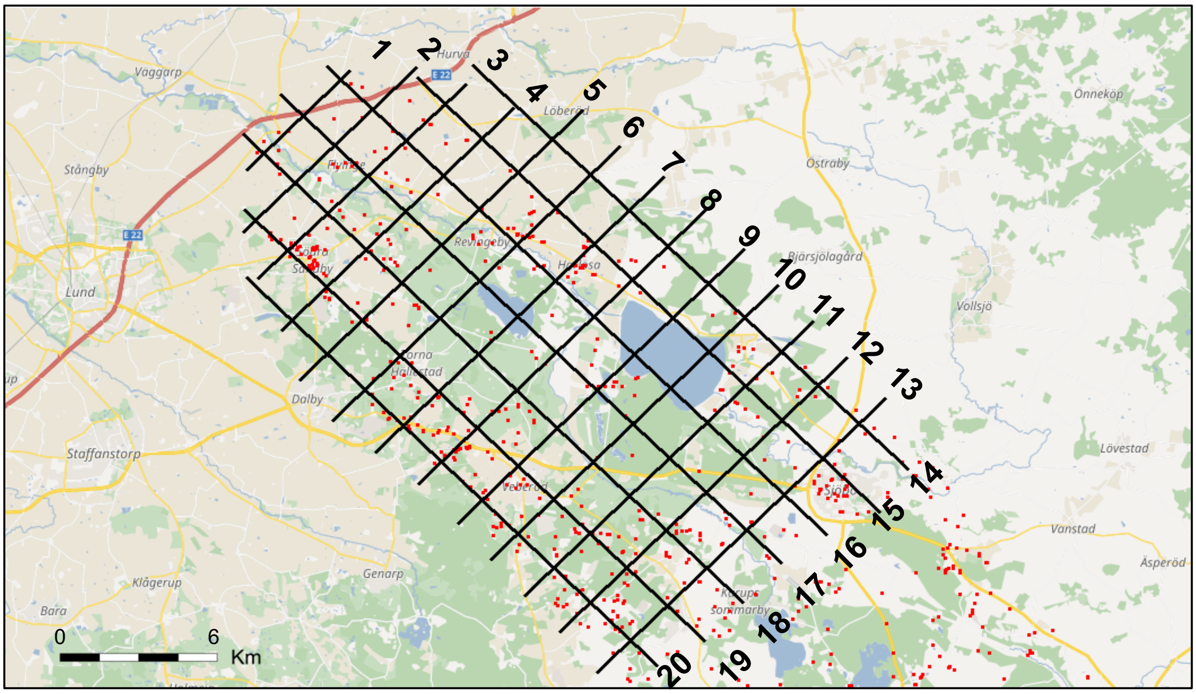


Fig. 10. To cover most parts of Vombsänkan and for setting the interpretation points, two profile groups were created. The grid consists of 13 SW-NE-directed profiles and seven perpendicular, NW-SE-directed profiles. The location of the wells is shown with red squares.

For example, a layer can be defined above a unit but below another one. After running the grid adjustment tool, the pinch out problem is fixed, and the model is valid from the geological perspective. The position and situation of the layers are strongly depended on the grid adjustment settings. Indeed, different grid adjustments can result in completely different conceptual models. Therefore, it is very important to consider available insight into the general stratigraphy of Vombsänkan based on previous studies to understand the geology of the area. Within this thesis work the grid adjustment settings were arranged in the following order from the surface towards greater depths:

1. Ground surface
2. Sand/gravel unit
3. Clay/silt unit
4. Till unit
5. Sedimentary rock unit
6. Igneous/metamorphic rock unit

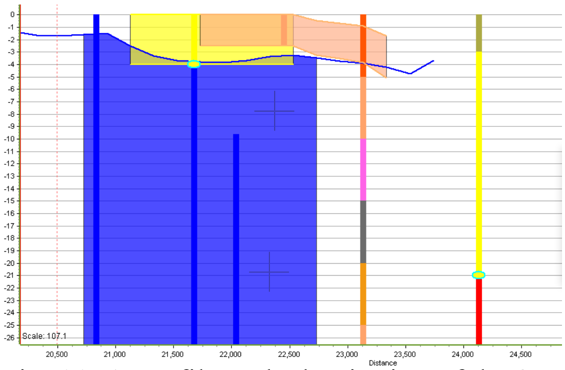


Fig. 11. A profile at the beginning of the 3D modelling process, showing pinch out. Pinch out in a profile is a false situation when two or more geological units overlap and co-exist together at the same location which does not occur in actual geological settings. Pinch out needs to be adjusted to create a realistic geological model.

3.1.7 Geophysical modeling

Geoscene 3D enhances the visualization and interpretation of geophysical surveys such as the resistivity method by 2D and 3D models that can be compared and interpreted at the same time. There are several ways to add a geophysical model in Geoscene 3D, including 2D geophysical data (ERT) from a tabular source, for example as a csv file or a RES2DINV file. In this study, the geophysical data were exported from RES2DINV and imported to Geoscene 3D. The first data block from the file can be used for the data import with the coordinates imported in a separate file (Geoscene 3D 2020). The xyz file exported from RES2DINV may contain data columns such as X, depth, resistivity and conductivity (Fig. 12). The coordinates are imported as a csv file containing three columns with id, X and Y, respectively. It is important that both the data file and the coordinate file are edited in a correct format as illustrated. After importing the geophysical data, the model can be visualized in Geoscene 3D (Fig. 13), and it is possible to add or change the colour scale of the geophysical model. Here a pre-defined colour scale available in the Geoscene database was used. The interpretation of the geophysical models can be done with the same methods as used for the layer-based 3D models by editing the XYZ points, interpolating them to surfaces or edit and manipulate each point values. For example, it is possible to assign specific resistivity values to certain points.

RES2DINV-EXPORTED XYZ FILE

```
/Name of survey line is XXX
/Number of blocks is 1496
/The x and z coordinates of the centres of the model blocks, and
/The resistivity and conductivity of each block is given below.
/        X          Depth      Resistivity   Conductivity
        12.50       -0.94        27.83        0.0359
        17.50       -0.94        29.48        0.0339
        22.50       -0.94        32.86        0.0304
        27.50       -0.94        32.91        0.0304
        32.50       -0.94        26.81        0.0373
        37.50       -0.94        22.80        0.0439
        42.50       -0.94        16.79        0.0595
        47.50       -0.94        14.90        0.0671
        52.50       -0.94        12.34        0.0810
        57.50       -0.94        12.31        0.0812
        62.50       -0.94        10.99        0.0910
        67.50       -0.94        11.96        0.0836
        72.50       -0.94        12.66        0.0790
        77.50       -0.94        15.94        0.0627
        82.50       -0.94        18.50        0.0540
```

COORDINATES CSV FILE

```
id;X;Y
1;334128;6436838
1;334031;6436813
1;333937;6436782
1;333840;6436753
1;333746;6436724
```

Fig. 12. An example of the XYZ file containing geophysical data to import into Geoscene 3D and coordinates of the electrodes in a separate csv file.

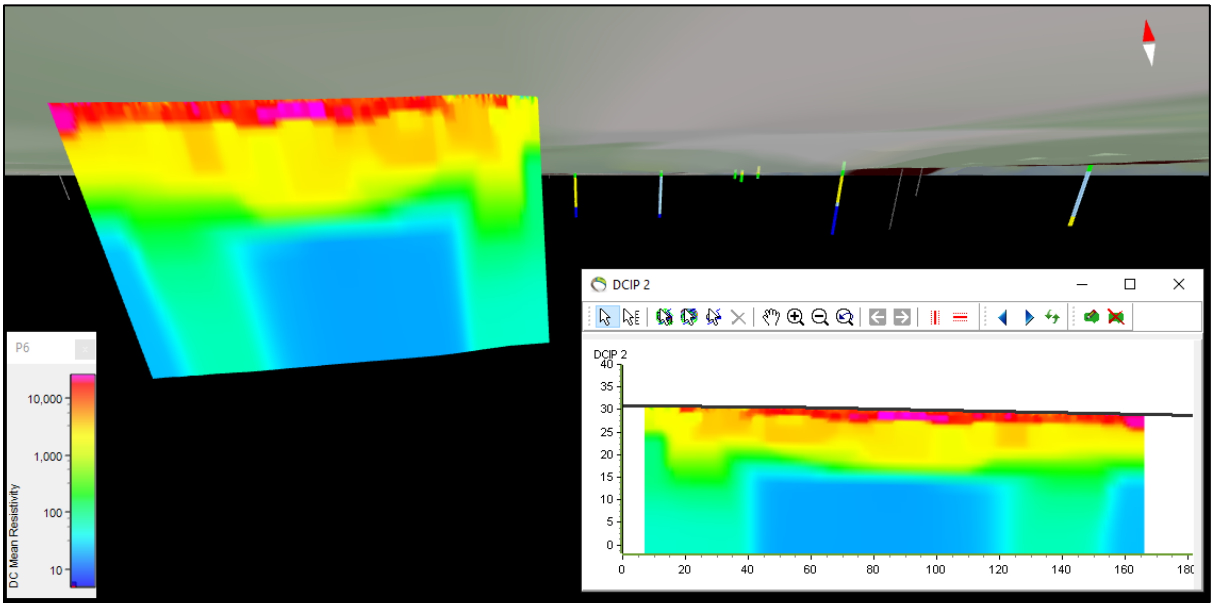


Fig. 13. Visualization of the geophysical data next to the boreholes at Vombverket. The data were processed and inverted in RES2DINV, and the results can be illustrated in Geoscene 3D, providing a useful comparison between the resistivity profile and the adjacent boreholes.

3.2 Resistivity method

The resistivity survey is an efficient way to create images of the subsurface. The method is based on the electrical resistivity ρ (Ω.m). The difference between the flow of electrical currents to the ground is measured. An electrical potential difference (Voltage) develops around current-carrying electrodes. A pair of electrodes inject the electrical current through the subsurface and the electrical potential is measured as the current moves through the geological environment (Binley, 2015). Each single resistivity measurement uses four electrodes. The current is transmitted through two electrodes A and B and the other two electrodes (M and N) measure the potential difference (Fig. 14). The following equation is used to calculate the Ohmic resistance (R) of the ground:

$$R = \frac{V}{I} \qquad (1)$$

The equation defines that R is related to the potential difference (V) and the injected electrical current to the ground (I). The electrical resistivity can be calculated by considering the positions of the four electrodes (AM, BM, AN and BN in Fig. 14) using the equation 2 and 3:

$$\rho = R\frac{2\pi}{G} \qquad (2)$$

G is a geometric factor and can be calculated with the equation:

$$G = \frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN} \qquad (3)$$

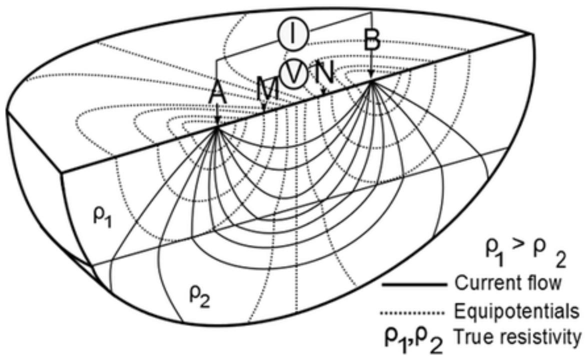


Fig. 14. Single resistivity measurement (Knödel et al. 2007).

Equation (2) indicates the electrical resistivity of a homogenous and isotropic material. However, most geological materials are heterogenous and therefore, the calculated resistivity is not valid as a true electrical resistivity of the underground. This resistivity is called apparent resistivity, and it illustrates a weighted average value that is not mathematically correct for the resistivities of the different subsurface materials (Cook and Van Nostrand 1954).

3.3 Electrical Resistivity Tomography (ERT)

Using four electrodes or a quadrupole that indicates a single measurement as described in the previous section, gives very limited information about the subsurface because the geological conditions are often heterogenous. Thus, in ERT surveys several electrodes that are connected to the instrument conduct hundreds of single measurements. A series of single measurements with four electrodes are performed by the instrument. The measurement continues based on a given predefined sequence until all the desired four electrode combinations are measured (Fig. 15).

The most common configuration is called electrode arrays, but the total number of possible combinations varies greatly (Dahlin 1996; Nivorlis 2023). As inferred from the previous sections, the current is sent to the ground and the potential difference between several receiver pairs is measured. The multiple-gradient arrays method has several advantages for the 2D model. For example, it has a high signal to noise (S/N) ratio making it particularly suitable for IP measurements. In this thesis work the multiple-gradient array approach (Dahlin and Zhou, 2006) is used. A pseudo-section is a 2D-profile that illustrates the measured resistivity (apparent resistivity) that is plotted against the position of the electrodes (distance). As an example, a pseudo-section that is created at this study is illustrated in Fig. 16.

3.3.1 Inversion

Although it is relatively straightforward to calculate the response of an array, the distribution of the electrical properties is usually unknown. An iterative process called inversion is used to determine the distribution of the electrical properties. This method is based on finding the distribution of the parameters that gives theoretical measurements that match best with the real data (Dahlin 1996).

The algorithm used in this study to solve the inversion problem is called the smoothness constrained inversion (Tsourlos and Ogilvy 1999) (Fig. 17). The initial model is usually considered as homogenous representation of Earth. The model response is calculated, and the result is compared with the observed measurements. Then the misfit is computed, and the process repeats until one of the stopping criteria is met to terminate the process. Some of the examples of these criteria include: a maximum number of iterations, no further improvements in the solution, or a solution with an acceptable misfit.

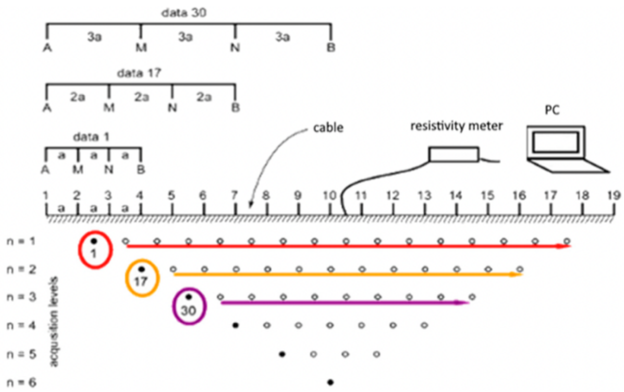
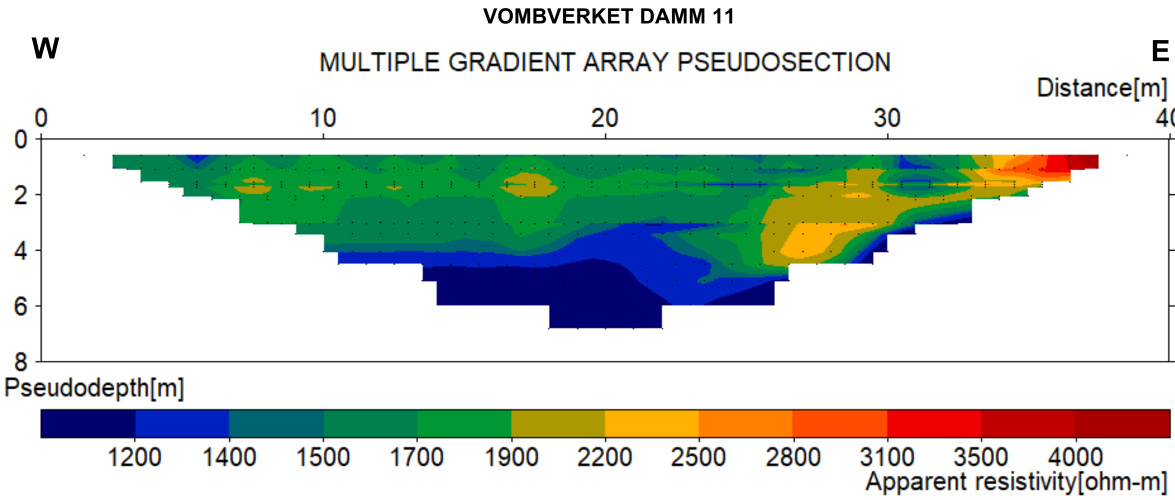


Fig. 15. ERT survey showing how the measurement is performed in the field, as well as the settings and positions of the electrodes (Loke and Barker, 1996).

FIG. A



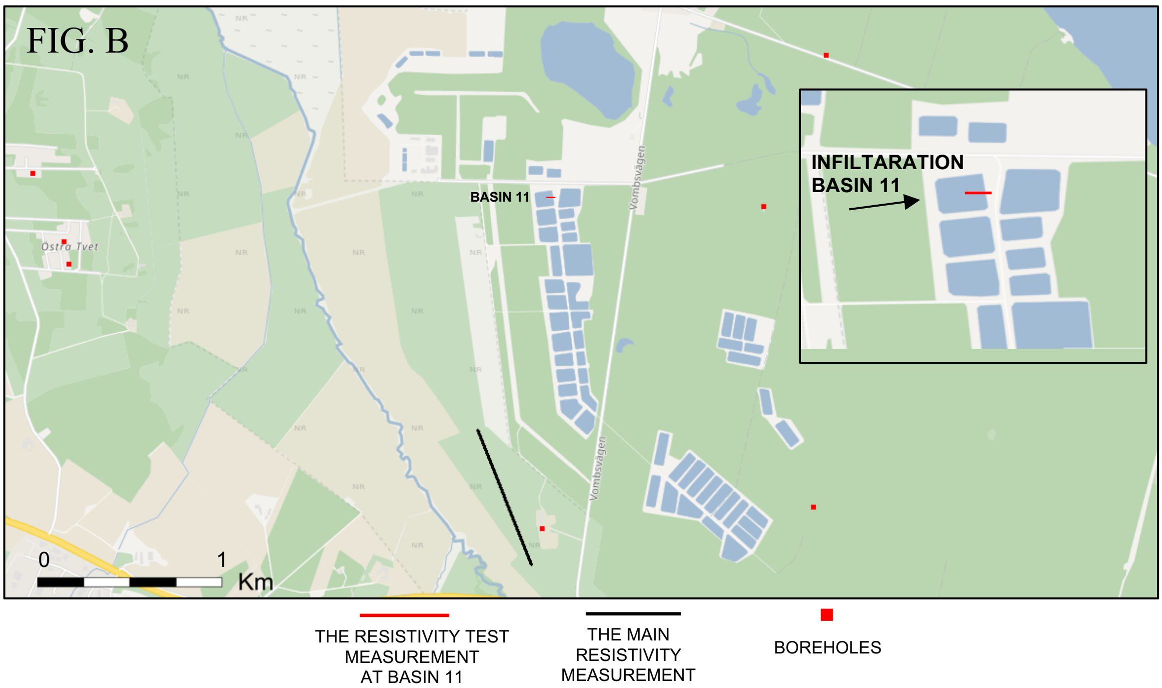


Fig. 16. A pseudo-section of a short, 40 m resistivity line conducted in this study (Fig. A), illustrates the distribution of apparent resistivities in the ground (observations). (Fig. B) The location of the survey at infiltration basin 11, Vombverket, South of Lake Vombsjön is illustrated with a red line. The main resistivity measurement at this thesis work is conducted at South of the infiltration basins, is shown by a black line. The survey was conducted in form of a test. Therefore, the results of the measurements are not used for the interpretation.

The inversion algorithm uses the observations to find the distribution of the parameters (resistivities) that will generate synthetic measurements (forward response). The inverted profile that indicates the distribution of the electrical properties can be used to interpret the lithology and the location of the groundwater table (Fig. 18 and appendix 4). However, for a better understanding of the connection and association of the profile with the geological conditions, prior information about the investigation area is recommended. There are several factors that influence the distribution of the electrical properties through time, such as seasonal variations in temperature, precipitation, groundwater level groundwater chemistry (Nivorlis 2023).

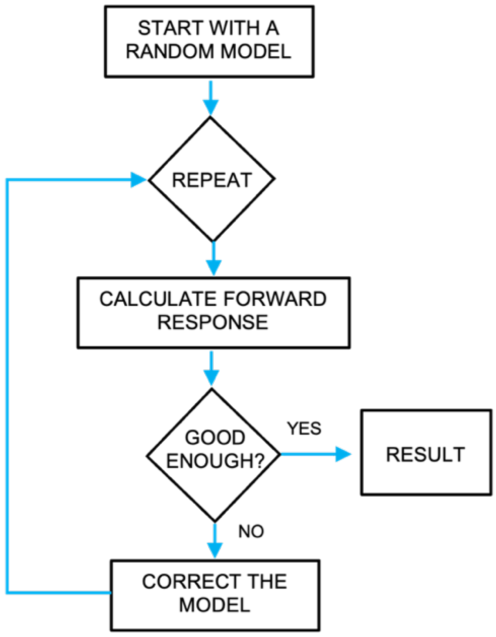


Fig. 17. Simplified diagram of the general inversion method ((Tsourlos and Ogilvy 1999; Nivorlis 2023).

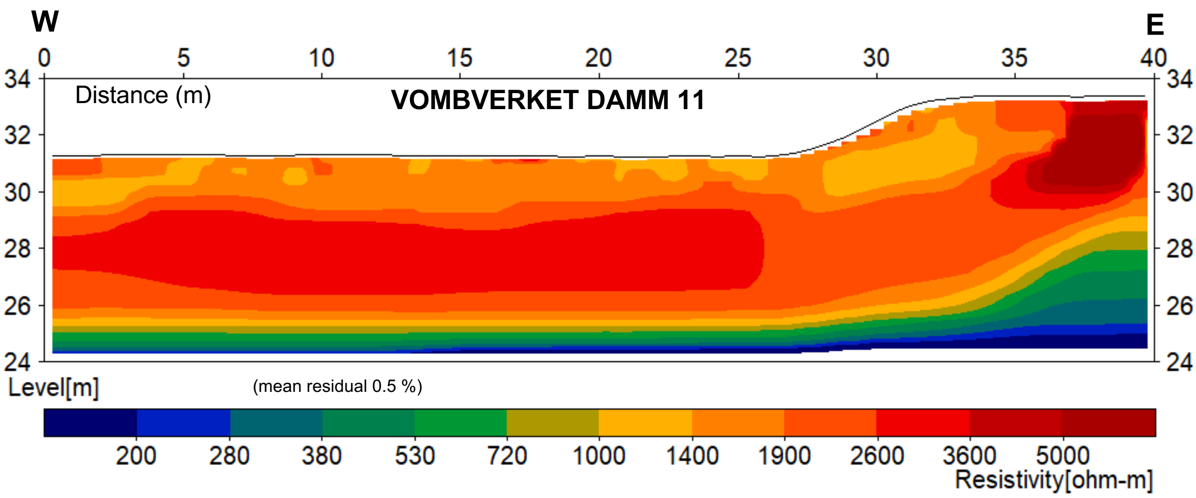


Fig. 18. A short (40 m) test line of resistivity conducted at infiltration basin 11 at Vombverket (Fig. 16). The profile illustrates the calculated distribution of resistivity in the subsurface. Note the high resistivity of the uppermost unit. The resistivity of the first 6–8 m is more than 1000 Ω. The resistivity profile implies a clearly decreasing pattern with the depth in infiltration pond 11.

4. Results

The presentation of the results includes the conceptual modelling and the resistivity. This chapter demonstrates the results of the 3D modelling that are based on three different models 1. The northern part of Vombsänkan. 2. Hydrogeological conceptual model and 3. Vombverket model. However, according to the rules at Sydvatten the results of the Vombverket model cannot be published.

4.1 3D modelling of the northern part of Vombsänkan

The 3D modelling resulted in visualization of the units (layers in Geoscene 3D) that are defined from the lower boundary of the upper unit to the lower boundary of the unit itself (Fig. 19). For instance, the entire volume between the lower boundary of the sedimentary rock unit and the lower boundary of the igneous metamorphic rock unit is detected as the igneous metamorphic layer in Geoscene 3D. The bedrock geology of the study area is composed of two different units, igneous metamorphic bedrock (IMB) and sedimentary bedrock (SBR). In most parts of Vombsänkan, the SBR is predominantly composed of Cretaceous sedimentary rocks, mainly limestone and sandstone. The IMB, although present below the SBR, emerges at the surface in the horst zones of Romeleåsen in the Southwest and Linerödsåsen in the Northeast. Daniel (1992) described the Quaternary deposits of Vombsänkan as sand and gravel outwash, partly overlain by glaciolacustrine deposits dominated by sand and silt. The area Southeast of Lake Vombsjön is characterized by 30 m of sand and the western part by 20 m of fine-grained sand and silt, covered by 10-15 m of gravel-rich sand. Clay outcrops are present but less abundant compared to sand and gravel. The thickness of the glacial clay that underlies the sand is estimated to a maximum of 43 m (Daniel 1992). The thickness of the till reaches 20 m, mainly covered by approximately 40 m thick deposits of clay and silt (Daniel 1992). The uppermost unit consists of up to 20 m thick glaciofluvial sediments mostly gravel, sand and less abundant silt.

Based on the modelling results, the Quaternary deposits illustrate a recurring pattern. The thickness of the units significantly varies in the study area and the stratigraphy is characterized by several units which are mostly formed by similar grain size. The correlation of the Quaternary deposits between different boreholes is therefore difficult, and the 3D modelling results do not provide a clear order of the deposition of the units. At least three series of deposits from the Late Wechselian are observed within the profiles, including two till units, deposited during the last glacial advance phases and three series of glaciofluvial and glaciolacustrine deposits, mainly formed during the deglaciation and associated with the formation of dead ice and ice-dammed lakes. The setting can be described as discontinuous deposition of till, clay, silt, sand and gravel. Considering the diversity of the Quaternary deposits at Vombsänkan, the 3D modelling process is challenging. Based on the main features of the borehole data, the Quaternary deposits are classified into seven units, including (from older to younger):

1.Clay, silt and fine-grained sand 1 (CS1)
2.Till 1 (TL1)
3.Clay, silt and fine-grained sand 2 (CS2)
4.Sand and gravel 1 (SG1)
5.Till 2 (TL2)
6.Clay, silt and fine-grained sand 3 (CS3)
7.Sand and gravel 2 (SG2).

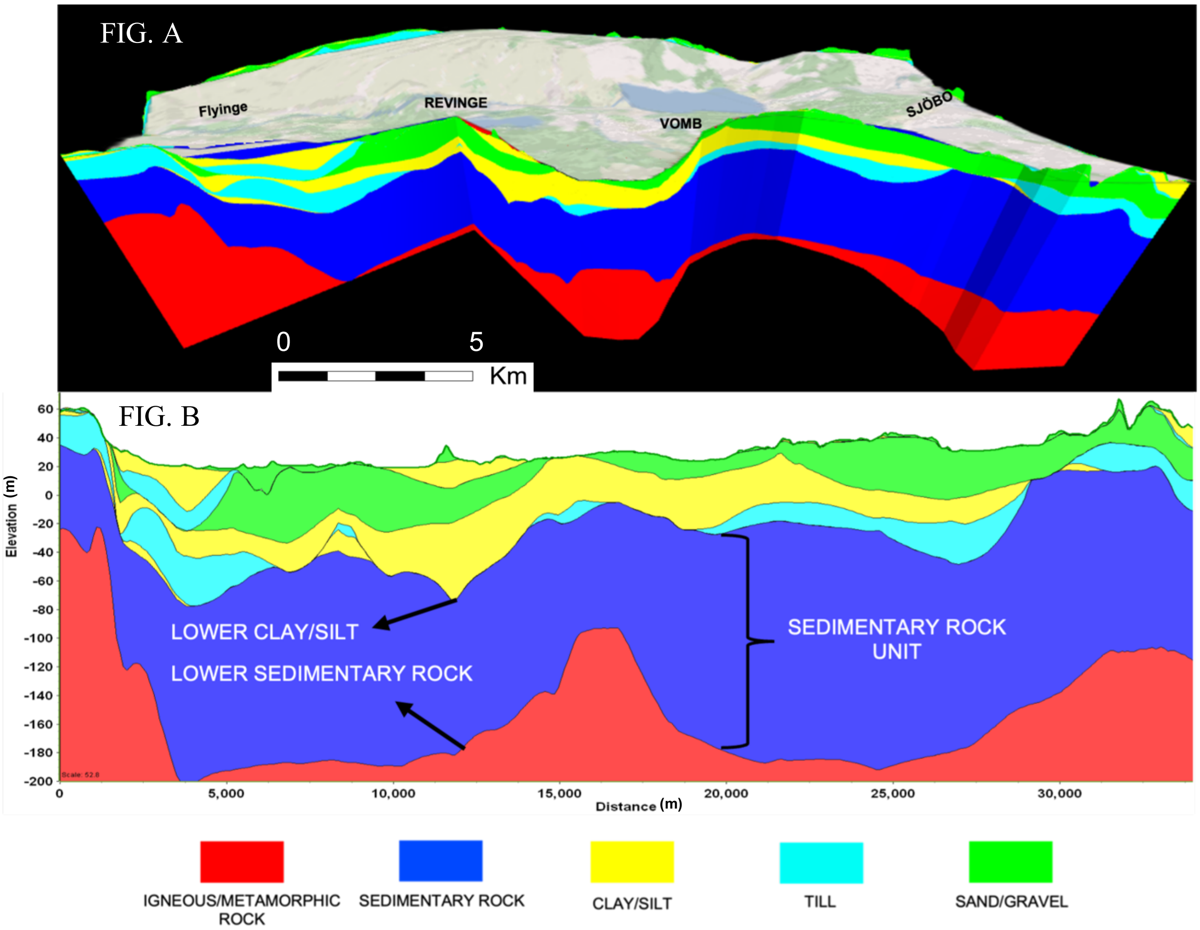


Fig. 19. (A): Geological 3D model of the northern part of Vombsänkan. The view is toward the East. (B): 2D profile of the same section (Fig. A). The user may define the upper and the lower surface of each unit within Geoscene 3D. In this study the sedimentary bedrock unit is defined as occurring between the lower clay/silt surface (upper boundary) and the lower sedimentary surface (lower boundary). On the other hand, the sedimentary bedrock unit (shown with dark blue) is always located between the lower clay/silt surface and the lower sedimentary rock surface.

In most parts of the study area CS1, TL2, CS3 and SG2 are absent. The main units are TL1, CS2 and SG1 that are generally deposited with significant thicknesses. The results of the 3D modelling of the northern part of Vombsänkan will be presented along three different zones and each zone includes four profiles.

4.1.1 The Södra Sandby–Löberöd zone

This zone is in the northernmost part of the modelling area from Södra Sandby to West of Löberöd (Fig. 20). The SW-NE-directed profiles 2, 3, 4 and 5 demonstrate the geology of the zone, which is 6 km wide and 9 km long (Fig. 21). Except for a few locations, most of the boreholes do not reach depths of more than 200 m. Therefore, the dimension of the units located deeper than 200 m are unknown. The boreholes that are projected too close to each other in the profiles, are disabled and are shown with transparent gray (Fig. 21, profile 3). In some locations, the boreholes indicate a distinct vertical variation, consists of several thin units. The identification of the units is therefore challenging.

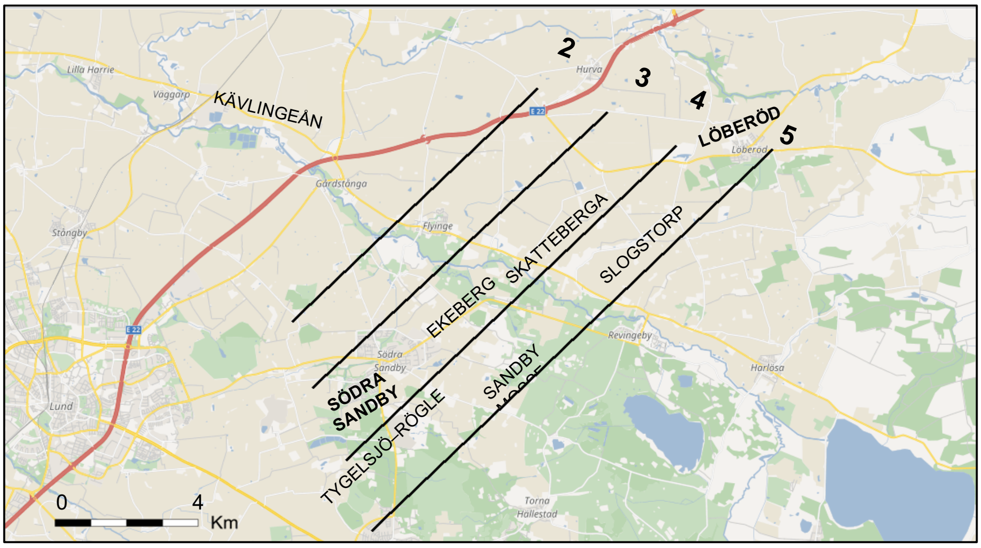


Fig. 20. Location of the SW-NE-directed profiles 2–5 that illustrate the geology of Södra Sandby–Löberöd zone. Södra Sandby is located East of Lund and Löberöd is located Northeast of Revingeby. The zone is approximately 54 km^2.

4.1.1.1 Bedrock

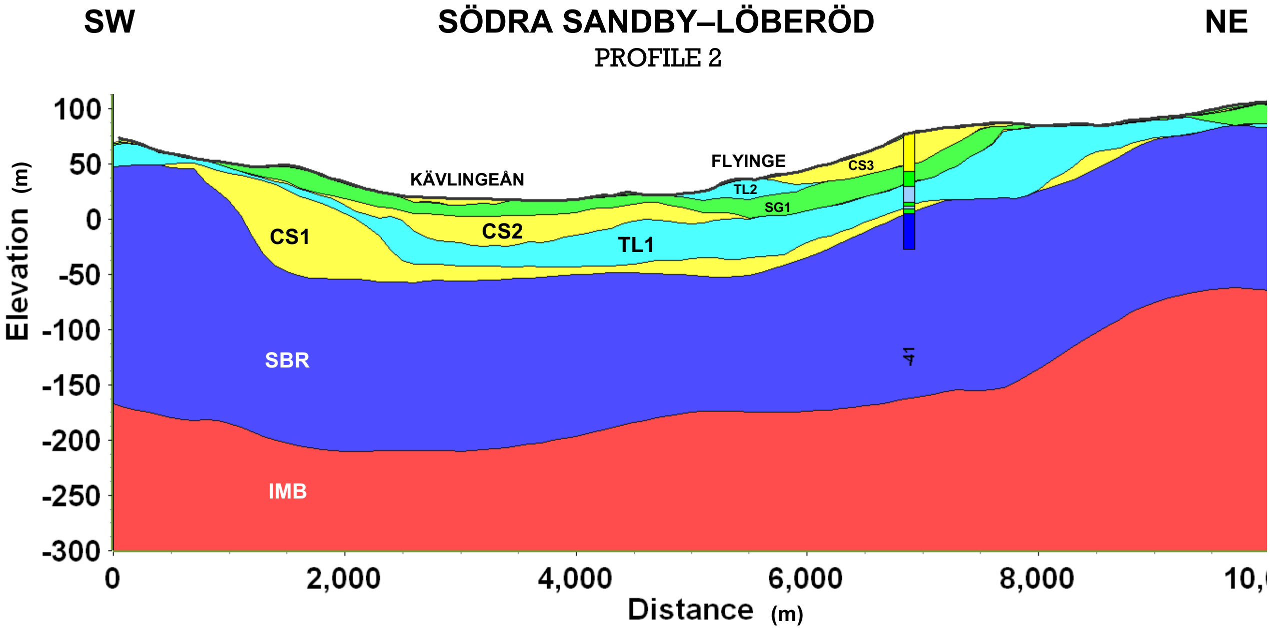
IMB

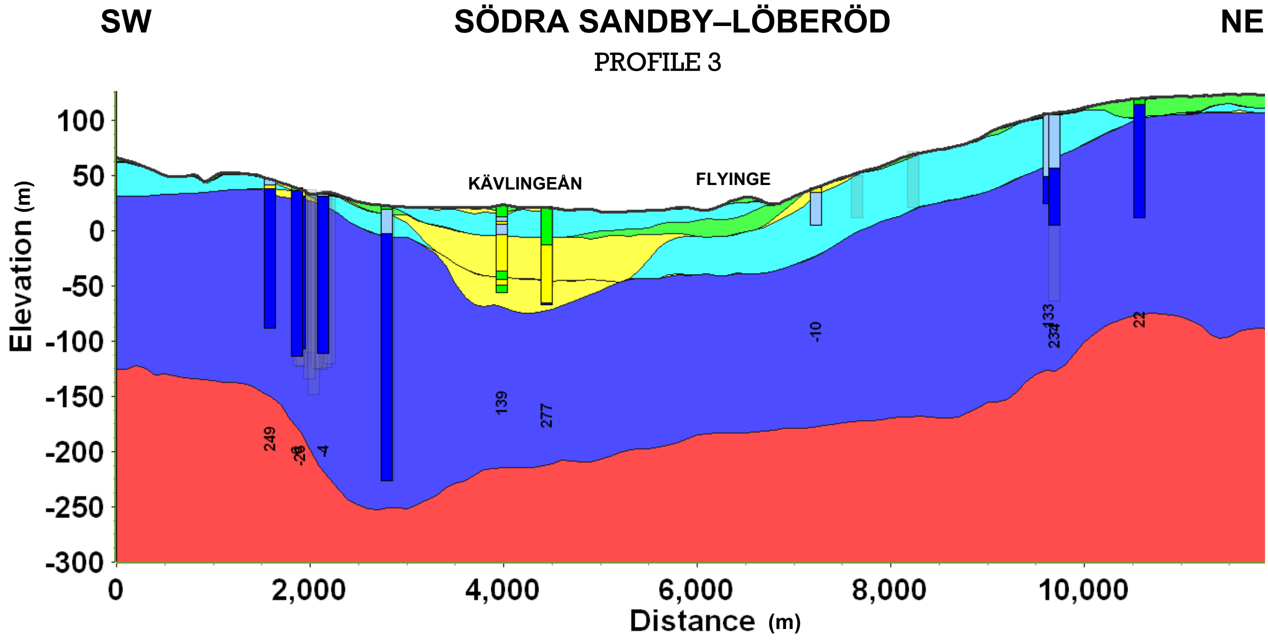
It is conveyed from profile 4 and 5 that the IMB is the dominant unit in North of Dalby along Tygelsjö–Rögle (Fig. 21). The maximum thickness of the IMB is unknown. Indeed, the limited information on the deeper units is only based on a few boreholes that penetrate around 200 m below the surface. In this thesis the lower boundary of the IMB is defined as an infinite boundary. Generally, the IMB follows the topography of the area and is overlain by the SBR. However, at some locations it is directly overlain by Quaternary deposits such as till as well as sand and gravel. Along Tygelsjö - Rögle the IMB is covered by 5 to 10 m of till.

SBR

Based on the borehole data the SBR is located approximately 10 m below the surface in the Southwest and the Northeast while in the middle of the zone at West of Revingeby around Skatteberga the SBR is situated relatively lower, reaching a maximum depth of 70 m below the surface. The position of the SBR follows the topography of the area that explains the tectonic setting of Vombsänkan, characterized by a mostly flat basin between the two horst zones. With the available information, it is not possible to determine the exact depth and the lower boundary of the unit.

The estimated thickness of the SBR is therefore not accurate in the 3D model. The depth estimation is based on the lithology of the wells along profile 3, where the maximum thickness is 220 m Northwest of Södra Sandby. The SBR is overlain by Quaternary deposits, most commonly TL1 and CS2 (Fig. 21 profile 5).


SW
SÖDRA SANDBY–LÖBERÖD
PROFILE 2
NE
KÄVLINGEÅN
FLYINGE
CS3
TL2
SG1
CS1
CS2
TL1
SBR
IMB
Elevation (m)
100
50
0
-50
-100
-150
-200
-250
-300
0
2,000
4,000
6,000
8,000
10,
Distance (m)


SW
SÖDRA SANDBY–LÖBERÖD
PROFILE 3
NE
KÄVLINGEÅN
FLYINGE
Elevation (m)
100
50
0
-50
-100
-150
-200
-250
-300
0
2,000
4,000
6,000
8,000
10,000
Distance (m)


IGNEOUS/METAMORPHIC ROCK
SEDIMENTARY ROCK
CLAY/SILT
TILL
SAND/GRAVEL

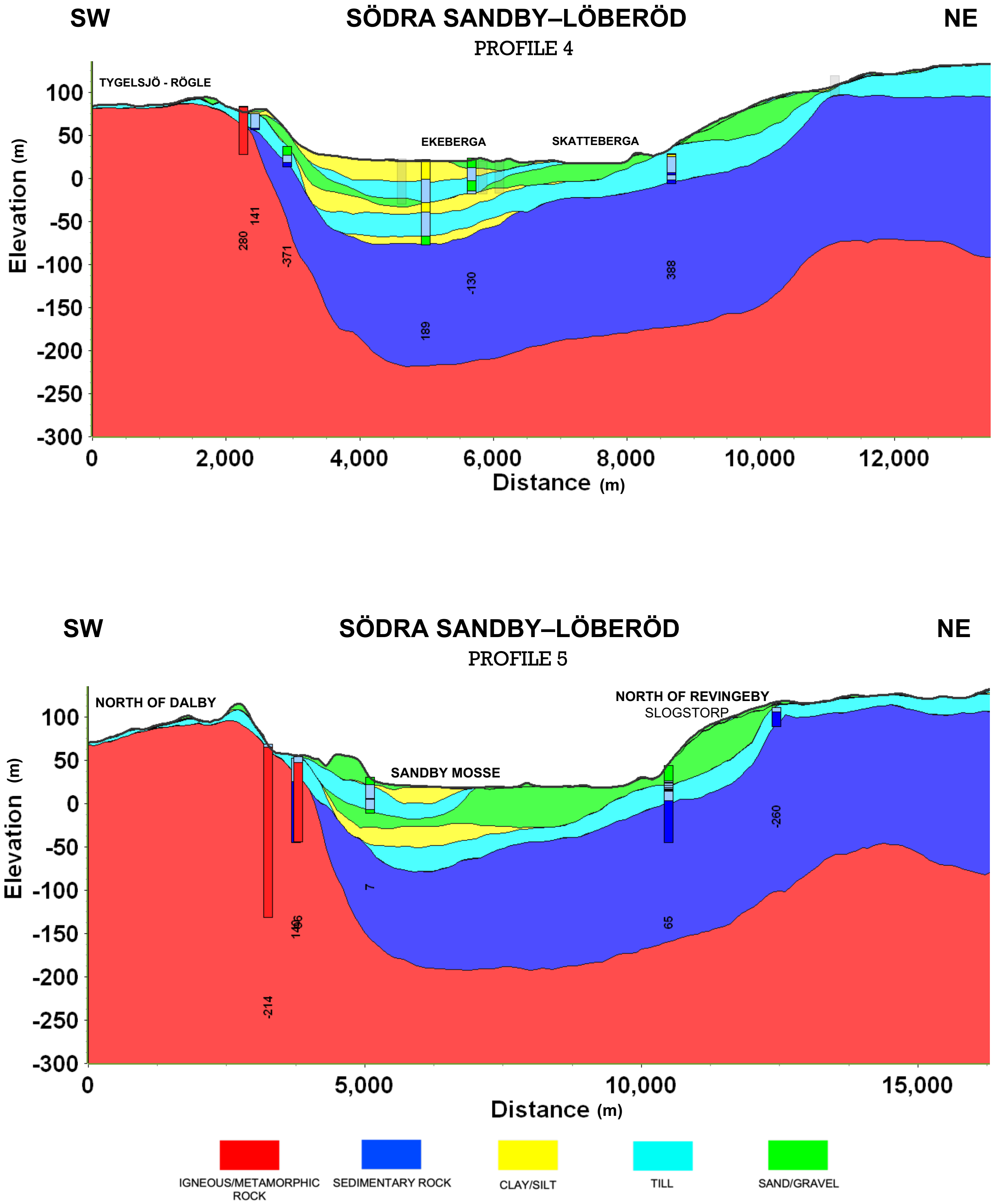


Fig. 21. Profiles 2–5 illustrating the geology of the Södra Sandby–Löberöd zone. The numbers below the wells are the borehole projection distances (the distance between the location of the borehole and the profile).

4.1.1.2 Quaternary deposits

The thickness of the Quaternary deposits reaches up to 80 m at West of Revingeby and South of Ekeberga along profile 4 (Fig. 21). The thickness decreases toward Romeleåsen in the Southwest, and Linderödsåsen in the Northeast. The average thicknesses of the Quaternary deposits in Vombsänkan are determined between 60−70 m, (Dahlqvist et al. 2021). Generally, the 3D model shows slightly greater thicknesses of the Quaternary deposits in the northern part of Vombsänkan.

CS1

Along profiles 2, 3 and 4 the Quaternary deposits consist of a sand unit that covers the SBR. The unit is characterized by a diverse lithology including sand and gravel as well as silt and clay. Thus, the classification of the unit into a specific group is difficult. On the other hand, to assume that CS1 represents a specific stage of deposition more information is needed. Furthermore, considering that CS1 is usually located below TL1, correlating the unit together with CS2 is problematic. To facilitate the modelling process this unit is classified within the group clay, silt and fine-grained sand (Clay silt). Toward the southern part of the area the thickness of CS1 is decreasing until it disappears at profile 5. The maximum thickness is typically less than 20 m.

TL1

Along profile 5, TL1 is directly deposited on top of the SBR. The thickness of the unit reaches up to 60 m and it is overlain by CS2 that is mostly less than 40 m thick. TL1 is a major unit among the Quaternary deposits as it is present with significant thicknesses in most parts of the study area.

CS2

To the SW and NE of the profiles toward the horst zones CS2 is absent. At SW of the Flyinge the thickness of CS2 is approximately 70 m. Typically, CS2 is the thickest unit among the Quaternary deposits, and it is mostly overlain by SG1.

SG1

The unit has a significant lateral extension, and the thickness varies through the northern part of Vombsänkan. The thickness decreases toward the center of the profiles South of Flyinge. While the maximum thickness increases to slightly more than 40 m toward North of Revingeby at Slogstorp in profile 5 (Fig. 21).

TL2

Locally, this unit is deposited on top of SG1 with an approximate thickness of 5–30 m. However, the deposition of TL2 is limited to a few locations within the zone and in most of the areas the unit is absent. Till 2 extends from the margin of Vombsänkan along Romeleåsen and it extends toward the Northeast with a lateral extent of 1−4 km.

CS3

The extension pattern of CS3 is similar to TL2, indicating a minor importance of the unit. CS3 is absent in most parts of the modelling area, and it locally overlies TL2 along profiles 2 and 4. Along profile 3 it occurs only as thin lenses and has an outcrop along profiles 2 and 4 West of Flyinge and around Ekeberga, respectively.

SG2

This unit has a relatively limited extension. SG2 mostly appears as small lenses and thin units in the uppermost part of the sequence. In the central parts of Vombsänkan, in the middle of profiles 3 and 4 the unit has small outcrops, and it locally forms sand and gravel ridges as illustrated in profile 5 around Sandby mosse.

4.1.2 The Veberöd-Vomb-Bjärsjölagård zone

The geology of the zone is illustrated by the SW-NE-directed profiles 8–11. The area is approximately 84.5 km^2 in size, measuring 6.5 km in width and 13 km in length (Fig. 22). The zone extends from East of Romeleåsen at Veberöd to Bjärsjölagård in the Northeast. Profiles 9 and 10 demonstrate the geology at the Vombverket water treatment plant Southwest of Lake Vombsjön (Fig. 22). The geology of the area is generally similar to the geology of the Södra Sandby–Löberöd zone.

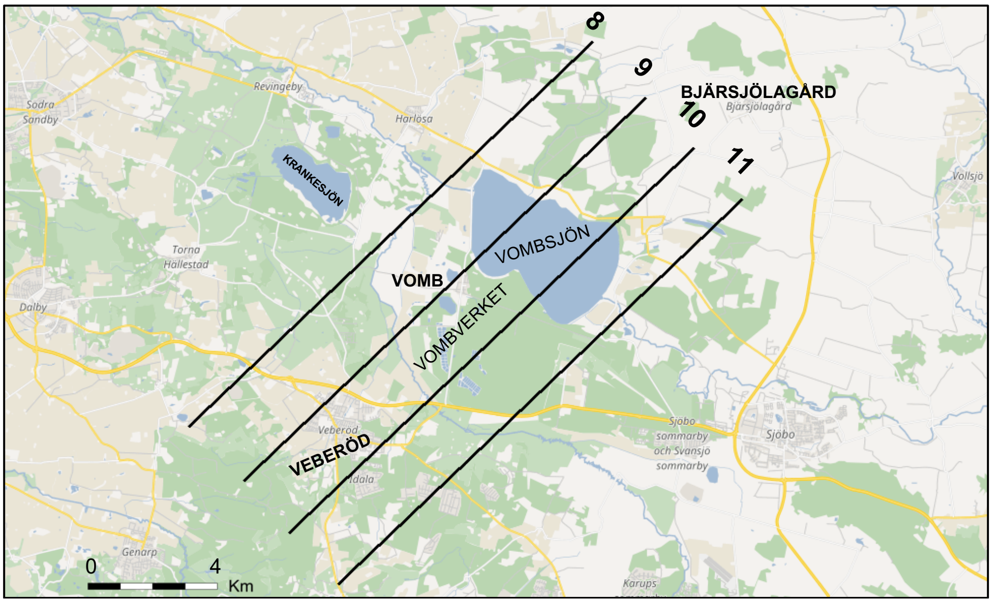


Fig. 22. Location of the SW-NE-directed profiles 8–11 that illustrate the geology of Veberöd-Vomb-Bjärsjölagård.

4.1.2.1 Bedrock

IMB

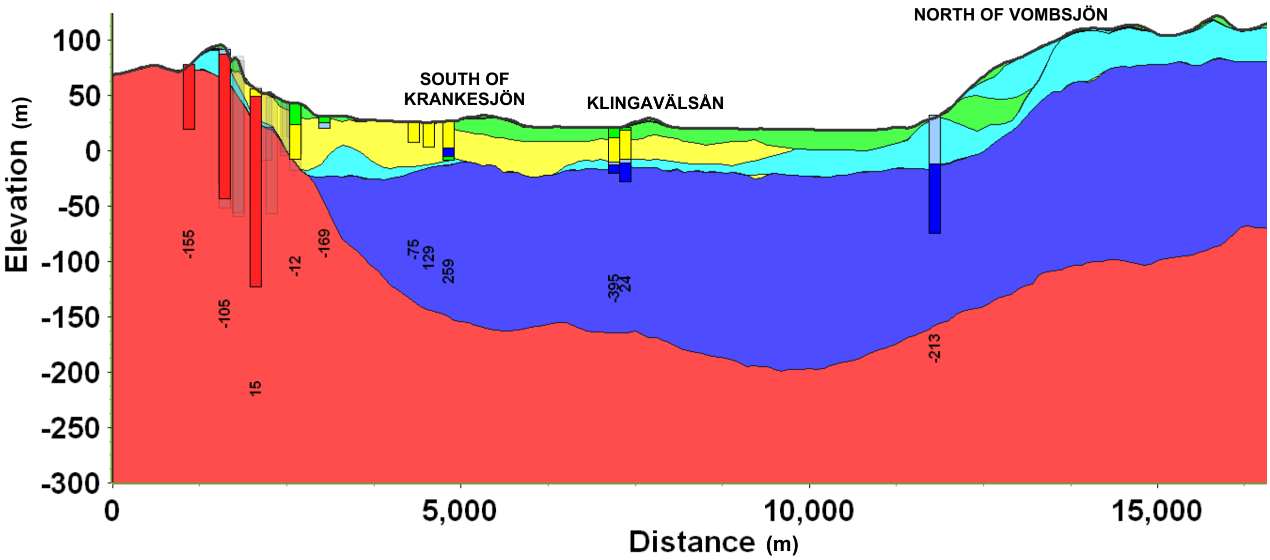
According to the borehole data up to 170 m of the IMB is documented in West of Veberöd (Fig. 23 profile 8). There are several boreholes on the Romeleåsen Horst that provide information on the Quaternary deposits, such as till, sand/gravel and clay/silt directly on top of the IMB. The information on the Linderödsåsen Horst is limited to a few wells. The model shows that to the SW at Råmeleåsen the IMB is located close to the ground surface whereas it is situated relatively deeper to the NE at Linderödsåsen.

SBR

The character of the SBR is quite similar to the Södra Sandby–Löberöd zone. The SBR is the most dominant unit through the northern part of Vombsänkan and in the middle of the area, around Vombverket, it reaches its maximum thickness of around 100 m. However, the actual thickness of the unit and the position of its lower boundary are unknown. There are no deep boreholes in the middle of profiles 8−11 that confirm the extent of the SBR on top of the IMB (Fig. 23). The SBR is generally covered by TL1. Based on the borehole data at profile 10, the SBR is not documented in the area. The 3D model does not show an accurate geometry of the SBR within the Veberöd-Vomb-Bjärsjölagård zone. To estimate the depth and the thickness of the SBR at Vombverket further investigations are needed.

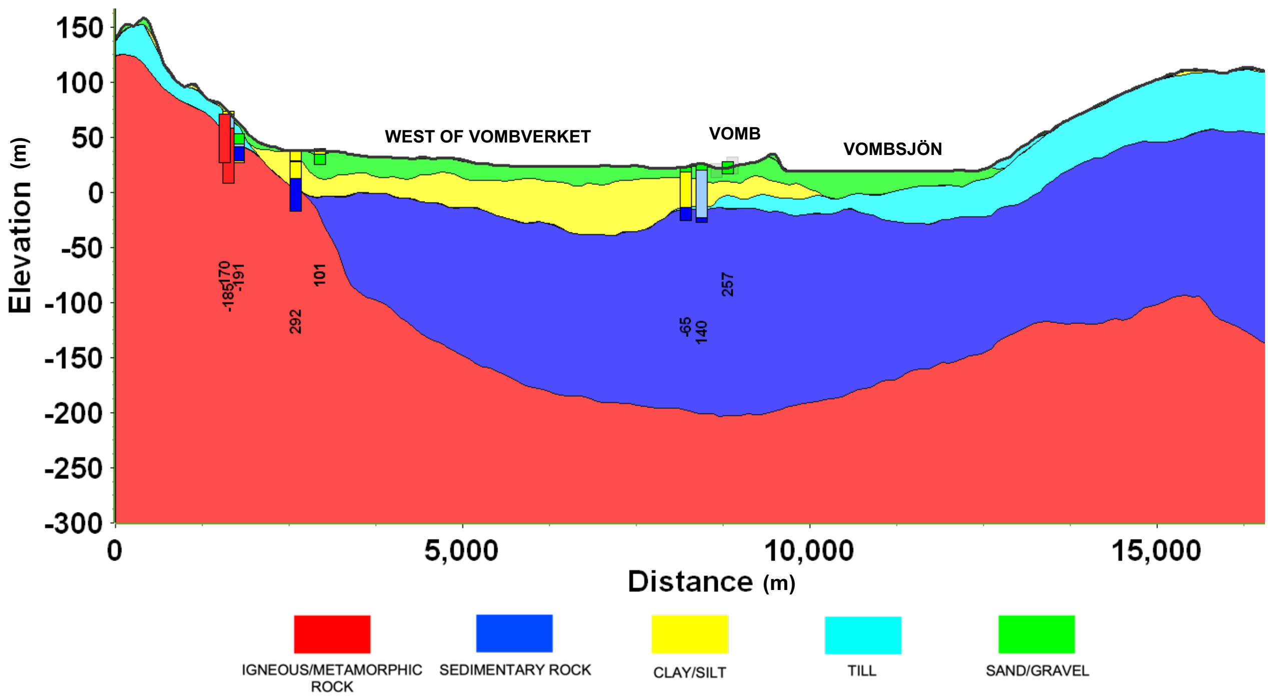
SW **VEBERÖD–VOMB–BJÄRSJÖLAGÅRD** **NE**

PROFILE 8



SW **VEBERÖD–VOMB–BJÄRSJÖLAGÅRD** **NE**

PROFILE 9



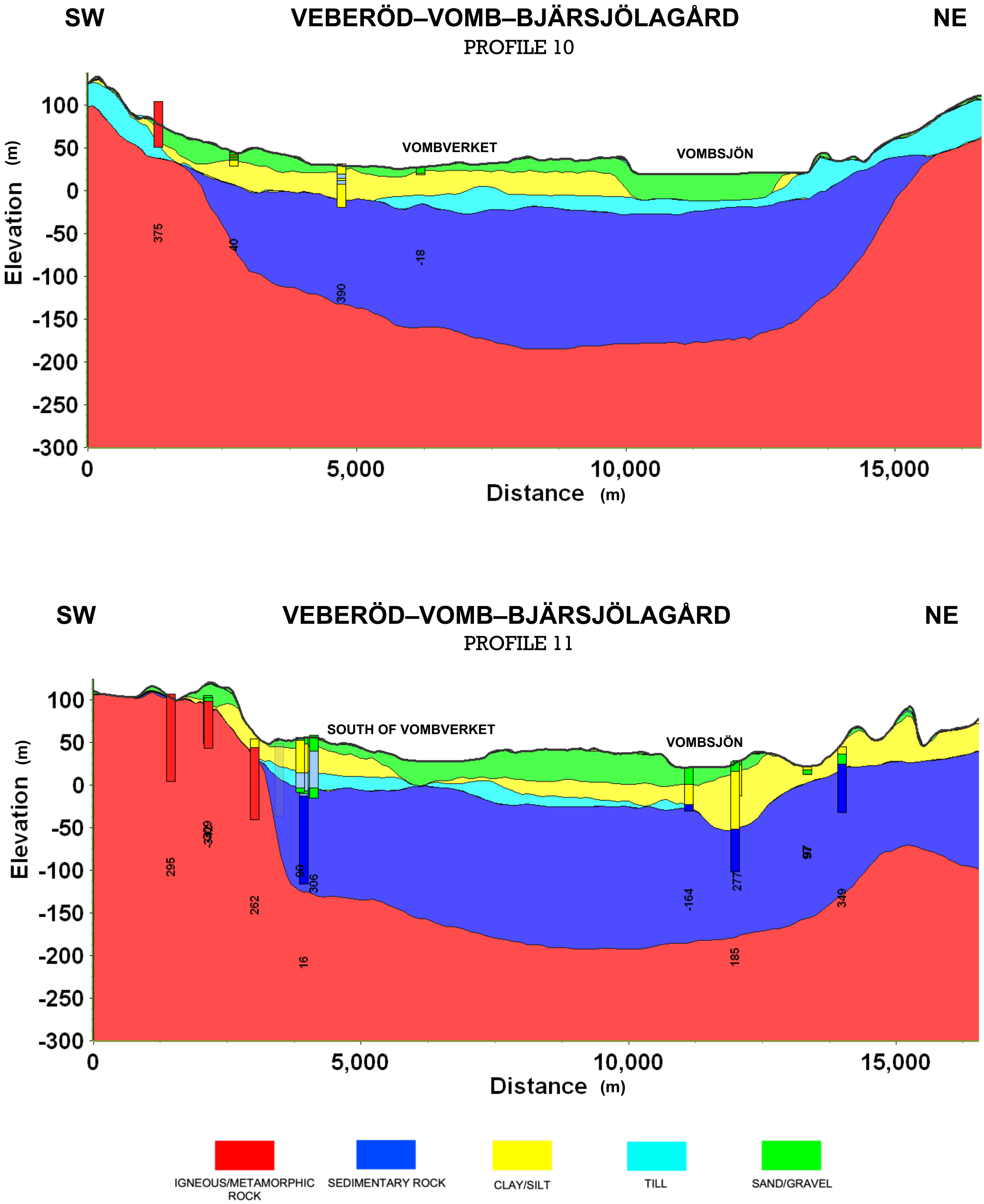


Fig. 23. Profiles 8–11, illustrating the geology of the Veberöd-Vomb-Bjärsjölagård zone.

4.1.2.2 Quaternary deposits

The Quaternary deposits display a simpler pattern compared to the Södra Sandby–Löberöd zone. CS1, TL2, CS3 and SG2 have insignificant thicknesses and there are fewer recurring till units.

TL1

CS1 is not present at this zone and typically, TL1 is directly deposited on top of the SBR. The thickness of the unit varies through the zone, and the maximum thickness is approximately 50 m North of Lake Vombsjön. Corresponding to the Quaternary deposits map, TL1 is the uppermost unit toward Romeleåsen and Linderödsåsen, where it covers the surface as a thin unit deposited directly on the IMB (Fig. 23).

CS2

South of Lake Krankesjön along profile 8 and East of Lake Vombsjön along profile 11, CS2 is deposited on top of the SBR where it reaches its maximum thickness of approximately 100 m. Generally, CS2 overlies TL2, and it has a significant thickness among the Quaternary deposits.

SG1

The uppermost unit within this zone is commonly exposed in the middle of the profiles around Vombverket in the form of a thin unit of sand and gravel. The position of the units at the surface, corresponds to the Quaternary deposits map. The thickness of the unit is between 10 and 50 m and it is commonly underlain by CS2.

In most parts of the zone, TL2, CS3 and SG2 are absent or have an insignificant thickness. In 3D modelling of a large and complex setting such as the northern part of Vombsänkan, considering units with insignificant thicknesses can be very time-consuming and complicated. Therefore, during creating the interpretation points and the surfaces, units that are thinner than 5 m are ignored during the modelling process.

4.1.3 The Gårdstånga–Ilstorp zone

The area is 182 km^2 in size measuring 26 km in length and 7 km in width. These profiles are perpendicular to the two previously presented zones (Fig. 24). The geology of partly the same area as described above is illustrated by profiles 16–19 (Fig. 25).

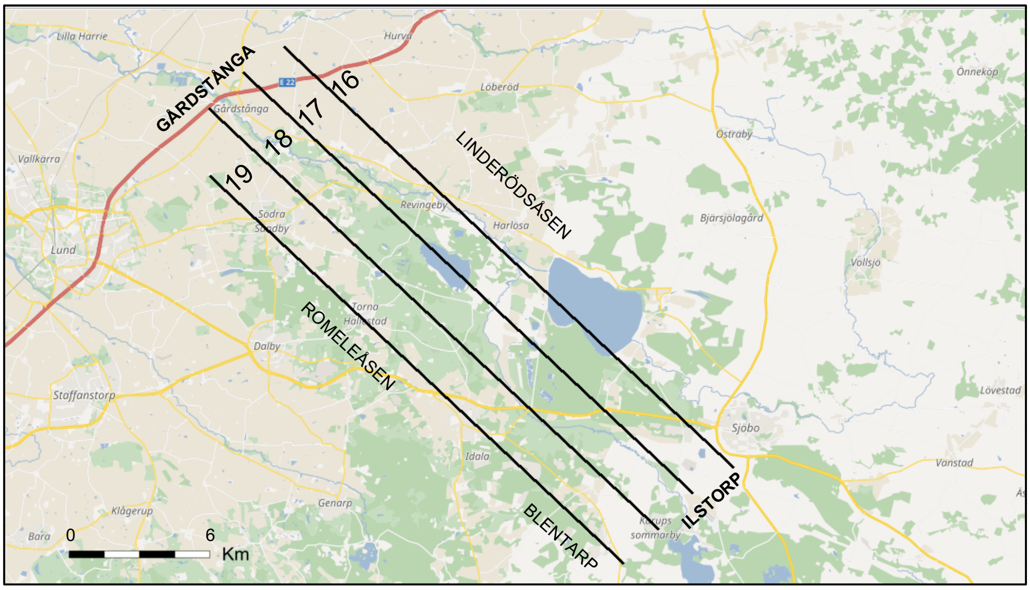
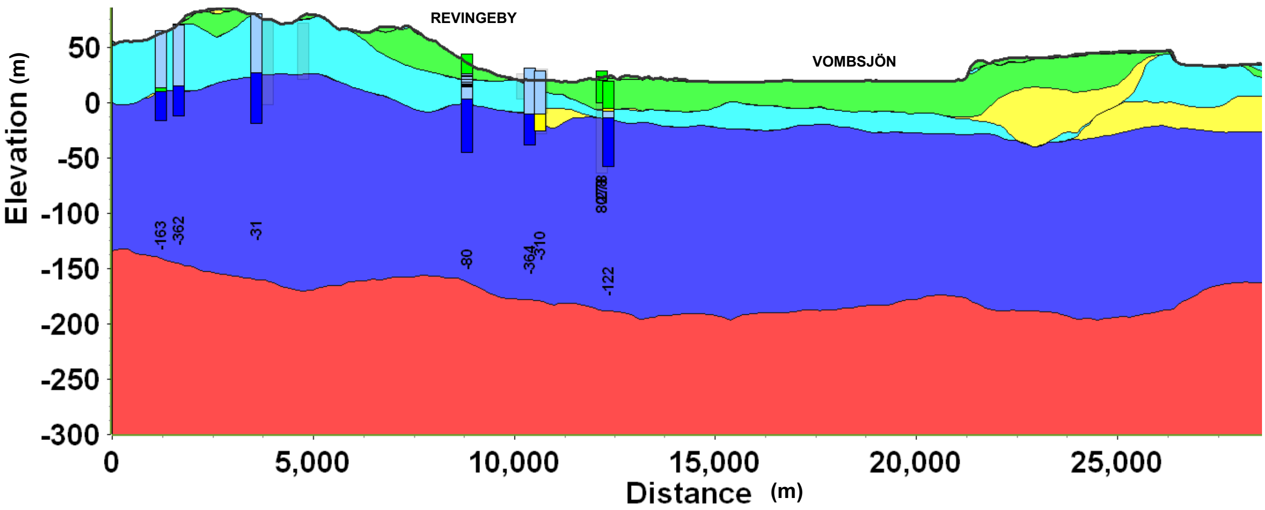


Fig. 24. Location of the NW-SE-directed profiles 16–19 that illustrate the geology of the Gårsdstånga–Ilstorp zone.

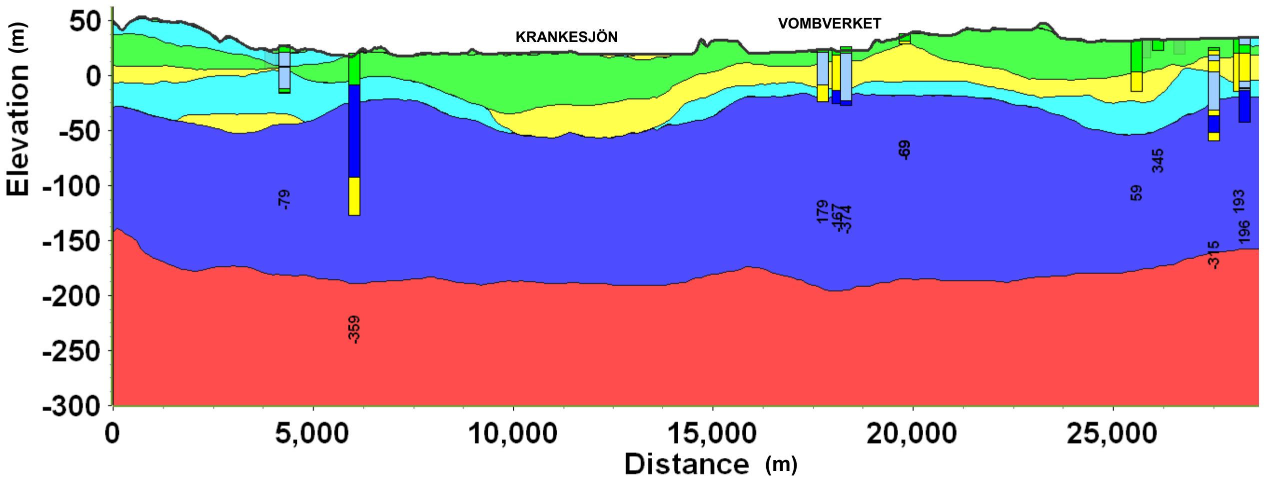
NW **GÅRDSTÅNGA–ILSTORP** SE

PROFILE 16



NW **GÅRDSTÅNGA–ILSTORP** SE

PROFILE 17



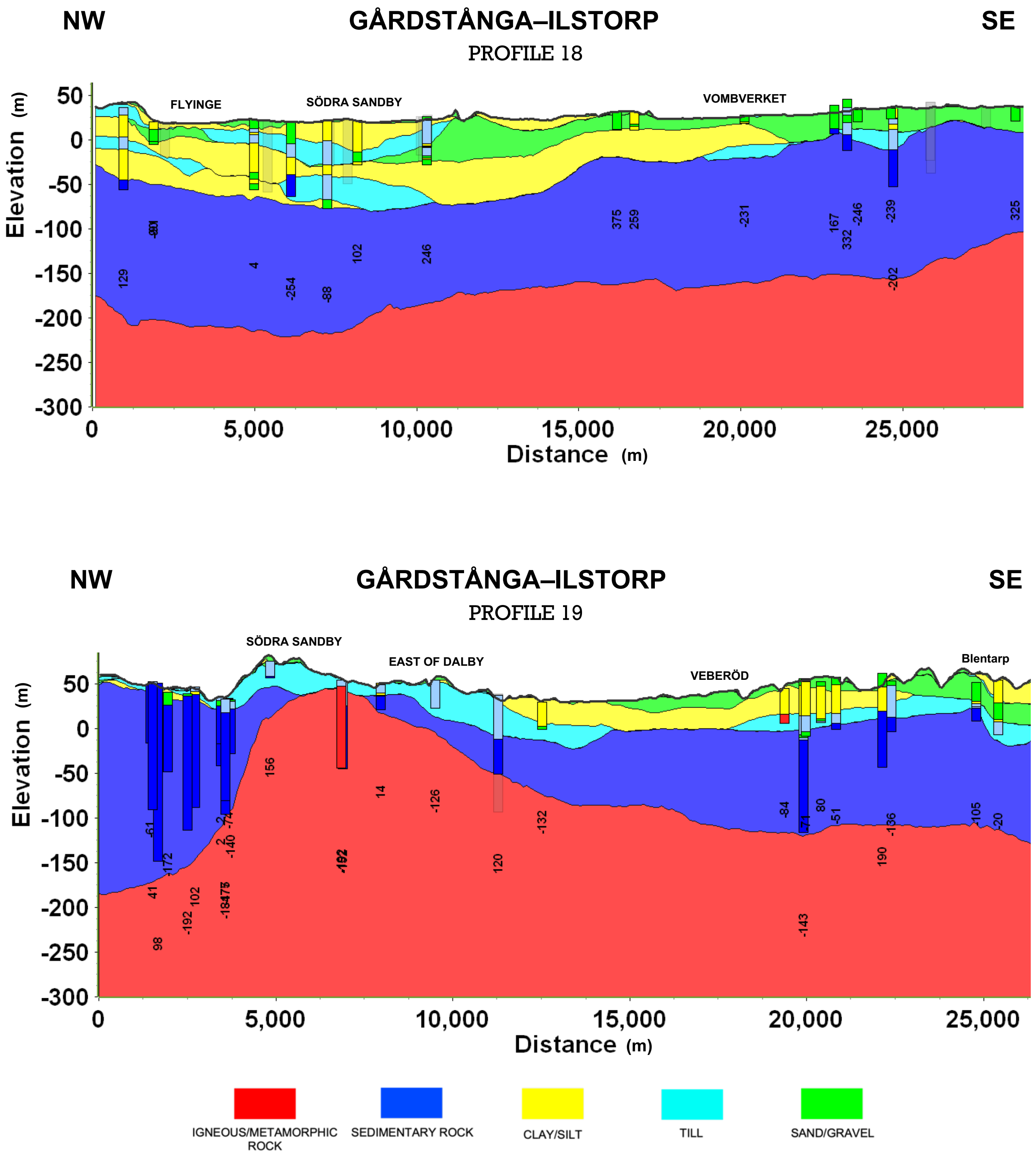


Fig. 25. Profiles 16–19, showing the geology of the Gårdstånga–Ilstorp zone.

4.1.3.1 Bedrock

The general geology of the bedrock of this zone is like the two other zones previously described. Except in the southern part of the area, along profile 19, the bedrock configuration is relatively uniform through the northern part of Vombsänkan. The thickness and the dimensions of the bedrock do not vary substantially.

IMB

Based on the borehole data there is no evidence of the presence of the IMB in the area. However, along profile 19 between Torna Hällestad and Södra Sandby, there are a few boreholes indicating that the IMB is located 5–10 m below the surface. The 3D model supports the appearance of the IMB within the crosscutting profiles (Appendix 5) such as profile 5 in the Södra Sandby–Löberöd zone. Towards the southern part of Romeleåsen along profile 19, the IMB is situated deeper. It is inferred that the thickness of the IMB is most probably decreasing towards Veberöd.

SBR

This unit is the thickest unit through the northern part of Vombsänkan as shown by the 3D modelling results at Södra Sandby where the SBR has a maximum thickness of 200 m along profile 19. This unit is characterized by a relatively uniform thickness, mostly 100–200 m. Notably, along Veberöd–East of Dalby at profile 19 the thickness of the SBR is decreasing. To the NW of Södra Sandby the thickness significantly increases again (Fig. 25).

4.1.3.2 Quaternary deposits

Generally, the thickness of the Quaternary deposits is uniform throughout the area and based on the 3D model, it can be estimated to 60–70 m. At Romeleåsen, the thickness is locally 0 or insignificant. Along profile 19 the Quaternary deposits consist of 5–10 m of TL1, while they are more complex and much thicker East of Dalby, up to 100 m overlying the SBR.

CS1

In contrast to the ubiquitous presence of TL1, CS2 and SG1, the deposition of CS1 is limited to a few locations, such as around Gårdstånga East of Dalby and around Ilstorp. CS1 is usually directly underlain by the SBR.

TL1

This unit is remarkably more dominant in the northern part of the zone around Revingeby and West of Sjöbo along profile 16, at Gårdstånga along profiles 17 and 18, as well as near the western parts at Romeleåsen. TL1 is underlain by SBR in major parts of the zone.

CS2

The thickness of this unit largely corresponds with that of TL1. The unit is characterized by a notable extension along profile 18, where it stretches across more than 20 km from South of Gårdstånga to South of Vombverket. Southeast of Lake Krankesjön along profile 18 the thickness of this unit exceeds 50 m.

SG1

Based on the 3D model, SG1 is the dominant unit in the northern part of the zone where it covers a large area South of Lake Vombsjön. SG1 is considerably widespread and extensive among the Quaternary deposits. Along profile 17, SG1 extends across more than 20 km from Flyinge to Ilstorp.

TL2

This unit has a restricted extension in the northern part of Vombsänkan, being limited to a few locations. In addition, the thickness of TL2 is generally smaller than that of TL1. However, it is difficult to distinguish this unit from TL1 because of the insignificant thickness of (or locally lack of) intervening deposits. At some locations, there is no strong evidence of the occurrence of two distinct till units. However, the 3D model clearly demonstrates the deposition of TL2 East of Flyinge along profile 16, Southwest of Gårdstånga and around Södra Sandby along profile 18.

CS3

This unit typically occurs at the surface and less extensively as compared to CS2 and SG1. Along profile 18, West of Flyinge and East of Södra Sandby, CS3 represents the uppermost part of the sequence, overlying TL2. At some locations, such as South of Lake Krankesjön, CS3 is located on top of SG1. Towards the Southeast near Blentarp, CS3 forms a 25 m thick outcrop (Fig. 25)

SG2

This unit is the least abundant among the Quaternary deposits in the northern part of Vombsänkan. SG2 is characterized by deposition of small sand and gravel lenses, for example North of Södra Sandby where the unit is underlain by CS3. SG2 is only observed at the surface, and it is usually less than 10 m thick.

4.2 Hydrogeological conceptual modelling

The hydrogeological conceptual model is basically the same model as the created model for the northern part of Vombsänkan. To estimate the hydrogeological conditions of the northern part of Vombsänkan, such as the structure and dimensions of aquifers more information such as the head data is needed. However, it is possible to assess the hydrostratigraphic units. Based on their hydrogeological characteristics, such as hydraulic conductivity (K) or permeability, the lithological units can be categorized into new groups (Table 1). This new classification results in a model based on the hydrostratigraphic units.

Table 1. Permeability of the Quaternary deposits (Larsson 2008).

TILL	
GRAVEL TILL	$10^{-5} - 10^{-7}$
SAND TILL	$10^{-6} - 10^{-8}$
SILT TILL	$10^{-7} - 10^{-9}$
CLAY TILL	$10^{-8} - 10^{-10}$
CLAY TILL (CLAY>15%)	$10^{-9} - 10^{-11}$
SORTED SEDIMENTS	
FINE-GRAINED GRAVEL	$10^{-1} - 10^{-3}$
COARSE-GRAINED SAND	$10^{-2} - 10^{-4}$
MEDIUM-GRAINED SAND	$10^{-3} - 10^{-5}$
FINE-GRAINED SAND	$10^{-4} - 10^{-6}$
COARSE-GRAINED SILT	$10^{-5} - 10^{-7}$
MEDIUM/FINE-GRAINED SILT	$10^{-7} - 10^{-9}$
CLAY	$< 10^{-9}$

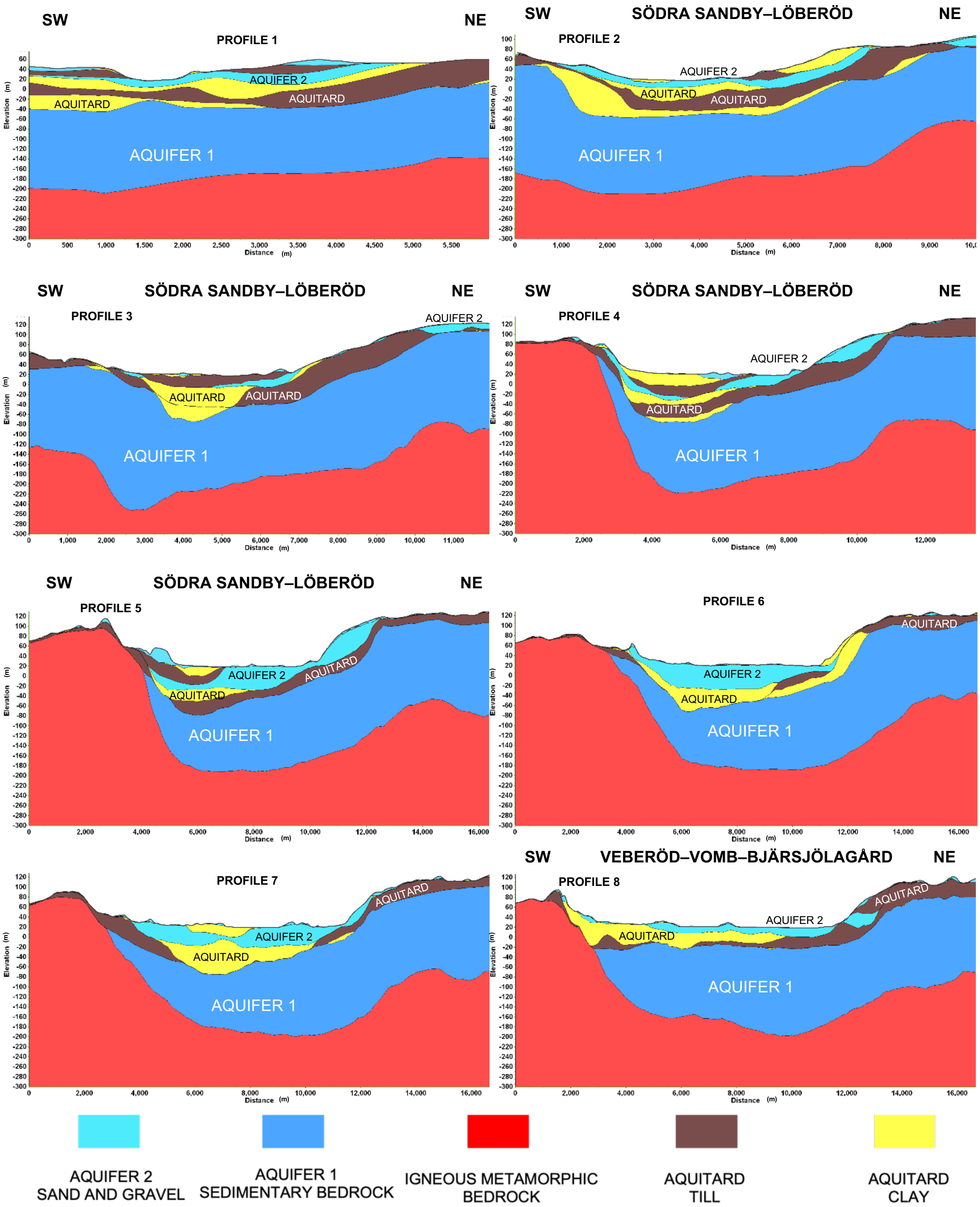
To define the hydrostratigraphic units, within the same model, the lithology is classified into five new groups, ranging from lower to higher hydraulic conductivity including:

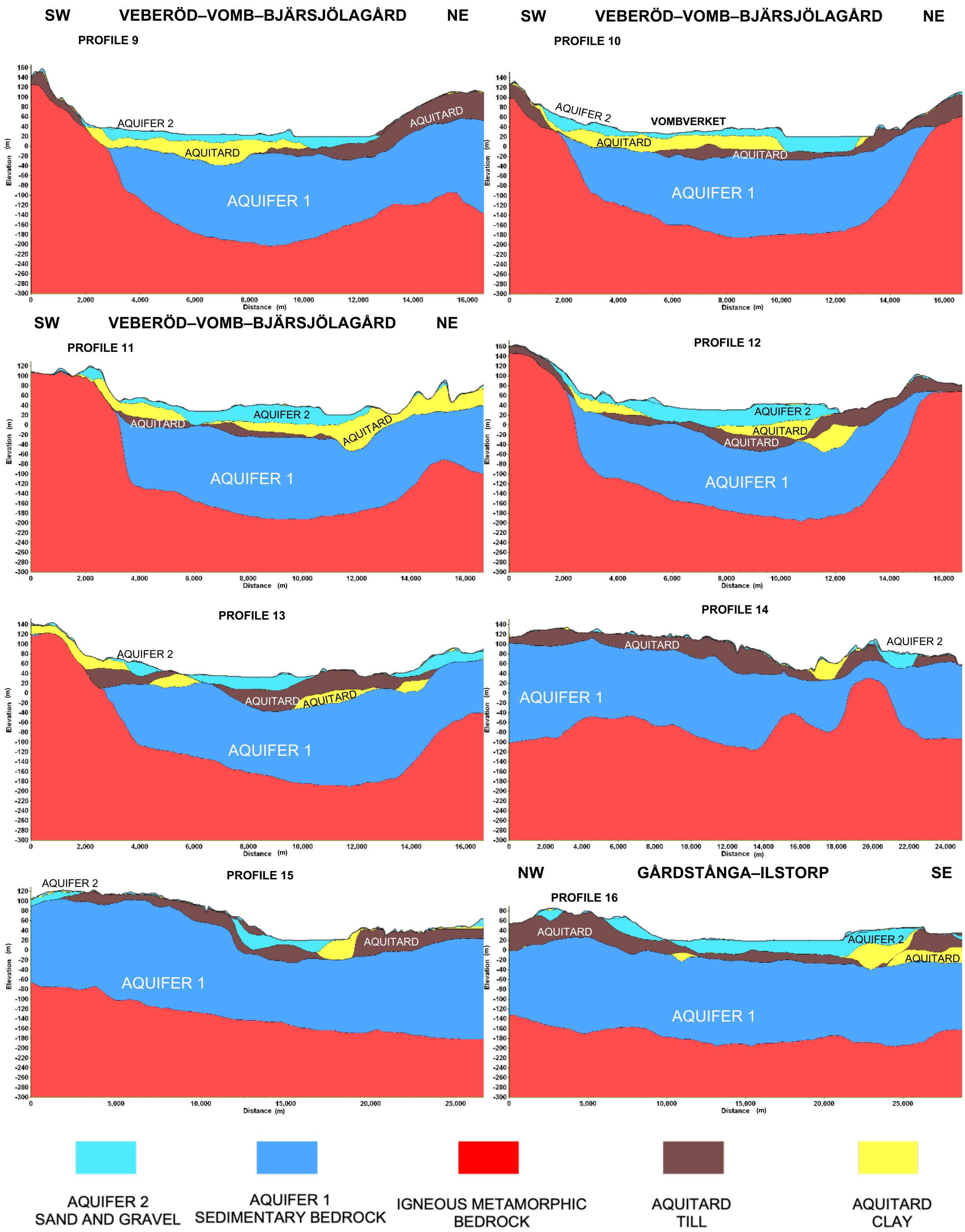
1. Clay/silt
2. Till
3. Igneous/metamorphic bedrock
4. Sedimentary bedrock
5. Sand/gravel

The hydrogeological conceptual model illustrates the hydrostratigraphic units that are characterized by two major types of aquifers (Fig. 26). The first aquifer type (aquifer 1) is the sedimentary bedrock, which is typically a confined aquifer. The second aquifer type (aquifer 2) commonly consists of an open aquifer near the surface, which is composed of sand/gravel. Locally, aquifer 1 is underlain by the IMB. The SBR is mostly covered by TL1 or CS2. Aquifer 2 commonly occurs at the surface as an open aquifer but also locally it is overlain by TL2 and CS3.

The results imply a large capacity of groundwater storage in aquifer 1 within the SBR. The dimensions and volume of this aquifer are considerably larger than those of aquifer 2. The confined aquifer within the SBR is largely ubiquitous and of remarkable extension throughout most part of the study area. In the northern part of Vombsänkan, the thickness of aquifer 1 is 140–200 m. Aquifer 2 has generally a much smaller volume. The thickness of the permeable sand/gravel unit of aquifer 2 is usually less than 50 m.

The average depth of the Quaternary deposits varies between 50 to 80 m in the northern part of Vombsänkan. At Vombverket the depth of the Quateranry deposits is 40–50 m.




SW VEBERÖD–VOMB–BJÄRSJÖLAGÅRD NE
PROFILE 9
AQUIFER 2
AQUITARD
AQUITARD
AQUIFER 1
SW VEBERÖD–VOMB–BJÄRSJÖLAGÅRD NE
PROFILE 10
AQUIFER 2
VOMBVERKET
AQUITARD
AQUITARD
AQUIFER 1
SW VEBERÖD–VOMB–BJÄRSJÖLAGÅRD NE
PROFILE 11
AQUITARD
AQUIFER 2
AQUITARD
AQUIFER 1
PROFILE 12
AQUIFER 2
AQUITARD
AQUITARD
AQUIFER 1
PROFILE 13
AQUIFER 2
AQUITARD
AQUITARD
AQUIFER 1
PROFILE 14
AQUITARD
AQUIFER 2
AQUIFER 1
PROFILE 15
AQUIFER 2
AQUITARD
AQUIFER 1
NW GÅRDSTÅNGA–ILSTORP SE
PROFILE 16
AQUITARD
AQUIFER 2
AQUITARD
AQUIFER 1
Elevation (m)
Distance (m)
AQUIFER 2 SAND AND GRAVEL
AQUIFER 1 SEDIMENTARY BEDROCK
IGNEOUS METAMORPHIC BEDROCK
AQUITARD TILL
AQUITARD CLAY

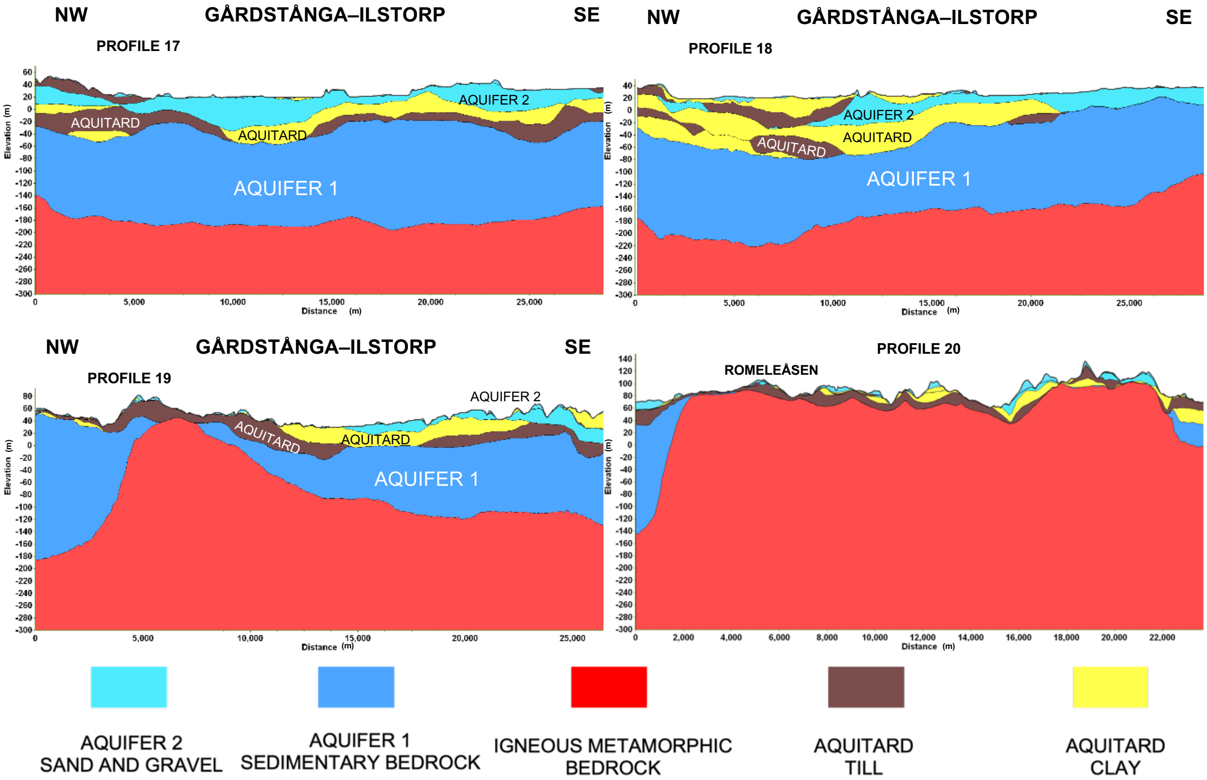


Fig. 26. Hydrogeological conceptual model of the northern part of Vombsänkan. Profiles 1–20 illustrate the hydrostratigraphic units that are defined based on their respective K values.

4.3 Resistivity

The location of the 800 m long resistivity line at the Vombverket water treatment plant is shown in Fig. 27. The measured resistivity was inverted with the software RES2DINV to create a 2D profile linked to the lithology, which and can be used for interpretation (Fig. 27). The resistivity results show a notably elevated resistivity close to the ground surface. The uppermost 3−10 m-part of the profile shows resistivity values exceeding 1000 Ω. The distribution of the resistivity at the surface is relatively persistent, corresponding to a unit with a uniform thickness of 3−10 m. At approximately 8 m depth a sharp decrease in resistivity was observed, directly under the unit of elevated resistivity. The resistivity of this unit is between 63–400 Ω. The third notable observation occurs around 20 m below the surface where the resistivity decreases to 56−180 Ω.

Around the depth of 37 below the surface the resistivity decreases notably to less than 16Ω. The resistivity results imply a clearly decreasing pattern with the depth, indicating at least three well-defined units. The two uppermost units show a relatively similar thickness of 5–10 m. While the two uppermost units exhibit a relatively uniform resistivity pattern, the underlying unit from around 20 m depth and below shows more variable resistivities and several horizontal changes. Indeed, the decreasing resistivity pattern most notably continues towards the depth of 20 m below the surface. From 20–80 m the resistivity shows lateral irregular variations.

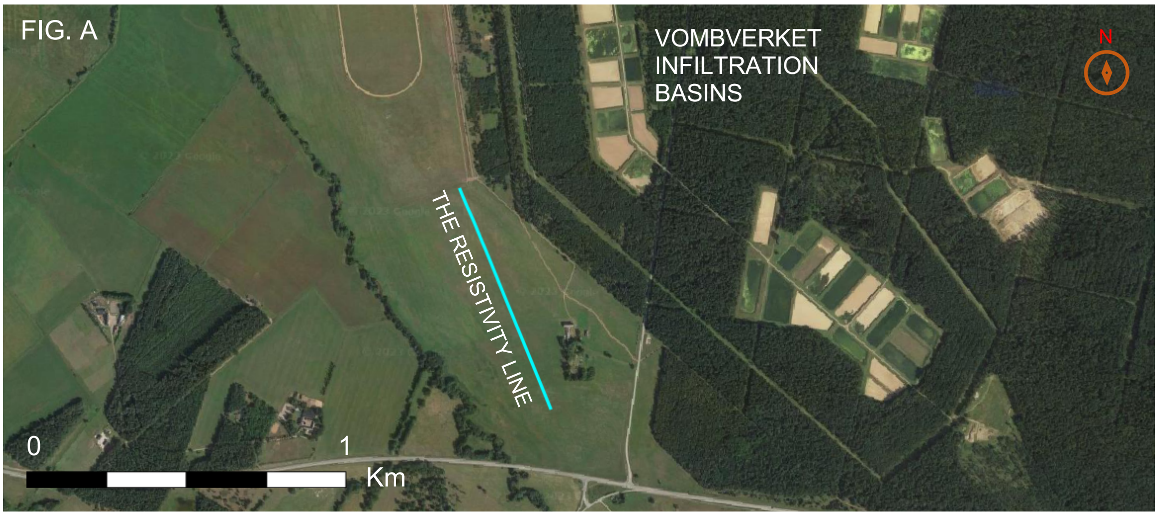


FIG. B

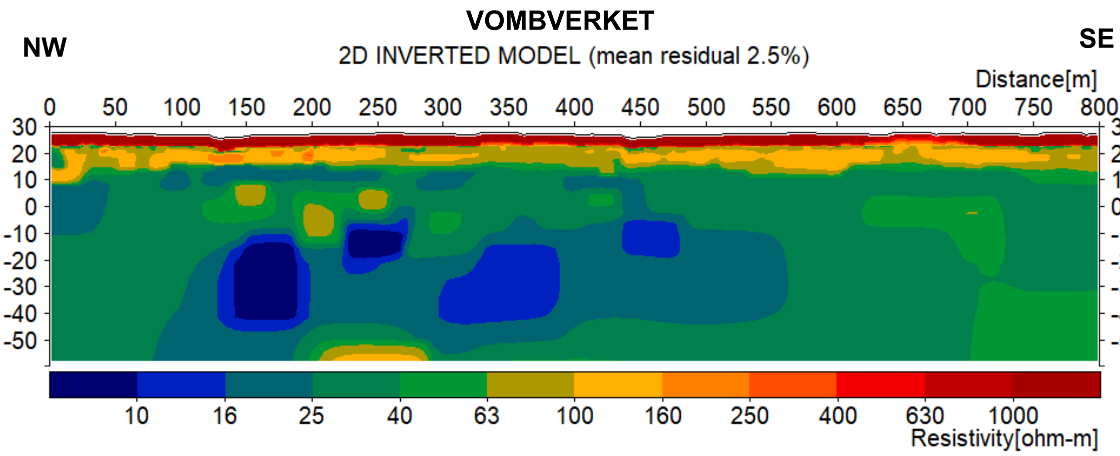
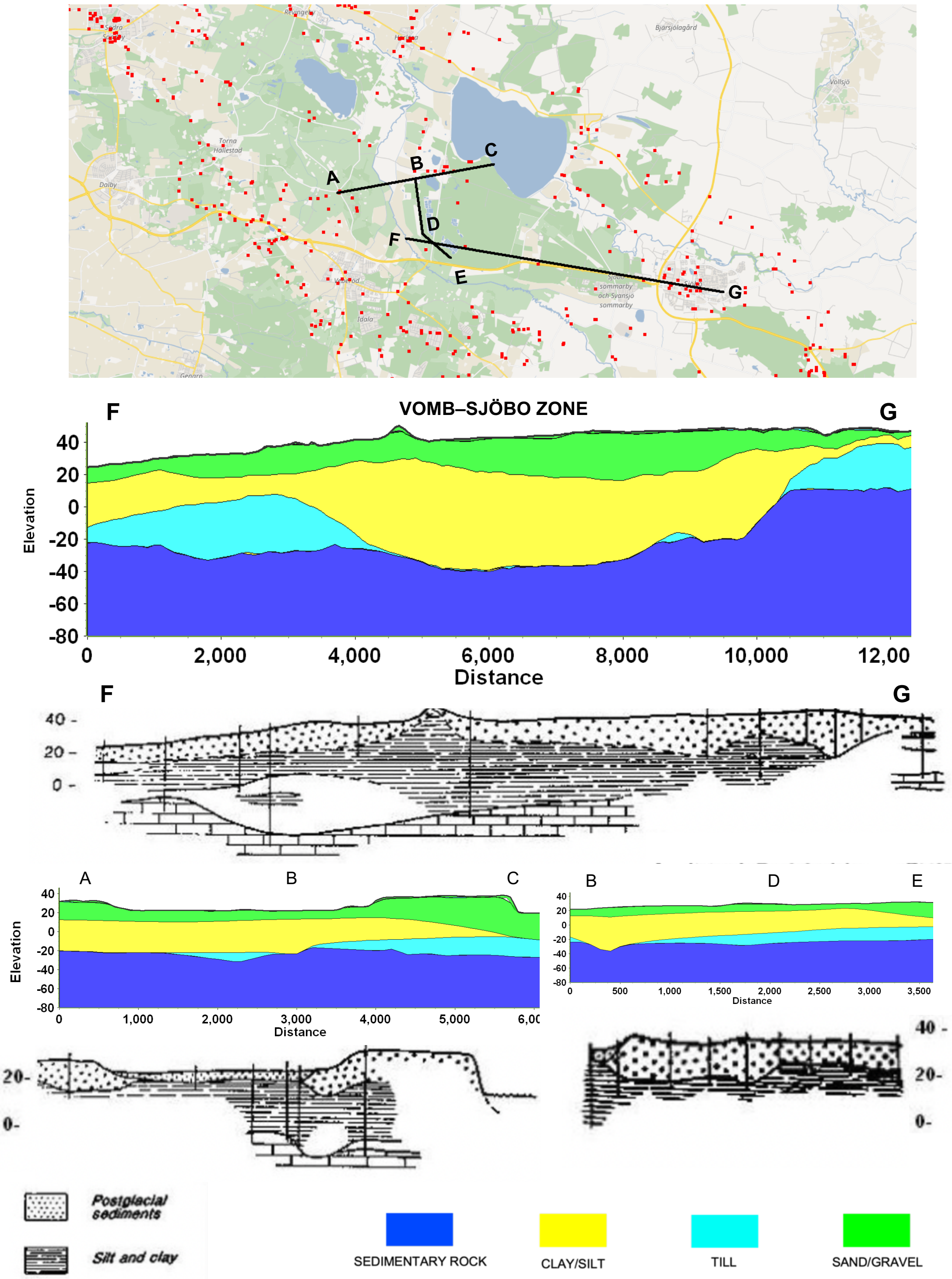


Fig. 27 A. Location of the resistivity line at the Vombverket water treatment plant. To illustrate the exact position of the line, the positions of the electrodes were measured by a GPS and the coordinates were imported to QGIS. Fig. 27 B. Inversion model of the resistivity line at the Vombverket water treatment plant. The profile is visualized in Erigraph.

5. Discussion

5.1 Geoscene 3D

The results of this thesis work indicate that the software can create reliable geological models. Generally, the models that are created for the northern part of Vombsänkan support the results of previous studies (Fig. 28 and Appendix 6). A part of this thesis work has been developed based on the self-learning experience of the 3D modelling with Geoscene 3D. The learning process developed from the first-time application of the software by the user, to create and interpret 3D geological and hydrogeological conceptual models from the northern part of Vombsänkan.



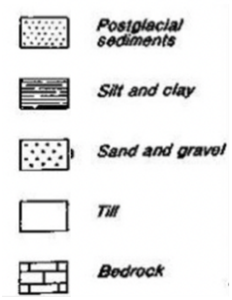


Fig. 28. The 3D modelling results compared to one of the fundamental previous studies illustrating the geology of the Vomb–Sjöbo zone (Daniel 1992).

There is a gap in previous studies using the software and there is no information available about the application of Geoscene 3D based on borehole data from Sweden. The instructions that are provided by Geoscene 3D (Geoscene 3D 2020) are often limited to simple examples which does not represent the geology of complex environments. Therefore, this thesis work is considered as a ground for the 3D modelling of complex geological settings based on borehole data. In addition, this study presents a useful evaluation of the application of the software in geological and hydrogeological assessments.

Advantages:

The software provides a useful overview of the geology allowing the user to simultaneously visualize and compare geological, hydrogeological and geophysical models. The learning process and the 3D modelling experience with Geoscene 3D is described as a functional user interface. The software is a practical modelling tool, provides most of the fundamental options required for geological interpretations. Navigating through the 3D environment and comparing several 2D and 3D models facilitate a more reliable and accurate interpretations. Creating stratigraphical profiles with Geoscene 3D is a quick and helpful way to approach the interpretations. For example, as a fundamental approach within this thesis work 2D profiles are created to compare the geophysical data with the stratigraphy and the lithology of the boreholes (Fig. 29). The overall performance of the software is evaluated as significantly accurate and efficient, providing simultaneous 2D and 3D views.

Disadvantages:

Despite a few useful functions that allow the user to automatically define the upper and lower boundaries of each unit, the 3D modelling requires manual interpretation as well. The manual interpretation includes creating the interpretation points (Fig. 8) and grid adjustments (Fig. 11; appendix 3). The first experience of the 3D modelling based on the borehole data is evaluated as an extremely time-consuming process. Some of the functions are difficult to understand that requires prior modelling experiences for a quick result. The grid adjustment that is a necessary procedure for an actual model, is confusing. It requires lots of practice and efforts that are not efficient for a complex geology like the northern part of Vombsänkan. The resolution of the geophysical visualization such as the resistivity profiles is poor which results in blurred profiles (Fig. 13). Therefore, other software such as Erigraph and Res2Dinv may have advantages (Fig. 27B).

5.2 Resistivity

The resistivity data from the Vombverket water treatment plant highlight the importance of geophysics as a complement to borehole data for detection of errors and uncertainties of the 3D modelling. The highest resistivity appears near the surface at 3–12 m below the surface (Fig. 29; Fig. 30). The unit is interpreted as glaciofluvial coarse-grained gravel and sand. A sand-till unit may also yield a high resistivity similar to the measured resistivity of the uppermost unit in this study.

The unit below the SG1, which shows significantly lower resistivities is interpreted as a glacial clay. The clay unit is located 10–15 m below the surface and has an approximate thickness of 25 m. The decreasing resistivity pattern of the section can be interpreted as a unit of glaciofluvial sand and gravel at the surface (resistivity greater than 630 Ω) which is underlain by the glacial clay (resistivity 25–250 Ω). The clay unit is capping the fractured SBR (resistivity less than 25 Ω).

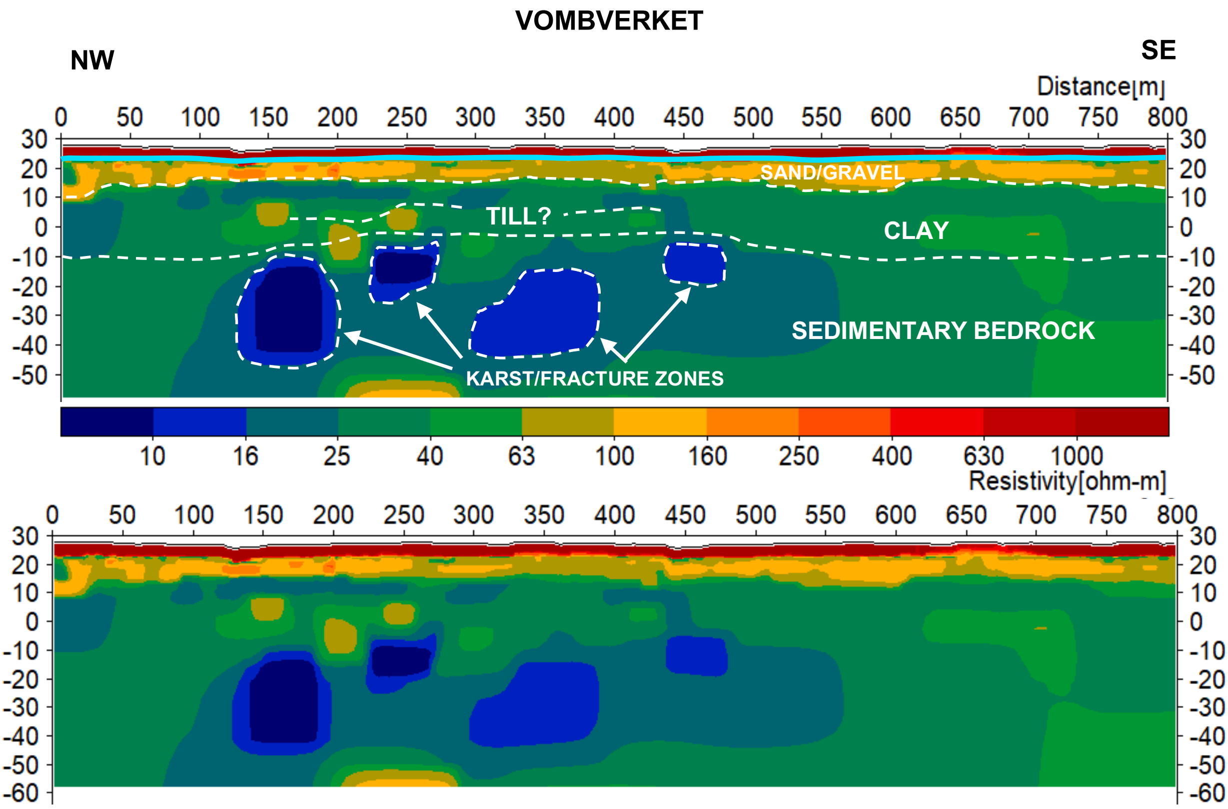
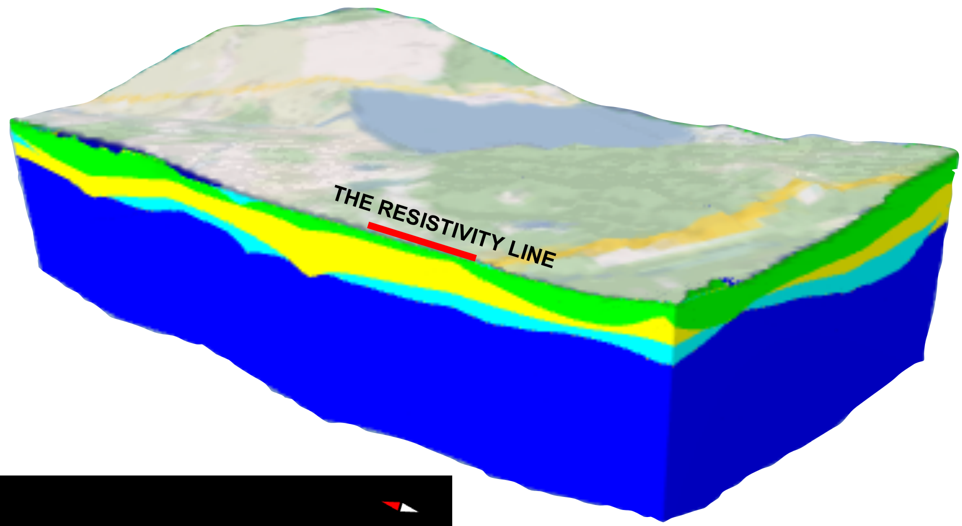


Fig. 29. Interpretation of the resistivity results at the Vombverket water treatment plant. The estimated groundwater level is illustrated with a blue line.



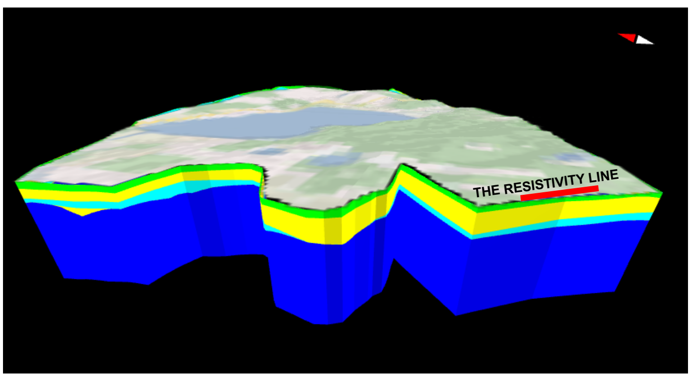


Fig. 30. 3D profiles illustrating the geological model of the resistivity line (800 m) at Vombverket.

Erlström et al. (2004) describe that the structure of the SBR is complex since the area has been exposed to tectonic deformations and erosions. The unit is characterized by a highly fractured structure composed of unconsolidated and weathered rocks. The irregular variations that are observed within the SBR at 35–65 m below the surface can be interpreted as the heterogenous structure of the SBR. Based on the borehole data in Revinge, the SBR is characterized by a fractured limestone at 32–90 m below the surface (Erlström 2013; Engvall 2015; Engleson 2017). The low resistivity parts within the SBR which are observed as rounded and semi-rounded areas, are interpreted as karst and fracture zones. The resistivity of the karst and fracture zones within the unconsolidated sedimentary bedrock is 0–16 Ω.

The ground water level at North of Revinge is 1 m below the surface and at Veberöd–Idala it is located 4.5 m below the surface (Dahlqvist et al. 2021). Based on the resistivity results, the groundwater level cannot be detected. The saturated zone shows generally lower resistivities compared to the unsaturated zone (Palacky 1987). According to the resistivity results, the thickness of the SG1 is estimated at 3−12 m. It is assumed that the groundwater level is located near the surface within the SG1. The decreasing resistivity pattern which is observed at 10–15 m below the surface can be explained by the groundwater level. Based on the resistivity model, the thickness of the SG1 and the previous studies, the author assumes that the groundwater level is located at 4–9 m below the surface (Fig. 30).

A till unit and a clay unit can yield similar resistivity values (Palacky 1987). Consequently, it is difficult to detect a till unit within the resistivity profile. Most probably a few meters on top of the SBR within the resistivity profile corresponds to the till unit that is documented in the area (Fig. 29; Fig. 30). However, further investigations are needed for an accurate conclusion about the depth of the groundwater level and the dimension of the till unit. According to the geophysical investigations, the main stratigraphic model corresponds to the geological model created by Geoscene 3D.

5.3 Hydrostratigraphic units

The following section is based on a combination of the three integrated. The geological model of the northern part of Vombsänkan, the hydrostratigraphic conceptual model and the Vombverket model, are used to evaluate the hydrogeology of the study area.

The geology of Vombsänkan provides extensive groundwater resources with a considerable volume and water uptake capacity. Daniel (1992) describes the hydrogeology of South of Lake Vombsjön. The area is characterized by two major types of aquifers. The confined SBR aquifer (aquifer 1) that is formed within the thick units of fractured and porous sandstone and limestone. An open pore aquifer (aquifer 2) is located near the surface, and it consists of coarse-grained glaciofluvial sediments. At Vombverket, the entire surface area corresponds to the extensive surface of the aquifer 2 (Fig. 26 profile 10). Therefore, aquifer 2 is highly vulnerable to groundwater contaminations, which stresses the importance of a systematic environmental protection of the groundwater and land system in the northern part of Vombsänkan. A study of the hummocky moraines in the Vomb area suggests a depositional model that is linked to both active ice margin and stagnant ice (Bjermo 2022). The last deglaciation of Skåne was complex. The area has been exposed to several ice advances followed by ice marginal recession and deposition of glaciofluvial deposits (Houmark-Nielsen and Kjaer 2003). The Quaternary deposits are characterized by a recurring pattern corresponding to the Late Weichselian glaciation and deglaciation. Ising (2020) created a 3D model of the southern part of Vombsänkan. The 3D model illustrates the deposition of five till beds in the area (Fig. 4). Each till unit is linked to an ice advance. The results of this study demonstrate the complex geology of Vombsänkan. At West of Revingeby at least four till beds occur in the basin (Fig. 7B). However, in most parts of the study area the stratigraphy is characterized by the deposition of two till beds. It is assumed that TL1 and TL2 are associated with two prominent ice advances of the last glacial cycle. The presence of glaciofluvial and glaciolacustrine sediments between the till units is associated with a recession of the ice margin. Despite the complex pattern of the Quaternary deposits in the northern part of Vombsänkan, it can be explained by a simple sequence based on the most frequent stratigraphy. The results of the 3D modelling (Fig. 21; Fig. 23; Fig. 25) can be summarized using a simple hydrostratigraphic model, including (respectively from older to younger):

1. The IMB
2. The SBR
3. TL1
4. CS2
5. SG1

The IMB is generally formed by igneous and metamorphic rocks such as gneiss, granite, amphibolite and diorite (Fig. 2). The IMB is locally covered by a thick unit of the SBR, which is typically composed of limestone and porous sandstone. The SBR is overlain by approximately 20–40 m of TL1. On top of TL1 there is 30–70 m of CS2. The uppermost unit consists of 5–10 m of unit SG1.

Unit CS2 is interpreted as glacial clay and unit SG1 is interpreted as glaciofluvial deposits. The glaciolacustrine deposits such as unit CS2 are commonly composed of clay and silt but at some locations sand and gravel are also documented. Daniel (1992) suggests a postglacial depositional model for the uppermost sand, silt and gravel units. He describes that the uppermost sand units are deposited as sand dunes. The sand dunes were formed by wind erosion of the glaciofluvial sand in the late Holocene.

Based on the available information it is difficult to assess the exact depositional process behind the formation of the Quaternary deposits. Different depositional environments result in deposition of sediments with similar grain sizes including sand, silt and clay (Holmberg and Johansson 1986; Daniel 1992). Since, both glaciofluvial and glaciolacustrine sediments may contain sand, silt and clay the interpretation of the depositional model is difficult. Thus, to link the depositional model of SG1 and SG2 to glaciofluvial, glaciolacustrine or sand dunes, further investigations are required.

Based on the 3D model, the SBR is overlain by a till unit with an approximate thickness of 5–10 m at Vombverket (Fig. 31A and appendix 7). In addition, Daniel (1992) suggests the deposition of a till unit in the area illustrated in the Vomb–Sjöbo geological cross section (Appendix 6), which is overlain by glacial clay. However, based on the resistivity model it is difficult to identify the till unit (Fig. 29). This contrast can be explained by the limitation of the 3D modelling that cannot provide accurate results in detail within a restricted area. The 3D model is created based on borehole data from the northern part of Vombsänkan and it does not provide sufficient details of the stratigraphy at Vombverket. The till unit is documented in a borehole East of the resistivity line (Fig. 31C). It is interpreted that the thickness of the till unit decreases northeast of the resistivity profile until it gets either very thin or disappears completely northeast of the resistivity line. It is concluded that for an accurate result with Geoscene 3D in smaller areas, it is essential to consider the details of the borehole data. For precise evaluations of the hydrogeology, creating a detailed 3D model is needed.

5.4 Groundwater resources in the Quaternary deposits

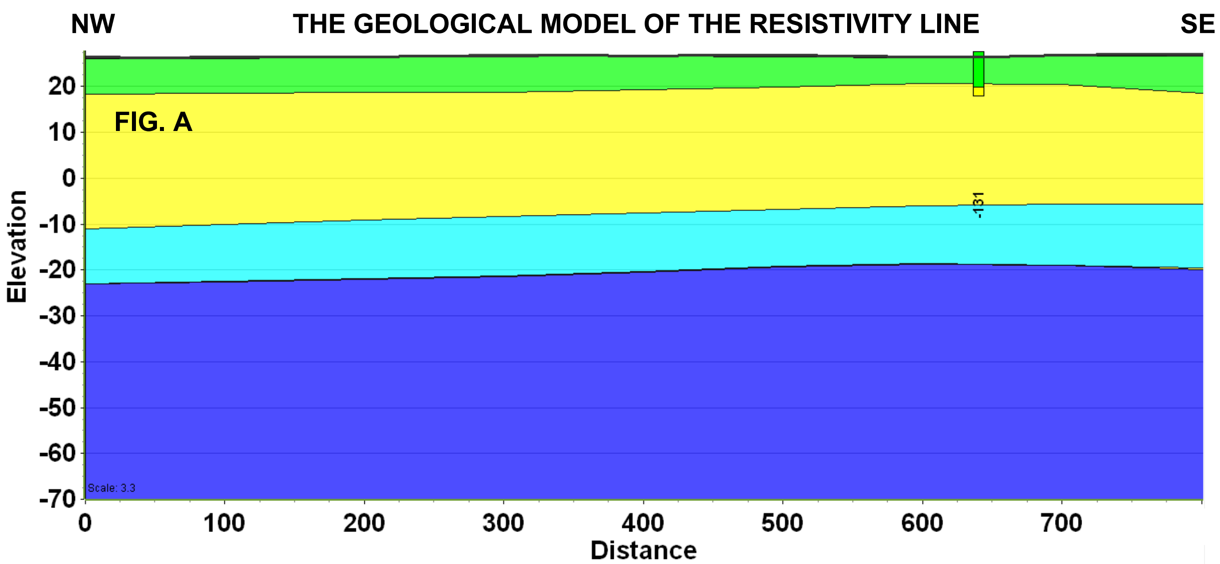
The annual groundwater formation for the sand and gravel open aquifer at Revinge, is estimated to 2,800,000 m^3/year (Engleson 2017). This amount indicates a groundwater formation capacity that exceeds a permanent pumping of 20 l/s (Khorshidian and Heister 2023). The groundwater recharge is therefore sufficient for a permanent groundwater extraction of 20 l/s. Kjessler and Mannerstråle (1989) calculated significantly high values of transmissivity (T) for aquifer 2 at Vomb, suggesting a substantial uptake potential of the unit. South of Lake Vombsjön around Vombs fure the uptake capacity is estimated to be up to 125 l/s. At some locations the transmissivity reaches 0.020 m^2/s allowing a groundwater uptake of 50–100 l/s. Furthermore, at Ilstorp, Rodhe et al. (2006) suggest a groundwater formation of 10.4 l/s per km^2. The aquifer at Ilstorp has an uptake capacity of 125 l/s (Lindberg Skutsjö 2021).

5.5 Groundwater resources in the sedimentary bedrock

Dahlqvist et al. (2021) describe the bedrock characteristics of Vombsänkan associated with the Vomb Formation, which is mostly composed of sand and clay-rich limestone. At some locations the major aquifer type is characterized by the sand-rich and permeable SBR that is located close to the surface. The average uptake capacity of the SBR is estimated to 5–20 l/s (Dahlqvist et al. 2021). Aquifer 1 is a large, confined aquifer that is typically capped by till or glaciolacustrine clay. Since the SBR has a considerable thickness, aquifer 1 is considered as the largest type of aquifer in most parts of Vombsänkan. With the available information, it is difficult to determine the extension of the weathering and the fracture system of the SBR.

5.6 Aquifer geometry

To explain the structure and dimensions of the hydrostratigraphic units, the volume, area and the thickness of each unit are calculated by Geoscene 3D. The aquifer geometry and dimensions of the groundwater resources in the northern part of Vombsänkan can be estimated. The volume of aquifer 1 is calculated to 60.7 km^3. The overall thickness of the unit is 111 m, and it covers 547.8 km^2. Aquifer 2 has a volume of 5.1 km^3 (SG1) + 1.4 km^3 (SG2) = 6.5 km^3 with an average thickness of 10 m. The area is calculated to 540.5 km^2 (Fig. 32; appendix 8).



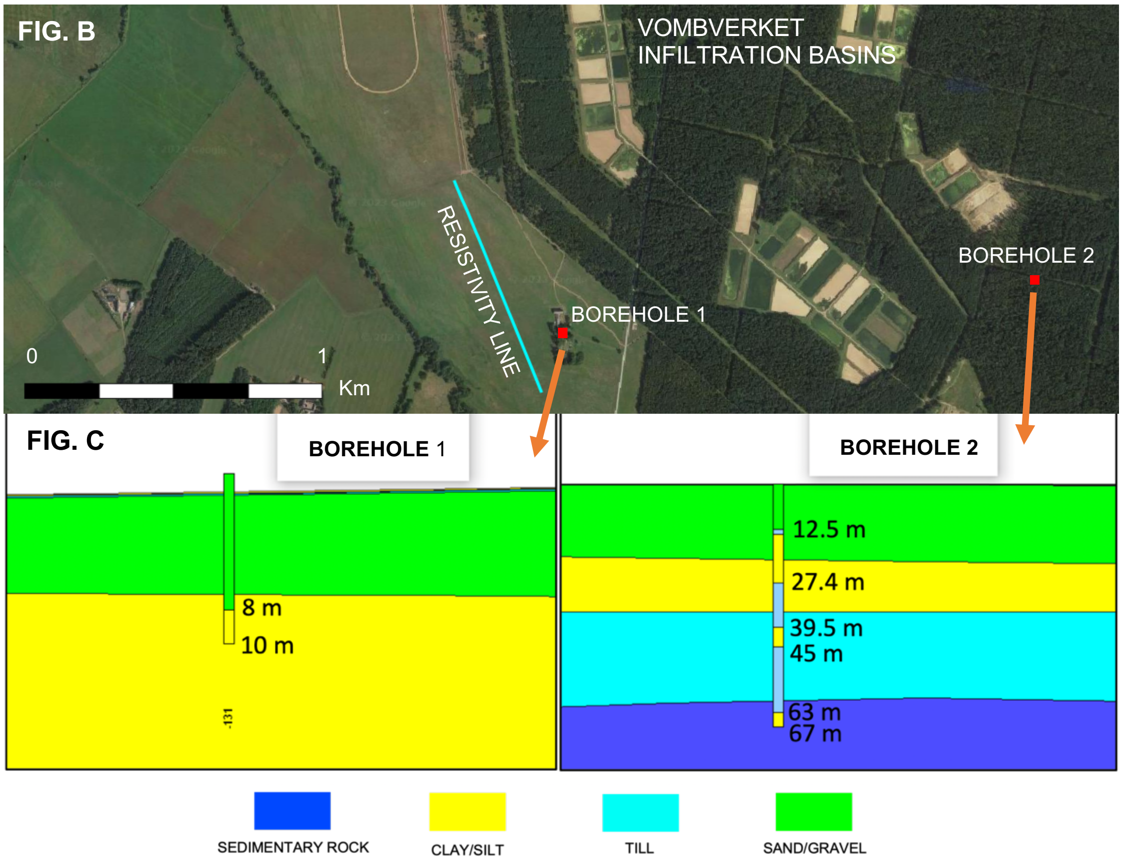


Fig. 31. The lithology of the nearest wells close to the resistivity line. It is inferred from the 3D model that TL1 is overlain by CS2. Despite the correct positions of the lithological boundaries at the borehole locations (Fig. A), the 3D modelling result shows inaccurate positions of the boundaries when zoomed in (Fig. C).

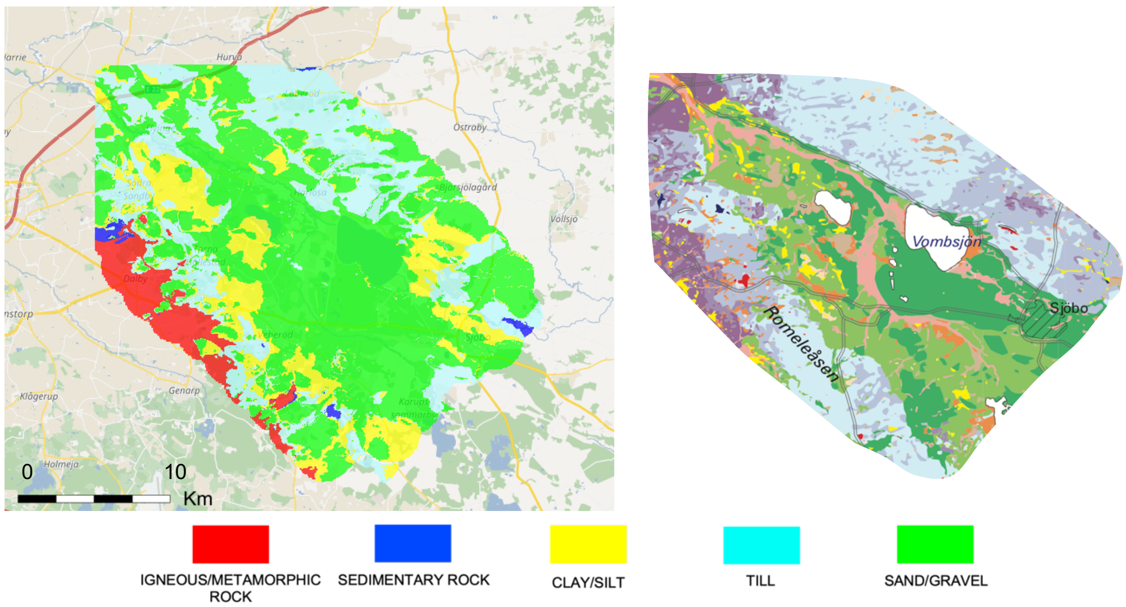


Fig. 32. The surface model of the northern part of Vombsänkan created by Geoscene 3D compared to the Quaternary deposits map. The depth increment is 5 m. In addition, a surface model with depth increment of 0.5 is created (appendix 8).

The aquifer geometry can be estimated based on the porosity of each unit. Since the lithology of the SBR is very diverse the estimation of its porosity is complicated. The SBR consists of shale, coal, limestone and porous sandstone as well as thin units of clay. The porosity is estimated to 2–30%. For an accurate estimation of the porosity further information is required. However, since the dominant rocks are relatively thick units of porous sandstone and limestone, it is assumed that the porosity is 15–30 % (Table 2). Consequently, the geometry of the SBR aquifer can be calculated as below:

$60.7\ km^3 \times 15\% = 9.1\ km^3$

$60.7\ km^3 \times 30\% = 18.2\ km^3$

Hence, the approximate volume of aquifer 1 is estimated to 9.1–18.2 km^3.

For SG1 and SG2, it is assumed that the porosity varies between 20–40 %. The geometry of aquifer 2 can be calculated as below:

$6.6\ km^3 \times 20\% = 1.3\ km^3$

$6.6\ km^3 \times 40\% = 2.6\ km^3$

Hence, the approximate volume is estimated to 1.3–2.6 km^3 for aquifer 2 within the overlying sand and gravel unit.

Table 2. Estimation of the aquifer geometry in the northern part of Vombsänkan.

AQUIFER TYPE	LITHOLOGY	VOLUME	POROSITY	GEOMETRY
AQUIFER 1	SEDIMENTARY BEDROCK	60.7 km^3	15–30 %	9.1–18.2 km^3
AQUIFER 2	SAND AND GRAVEL	6.6 km^3	20–40 %	1.3–2.6 km^3

5.7 Groundwater flow patterns

The main infiltration zones are the horst zones that have a higher topography. CS2 and CS3 units as an aquitard are not present or are relatively thin in these areas. For example, at the edge of the Romeleåsen Horst (Fig. 27, profile 20). The Romeleåsen Horst in the Southwest and the Linderödsåsen Horst in the Northeast are therefore considered as the major groundwater recharge zones. Karlhager (2014) suggests that groundwater recharge occurs from River Klingavälsån towards the Ilstorp aquifer, but it does not have a significant impact on the groundwater formation.

The groundwater flow in Holmbyåsen is towards the Southwest, associated with the topography. This can be explained by the groundwater flow direction from the northeastern parts, for example from higher elevations around Löberöd towards Holmbyåsen. At Hultan in the Vomb–Sjöbo area, the groundwater flow is directed towards Lake Vombsjön in the West and towards River Björkaån in the South (Dahlqvist et al. 2021). The groundwater flow processes in Revinge are described as North-directed flows along Klingavälsån. At North and Northeast of Lake Krankesjön where Klingavälsån joins Kävlingeån the groundwater flows toward the West (Engleson 2017). At Vombverket the groundwater flows from South of the infiltration ponds toward Lake Vombsjön at North (Holm 2011). However, the ground water flow directions at Vombverket can vary depending on the location of the active infiltration ponds and pumped wells. A groundwater flow direction toward the lower elevations at Klingavälsån is reported (Holm 2011). Generally, the groundwater flow is controlled by the topography.

With the available information it is difficult to estimate the structure and texture of the IMB on the contact boundary of the SBR.

The fracture systems and the degree of weathering of deeper, variably lithified units are strongly linked to the flow processes. For example, weathering of the igneous rocks results in the formation of the secondary clay minerals such as kaolinite. Even if the thickness of the weathered zone is only a few meters, it can significantly control the flow processes such as the aquifer leakage and the direction of the groundwater flows. A weathered clay-rich unit which has significantly lower K compared to the adjacent permeable units, can define the aquifer geometry and structure of the groundwater system. However, Erlström et al. (2004) suggest that the tectonic activities associated with the Tornquist zone resulted in an extensive degree of weathering and formation of highly fractured igneous and metamorphic rocks in major parts of Vombsänkan. According to the description of a few boreholes in Vombsänkan, the IMB is formed by partly fractured rocks. It is assumed that the IMB is a partly permeable unit along the extensive facture zones in major parts of Vombsänkan. It is therefore interpreted that the IMB incorporates into the formation of the aquifer 1 on the contact boundary of the SBR. The information on these properties is limited to a few descriptions within the borehole data and the previous studies. To estimate the extension and the location of the fracture system more investigations are needed.

6. Conclusions

- The major groundwater recharge occurs along the horst zones at higher elevations at the margins of Vombsänkan. At Vombverket, the groundwater flows toward Lake Vombsjön at North and Klingavälsån at West.
- The estimated aquifer geometry reveals the substantial hydrogeological potential of the northern part of Vombsänkan. The approximate surface area of the confined aquifer associated with the porous and fractured sedimentary rocks is estimated to 547.7 km^2 and the approximate volume is 9.1–18.2 km^3. The open aquifer within the sand and gravel unit has an approximate area of 540.5 km^2 and the approximate volume is 1.3–2.6 km^3.
- A complex 3D-model is proposed for the northern part of Vombsänkan. A thick unit of sedimentary bedrock (SB1) is overlain by 10–20 m of till (TL1). The till unit is locally underlain by relatively thin lenses of glaciofluvial and glaciolacustrine sediments that vary between sand, gravel, silt and clay (CS1). A 30 to 80 m thick unit of glacial clay (CS2) covers the till unit. The most widespread unit at the surface is composed of 5 to 20 m of sand and gravel (SG1). However, the unit is locally overlain by a second till unit (TL2). At some locations the uppermost unit consists of clay and silt, usually not exceeding 10 m in thickness (CS3) or small lenses of glaciofluvial sediments such as sand and gravel (SG2).
- The model in Vombverket is verified by resistivity measurements. To detect the errors and uncertainties and to create a more accurate model, verification of the model by additional geophysical investigations is the key.
- A simple hydrostratigraphic model is presented for the area around the Vombverket water treatment plant, corresponding to the main depositional model of the northern part of Vombsänkan. The sedimentary bedrock is located 40–50 m below the surface. At some locations, such as East of the infiltration basins, a till unit covers the bedrock. However, at the location of the resistivity measurements, 25–30 m of clay is directly deposited on top of the

sedimentary bedrock. The uppermost unit is composed of 5 to 10 m of sand and gravel.

7. Suggestions for future studies

- Creating a 3D model including more lithology groups can provide more accurate assessments. For instance, adding clay-till and fine sand silt to the current classification can increase the reliability of the models.
- A more detailed classification of the borehole data within the sedimentary bedrock is indeed for a better estimate of the hydraulic conductivity and porosity. For example, including limestone, sandstone, dimensions of clay-rich subunit and shale within the lithology would results in a more reliable estimation of the porosity.
- For a better estimation of the aquifer dimensions and structure, for examples to define the different types of aquifers within the sedimentary bedrock, using head data is an essential approach that must be considered in future studies.
- An extensive evaluation of the structure of the units such as determining the fracture zones and weathering within the Precambrian basement would be beneficial. Core logging can provide valuable information on the contact boundaries of the units as well as a better understanding of the classification of the unsorted lithologies such as co-appearance of gravel and clay. The structure of the units is an important parameter for the defining of hydrostratigraphic units.
- Controlling and correcting the accuracy of the model in zoom-in view and adjusting the mismatched areas between the model and the boreholes will significantly improve the accuracy of the model.
- The SkyTEM models are created but have not been used within this thesis work. A 3D model can be created from the SkyTEM for comparison. Moreover, 3D GPR geophysical surveys can add valuable information about the controversial geology of the subsurface in Vombsänkan.

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9. References

Andersson, CA. Sydvatten., 2009: Sydvatten AB Produktionsrapport 2009. 23 pp.

Binley, A., 2015, Tools and Techniques: Electrical Methods, in Schubert, G., ed., Treatise on Geophysics: Cambridge, MA, Elsevier Science, v. 11, p. 233–259, doi:10.1016/B978-0-444-53802-4.00192-5.

Bjermo, T., 2022: A reinvestigation of hummocky moraine formed from ice sheet decay using geomorphological and sedimentological evidence in the Vomb area, southern Sweden. Examensarbete i geologi vid Lunds universitet, 32p.

Cook, K.L., Van Nostrand, R.G., 1954. Interpretation of Resistivity Data Over Filled Sinks. Geophysics 19, 761–790.

Dahlin, T. (1996) 2D resistivity surveying for environmental and engineering applications, First Break, 14(7), p 275-283.

Dahlin, T. 2017. Geophysical mapping of aquifers in Bolivia, Torleif, Lund University, Lund, Sweden, SEG International Exposition and 87th Annual Meeting

Dahlin, T., Bernstone, C., & Loke, MH. (2002). A 3-D resistivity investigation of a contaminated site at Lernacken, Sweden. Geophysics, 67(6), 1692-1700. https://doi.org/10.1190/1.1527070

Dahlin, T., Zhou, B., 2006. Multiple-gradient array measurements for multichannel 2D resistivity imaging. Surf. Geophysics. 4, 113–123.

Dahlqvist, P., Åkesson, M., Erlström, M., Ising, J., Gustafsson, M., Brolin, C & Lundberg, F., 2021: Helikopterburna TEM-mätningar i Vombsänkan–Geologiska tolkningar och hydrogeologisk tillämpning. SGU-rapport 2021:23. Sveriges geologiska undersökning, 88 s.

Daniel, E., 1992: Beskrivning till jordartskartorna Tomelilla SV och Ystad NV. Sveriges geologiska undersökning Ae 99–100, 149 s.

Department of Engineering geology, Lund University. 2023. Project description. Blue Transition. (https://www.tg.lth.se/forskning/blue-transition/)

Engleson, K., 2017. Miljökonsekvensbeskrivning Revinge Brunnsfält. Geologiska Institutionens provpumpningsanläggning på P7 i Revingehed. Kandidatarbete, Lunds universitet, Lund. 28 p.

Engvall, E., 2015. En studie av ett grundvattensystem. Geologiska Institutionens provpumpningsanläggning på P7 i Revingehed. Kandidatarbete i geologi Lunds universitet, Lund. 66 p.

Erlström, M., Sivhed, U., Wikman, H. & K-A. Kornfält., 2004: Beskrivning till berggrunds kartorna 2D Tomelilla NV, NO, SV, SO 2E Simrishamn NV, SV 1D Ystad NV, NO 1E Örnahusen NV. Sveriges geologiska undersökning Af212–214, 1–141.

Geoscene 3D. 2020, Geoscene 3D products. (https://geoscene3d.com/Portals/1/Files/ProductSheets/GeoScene3D_Folder_Products_Light_uden_bagside.pdf?ver=2020-03-31-000000-000).

Holmberg, G. & Johansson, L., 1986: Sedimentologisk undersökning av de övre glacifluviala avlagringarna i Vombsänkan, södra Skåne. Examensarbete Lunds universitet, Geologiska Institutionen.

Houmark-Nielsen, M., & Kjær, K. (2003). Southwest Scandinavia, 40–15 kyr BP: palaeogeography and environmental change. Journal of Quaternary Science, 18(8), 769-786. doi: 10.1002/jqs.802

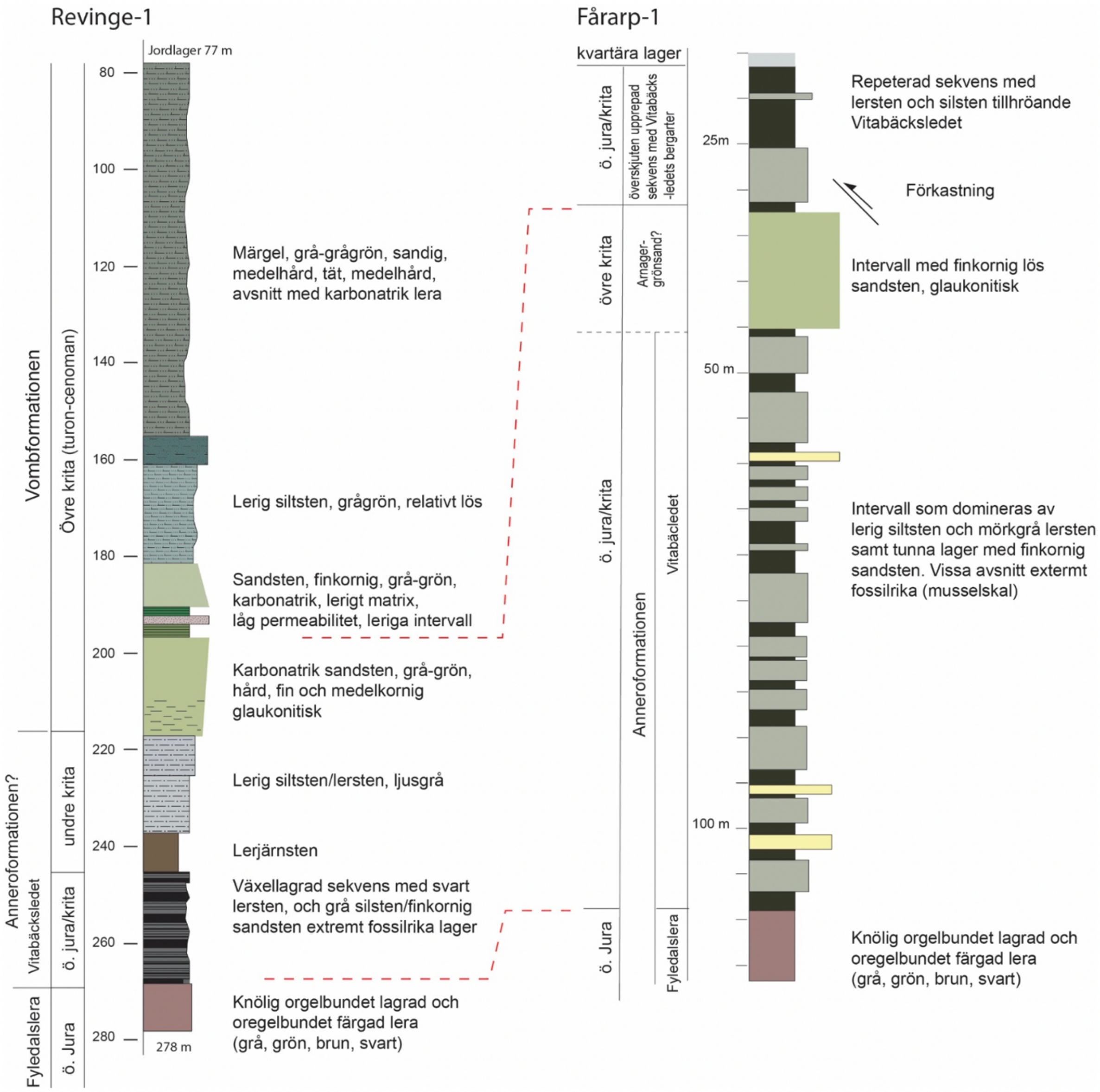
Hughes, A. L. C., Gyllencreutz, R., Lohne, Ø. S., Mangerud, J., & Svendsen, J. I. (2016). The last Eurasian ice sheets–a

chronological data- base and time-slice reconstruction, DA TED-1. Boreas, 45(1), 1-45. doi: 10.1111/bor.12142
Interreg North Sea. 2023 (https://www.interregnorthsea.eu/blue-transition/news/driving-change-advancing-sustainable-water-solutions-in-northern-netherlands)
Ising, J., 2020: Geologisk 3D-modell, Södra och mellersta Vombsänkan, Skåne. SGU-rapport 2020:31. Sveriges geologiska undersökning, 13 s.
Sparrenbom, Charlotte & Åkesson, Sofia & Johansson, Sara & Hagerberg, David & Dahlin, Torleif. (2016). Investigation of chlorinated solvent pollution with resistivity and induced polarization. Science of The Total Environment. 575. 10.1016/j.scitotenv.2016.09.117.
Holm, J. 2011: Geofysisk utvärdering av grundvattenskydd mellan väg 11 och Vombs vattenverk. Examensarbete i geologi vid Lunds universitet, 28p.
Karlhager, A., 2014: Grundvattenmagasinet Ilstorp. Sveriges geologiska undersökning K 459, 17 s.
Khorshidian, F., Heister, G. 2023. Provpumpning och vattenkvalitet i Revinge brunnsanläggning, öst om Lund, Skåne, Projektuppgift i Hydrogeologi, GEOP05, vid Lunds universitet. Opublicerad. 7 s.
Kjessler & Mannerstråle AB, 1989: Grundvattenundersökningar, Bedömning av Framtida utbyggnads-möjligheter, Sammanfattande hydrogeologisk rapport 1988-89. Ordernummer 206931, Kund: AB Sydvatten, Vombverket. Konsult: Kjessler & Mannerstråle AB, Halmstad. 18 pp. Opublicerat.
Knödel, K., Lange, G., Voigt, H.-J., 2007. Environmental Geology: Handbook of Field Methods and Case Studies. Springer-Verlag, Berlin Heidelberg. https://doi.org/10.1007/978-3-540-74671-3.
Larsson, R. 2008. Jords egenskaper. Statens geotekniska institut. Linköping.
Lindberg Skutsjö, L., 2021: Geologiska och hydrogeologiska tolkningar av SkyTEM-data från Vombsänkan, Sjöbo kommun, Skåne. Examensarbete i geologi vid Lunds universitet, 25 s.
Loke, M., Barker, R.D., 1996. Rapid Least-Squares Inversion of Apparent Resistivity Pseudosections Using a Quasi-Newton Method. Geophys. Prospect. 44, 131–152. https://doi.org/10.1111/j.1365-2478.1996.tb00142.x.
Nivorlis, A., 2023. Advances in time-domain induced polarization monitoring with application on chlorinated solvents contamination: Towards scalable real-time geophysical monitoring. Engineering Geology, Lund University. Examensarbete i geologi vid Lunds universitet, 72p.
Palacky, G.V. (1987), Resistivity characteristics of geologic targets, in Electromagnetic Methods in Applied Geophysics, Vol 1, Theory, 1351.
Rodhe, A., Lindström, G., Rosberg, J. & Pers, C., 2006. Grundvattenbildning i svenska typjordar - översiktlig beräkning med en vattenbalansmodell. Institutionen för Geovetenskaper, Uppsala universitet, Uppsala Report (ISSN).
Stroeven, A. P., Hättestrand, C., Kleman J., Heyman J., Fabel D., Fredin O., Goodfellow B. W., Harbor J. M., Jansen J. D., Olsen L., Cirkaffee M. W., Fink D., Lundqvist J., Rosqvist G. C., Stömberg B. & Jansson K. N., 2016: Deglaciation of Fennoscirkandia. Quaternary Science Reviews 147, 91–121.
Tsourlos, P.I., Ogilvy, R.D., 1999. An algorithm for the 3-D inversion of tomographic resistivity and induced

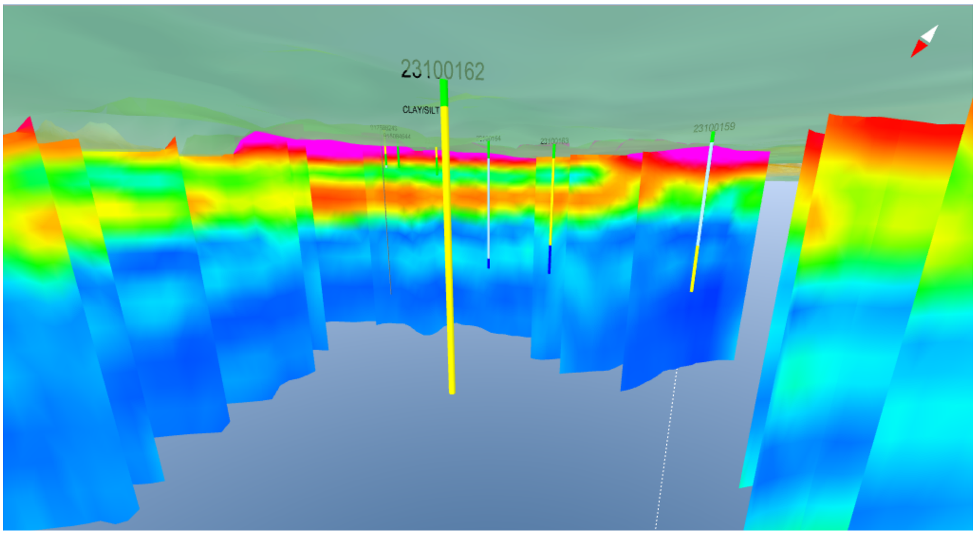
polarisation data: Preliminary results. J. Balk. Geophys. Soc. 2, 30–45.

Whitehead, P. G.; Wilby, R. L.; Battarbee, R. W.; Kernan, M.; Wade, A. J., 2009: A review of the potential impacts of climate change on surface water quality. Hydrological Sciences Journal. 54 (1):101–123. doi:10.1623/hysj.54.1.101. ISSN 0262-6667.

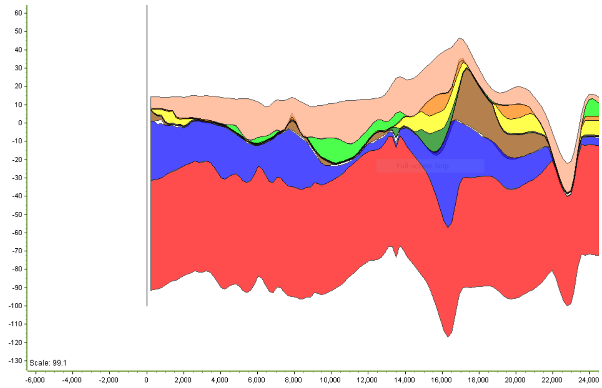
10. Appendix



Appendix 1. Stratigraphy of the sedimentary bedrock in Revinge and Fårap (Erlström et al. 2004).



Appendix 2. The 3D view of the SkyTEM geophysical models at Vombverket, visualized in Geoscene 3D.



Appendix 3. A profile at the beginning of the modelling process illustrating the position of the surfaces and the layers after the grid adjustment. The profile has not been used for the interpretation since it failed to follow the lithology of the wells. The problem is solved after the manual interpretation and inserting the interpretation points. Grid adjustment is a time-consuming process that often require several attempts to create a realistic model.

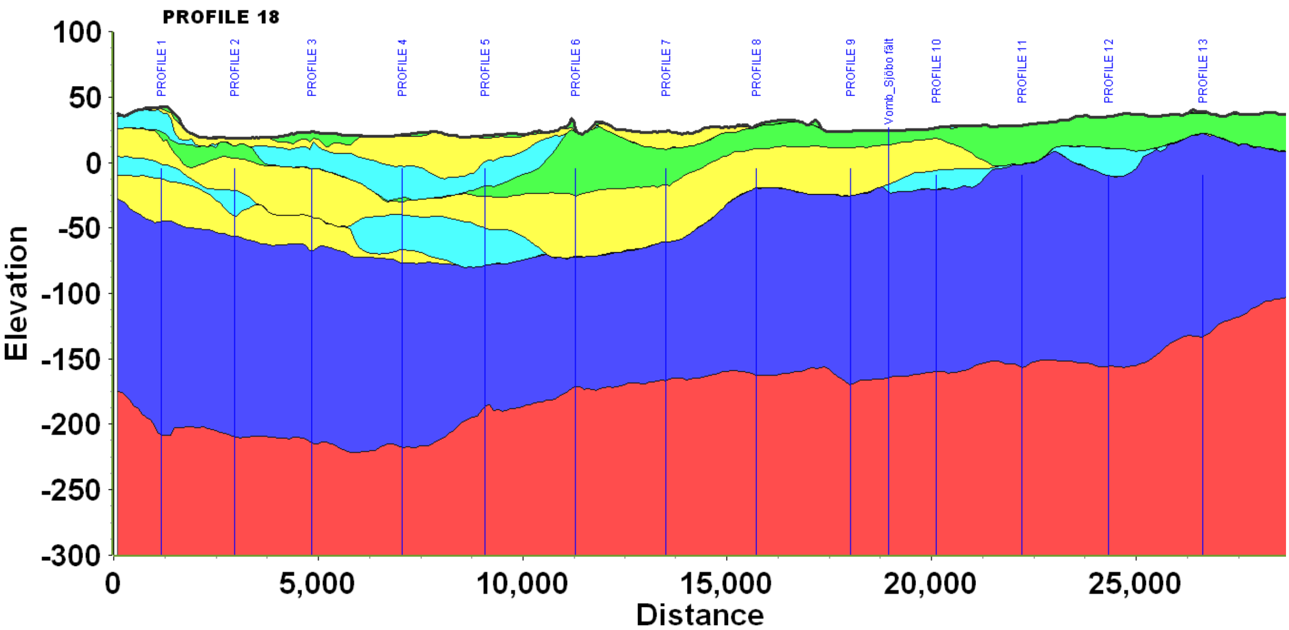
Appendix 4. Inversion settings

Initial damping factor (0.01 to 1.00)
0.1500
Minimum damping factor (0.001 to 0.75)
0.0200
Local optimization option (0=No, 1=Yes)
1
Convergence limit for relative change in RMS error in percent (0.1 to 20)
1.0000
Minimum change in RMS error for line search in percent (0.5 to 100)
0.5000
Number of iterations (1 to 30)
20
Vertical to horizontal flatness filter ratio (0.25 to 4.0)
0.2500
Model for increase in thickness of layers(0=default 10%, 1=default 25%, 2=user defined)

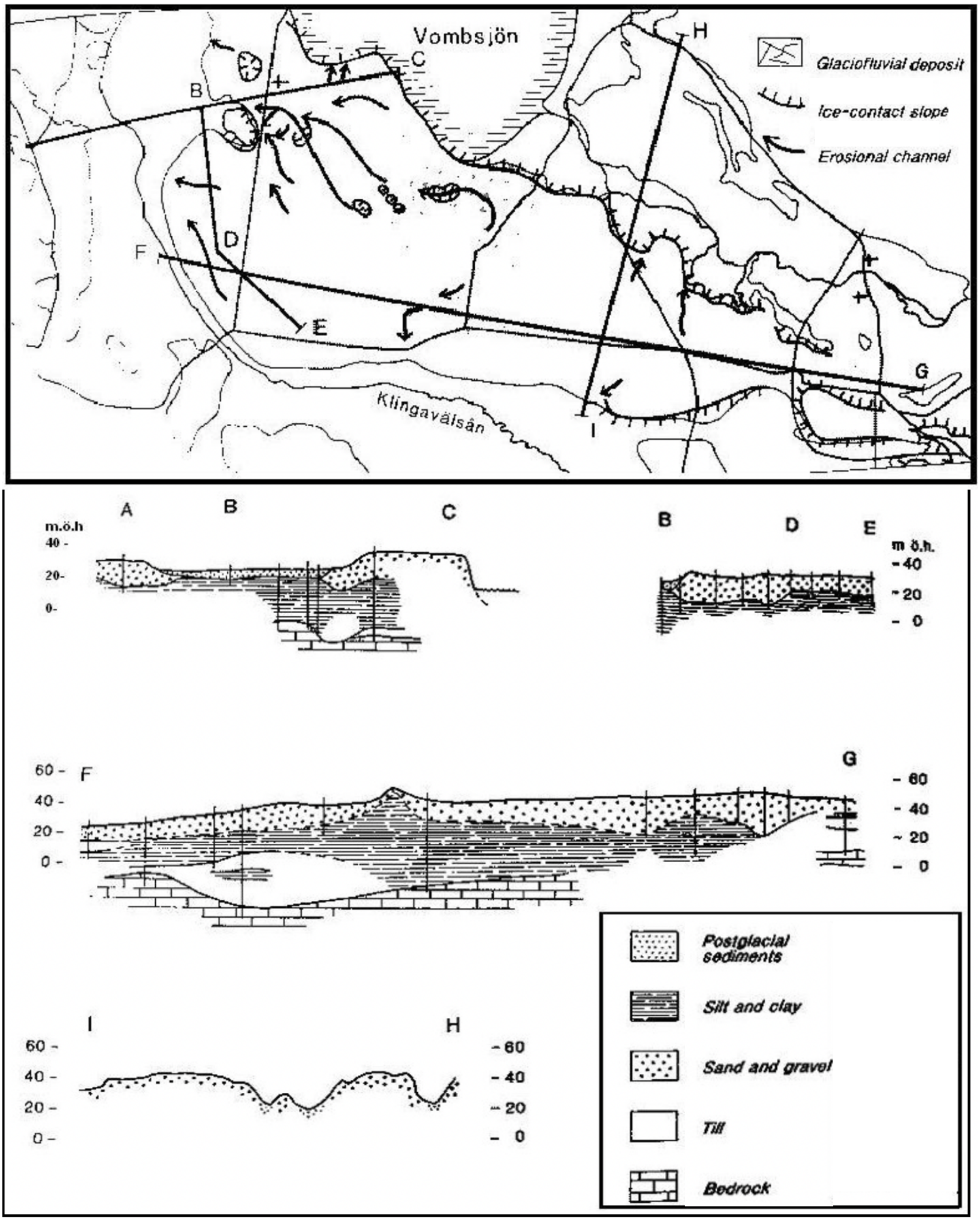
2
Number of nodes between adjacent electrodes (2 or 4)
4
Flatness filter type, Include smoothing of model resistivity (0=model changes only,1=directly on model)
1
Reduce number of topographical data points? (0=No,1=Yes. Recommend leave at 0)
0
Carry out topography modeling? (0=No,1=Yes)
1
Type of topography trend removal (0=Average,1=Least-squares,2=End to end)
0
Type of Jacobian matrix calculation (0=Quasi-Newton, 1=Gauss-Newton, 2=Mixed)
1
Increase of damping factor with depth (1.0 to 2.0)
1.0000
Type of topographical modeling (0=None, 1=No longer supported so do not use, 2=uniform distorted FEM, 3=underwater, 4=damped FEM, 5=FEM with inverse Swartz-Christoffel)
4
Robust data constrain? (0=No, 1=Yes)
1
Cutoff factor for data constrain (0.0001 to 0.1))
0.0500
Robust model constrain? (0=No, 1=Yes)
1
Cutoff factor for model constrain (0.0001 to 1.0)
0.0050
Allow number of model parameters to exceed data points? (0=No, 1=Yes)
1
Use extended model? (0=No, 1=Yes)
1
Reduce effect of side blocks? (0=No, 1=Slight, 2=Severe, 3=Very Severe)
1
Type of mesh (0=Normal,1=Fine,2=Finest)
2
Optimise damping factor? (0=No, 1=Yes)
1
Time-lapse inversion constrain (0=None,1&2=Smooth,3=Robust)
3
Type of time-lapse inversion method (0=Simultaneous,1=Sequential)
0
Thickness of first layer (0.25 to 1.0)
0.5000
Factor to increase thickness layer with depth (1.0 to 1.25)
1.1000
USE FINITE ELEMENT METHOD (YES=1,NO=0)
1
WIDTH OF BLOCKS (1=NORMAL WIDTH, 2=DOUBLE, 3=TRIPLE, 4=QUADRAPLE, 5=QUINTIPLE)
1
MAKE SURE BLOCKS HAVE THE SAME WIDTH (YES=1,NO=0)
1
RMS CONVERGENCE LIMIT (IN PERCENT)

0.100
USE LOGARITHM OF APPARENT RESISTIVITY (0=USE LOG OF APPARENT RESISTIVITY, 1=USE RESISTANCE VALUES, 2=USE APPARENT RESISTIVITY)
0
TYPE OF IP INVERSION METHOD (0=CONCURRENT,1=SEQUENTIAL)
0
PROCEED AUTOMATICALLY FOR SEQUENTIAL METHOD (1=YES,0=NO)
0
IP DAMPING FACTOR (0.01 to 1.0)
1.000
USE AUTOMATIC IP DAMPING FACTOR (YES=1,NO=0)
0
TYPE OF CROSS-BOREHOLE MODEL (0=normal,1=halfsize)
0
LIMIT RESISTIVITY VALUES(0=No,1=Yes)
0
Upper limit factor (10-50)
50.000
Lower limit factor (0.02 to 0.1)
0.020
Type of reference resistivity (0=average,1=first iteration)
0
Model refinement (1.0=Normal,0.5=Half-width cells)
0.50
Combined Combined Marquardt and Occam inversion (0=Not used,1=used)
0
Type of optimisation method (0=Gauss-Newton,2=Incomplete GN)
2
Convergence limit for Incomplete Gauss-Newton method (0.005 to 0.05)
0.005
Use data compression with Incomplete Gauss-Newton (0=No,1=Yes)
0
Use reference model in inversion (0=No,1=Yes)
1
Damping factor for reference model (0.0 to 0.3)
0.01000
Use fast method to calculate Jacobian matrix. (0=No,1=Yes)
0
Extra damping factor for first layer (1.0 to 100.0)
5.00000
Type of finite-element method (0=Triangular,1=Trapezoidal elements)
1
Factor to increase model depth range (1.0 to 5.0)
1.050
Factor to control the degree variations near the boreholes are reduced (2 to 100)
5.0
Factor to control variation of borehole damping factor with distance (0.5 to 5.0)
1.0
Floating electrodes survey inversion method (0=use fixed water layer, 1=Incorporate water layer into the model)
1
Resistivity variation within water layer (0=allow resistivity to vary freely,1=minimise variation)
1

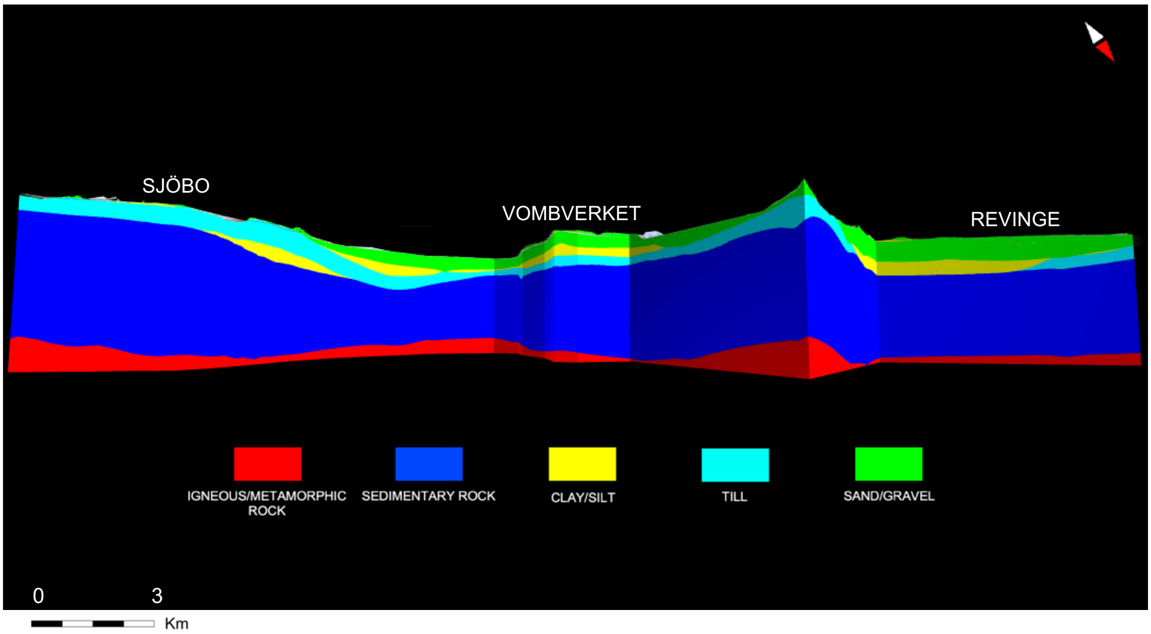
Use sparse inversion method for very long survey lines (0=No, 1=Yes)
0
Optimize Jacobian matrix calculation (0=No, 1=Yes)
0
Force resistance value to be consistant with the geometric factor (0=No, 1=Yes)
0
Shift the electrodes to round up positions of electrodes (0=No, 1=Yes)
0
Use difference of measurements in time-lapse inversion (0=No,1=Yes)
0
Use active constraint balancing (0=No,1=Yes)
0
Type of active constraints (0=Normal,1=Reverse)
0
Lower damping factor limit for active constraints
0.4000
Upper damping factor limit for active constraints
2.5000
Water resistivity variation damping factor
8.0000
Use automatic calculation for change of damping factor with depth (0=No,1=Yes)
0



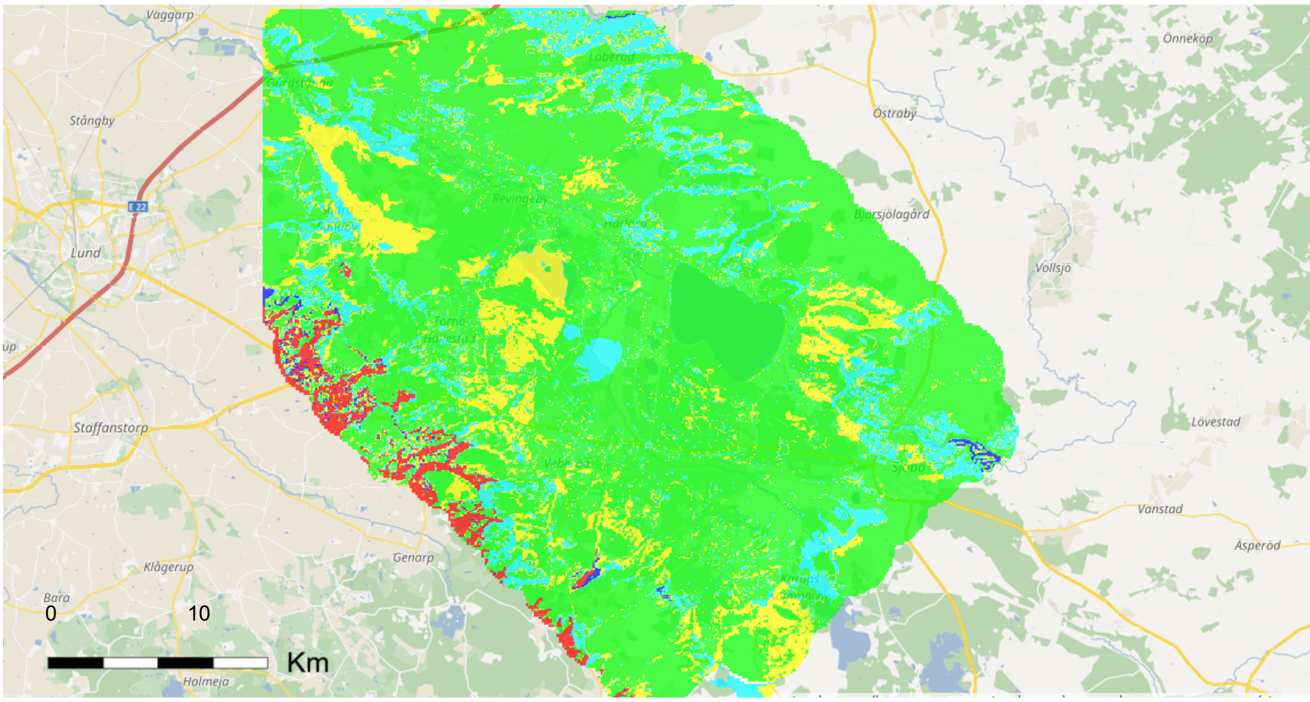
Appendix 5. The crosscutting profiles along profile 18. The geology of the crosscutting profiles is beneficial for estimation of the stratigraphy of the areas where there are no adjacent boreholes.



Appendix 6. The geological cross sections along Vomb-Sjöbo South of Vombsjön (Daniel 1992).



Appendix 7. A 3D section of the northern part of Vombsänkan, illustrating the geology of Sjöbo, Vombverket and Revinge.



Appendix 8. The surface model results shown with a depth increment of 0.5 m.

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