A contribution to the knowledge of Fårö's hydrogeology

Henric Thulin Olander

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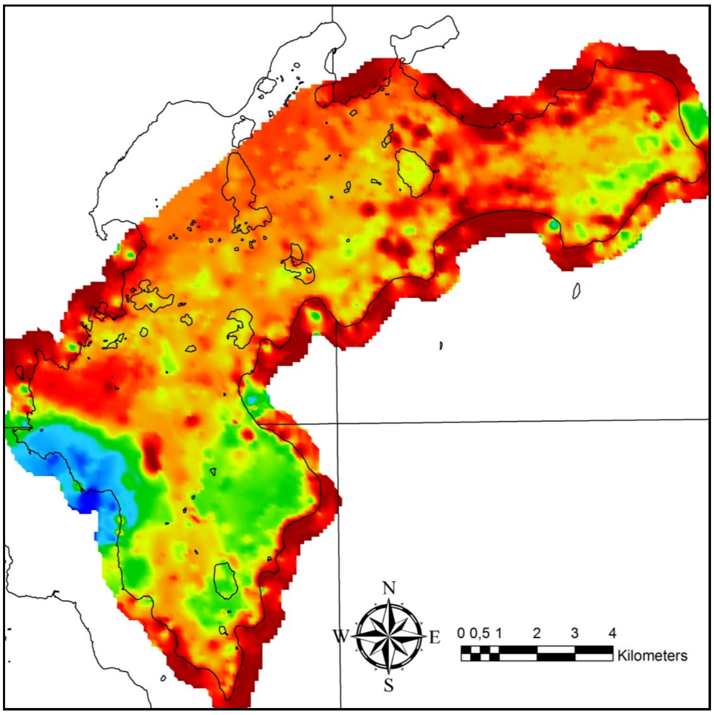

Department of Geology
Lund University
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Cover Picture: Illustration of depth towards the first good electric conductor of Fårö by Henric Thulin Olander.

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Abstract: Fårö, Sweden´s ninth largest island, is suffering from poor groundwater management. A rampant development within tourism on Fårö to uphold its socioeconomic status has led to insufficient water quality and quantity in the municipal water supply. In order to support the progress of Fårö´s water supply, a contribution to the knowledge of its hydrogeology is presented.

Recent evolution in airborne geophysics has culminated in SkyTEM, a helicopter electromagnetic system specifically developed for hydrogeological surveys. For the first time after an initial pilot study, the SkyTEM system is used on a large scale in Sweden. Four areas on Gotland were investigated by the Geological Survey of Sweden, SGU, and one of these areas was Fårö. By combining data collected with SkyTEM with previously collected data and also newly acquired field measurements, new light has been shed upon Fårö´s hydrogeology. The results reveal promising potential and two previously unexploited areas on Fårö have been highlighted to have favorable hydrogeological conditions. Both areas are currently used only for private water supply and have sizes of 2 and 20 km^2 respectively. Additionally, the boundary between fresh and saline groundwater is discussed and an updated interpretation following the work of Tullström (1954) is presented.

Keywords: Fårö, Gotland, groundwater, water supply, Silurian, hydrogeology, SkyTEM, RMT, geophysics

Supervisors: Charlotte Sparrenbom - Lund University, Peter Dahlqvist - Geological Survey of Sweden and Torleif Dahlin - Lund University

Subject: Quaternary geology (Hydrogeology)

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Ett bidrag till kunskapen om Fårös hydrogeologi

HENRIC THULIN OLANDER

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Sammanfattning: Sveriges nionde största ö, Fårö, lider av bristfällig hantering av sitt grundvatten. En okontrollerad ökning av turism till Fårö har tillåtits ske för att upprätthålla dess socioekonomiska status. Till en följd av detta råder för närvarande en brist på dricksvatten av god kvalite. Som ett stöd till utvecklingen av Fårös dricksvattenförsörjning presenteras här ett bidrag till kunskapen om Fårös hydrogeologi. Ny utveckling inom karteringsmetodik av grundvattenförekomster har kulminerat i helikopterburen geofysik. Ett sådant system är SkyTEM, specifikt utvecklat för grundvattenundersökningar, som använts av Sveriges Geologiska Undersökning, SGU, för att samla in geofysisk data från fyra områden över Gotland. Ett av dessa områden är Fårö, där datan kombinerats med tidigare insamlat material och nyligen insamlade data ifrån fältundersökningar för att skapa ett nytt kartunderlag över Fårös grundvattentillgångar. Resultaten avslöjar två hydrogeologiskt lovande områden som är sedan tidigare outnyttjade och används närvarande enbart för enskild vattenförsörjning. Områdena har en respektive storlek på 2 och 20 km^2. Dessutom presenteras en uppdaterad tolkning av gränsen mellan färskt och salint grundvatten baserat på den nyinsamlade informationen ifrån undersökningarna.

Nyckelord: Fårö, Gotland, silur, hydrogeologi, grundvatten, dricksvattenförsörjning, geofysik, SkyTEM, RMT

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1 Introduction

1.1 Background

Hydrogeological mapping should be the foundation of every nation’s drinking water management. Without a national mapping programme of groundwater, inhabitants in rural areas with no access to surface water would be left with empirical methods to find a suitable source of drinking water. Without access to the basic knowledge of an area´s hydrogeological properties, a heavy burden is placed upon the individual to find and establish a source of drinking water. An area where population is dense compared to the availability of groundwater is especially sensitive to this approach and problems caused by unregulated use and unsustainable overuse of groundwater might arise as a consequence (Giordano 2009). One important reason to map groundwater resources are to ensure their protection. To secure future groundwater extraction from quality complications, a groundwater map can be used in a risk assessment to determine possible threats to groundwater quality. Frequently occurring risks are saltwater intrusion, various naturally occurring contaminants, overuse, changes in the natural conditions and anthropogenic contaminants from land use.

The densest populated areas of Europe overlap with areas dominated by major groundwater basins, see Fig. 1 (BGR & UNESCO 2008). In a national perspective, extensive aquifers are rare in Sweden and in most parts of the country only shallow aquifers are used for regional drinking water suppliance. The exeptions are Scania and the islands of Öland and Gotland, which are made up of sedimentary bedrock. This leads to special demands to manage the groundwater resources of Sweden compared to the rest of Europe. At a national scale it leads to special demands to manage the groundwater resources of Scania, Öland and Gotland compared to the remainder of Sweden.

This thesis aims to map the groundwater of Fårö, a 109 km^2 large island north east of the main island of Gotland. The method primarily used, airborne transient electromagnetic groundwater exploration, is for the first time used on a large scale in Sweden after an initial test by the Geological Survey of Sweden, SGU (Dahlquist *et al*. 2012). Fårö is an island without surface water suitable as drinking water and is currently suffering from lack of knowledge and guidelines for the use of groundwater. During summer, when demands rise due to an inflow of tourism, problems with

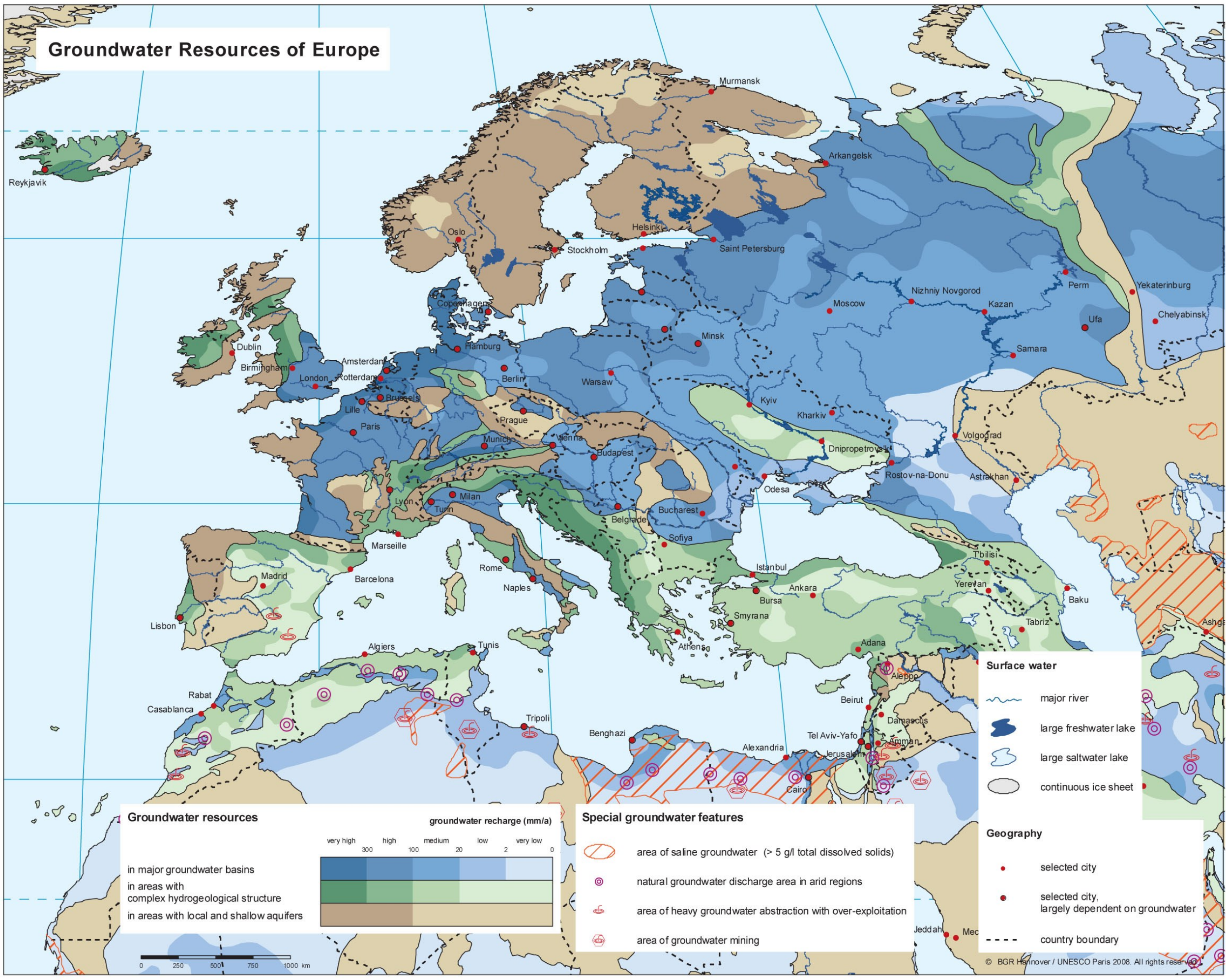

Figure 1. An overview of Europes groundwater reservoirs, a continent dominated by major groundwater basins. Note that Sweden is mostly covered by shallow aquifers. Figure used with permission by (BGR & UNESCO 2008)

quality and quantity increase. Every year, over 300 000 visitors make the trip across Fårösund to Fårö and tremendous pressure is put open the water supply (Region Gotland 2014). As a result, drinking water demands are temporarily sustained by water transports by car from the main island for a majority of the summer (Region Gotland 2014).

1.2 Previous work

Geological mapping of Fårö done by the Geological survey of Sweden, SGU, date back to 1936 when Munthe *et al*. (1936) published a combined geological map over the soil and bedrock of Fårö. Previous hydrogeological mapping done by SGU covering Fårö also include the work by Karlqvist *et al*. (1982) and a new version is currently in the process of development.

In a land-use plan by Region Gotland (2014) a risk assessment map for the groundwater of Fårö is published. The study concludes that the majority of Fårö is mapped to belong to the highest vulnerability category on a scale from 1 (high) to 5 (low) due to a thin or non-existing soil cover. In the report, a compilation of potential contaminated sites is also presented.

A survey by Miljö- och hälsoskyddsnämnden Gotlands kommun (2010) concludes that groundwater aquifers on Gotland are in general very sensitive to contamination and respond quickly to rapid changes.

The environment and public health committee of Gotland measures groundwater quality of 100 randomly selected wells used for private water supply in a survey called the 100-survey every 5 years (Karlsson 1996). The survey aims to determine the extent of groundwater quality problems in private wells over time and has been executed in the years 1990, 1996, 2000, 2005 and 2010. Three wells have been tested on Fårö every time the survey has been conducted.

According to Vangkilde-Pedersen *et al*. (2011), regular problems threatening water quality in limestone aquifers are naturally occurring contaminants such as fluoride, strontium, arsenic and nickel. Unfortunately the 100-survey does not include these elements, but in the 2010 survey 50 wells across Gotland were sampled for boron. Although there is no concentration limit for boron in private wells, 33 out of 50 wells had values of boron higher than 1 mg/l, which is the limit for boron in public water supply in Sweden (Livsmedelsverket 2001).

Oljeprospektering AB, OPAB, conducted hydrocarbon exploration on Fårö during the early 1980´s. Data from the exploration are extensive and include several surveys, such as seismic surveys and well drillings, on Fårö (Varadi 1982). However as hydrocarbons were the primary target, relevant hydrogeological data from the exploration on Fårö is sparse.

1.3 Aim

As previous work points out that groundwater resources are scarce and vulnerable on Fårö, new light needs to be shed on the hydrogeology of Fårö due to increasing demands. The working hypothesis for this thesis is that unmapped aquifers exist on Fårö. In order to increase the knowledge of the hydrogeological properties of Fårö this thesis aims to map the groundwater of Fårö in a joint project between the national geological survey and Lund university. By mapping the hydrogeological properties of Fårö the aim is to contribute to the public knowledge and enable easier groundwater management for the region of Gotland. Specific aims are:

- Identify and delimit aquifers on Fårö
- Quantify relative possible extraction of groundwater for the identified aquifers
- Compile a risk assessment for the groundwater of Fårö

1.4 Location

Fårö is situated northeast of the main island of Gotland at 57° 56´ N and 19° 9´ E (WGS 84), see Fig. 2. The island has a size of 109 km^2 and a population of 551 permanent inhabitants. However, due to its popularity during the summer months it is estimated that the population peak at 10 000 during summer (Region Gotland 2014). Fårö is situated in a temperate climate with an average annual precipitation of 508.7 mm (Sveriges meteorologiska och hydrologiska institut 2014), see Fig. 3. Topography is gently undulating and the highest point is approximately 27 meters above sea level.

2 Geological setting

Several classification schemes exist for the stratigraphy of Gotland. As the hydrogeological properties of bedrock are closely related to its physical properties, the most useful stratigraphic classification to use in this hydrogeological work is a classification based on lithology. Such a classification for Gotland has been established by Erlström *et al*. (2009) and the following chapter is heavily based on their work. See Fig. 4 for a map of the bedrock of Fårö.

The island of Fårö consists of sedimentary bedrock of Cambrian to Silurian age, deposited on top of Precambrian granite at a depth of 250-450 meters below sea level. Knowledge about the Precambrian, Cambrian and Ordovician bedrock has been derived from oil prospecting performed in the 1980's (Varadi 1982). A tectonic zone is found in the Cambrian bedrock running in a north northwestern direction between the main island of Gotland and Fårö. This tectonic zone originates from Cambrian subduction and has led to large variations in the thickness of the Cambrian bedrock on Fårö with a spread between 60 – 175 meters. The Cambrian bedrock is built up of interlayering siltstone, shale and sandstone and its stratigraphy is known only from borings.

Ordovicium is represented on Fårö by three units with a total thickness of 90 – 100 meters. No outcrops are present. The lowermost unit is an argil-

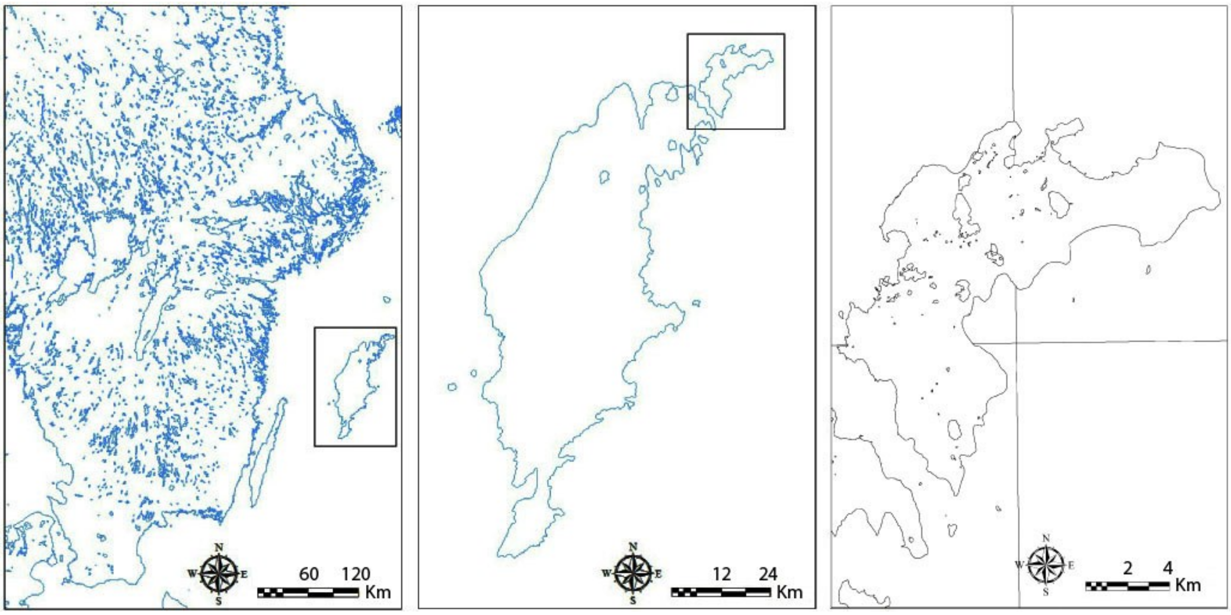

Figure 2. Fårö is located northeast of the main island of Gotland at 57° 56´ N and 19° 9´ E (WGS 84). Map constructed from data by © Sveriges geologiska undersökning.

laceous limestone and is 30 – 50 meters thick, the middle Ordovician unit is a 2 – 10 meter thick unit of claystone and shale and the uppermost Ordovician unit is a 25 – 75 meter thick limestone unit, Fig. 5.

Of greatest interest from a hydrogeological point of view is the Silurian bedrock as it is therein the majority of the fresh groundwater on Fårö is found. Reports from the oil prospecting on Fårö unfortunately do not contain thorough information about the physical properties of the Silurian bedrock, but the lateral distribution of bedrock at the surface is well known from Erlström *et al*. (2009). Outcrops of Silurian bedrock are dominating the ground of the entire island except for the peninsula of Avanäs in the east where there are widespread quaternary deposits, varying greatly in thickness of up to over 15 m according to the national well archive. The Silurian strata are approximately 200 meters and has a complex stratigraphy, generally with a higher clay content at depth compared to the shallower limestone lithology. Identified rock types on Fårö, in no specific order, from outcrops by Erlström *et al*. (2009) are:

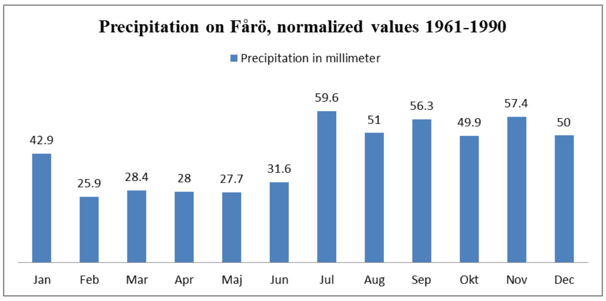

Figure 3. Precipitation on Fårö, normalised values 1961-1990. Original data are from Sveriges Meterologiska och Hydrologiska Institut (2014).

- Coarse crystalline limestone and argillaceous medium crystalline limestone (calcarenite)
- Marlstone and marl
- Medium crystalline limestone (calcarenite) and marlstone
- Reef limestone and stromatoporid limestone
- Medium crystalline limestone (calcarenite) with scattered beds of stromatoporoid limestone

See Fig. 4 for the distribution of the above mentioned rock types.

Quaternary sediments on Fårö are largely of post glacial age. After reworking and redeposition by wave - and wind processes the dominating sediments are made up of shingle beach deposits, reworked gravel, postglacial sand and aeolian sand (Svantesson 2008). Only minor areas are covered by till deposits from the Weichsel ice sheet and the island has been heavily influensed by the complex geological history of the Baltic sea during the Holocene (Björck 1995). However, quaternary deposits are in some areas covered by younger sediments (Svantesson 2008). As previously mentioned the peninsula of Avanäs, located on eastern Fårö, is the area with the greatest extent of quaternary sediment cover. Aeolian dunes cover most of the peninsula and were described as early as 1745 by Linnaeus (1745). The largest dunes rise approximately 15 meters above their surroundings, indicating that large sediment thicknesses can be found. Svantesson (2008) describes that primary deposited glaciofluvial sediments are found beneath some dune covered areas on Avanäs; this interpretation is based on marine surveys by Elhammer *et al*. (1986).

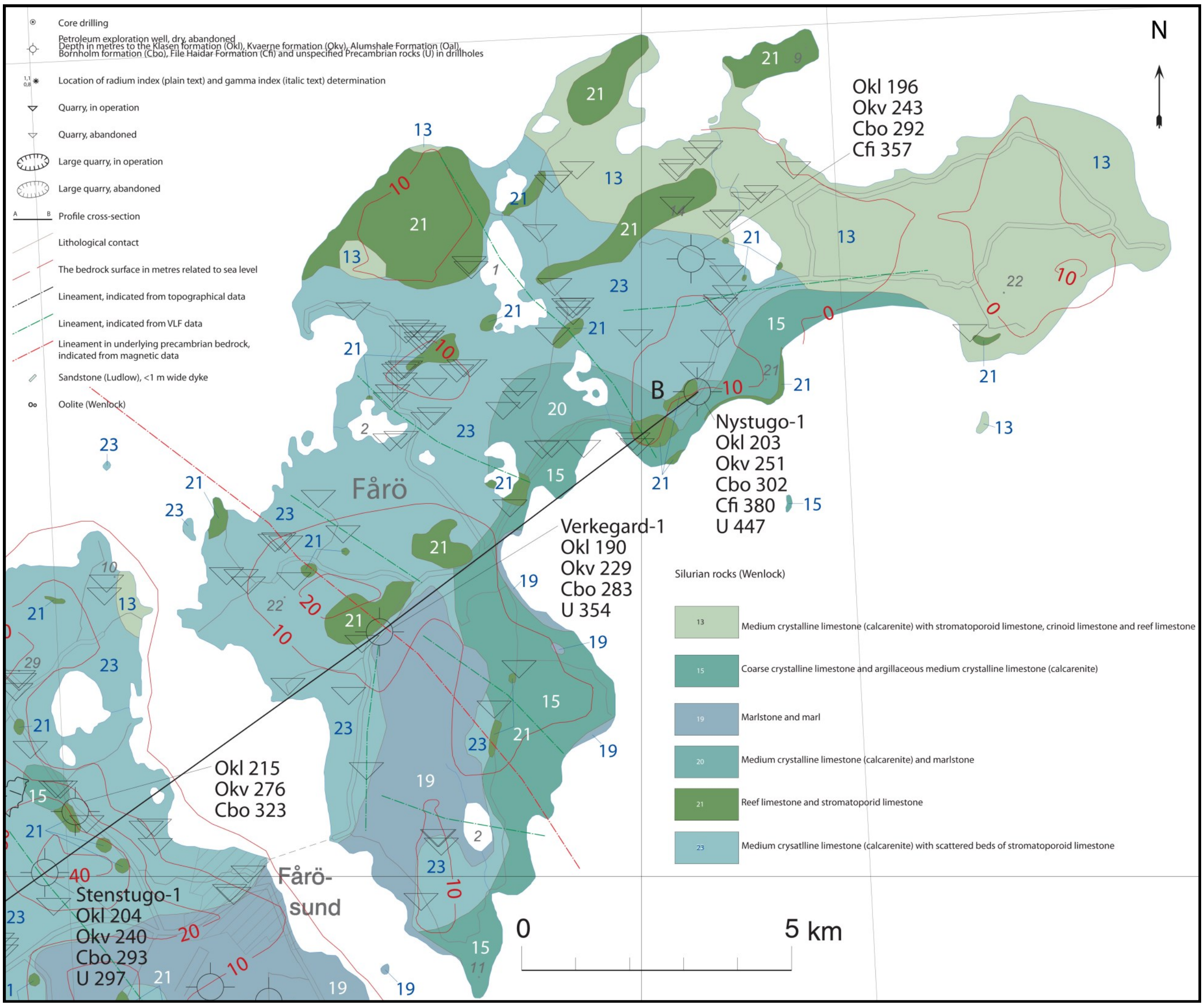

Figure 4. Bedrock map of Fårö, modified from Erlström *et al.* (2009).

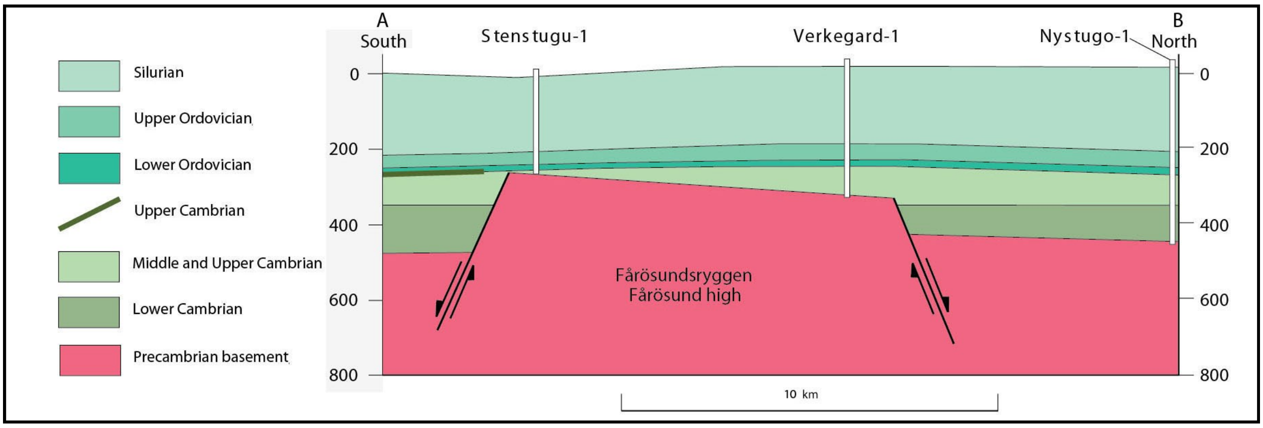

Figure 5. Transect of Fårö and Fårösund's bedrock. See Fig. 4 for orientation. Note that the resolution is too low to display the middle Ordovician unit. Modified from Erlström *et al.* (2009).

3 Method

When deciding which method to use to map a region's hydrogeological properties, the geological setting is the most deciding factor. Since groundwater in Sweden usually is extracted from shallow aquifers in quaternary deposits, the methods used to map an ordinary aquifer in Sweden can't be applied for the bedrock of Fårö. Whatever method used it is always of great importance to collect dense spatial information in order to construct a reliable hydrogeological model.

Worldwide, countries have taken contrasting paths to establish their drinking water suppliances. In Sweden, approximately 50 % of drinking water is supplied from surface water and 25 % from groundwater and 25% from artificially infiltrated groundwater. Among the extreme examples, Denmark and Hong Kong are worth mentioning. Denmark's water supply is based 99,4 % on groundwater and Hong Kong's is 100 % based on surface water (Wong *et al*. 2010). Set in totally different geological settings, Denmark is situated on sedimentary bedrock and Hong Kong is dominated by granite bedrock, it is understandable that these countries have chosen unique solutions. Understanding the importance of adapting to the geological situation is a key to success in hydrogeological mapping and with a resemblance in geology between Denmark and Fårö, Danish groundwater mapping methods have served as a source of inspiration for this thesis.

3.1 Hydrogeological conceptual model

Mapping the hydrogeology of a limestone island requires an approach different than the one regularly used by the SGU to map open aquifers in Quaternary settings, even though the aim of the mapping is the same; to determine the hydrogeological properties of an area. The reason for this is the complexity of groundwater transport in a limestone aquifer. In a porous media e.g. glaciofluvial sediments the main groundwater flow is through the effective porosity of the sediment. In a limestone aquifer on the other hand, the media has multi-scale heterogeneities leading to complex hydrogeological properties and groundwater flow is not only determined by a single or dual porosity but also by fractures and conduits through the bedrock. So, when mapping aquifers in these two separate environments, the primary variable determining the hydrogeological properties is deviating and thus requiring various approaches.

As seen in the bedrock map of Fårö, Fig. 4, the island has a heterogeneous structure at the surface and this can also be expected for the subsurface. Such a heterogeneous environment creates problems when building hydrogeological models because of its complexity: individual layers can differ greatly in permeability, fracture tendencies can shift between layers and geochemistry might vary, posing quality differences etc. When modeling the hydrogeology of such an environment it's therefore necessary to have a solid foundation with information about layer distribution and properties, reef structures, fracture orientation and fracture zones.

In order to establish new knowledge of the hydrogeological properties of Fårö the goal of this thesis is to produce a 2D map of Fårö showing the extraction potential of groundwater from Fårö´s bedrock. The map is based on previous work as well as new unpublished data. During the author´s workflow a conceptual model of the hydrogeology of a limestone island has been developed and used, Fig. 6. The model is used as a backbone when interpreting data and drawing conclusions.

3.1.1 Hydraulic properties

The heterogeneity of limestone aquifers poses the greatest problem when mapping them. Hydraulic conductivities can vary on a scale of several magnitudes within the same units (Atkinson 1977). Hydraulic properties in limestone aquifers are directly related to variables such as effective porosity and frequency and properties of fractures and conduits.

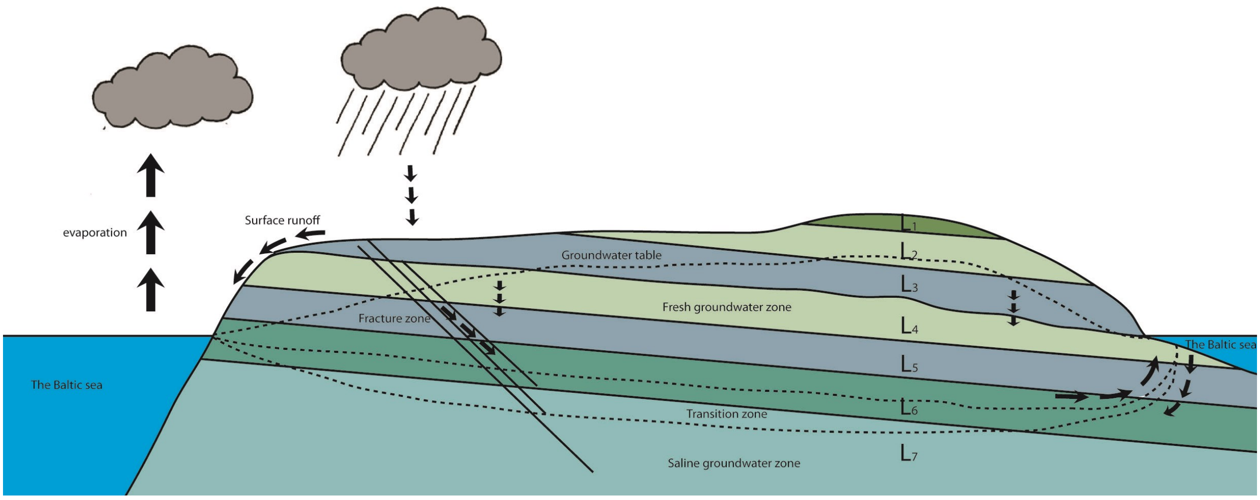

Figure 6. Conceptual model of a sedimentary island´s hydrogeological cycle. The model was given an arbitrary amount of bedrock layers L_n, represented in the figure by individual colors.

3.1.1.1 Hydraulic conductivity of fractures

The hydraulic conductivity of limestone can vary greatly as a factor of its homogeneity and in most limestone aquifers groundwater flow is primarily conducted through fractures (Gunn *et al.* 2006). As a result, large contrasts in a limestone aquifer can exist within close proximity. To visualize the importance of a single fracture or a fracture zone for the absolute hydraulic conductivity of limestone aquifers it is important to understand the physic theory behind fluid flow in fractures. Flow of fluids in fractures is discussed thoroughly in Bear (1972), Witherspoon *et al.* (1980) and Zimmerman & Bodvarsson (1996). In accordance to their work, the simplest approximation for flow in a fracture is laminar flow between two parallel plates. The transmissivity of such a fracture is in proportion to the cube of the size of the fracture (Christiansen *et al.* 2009), eq. I.

$$T_f = \frac{\rho g (h)^3}{12\mu} \qquad \textit{(Eq. I)}$$

Where T_f is the fracture's transmissivity, ρ is the density of water, g is the earth's gravitational acceleration, h is the aperture of the fracture and μ is the dynamic viscosity of water. At a constant temperature:

$$T_f = C(h)^3 \qquad \textit{(Eq.II)}$$

Where C is a constant, this gives

$$T_f \propto h^3 \qquad \textit{(Eq.III)}$$

For this theoretical approximation of a fracture, the transmissivity will increase very rapidly with increasing aperture of the fracture according to Eq. I, as can be seen in table 1. Even though only an approximation, it is noteworthy that the contribution from a seemingly small fracture to a rock's hydraulic properties may be significant.

The genesis of fractures could also affect their hydraulic conductivity. In a study by Audouin *et al.* (2008) performed in a limestone setting, 32 boreholes were logged and investigated. 390 fractures were identified in the boreholes and only 11 of those were found to be active ground water conductors. The authors conclude that the genesis of the fractures influenced the conductivity; fractures with compressional genesis were active to a lesser degree compared to fractures of tensional genesis.

In a study by Klitten & Steen Wittrup (2006) 134 borings were logged and investigated on northeastern Zealand, Denmark. One of the aims of the study was to highlight the distribution of groundwater inflow from horizontal and sub-horizontal fractures. The study concluded that regional groundwater conducting fractures are rare and only one regional fracture was identified over the distance of several kilometers.

Consequently not only the aperture or frequency of fractures affects their impact on the hydrogeology but also the genesis and lateral extent of these fractures.

Table 1. Size of fractures between two parallel plates required to achieve the given transmissivities. Calculated from Eq. II with C = 626 * 103 at a water temperature of 10 °C.

Aperture of fracture (m)	**Transmissivity (m/s^2)**
$5.43*10^{-5}$	10^{-7}
$1.17*10^{-4}$	10^{-6}
$2.52*10^{-4}$	10^{-5}
$5.43*10^{-4}$	10^{-4}
$1.17*10^{-3}$	10^{-3}
$2.52*10^{-3}$	10^{-2}
$5.43*10^{-3}$	10^{-1}

3.1.1.2 Groundwater recharge

Groundwater recharge might vary in time and space for the same aquifer (Lerner *et al.* 1990). The main factors that determine groundwater recharge are: precipitation, evapotranspiration and runoff.

Geological variables that affect groundwater recharge in a limestone area are e.g. thickness of soil cover, grain size distribution of soil cover and the permeability of the limestone. Attributes that will affect groundwater recharge negatively can be a thick low-permeable soil cover such as clay and low permeable horizons in the bedrock such as marlstone. Groundwater recharge in limestone aquifers is largest in areas with heavily fractured bedrock and with a thin and coarse or no soil cover (Vangkilde-Pedersen *et al.* 2011).

3.1.2 Interpretation of resistivity data

Electrical resistivity of various bedrock units has a wide range of values (Telford *et al.* 1976; Loke 1999 and Reynolds 2011). During SGU´s SkyTEM survey of Gotland a table with specific resistivity values of Gotland was developed, see table 2. (Sveriges Geologiska Undersökning, under publication). As bedrock units of Fårö often have a gradual change of lithology (Varadi 1982) it can be problematic to sharply delimit individual units from eachother. As further discussed in chapter 5, interpretation of resistivity data from geophysical surveys were mainly done by using the values of table 2.

3.1.2.1 Saline groundwater

The TEM-methods has high accuracy in delimiting low resistive layers and can therefore with great success be used to determine the saltwater-freshwater boundary (Christiansen *et al.* 2009). In combination with the comprehensive data collected by the municipality in the 100-survey (Karlsson 1996; Gotlands kommun 2000, 2005 and 2010), this creates a solid foundation to determine the depth to the fresh/saline groundwater boundary.

Studies that investigate the boundary between fresh and saline groundwater in geological settings similar to Fårö's include Klitten *et al.* (2006) and Larsen *et al.* (2006). Variables that affect the boundary between fresh and saline groundwater are dilution and diffusion. However, a study by Klitten & Wittrup (2006) concludes that the boundary between fresh and saline groundwater is predominately determined by geological factors and not by the existing fresh groundwater pressure. Low permeable horizons and bedrock boundaries in the Danish bedrock were shown to conform in most cases with the boundary between fresh and saline groundwater. The study also concluded that fault lines could greatly affect the level at where the boundary is found, usually displacing the boundary towards shallower depth.

Saline groundwater is usually from one of two origins, relic or from marine intrusion. Björck *et al.* (2008) points out that sea level during Holocene has been at higher levels than at present and at times covered the majority of Fårö; thus relic salt water can be a viable risk. Intrusion of saline water from the Baltic Sea is also a possibility in coastal areas of continuous overuse of groundwater. Anthropogenic land use can in this way change the natural dynamics and affect the distribution of saline groundwater.

3.1.2.2 Boundary between saline and fresh groundwater

In a fresh water aquifer delimited downwards by saline groundwater, the boundary between the fresh and saline groundwater can be defined as a transition zone, i.e. the boundary is not discrete. Due to diffusion and dilution the boundary thickness may vary greatly but is nonetheless important to quantify. The Geological survey of Denmark and Greenland, GEUS, has developed a methodology that is used in this thesis to interpret the boundary from TEM-data (Vangkilde-Pedersen *et al*. 2011).

A chloride concentration of 100 mg/l in groundwater is used as a national benchmark in Sweden (SGU 2013). In Denmark, which has similar geology to Fårö, a limit of 250 mg/l is applied for drinking water. Another limit that can be used when mapping fresh groundwater is 300 mg/l which is the concentration limit when it is possible to notice the taste of chloride. Since the resistivity of groundwater is dependent on its ion concentration, it is important to choose an appropriate concentration limit when defining the interface between fresh and saline groundwater.

In order to describe the relationship between the resistivity of a given bedrock saturated with pore water and the resistivity of its pore water, Archie´s law can be used (Archie 1942):

$$F = \frac{R_0}{R_w} \qquad \text{(Eq. IV)}$$

Where R_0 is the resistivity of the saturated bedrock, R_w is the pore water resistivity and F is the formation factor. F can also be described by:

$$F = \phi^{-m} \qquad \text{(Eq. V)}$$

Where ϕ is the porosity and m is a constant depending on consolidation ranging between 1.3 for loosely packed unconsolidated sediments and 2 for well consolidated sedimentary rocks (Archie 1942). Thus a low porosity and a high m-value results in a high formation factor.

In order to quantify the boundary between fresh and saline ground water, a formation resistivity must be chosen for interpretation. By using Archie´s law a formation resistivity of 40 ohmm is equal to an aquifer with a formation factor of 4 and chloride concentrations of 300 mg/l in a geological setting like Denmark's. A formation resistivity of 100 ohmm is equal to a chloride concentration of 100 mg/l in the same aquifer (Vangkilde-Petersen *et al*. 2011). By using site -specific measurements on Fårö, a similar calculation is performed to be used to interpret the boundary between fresh and saline groundwater.

Table 2. Table of typical resistivities of Gotland´s geology. Modified with permission from SGU (under publication)

Stratum	**Groundwater environment**	**Resistivity interval (Ohmm)**
Peat, gyttja, clay	Fresh	10-50
Sand, gravel	Above groundwater table	>300
Sand, gravel	Fresh	80-200
Agricultural soil	Fresh	10-50
Till (clayey)	Fresh	30-80
Limestone	Above groundwater table	>1000
Limestone	Fresh	200-1000
Limestone	Saline	10-200
Marl/Marlstone	Fresh	50-200
Marl/Marlstone	Saline	10-80

However, when interpreting results from a model the results will not totally confine with reality. A sharper transition zone will give higher accuracy in TEM measurements when determining the boundary between saline and fresh groundwater. The more diffuse this transition zone is, the weaker the results will be. The sharpness of the transition zone is expressed by its change in conductivity over depth, mS/m^2. The sharpness of the zone will affect how the computed model displays the results. Danish studies have shown that when the transition zone has a conductivity gradient of over 5 mS/m^2, TEM models of the interface will result in one good conductor with a resistivity of 15 ohmm or less and the modeled boundary will be situated approximately 10 m below the top of the transition zone (Vangkilde-Petersen *et al.* 2011). In another study by Poulsen *et al.* (2006), the true displacement of the transition zone was situated 20-30 meters below the top of the modeled boundary. Consequently it is problematic to interpret the displacement of the transition zone only from numerical modeling. In order to find the site specific displacement of the boundary between fresh and saline groundwater on Fårö it is important to calibrate modeled results with site specific borehole measurements.

Poulsen *et al.* (2006) performed a numerical model where the theoretical response from a SkyTEM survey of 13 various geological 1D models were calculated. The results from this calculation are presented in Fig. 7. The study points out that for 1D models with a transition zone with a sharp electrical conductivity gradient, a numerical determination of the boundary between fresh and saline groundwater can be used with success, as the modelled boundary and its true displacement are more or less coherent. However for models with a moderate or sedate gradient, the response will display a more diffuse transition zone and using a numerical value to define the displacement of the boundary between the fresh and saline groundwater will be less favorable.

3.2 Transient electromagnetic (TEM) exploration

Delivering a detailed review of the transient electromagnetic (TEM) method is beyond the scope of this thesis. This chapter should only be considered as an introduction to the method, for deeper knowledge please turn to Ward & Hohmann (1988).

Electromagnetic methods in geological exploration in Sweden date back to the early 1900's; groundbreaking work include Petersson (1907), Bergström (1914) and Nathorst (1919) among others. The primary target of the exploration has historically been mineral deposits. Due to technological development, TEM has also been used for exploration of groundwater since the 1980's (Christiansen *et al*. 2009). During the development of various TEM technologies several setups have

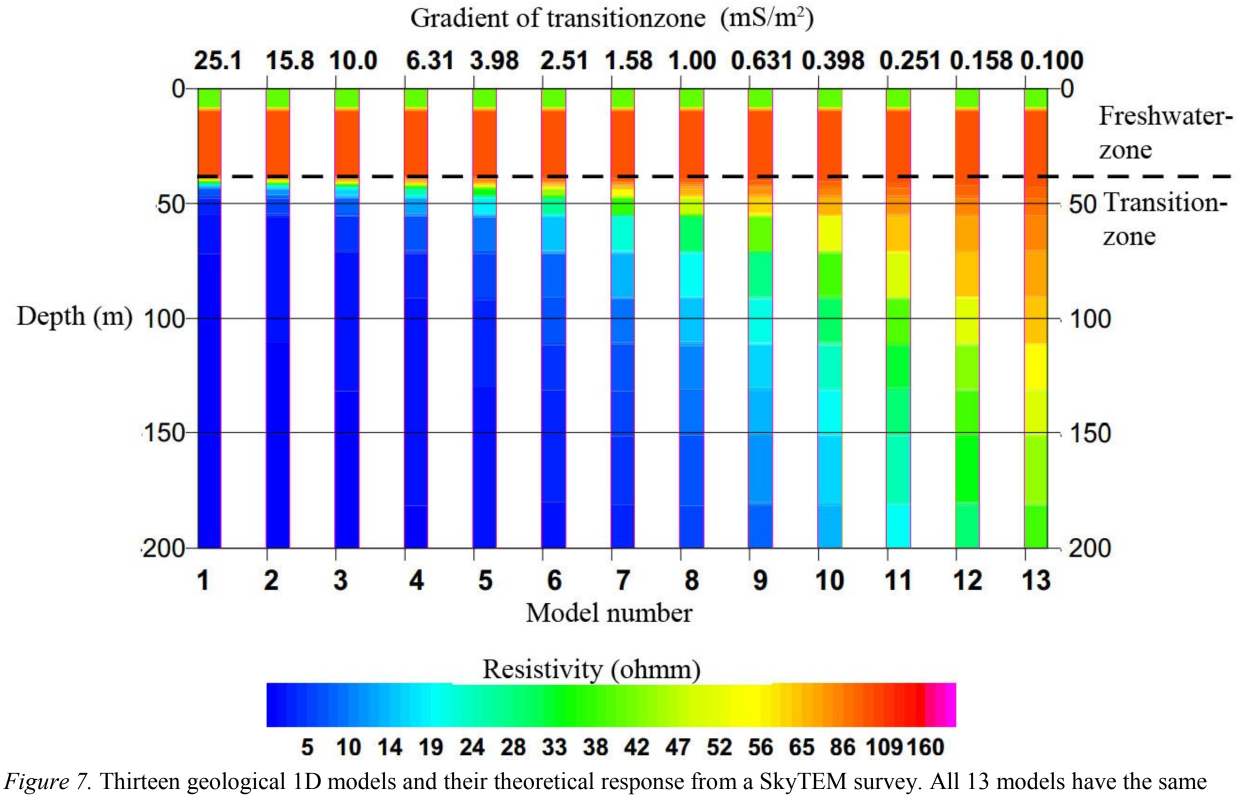

Figure 7. Thirteen geological 1D models and their theoretical response from a SkyTEM survey. All 13 models have the same stratigraphy, from top to bottom: 10 m of clay with 30 ohmm, 30 m of limestone with 100 ohmm, 160 m of limestone saturated with saline groundwater. The top X-axis displays each transition zone´s electrical conductivity gradient. As a conclusion, the displacement of the boundary between fresh and saline groundwater can more easily be determined if the transition zone´s gradient is sharp. Modified from (Poulsen *et al.* 2006).

been used, such as stationary arrays, pulled arrays and airborne arrays. In common for all these arrays are that they are based on the same physical principles of the Maxwell's equations (Maxwell 1863). Just among the airborne systems more than 30 different systems have seen daylight since 1948 (Sørensen & Auken 2004). One of these is SkyTEM, which is the only airborne TEM system specifically developed for exploration of groundwater. The data in this thesis was collected with SkyTEM by SGU during autumn 2013.

3.2.1 SkyTEM

Specifically developed for hydrogeological surveys, SkyTEM is a helicopter based TEM method measuring the near surface response from an induced electromagnetic field as the function of time (Sørensen & Auken 2004). For a visualization of the setup see Fig. 8. Simplified, the method works as follows:

1. A current is transmitted through the transmitter loop.
2. The current is abruptly turned off.
3. A current is induced in the subsurface resulting in a secondary magnetic field.
4. The secondary field induces a current in the receiver loop which is measured.
5. The induced current in the ground is attenuated by the resistance of the subsurface geology as the current is spread downward and outwards.
6. Continuous measurements of the secondary magnetic field are made as diffusion of the induced current progresses.
7. After the measurement is completed (one transient), the procedure is repeated.

The diffusion of the induced current is dependent on the electrical conductivity of the geology and since continuous measurements of the secondary field are made over time as the induced current progresses deeper, the transients will contain information about the electrical conductivity of the subsurface as the function of depth (Christiansen *et al.* 2009).

3.2.1.1 Resolution

The amount of time to measure one transient is dependent on the time before the induced current is diffused to the degree that the signal to noise (S/N) level is too low to interpret the data. In order to acquire quality data from deeper strata, longer measurements times are required in order to get higher S/N-levels. This can be achieved by increased stacking (repeating and averaging of the signals) but is also achieved by increasing the transmitted current every second transient, also known as a high moment transient. Vertical resolution is increased due to the use of high moment transients, but at the price of longer measurement times.

The transmitter- and receiver loop is carried underneath the helicopter as a sling load. As the helicopter propels forward transients are made continuously. Lat-

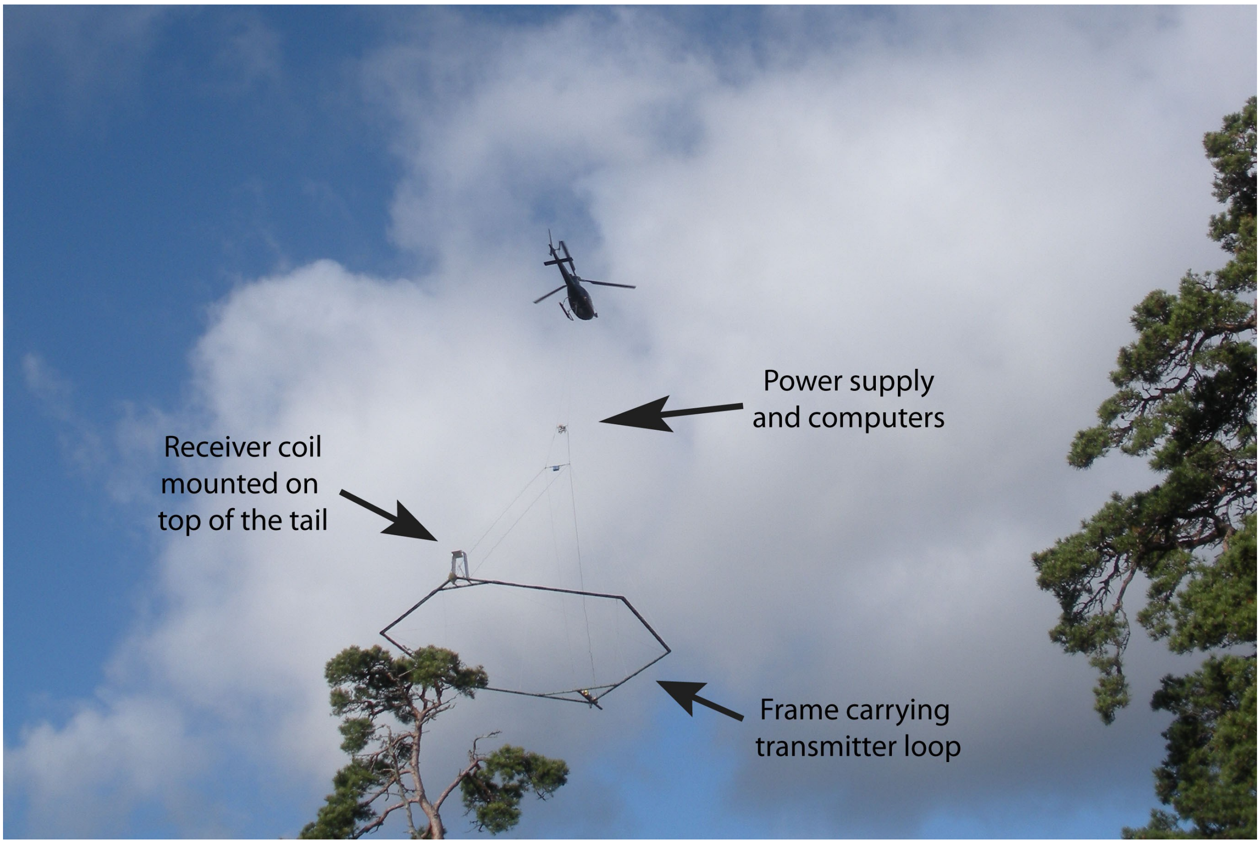

Figure 8. Setup of the SkyTEM array which was used to collect data from Fårö. Picture taken by and modified with permission from Mattias Gustafsson, Sveriges Geologiska Undersökning.

eral resolution is related to the rate of which transients are collected and also to the velocity of the helicopter. To acquire dense spatial data, quick transients and a low helicopter velocity is desired. But as the rate at which transients can be collected are also related to the vertical resolution, there will be a tradeoff between vertical and lateral resolution. Both can therefore be increased by lowering the helicopters velocity, which enables both longer measurements and maintaining a high spatial density (Christiansen *et al*. 2009).

3.2.1.2 Accuracy

Accuracy of data varies with variables such as altitude of instruments. The depth, thickness and resistivity of geological layers also affects the reliability of the data.

Man-made infrastructure has the greatest impact on the results. The conductivity of man-made conductors can be up to 8 magnitudes larger than that of geological targets in groundwater prospecting. These conductors can be power lines, water pipes, roads etc. Since their conductive properties are so great in contrast to natural occurring materials, they will greatly distort measurement results and force these to be discarded. The larger the contrast in conductivity between man-made and natural conductors, the greater safety distance is required. In an arbitrary setting with Quaternary cover a safety distance of >100 m is used (Christiansen *et al*. 2009). To ensure high quality, data collected within this distance of man-made conductors that might distort the data was discarded during processing.

As the instrumentation is carried beneath a helicopter the instruments will always be at an altitude above a safety limit when measurements are made. The data in this thesis was acquired at a nominal flight height of 30 – 50 m. The induced current and hence the earth's response signal will be weaker with increased flight altitude, see Fig. 9. At increasing altitudes, the response from manmade conductors from further distances will increasingly affect the measurements, resulting in a need for larger safety distance from infrastructure in order to acquire reliable data (Christiansen *et al*. 2009).

The resistivity of bedrock layers will affect the diffusion speed of the induced current; diffusion speed will be smaller in low resistive layers and larger in high resistive layers. Lower diffusion speed in low resistive layers will lead to a higher current density. As a result the current flows are larger in low resistive layers which lead to higher accuracy when measuring conductive layers. See Fig. 9 for examples and standard deviations of measurements.

Other possible errors are model equivalence. As measuring error increase, several models can produce similar responses and are therefore equivalent. Geological scenarios which are especially vulnerable to these model errors are high resistive layers in between two conductive layers, see Fig. 10, and layers with progressively increasing conductivity. Both these scenarios are expected to be present at Fårö as limestone layers are interlayered by marl/marlstone layers or a conductive boundary towards saline groundwater. The latter scenario can also be expected at Fårö as clay content vary in limestone and is known to increase with depth from OPAB´s drillings (Varadi 1982).

3.2.1.3 Data acquisition and processing

In order to create a reliable hydrogeological model in such a heterogeneous area as Fårö the single most important parameter is to collect spatially dense data. Data used in this thesis has been collected by SGU with the aim of following the standards set by the HydroGeophysics Group (2011). Processing of collected data has been performed by SGU following these guidelines and standards.

3.2.1.4 SkyTEM strengths and weaknesses

In order to help the reader interpret the results, a summary of the strength and weaknesses of using SkyTEM in hydrogeological mapping is presented:

- SkyTEM has high precision when determining the resistivity in low resistive layers.
- A weakness for the TEM methods is poor ability to determine the absolute resistivity in high resistive layers.
- Deeper strata have increased standard deviations in resistivity and thicknesses due to TEM being a diffusive method.
- Low flight velocity enables both long measurement times and high spatial density data collection, thus increasing both the vertical and the lateral resolution.
- Low flight altitude is desired when collecting data, as this increases signal to noise levels and lowers safety distance to manmade conductors. High signal to noise levels results in larger possible depths of investigation.
- In high resistive areas the needed safety distance to infrastructure increases.

3.2.1.5 Inversion of raw data

Following the processing of raw data by SGU two inversions were performed, one spatially constrained 19 layer model and one spatially constrained five layer model. The processing and inversion of data were done using Århus Workbench following the guidelines in HydroGeophysics Group (2011). Based on these inversions, rasters representing the subsurface in five meter intervals were created containing data of the mean resistivity for both respective inversions. Rasters made from the 19 layer model are presented in appendix B. Additionally, profiles of the mean resistivity were created and used for interpretation.

In a few layer model the model boundaries are set to correlate with the true lithological boundaries of the subsurface. In such a complex geological setting as Fårö the use of a five layer model would not yield sat-

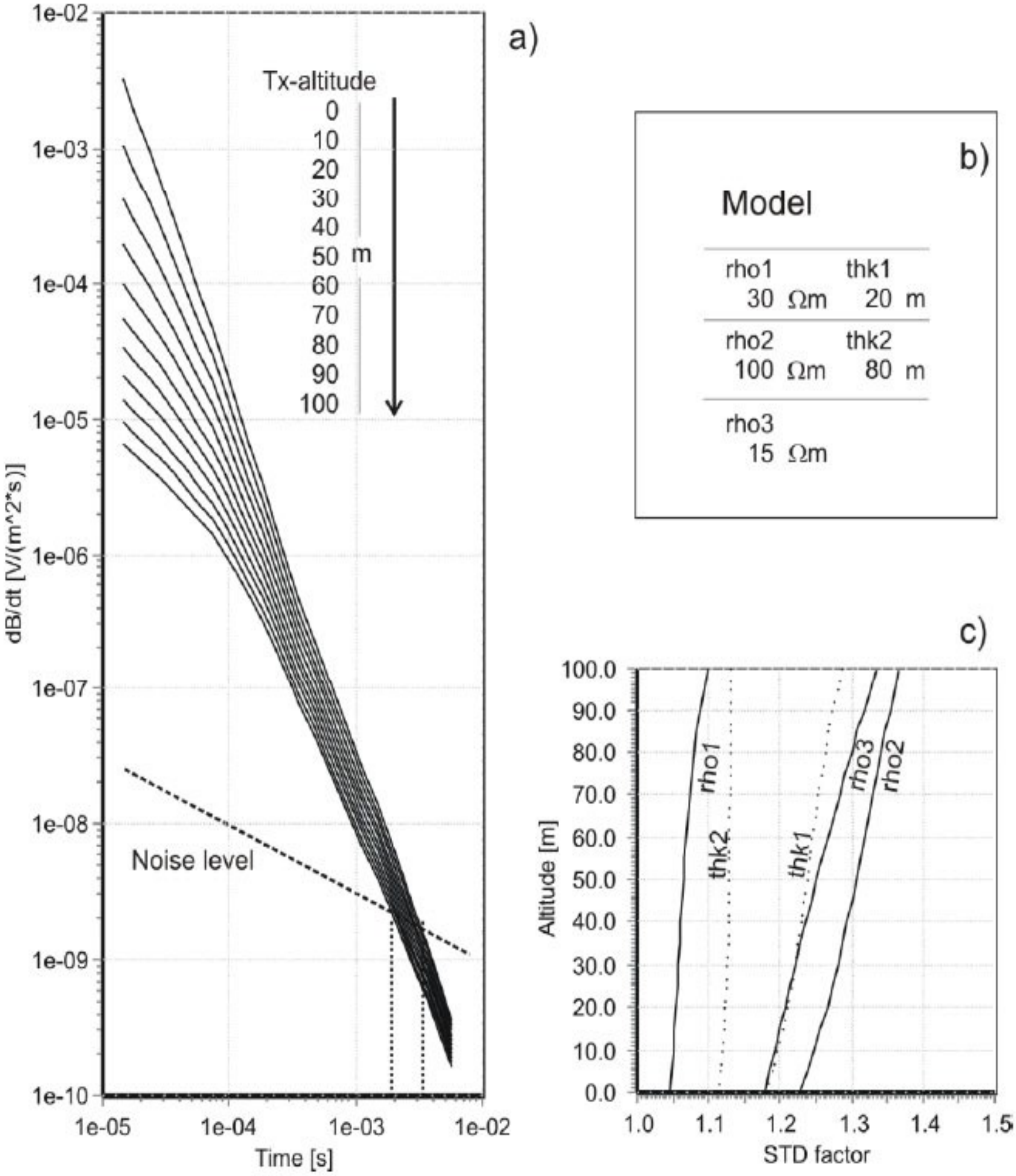

Figure 9. Two plots showing the effects on data accuracy due to altitude of the instrumentation. a) The earth's response from a three layered model with resistivities, rho, and thicknesses, thk, defined at b) as a function of the altitude of the instrumentation. The plot shows that measurement time can be almost doubled at 0 m altitude compared to 100 m altitude, thus resulting in interpretable data from deeper strata. c) Standard deviations, STD, for determined resistivities and thicknesses of the three layered model from varying altitude from 0 to 100 m. Standard deviation is small for low resistive layers and increases with altitude. Figure by Christiansen *et al.* (2009).

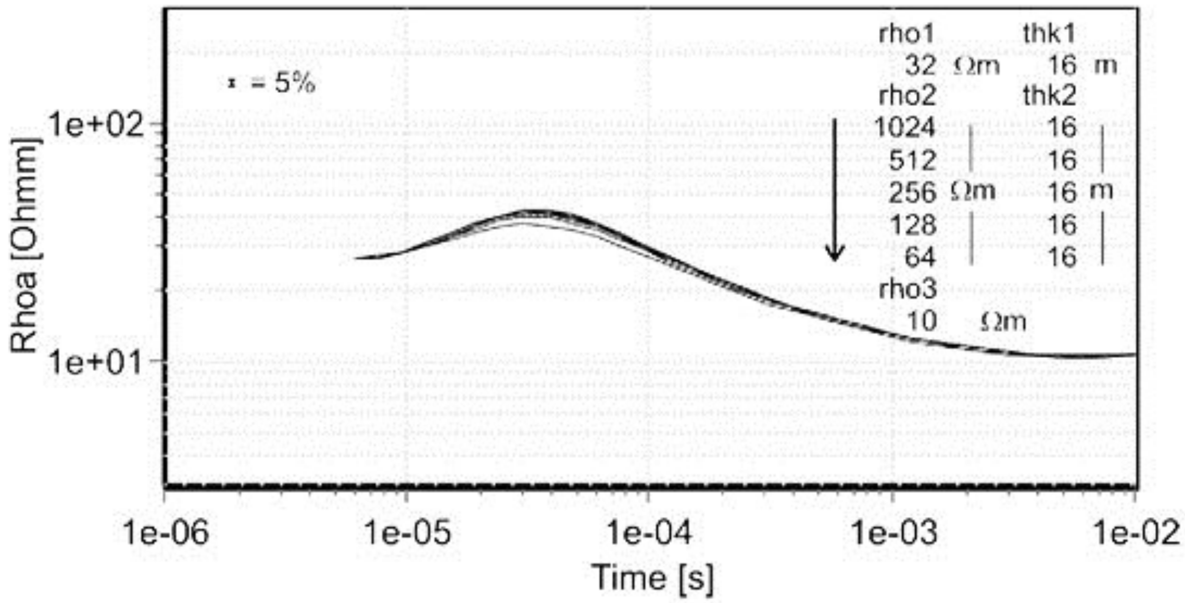

Figure 10. Illustration of resistivity equivalence in a high resistive layer between two conductive layers. This geological scenario is expected at Fårö, as marl and limestone is known to interlayer each other (Erlström *et al.* 2009, Varadi 1982 & Brunnsarkivet). Figure by Christiansen *et al.* (2009).

isfactory results for the entire island, as the knowledge of the substrata is not available at present. As the number of lithological layers in the groundwater saturated zone varies from one to at least five in various areas of the island, the use of individual inversions for each independent area with unique lithology would be required to acquire high qualitative results (HydroGeophysics Group 2011). The 19 layer inversion is a so called smooth model where the layers are given a constant thickness. The smooth model is preferable to use when modeling complex stratigraphies, due to lower requirements of previous knowledge of the stratigraphy and due to that is also less time consuming (HydroGeophysics Group 2011). For these reasons, the 19 layer inversion was primarily used for interpretation in this thesis.

3.3 Well inventory

Data from previously drilled or dug wells have been used as a source of information when constructing the hydrogeological model in this thesis. The Swedish geological survey's well inventory, Brunnsarkivet, contains information of 511 wells on Fårö drilled or dug from 1916 and onwards and information has been collected according to the law (SFS 1975:424). Out of these wells, 378 are used for household, recreational or smaller agricultural needs, 118 have unspecified usage, 11 are used for geothermal energy, 3 are used for larger agricultural needs and one well is used for industrial purpose. The depths of the wells vary between 1 – 213 meters, with an average depth of 28 m. The deepest well not used for geothermal purposes is 63 m. The archive contains information on groundwater tables in 329 wells. The groundwater tables in those wells have a median depth of 3 m below surface and an average value of 4.2 m below the surface.

Stratigraphic information from 335 wells have been compiled and simplified, see Fig. 11. The stratigraphy is originally described by the drilling company and can be heavily biased by individual entrepreneurs. After an initial compilation, the stratigraphy of every single well was simplified into five units:

- Cohesive sediments
- Non-cohesive sediments
- Limestone
- Marlstone/marl
- Unknown

These lithostratigraphies have been used in combination with the newly acquired geophysical data in order to strengthen the hydrogeological model.

3.3.1 OPAB exploration

Oljeprospektering AB (OPAB), a Swedish oil company now known as Svenska Petroleum Exploration AB, performed seven drillings on Fårö during the early 1980's (Varadi 1982). Additionally, seismic lines were shot across Fårö. The target of OPAB's prospecting was mainly Ordovician strata but some stratigraphic information from Silurian strata is also described in Varadi (1982), see Fig. 11 for orientation and appendix C for coordinates and the described Silurian stratigraphy of OPAB´s seven boreholes on Fårö.

Borehole logs are valuable tools when building hydrogeological models, unfortunately only one borehole was logged with geophysical methods during the oil

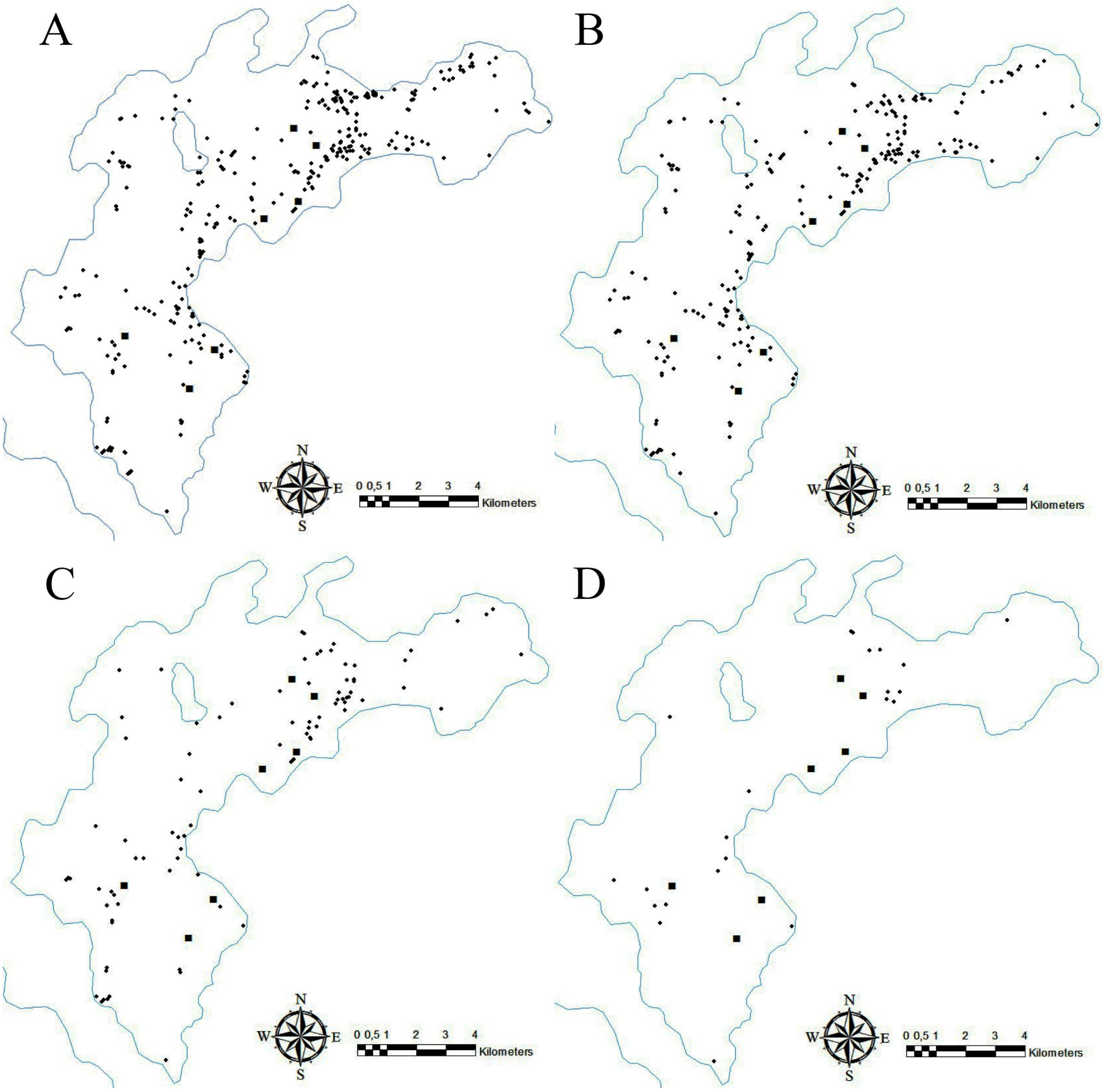

Figure 11. Data from existing wells contain limited information of the geology at depths of over 40 m. Well positions from the national surveys well archive are plotted as a function of depth. A: Positions of 335 wells used in the hydrogeological model. B: Positions of 257 wells with a depth of at least 20 m. C: Positions of 119 wells with a depth of at least 30 m. D: Positions of 24 wells with a depth of at least 40 m. Dots represent wells from the national well archive and squares represent wells from oil exploration. Modified from (© Sveriges geologiska undersökning)

prospecting on Fårö. The log is a sonic log acquired in the borehole Myrhaga-1 (Geophysical microlog AB 1981). Stratigraphies and one sonic log from these oil prospectings have been compiled with geophysical data and data from the well archive and served as a foundation in this thesis for interpretations and conclusions.

3.4 Field work

3.4.1 Spatial variability of the electrical conductivity of groundwater

In order to strengthen and calibrate the hydrogeological model, field work on the island of Fårö was conducted as part of this thesis. The field work was mainly focused on measuring the electrical conductivity of groundwater in previously drilled wells. The relation between electrical conductivity of groundwater and its chemical composition is used to log spatial variations in groundwater composition of Fårö. Electrical conductivity of water is mostly dependent on its solute ions and variations in electrical conductivity can be used as a strong indication of changes in ion concentrations (Tutmez *et al.* 2006; McNeely *et al.* 1979). In environments with low ion concentrations, electrical conductivity is used by SGU to estimate chloride concentrations. However in areas where groundwater has naturally high ion concentrations a separate chloride analysis might be required (SGU 2013).

By using a Solinst® TLC meter (Temperature Level Conductivity meter) data was collected from privately owned wells. Measurements of the groundwater level were recorded along with measurements of temperature and conductivity at depths of every five meters. The field work was conducted during the last two weeks of July 2014. Data was then correlated to sea level and logged in a geographic information system. Groundwater level measurements were used to model groundwater flow directions and the electrical conductivity was used to model spatial variations in groundwater composition and to calibrate the depth to the modeled saline groundwater boundary.

3.4.2 Radiomagnetotelluric (RMT) measurements

In order to verify data collected in the SkyTEM survey, three profiles were measured with the radiomagneto-telluric (RMT) method (Cagniard 1953; Bastani 2001). The bedrock resistivity was calculated by measuring the electric and the magnetic field in two and three perpendicular angles, respectively, along points every ten meters on a profile (Bastani 2001). The profiles are distributed in areas C and D according to Fig. 12. As measurements were made along short profiles, approximately 1000 m each, data could be collected spatially dense; one measurement per 10 m. This allowed for high resolution data and results can be compared to SkyTEM data in order to verify and strengthen one another.

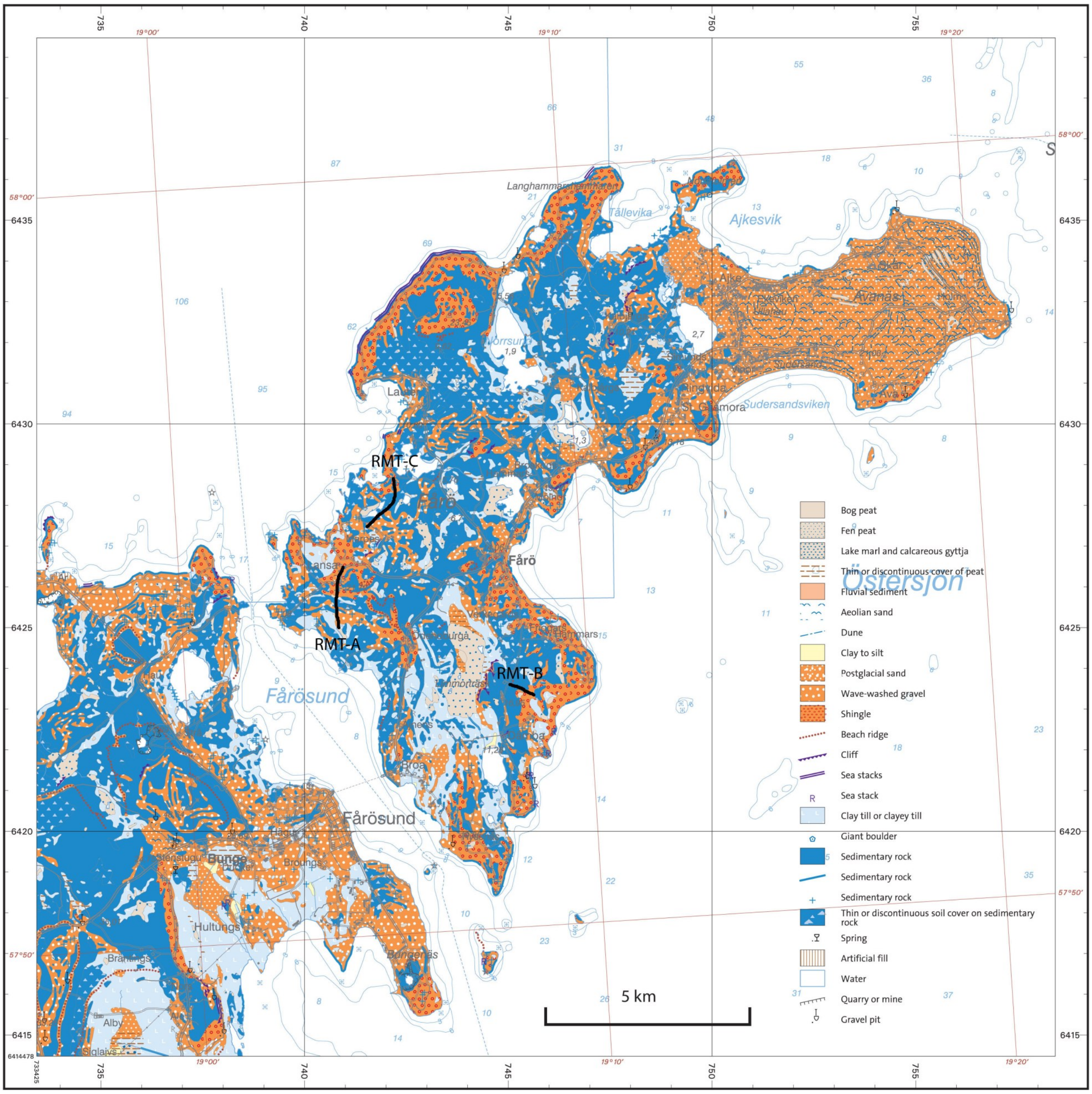

Figure 12. Positions of Radiomagnetotelluric measurements performed on Fårö, overprinted on a map of the Quaternary deposits with permission from (© Sveriges geologiska undersökning).

3.5 Well drillings

Based on the data from the SkyTEM and RMT surveys, three sites were selected in agreement with SGU, for additional investigation by establishing new surveillance wells: 91461026, 914610436 and 914610468. The sites for well drillings, Fig. 13, were chosen based on their distinction in geology, which is further discussed in chapter 5. Once established, one of the wells, 914610436, was logged with respect to its properties by the drilling entrepreneur and also by geophysical borehole logging. The geophysical logging was carried out by the Faculty of Engineering at Lunds University using equipment from Robertson Geologging. By using resistivity data from the well drilling, appendix D, an attempt was made to calibrate the modeled boundary between fresh and saline groundwater by determining the true displacement of the boundary in well 914610436. Poulsen *et al*. (2006) measured the electrical conductivity of pore water in drill cores in order to determine the top of the transition zone. As no drill core was secured to extract pore water from, instead the resistivity data from geophysical logging was used to determine the top of the transition zone. The results were then used to interpolate the modeled boundary over a large lateral extent.

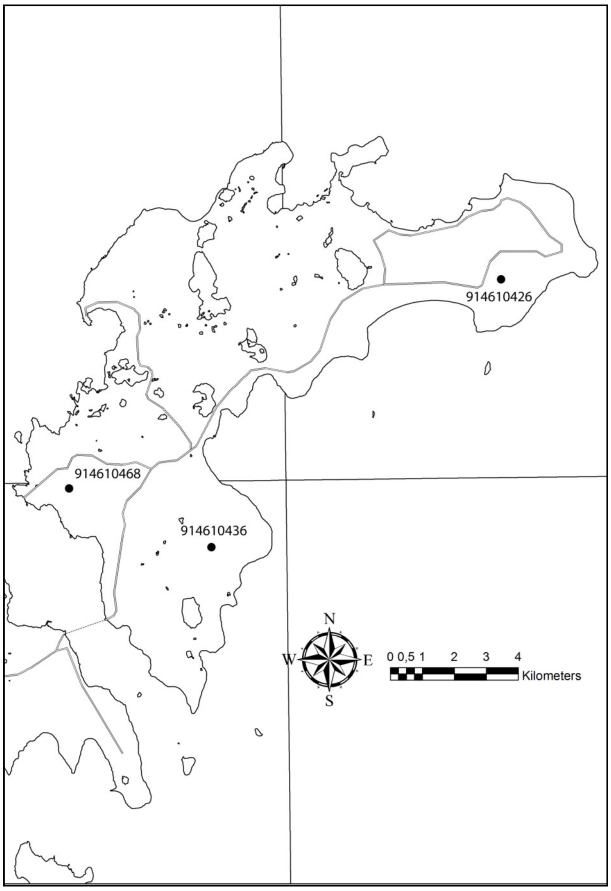

Figure 13. Positions of well drillings performed by SGU during autumn 2014, the positions were chosen in areas where SkyTEM and RMT data indicate especially favorable (914610436 and 914610426) and unfavorable (914610468) hydrogeological conditions.

3.6 Risk assessment

Previous work done on Fårö includes the land-use plan for Fårö (Region Gotland 2014). The plan includes guidelines for water and wastewater management. These guidelines state that the primary goal to solve the water and wastewater problems of Fårö is to connect all property to the municipal water and sewage system, secondarily through smaller community plants and in third hand by individual solutions. As a last resort the plan also mentions a desalination plant. As a consequence, the demand for groundwater as a source for drinking water is high on Fårö.

Ahead of the land-use plan, a water supply and sanitation plan was published by Palmer Rivera *et al.* (2011). The land-use plan compiled a risk assessment for the groundwater of Fårö. The assessment concludes that the majority of Fårö is classified in the highest vulnerability category (Fig. 14). Under such vulnerable geological conditions, the groundwater is unprotected from contamination. The land-use plan also contains a map of potentially contaminated soil on Fårö (Fig. 15). In order to protect the groundwater from such hazard it is of great importance to establish a water protection area. According to SFS 1998:808 a water protection area can be established in order to protect a groundwater resource that is used or can be assumed in the future to be used for water supply, heat extraction or irrigation. Consequently, the groundwater aquifers of Fårö fulfill the requirements to be protected

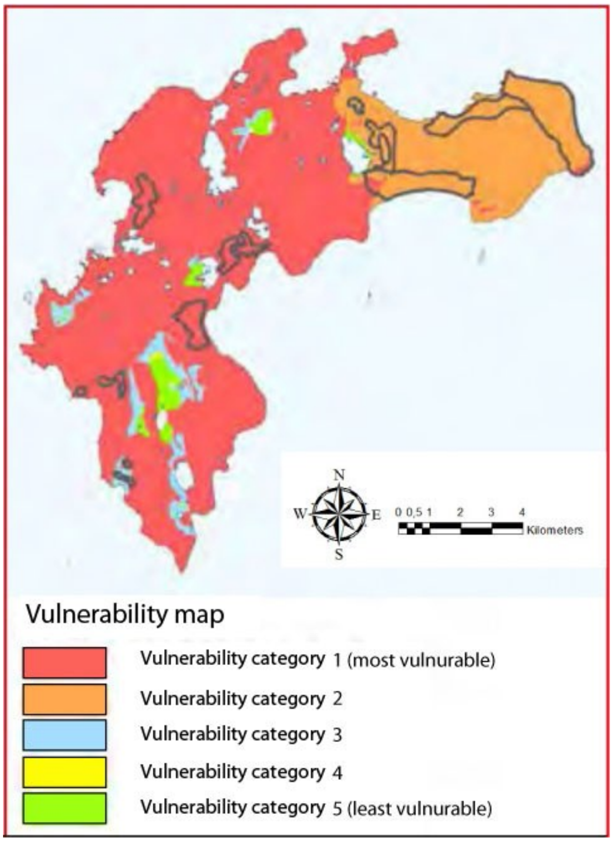

Figure 14. The land use plan includes a vulnerability map of Fårö´s groundwater. Modified from (Region Gotland 2014)

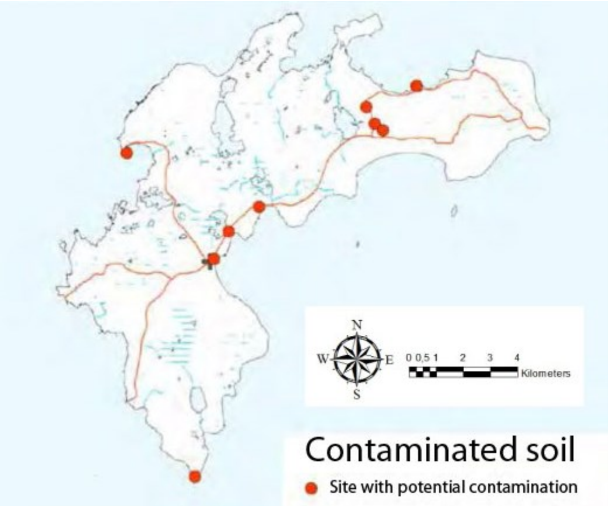

Figure 15. Sites on Fårö which contain potential contaminations. Modified from Region Gotland (2014).

by a water protection area; thus enabling the groundwater resources to safely be used for drinking water supply in the future.

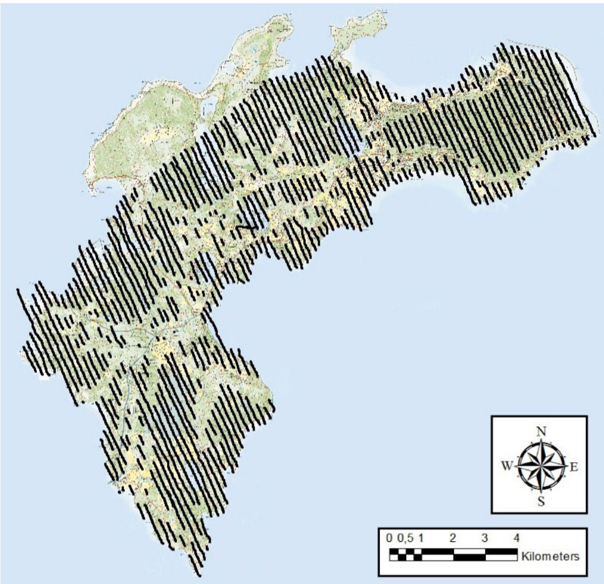

Figure 16. Areas containing data from the SkyTEM survey. Blank areas were filtered out due to insufficient quality during processing, mainly due to coupling effects with man-made structures.

4 Results

4.1 SkyTEM

Post processing was performed by SGU and inversions of the raw data were successfully created by SGU following guidelines from the HydroGeophysics group (2011). Data were collected from over 10 000 individual soundings that are distributed as presented in Fig. 16.

4.1.1 Elevation of first conductive layer

In order to estimate the depth to the saline groundwater, a first step was taken by modeling the first conductive layer. Following the method developed by Vangkilde-Pedersen *et al.* (2011), rasters were created containing information of the depth to the first good electrical conductor. Constructed layers were then used during the work to interpret the boundary between saline and fresh groundwater and to identify anomalies.

Presented in Fig. 17 is a raster showing the elevation of the first modeled layer with a set maximum electrical resistivity. In the figure a formation resistivity of 100 ohmm was used to model the raster. For reference, two rasters where a formation resistivity of 40 and 20 ohmm was used is presented in appendix A. All rasters illustrate the same trend, the boundary has a shallow displacement in the northwest and is increasing in depth towards the southeast. The difference in depth between northwest and southeast for both models is approximately 30 meters or equal to a dip of 0.2°. The strike and dip of the modeled layer coincide with the corresponding values of the strata (Erlström *et al.* 2009).

4.1.2 Mean resistivity

Presented in appendix B are figures of the subsurface's mean resistivity in intervals of 5 meters. Results are presented from the 19-layer inversion.

4.2 Field work

Groundwater levels of ten privately owned wells are presented in Fig. 18. Four of ten investigated wells had elevated electrical conductivities of >100 mS/m. Two of these wells showed a gradual increase in electrical conductivity downwards and could be used to interpret the boundary between saline and fresh groundwater. Results are plotted along with measured groundwater tables in Fig. 18. The wells with elevated electrical conductivities are marked with red triangles.

4.2.3 Radiomagneto-telluric (RMT) measurements

Results from the radiomagneto-telluric (RMT) measurements are presented in Fig. 19. In a comparison to the SkyTEM data, RMT show a higher degree of detail, but in general the results from the two methods agree for all three areas.

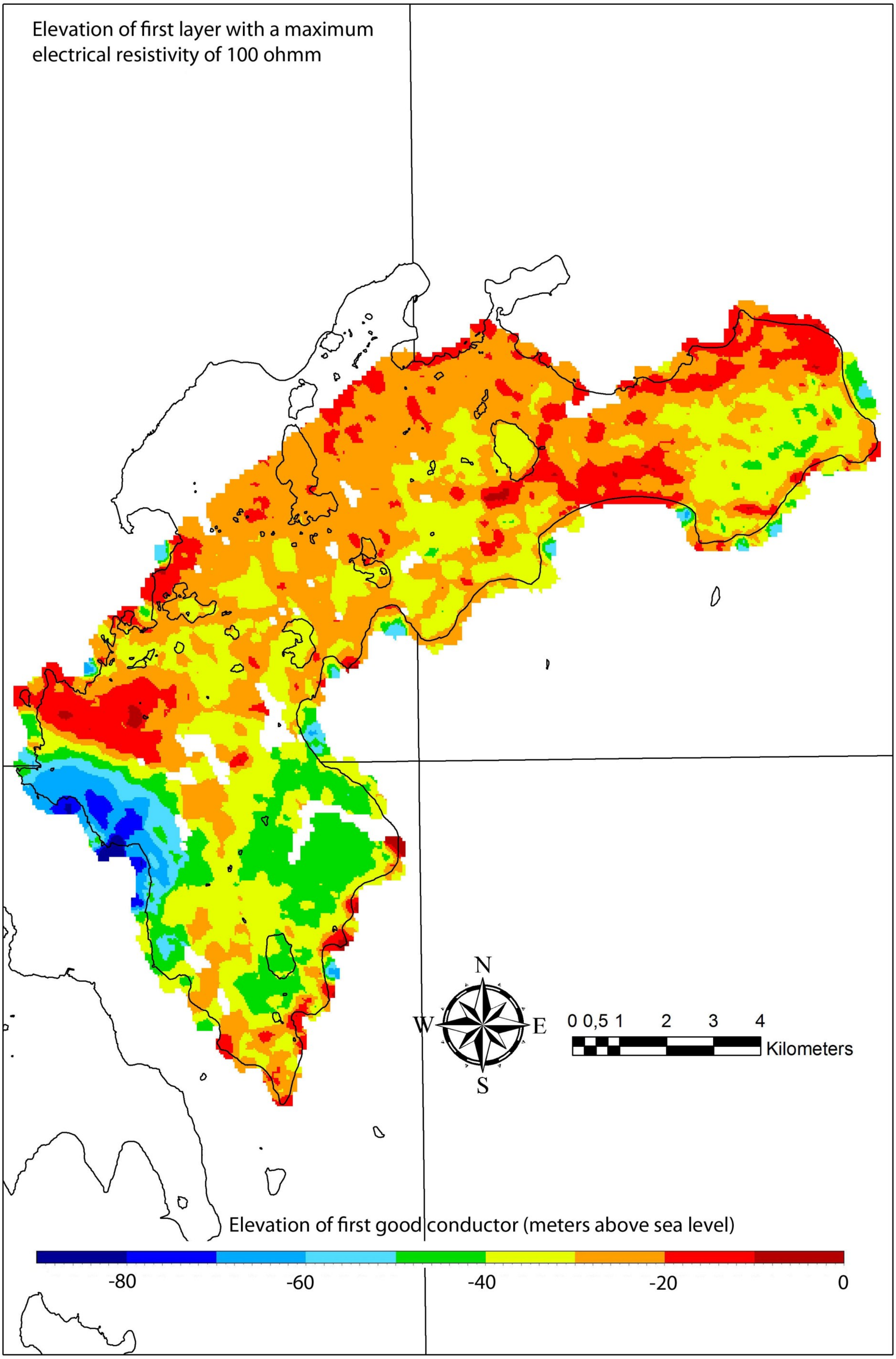

Figure 17. Elevation of the first conductor with a maximum resistivity of 100 ohmm.

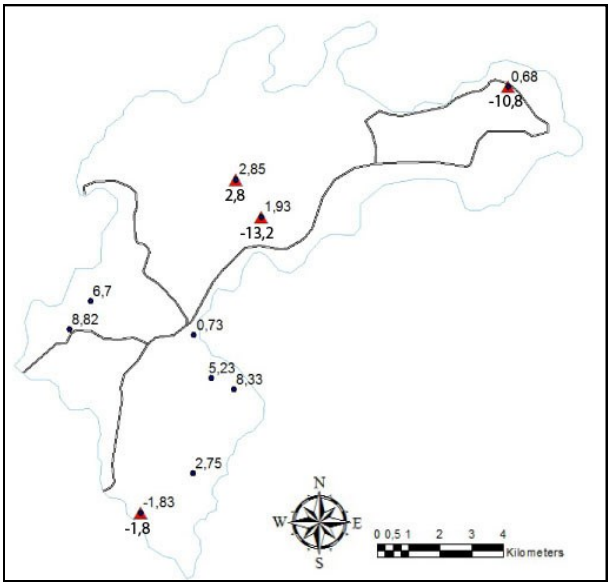

Figure 18. Groundwater levels in m.a.s.l. in ten privately owned wells. Wells with elevated electrical conductivities are marked with red triangles. The level of the elevated conductivities are presented below the red triangles in m.a.s.l..

5 Interpretation and discussion

In order to more accurately discuss and describe the hydrogeology of Fårö, a division of the island has been made into four areas according to Fig. 20. The division was made based upon areas with corresponding geology and results from the SkyTEM survey: Area A is the peninsula of Avanäs, the peninsula covered by post glacial aeolian deposits and today a popular tourist attraction. Area B is defined by a thin or non-existent sediment cover and the first good conductor is modeled at an elevation between 0 and 30 meters below sea level. Area C is defined by two large anomalies in the electrical resistivity and area D is defined by its greater depth to the first good electrical conductive layer.

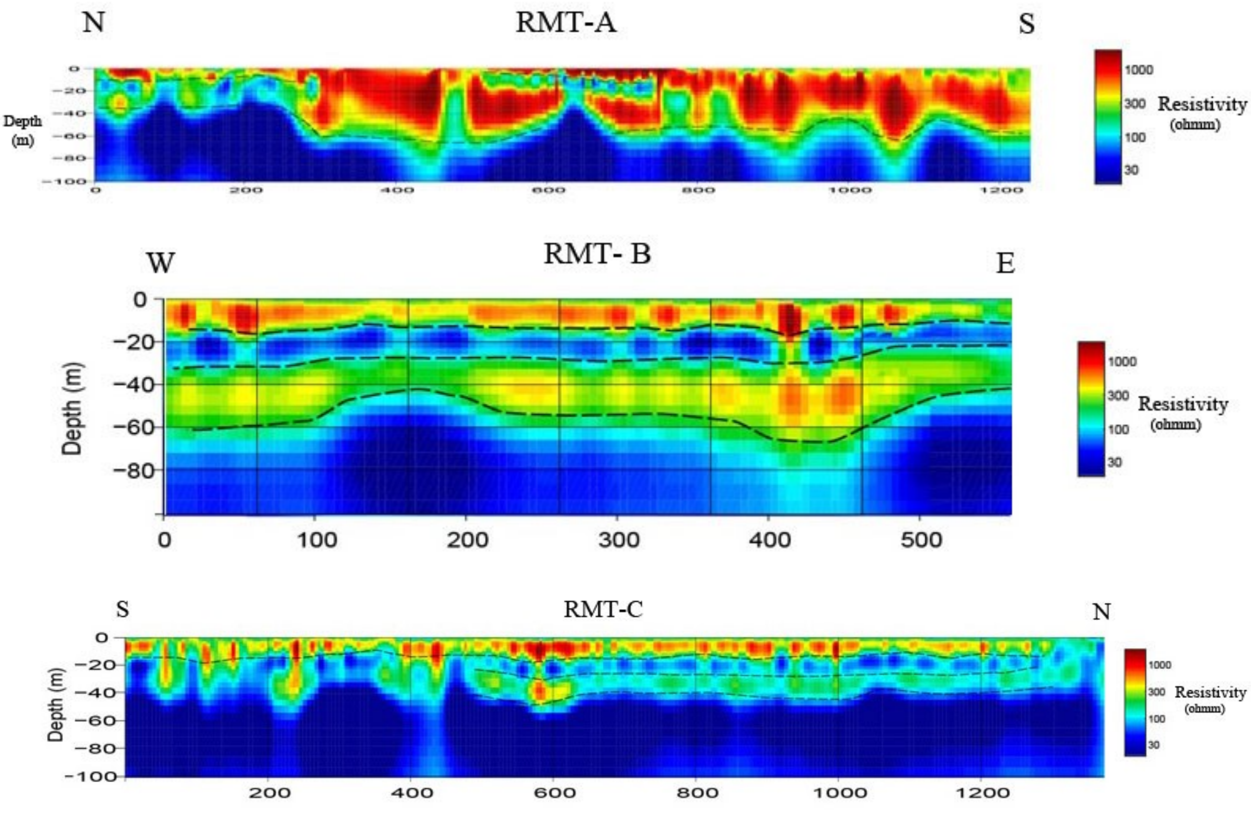

Figure 19. Results from RMT measurements. The profiles positions are displayed in Fig. 12.

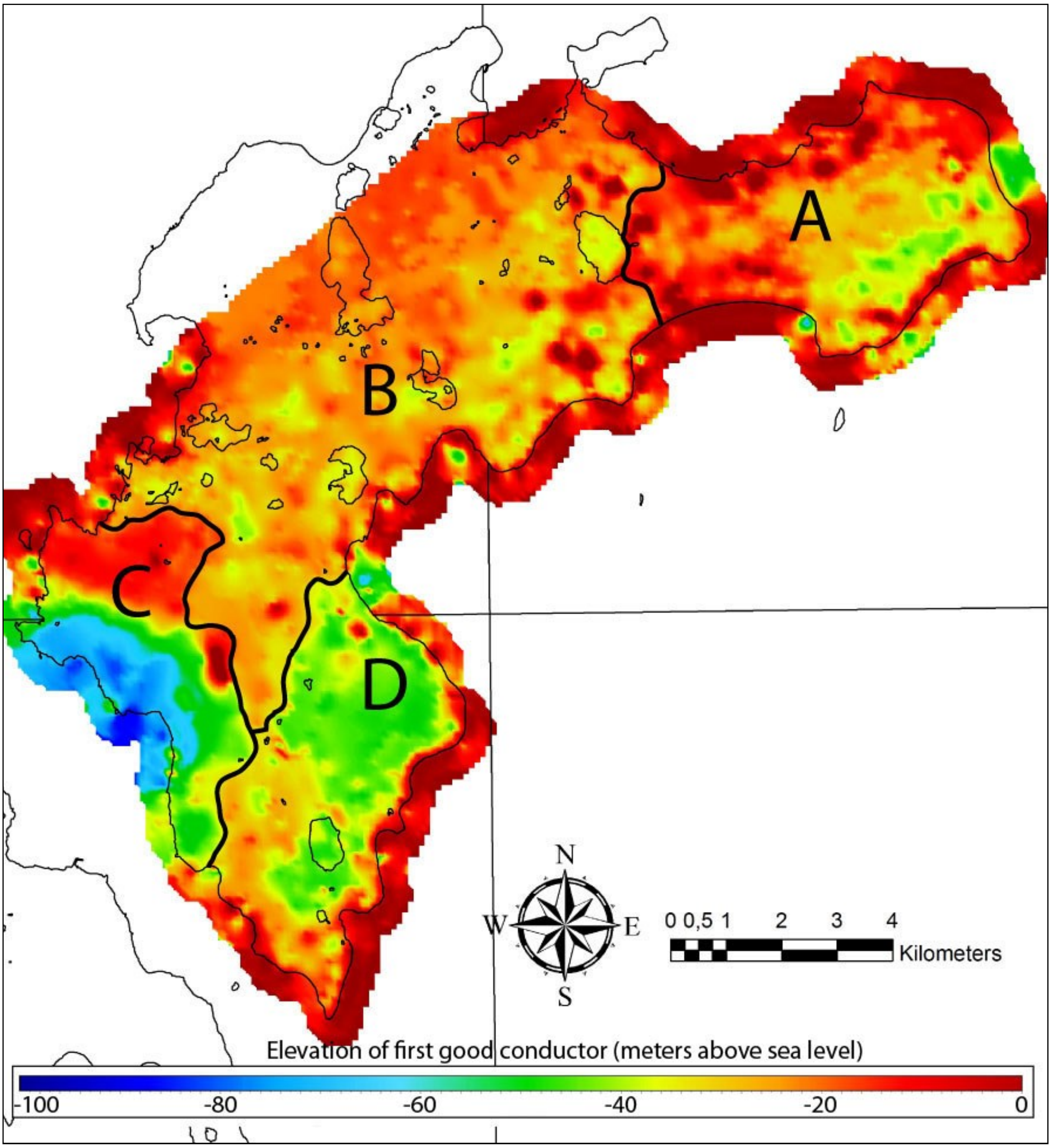

Figure 20. Four areas of Fårö that are discussed more thoroughly in chapter 5. The background raster displays the elevation of the first good conductor (100 ohmm) on a continuous colorscale.

5.1 Area A: Avanäs

The peninsula of Avanäs is deviant in its geology in comparsion to the other areas of Fårö due to its relative thick soil layer, with reported values in Brunnsarkivet of up to 15 m. The area is dominantly covered by post glacial sand.

As seen in Fig. 21 areas filtered out during processing coincide with areas where the depth to the first good conductor is shallow. This is due to processing settings where a background value of 100 ohmm is given during modeling to areas lacking data. Extra caution has therefore been taken when interpreting data from areas where large amounts of data has been filtered out.

5.1.1 Boundary between saline and fresh groundwater

The A-01 profile presented in Fig. 22 and 23 across the peninsula indicates that the first good electrical conductor has a sharp transition and is situated at approximately -20 to -30 m.a.s.l. in the north and approximately -40 m.a.s.l. in the south. This conductor is interpreted as the boundary between saline and fresh groundwater, see Fig. 24, and its dip seems to coincide

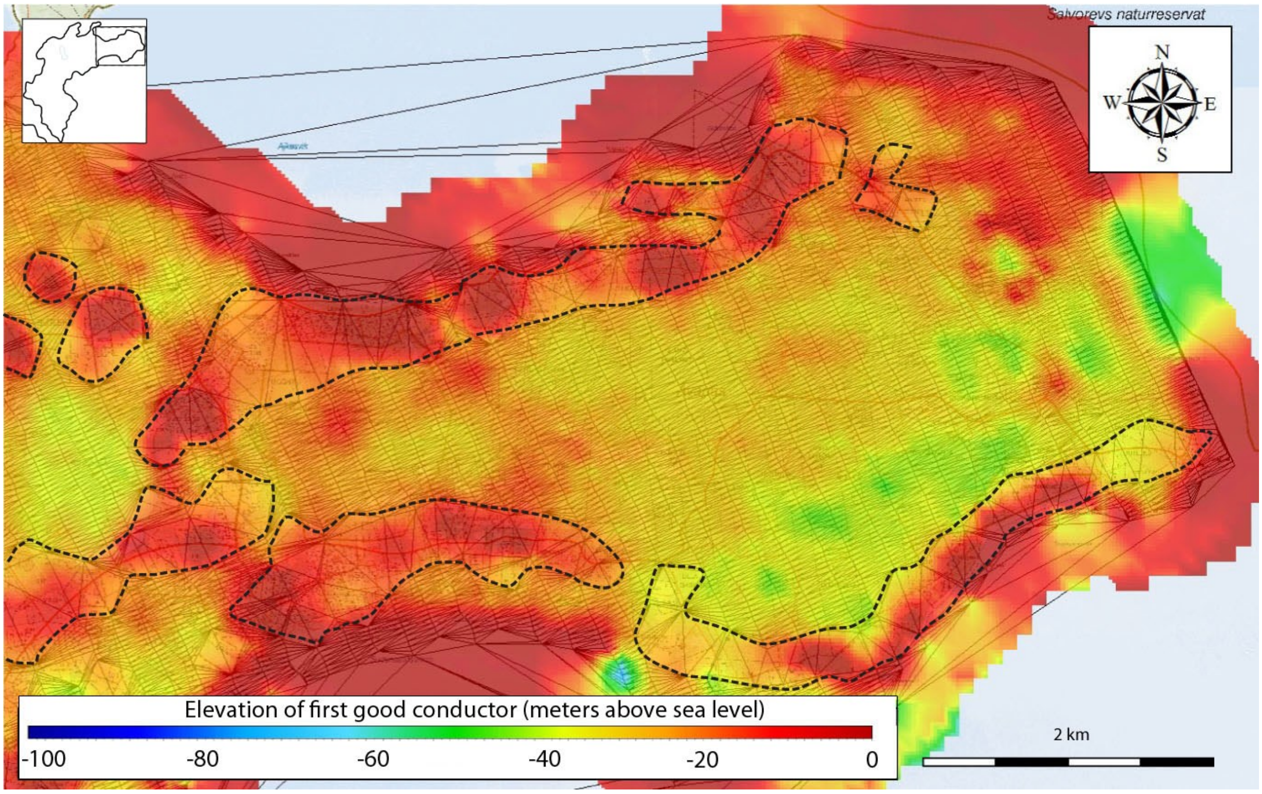

Figure 21. Constraints of data points from the SkyTEM survey plotted on top of a raster showing the depth to the first conductor with maximum electrical resistance of 100 ohmm. Note how areas marked with dashed lines without data coincide with areas where the modelled conductor is shallow.

with the dip of the geological strata. An anomaly in this conductor at the 3400 meter mark of profile A-01 is situated in an area where data has been filtered out during processing due to coupling effects with man-made conductors. This anomaly should thus not be interpreted as a shallow interface between saline and fresh groundwater.

The western part of Avanäs, surrounding the Ullahau dune, is the densest populated area which results in some problems with interpretation due to heavy filtering among raw data to avoid coupling effects from man-made structures. This is also the area where the waterworks of Fårö is situated. In the populated areas it is hard to draw any conclusions of the depth to the saline interface but in the barren areas of Ullahau the results shows a relatively shallow conductor, something that most likely is valid for the surrounding areas of Ullahau as well. Results of a shallow conductor interpreted as shallow saline groundwater is coherent with Tullström (1954), who verifies that saline groundwater can be found already at levels of -10 m.a.s.l. in the surrounding areas of Ullahau.

Along profile A-02 in between the 1000 and 2000 meter marks there is a large anomaly in the resistivity data showing a good conductor in the shape of a lens. Observations made by Svantesson (2008) points out that peat have been deposited along depressions parallel to palaeo beach ridges in this area. Field measurements have shown that groundwater levels are shallow on Avanäs and as a result the peat is saturated with groundwater and affect the quality of the groundwater. The low electrical resistance is interpreted to originate from higher ion concentration, such as dissolved organic content, in pore water associated with the peat.

5.1.2 Groundwater extraction potential

Estimated potential of groundwater extraction in the area is believed to vary largely with local bedrock fractures and this is strengthened by data from the well archive where large variations are found in quantities of groundwater in wells. Groundwater recharge is believed to have high potential due to porous sediments at the surface and is also believed to vary depending on local fracture patterns. Results from the recently drilled well 91461026 indicate that extraction potential is high compared to average values for Fårö in the national well archive.

Avanäs is the densest populated area of Fårö, most of the habitation is recreational buildings situated along the coast. In order to avoid contaminations from anthropogenic sources as well as from the local peat (Fig. 22) and the increased salinity along coastal areas, the highest probability to find any qualitative and quantitative groundwater is thought to be in the central to southeastern parts of Avanäs, where population is less dense. There is no mapped peat and the boundary between saline and fresh groundwater is interpreted to be on a depth of up to -40 m.a.sl., see Fig. 24.

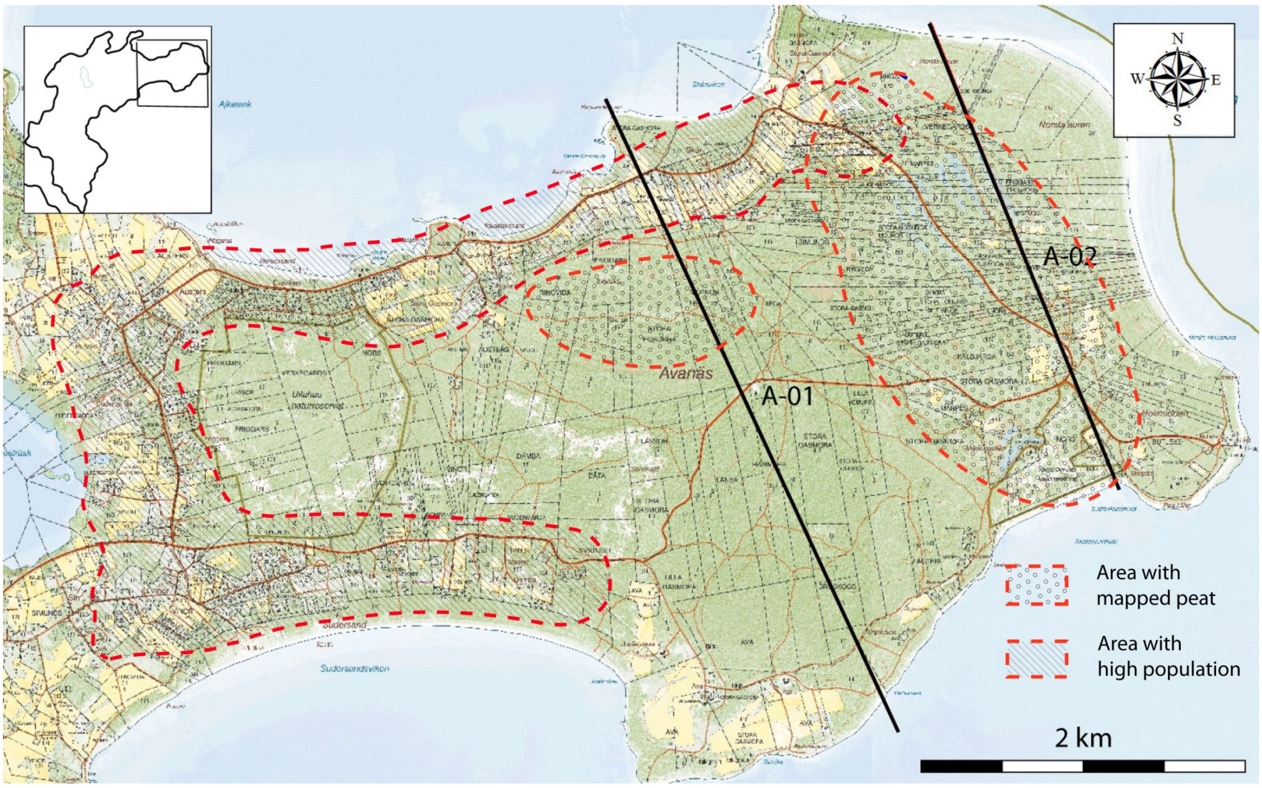

Figure 22. Locations of profile A-01 and A-02 at the Avanäs peninsula. Areas where quality problems might arise due to specific conditions such as anthropogenic pressure or dissolved organic content from peat deposits are highlighted with red. A property map is shown as a background with permission from Lantmäteriet.

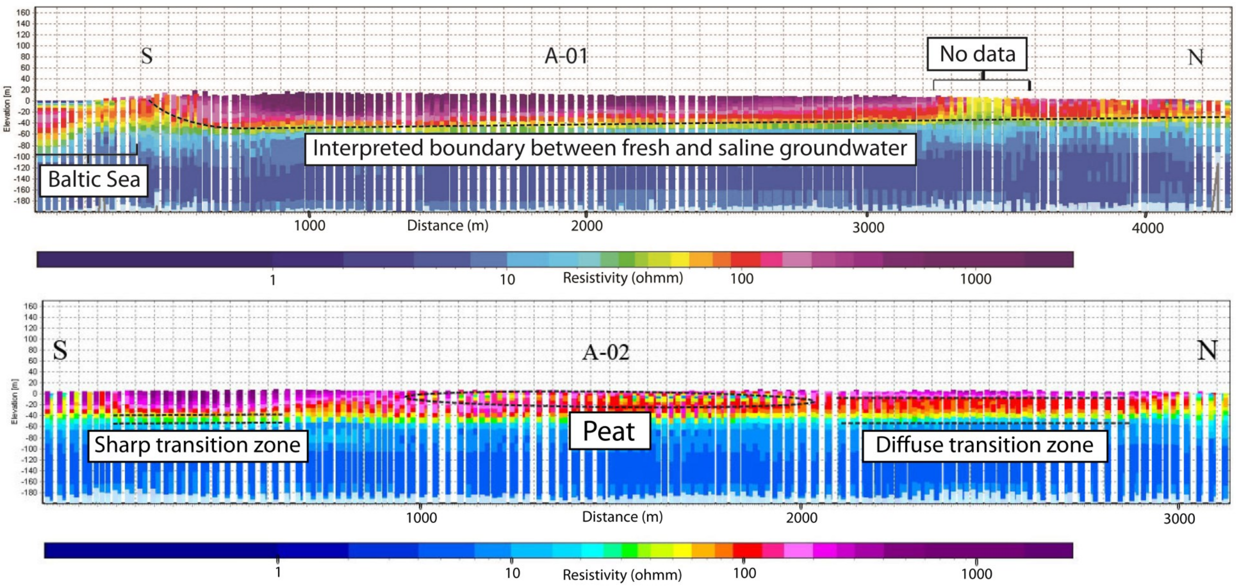

Figure 23. Top graph contains data of the mean resistivity in profile A-01 and the bottom graph contains corresponding data for profile A-02. Note the gradually increasing depth of the conducting layer in profile A-01 from north to south. Profile A-02 visualizes the peat which has been deposited along palaeobeaches on the eastern parts of Avanäs. The peat is seen as low resistive layers.

5.1.3 Risk assessment

The entire peninsula of Avanäs is mapped to belong to the second highest vulnerability class in the risk assessment performed by Region Gotland (2014), see Fig. 14. In the same report four sites within area A is mapped as potentially contaminated sites that might threaten the groundwater quality, see Fig. 15. The sites are located in the western and northern Avanäs and consist of a fishing harbor, two filling stations and a shooting range. Avanäs is the most densely populated area of Fårö and the anthropogenic pressure on the groundwater quality is therefore high, especially in the highlighted areas of Fig. 22. Avanäs is the only part of

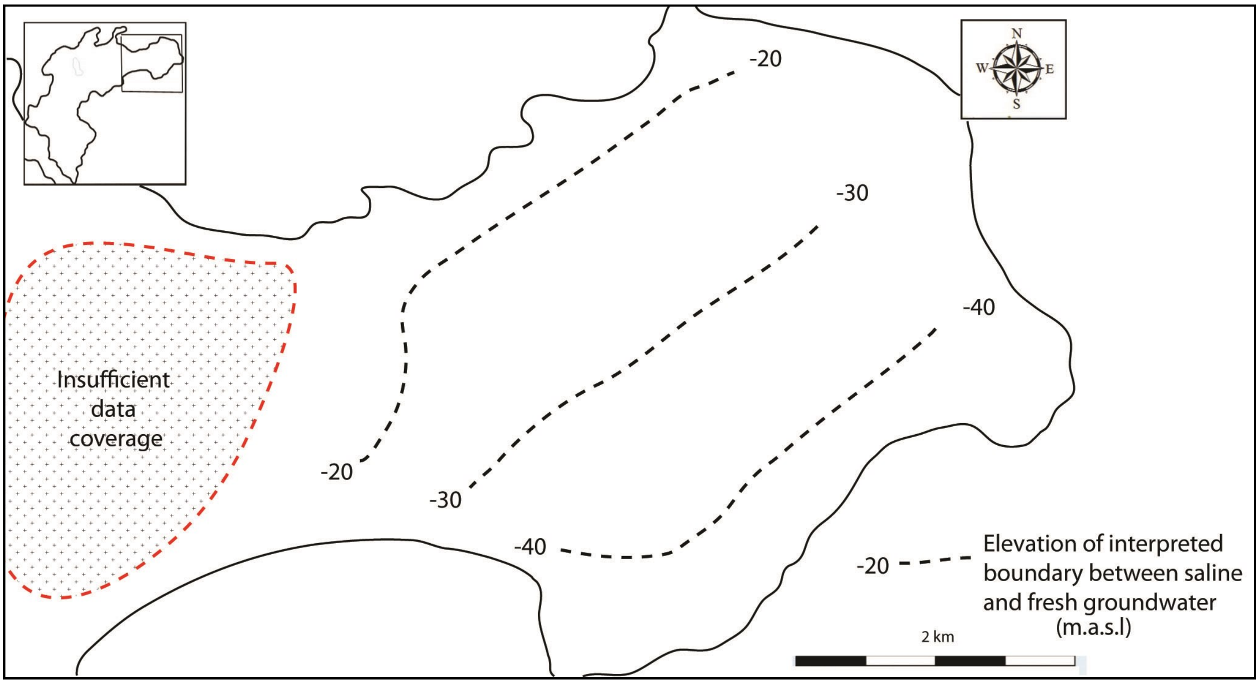

Figure 24. Interpretation of boundary between saline and fresh groundwater in area A, Avanäs. As discussed, these values should not be interpreted as absolute values of a sharp boundary.

Fårö with a public water work and wastewater plant, even though only a small part (western part) of the entire peninsula is catered by it. Also, in the water and sanitation plan by Palmer Rivera (2011) the public wastewater plant is deemed to be in need of review and new measures. Other potential threat towards the groundwater quality is the peat deposited along the beach ridges of northeastern Avanäs, see Fig. 22.

Under these prevailing conditions, in combination with a shallow boundary towards the saline groundwater, the groundwater quality of western Avanäs is expected to be insufficient to fulfill the quality and quantity requirements during summer.

The southeastern area of Avanäs shows the greatest depths to the first good conductor, Fig. 21. No peat deposits can be seen around this section on the SkyTEM data or have previously been mapped by Svantesson (2008) and the potentially contaminated sites are over 2 km away. Therefore the southeastern part of Avanäs is interpreted to have the most favorable conditions of Area A to find any larger quantities of high quality groundwater.

5.2 Area B: Ajkesträsk –Marpesträsk

The subsurface geology is similar in area B compared to area A, but is accounted for separately as it is not covered by any significant thicknesses of unconsolidated sediments as is the case in area A. Area B is a largely homogenous area consisting of medium crystalline limestone (calcarenite) with scattered beds of stromatoporoid limestone and with occasional patches of reefstone (Erlström *et al*. 2009), see Fig. 4. The area has a surface layer resistivity of in general 200-300 ohmm and as high as >1000 ohmm in the patches of reefstone, see appendix B.

Surface waters are dominantly present along two topographic low points along NNW-SSE around Alnästaträsk-Norrsund-Bondansträsk and along a WNW-ESE low point at Farnavik-Mölnorträsk.

Along the southeastern coast an anomaly in the resistivity data can be found, which is coherent with the bedrock boundary towards coarser limestone (Erlström *et al*. 2009). These coastal anomalies are interpreted as a lithostratigraphy consisting of three units: calcarenite, marlstone/marl and a grey clayey limestone. The same stratigraphy is found more widespread in area D. When viewing profile B-01 in Fig 25, the transition from the homogenous area with patches of shallow reefstone over to a stratigraphy with a distinct marlstone and/or marl layers is clearly visible in the southeast.

5.2.1 Boundary between saline and fresh groundwater

Profile B-01 displays a sharp transition zone between layers with high and low resistivity, see Fig. 25. Following the work done by Poulsen *et al*. (2006) this can be interpreted as if the true displacement of the boundary between saline and fresh groundwater is in close proximity, ±10m, to the first modeled layer with high electrical conductivity. However, as no geophysical logging has been performed in any wells in area B, it would be possible to more accurately determine the boundary´s displacement by measuring the saline transition zone in wells. Consequently the depth to first good conductor is deemed a good approximation for the depth to the boundary between saline and fresh groundwater for the majority of area B, see Fig. 26 & Fig. 27 for an interpretation.

The depth to the 100 ohmm conductive layer varies

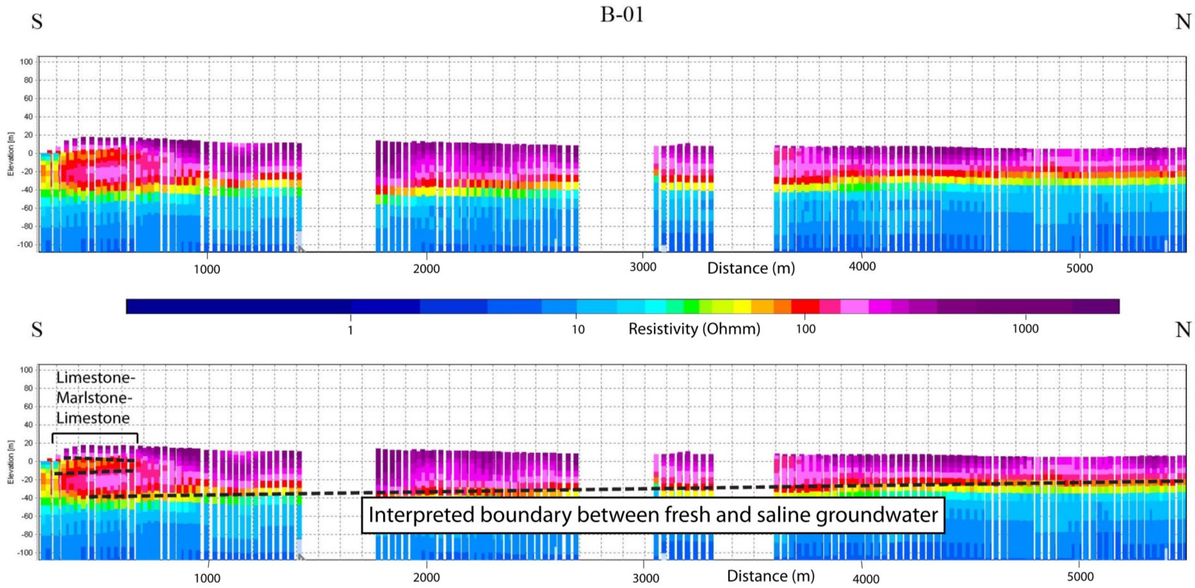

Figure 25. Profile B-01 viewing the homogenety of area B where low resistive limestone dominate. The top transect displays the unmodified results and the bottom transect is presented with interpretations. In the southeast a clear transition over into a stratigraphy with a distinct conductive marlstone and/or marl/marlstone layer at approximately 0-15 masl.

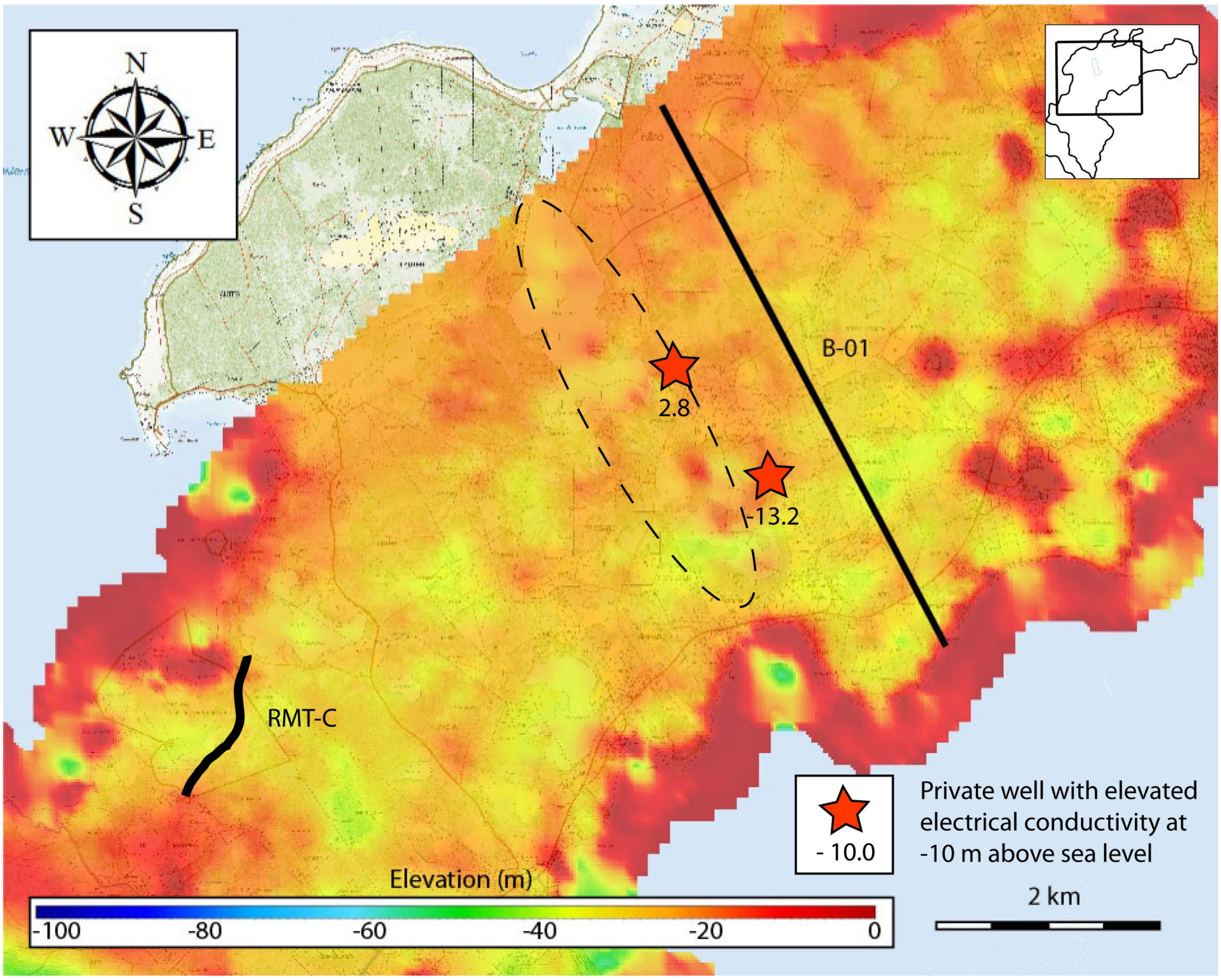

Figure 26. Visualization of the depth to an electrical conductor with a maximum resistivitiy of 100 ohmm. Area B shows a homogenous depth to the first good conductor in comparison to the other areas. The conductor gently increases in depth towards the southeast in the same direction as the geological dip. The dashed area is the topographic lowpoint of Alnästaträsk-Norrsund-Bondansträsk, along which indications of shallower depth toward the saline groundwater exist. Also visible is the location of profile B-01 and RMT-C

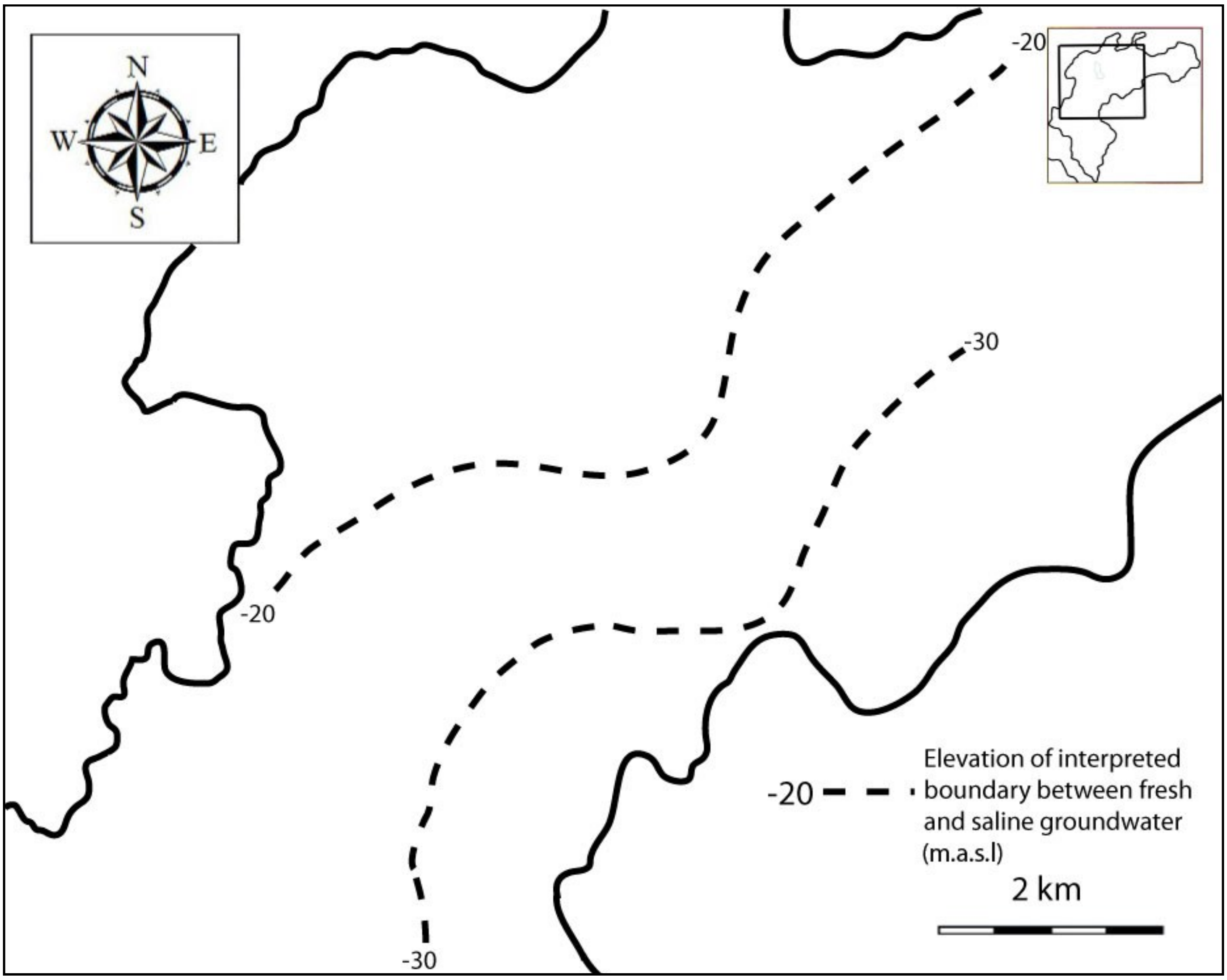

Figure 27. Interpretation of boundary between saline and fresh groundwater in area B. As discussed, these values should not be interpreted as absolute values of a sharp boundary. The impact on the boundary as an effect of the lineament between Alnäsaträsk-Norrsund-Bondansträsk is largely unknown. Data points towards locally shallow elevation, but as conductivity measurements were performed in a disturbed environment, larger errors are expected.

from approximately -15 m.a.s.l. in the northwest towards -35 m.a.s.l. in the southeast and has a slightly undulating profile. The displacement of a modeled 40 ohmm conductor is approximately -25 m.a.s.l. to -45 m.a.s.l in the same area. This equals to a dip of 20 meters over 5000 meters, which is equal to approximately 0.2 degrees. Just as in area A it seems as if the saline boundary is parallel to the dip of the geological strata.

During field work the electrical conductivity of the groundwater was measured in two privately owned wells in area B. Both wells showed elevated electrical conductivities (Fig 18) which could be interpreted as an indication of relic saline groundwater. Other explanations are deficient wastewater management or local intrusion of saline groundwater through fractures. Lineaments running parallel to the topographic low of Alnästaträsk-Norrsund-Bondansträsk (Fig. 26) are indicated from VLF data in Erlström *et al*. (2009). Data from the SkyTEM survey presented in the appendix B shows elevated electrical conductivity imprinted below the low point of Alnästaträsk-Norrsund-Bondansträsk in the mean resistivity layers (appendix B9-B12) down to a depth of -30 m.a.s.l.. The previously known lineament in combination with the measured elevated electrical conductivities of the groundwater and the newly acquired SkyTEM data, points towards a possible fault or fracture zone running along Alnästaträsk-Norrsund-Bondansträsk, a zone where saline groundwater is found at superficial level.

5.2.2 Groundwater extraction potential

The largest quantities of groundwater are interpreted to be available along the southeastern part parallel to the coast where the fresh groundwater zone has the largest thickness. The thickness of the fresh groundwater zone is interpreted to increase from northwest along the dip of the geological strata towards SSE. Large variations in local hydraulic conductivity are expected as the conductivity varies greatly with fracture patterns and rock permeability properties. This is confirmed by data in the national well archive, where reported capacities of groundwater in private wells in this area ranges from 0.09 – 12 m^3/h within area B.

Along the RMT-C profile in the western most part of area B (Fig. 12 & Fig. 19) a low resistive layer, < 100 ohmm, is found at a depth of approximately 20 meters subsurface. Beneath the layer, which has a thickness of approximately 10 meters, a vague layer with a resistivity of 100-200 ohmm is found. This interlayering stratigraphy, which is interpreted as calcarenite-marlstone/marl-calcarenite, is not as clearly visible in SkyTEM data in the same area and its extent is not fully known. Possibilities are that the marl/marlstone layer is present at a large extent and that the SkyTEM data does not have sufficient resolution due to resistivity equivalence (Fig. 10) to display it. The marl/marlstone layer could act as a confining layer with respect to hydrogeological properties. As a result the lowermost layer of calcarenite could act as a confined aquifer, although its thickness is interpreted to be of limited significance to yield a large aquifer, as seen on the profile RMT-C in Fig. 19.

5.3 Area C: Marpes – Ajnestadar

Area C is defined by strong heterogeneities in the resistivity data; the two largest anomalies of the island boarder each other within area C. A southwestern lens of high resistive bedrock have surface layer resistivity of >2000 ohmm and modelled layers show a resistivity of over 300 ohmm down to more than -70 m.a.s.l., see appendix B. The resistivity of the lens at these depths is elevated compared to the rest of Fårö. 300 ohmm values are comparable to values of surface resistivity for the majority of Fårö, but within the high resistive anomaly in area C values of this magnitude are found at great depths, see Fig. 28. Just north of the high resistive anomaly is an area with the shallowest elevation towards the first good electrical conductor. This low resistive anomaly stands out when modeling the first good electrical conductor in all three rasters presented in the appendix A. In combination, these two anomalies with great contrast in their resistivity define area C.

The high resistive lens has not previously been described in any geological literature. Its lithology is previously undescribed, although the area is mapped as calcarenite by Erlström *et al*. (2009). But some conclusions can be drawn based solely on data from the

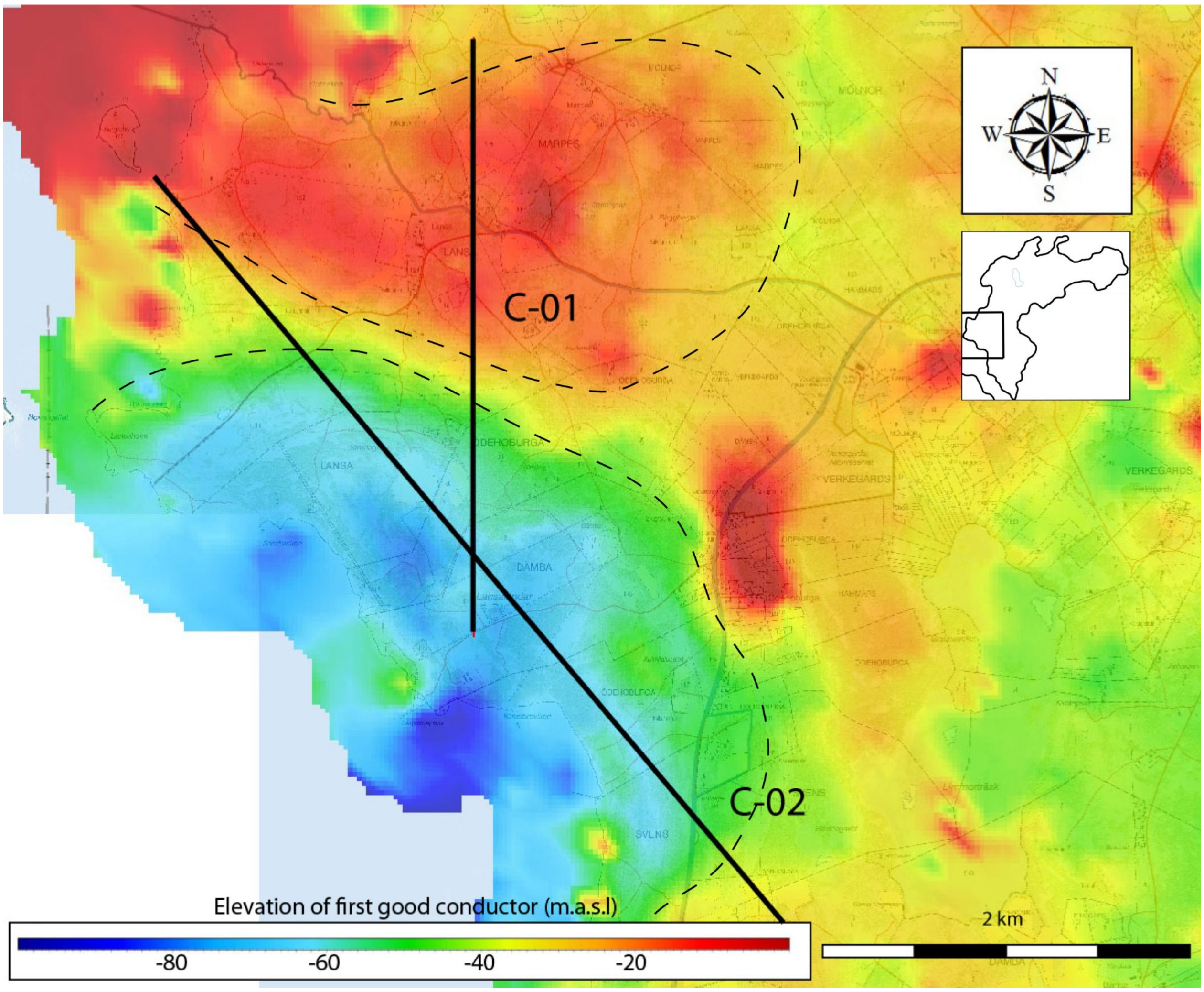

Figure 28. Profile C-01 and C-02 cross the diagnostic anomalies of area C, which are highlighted by dashed lines. The northern area close to Marpes nature reserve with a shallow conductor is interpreted to represent a shallow marl/marlstone layer and the southern high resistive lens is interpreted as a massive low-porous bedrock lens.

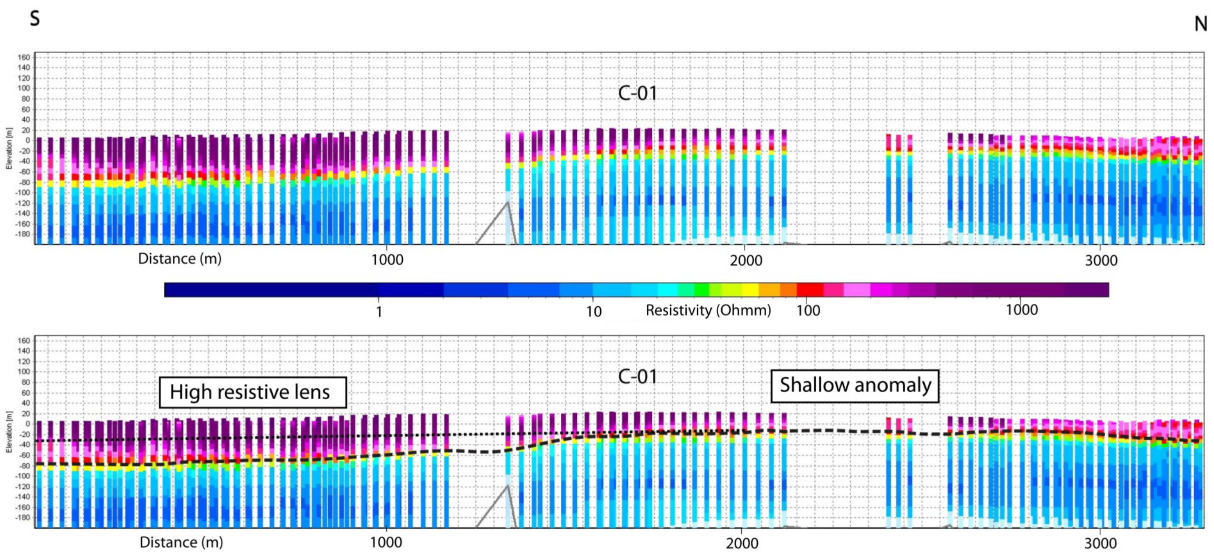

Figure 29. Profile C-01 displays the largest contrast in electrical resistivity in the bedrock of Fårö. The transect shifts from the high resistive lens in the south over to an area with a shallow conductor in between 1600 – 3000 m. To highlight the rampant anomaly a dotted line with a dip of 0.6 degrees is plotted as a reference line, an otherwise high value for the first good conductive layer of Fårö.

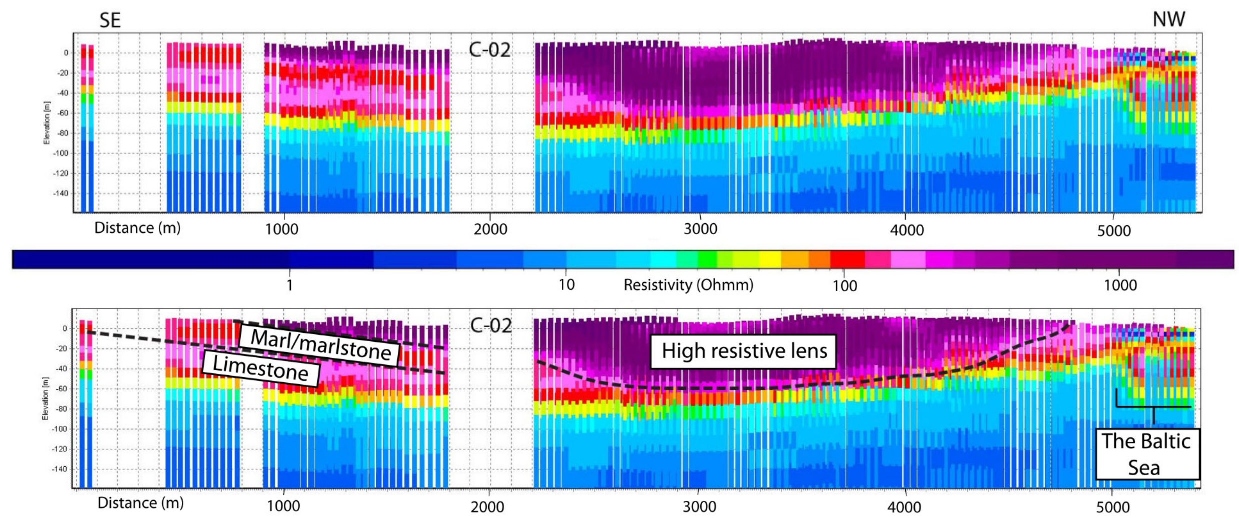

Figure 30. Resistivity data from profile C-02, the top transect is presented without and the bottom transect with interpretation. The southeastern part shows a lithology with dip towards northwest, which is the total opposite compared to the majority of Fårö.

SkyTEM survey. As can be seen in profile C-01 and C-02, the lens is overlying a sequence in the eastern area with an identical resistive pattern to the geological strata in area D and the coastal areas in area B, Fig. 29 and 30. The geology southeast and beneath the lens has a higher dip, approximately 1.3°, and in the opposite direction compared to the rest of Fårö. This is interpreted as that the lens and its possibly higher density has led to local subsidence of the underlying strata.

Archie´s law state that a high formation factor is favored by low porosity and a high amount of consolidation. Even below the level where the saline groundwater boundary would be expected compared to the remainder of Fårö (-20 to –50 m.a.s.l.) measurements from the lens yields a resistivity of over 300 ohmm. Such a high resistivity could only be achieved in bedrock saturated with saline groundwater if porosity would be sufficiently low according to Archie's law, <6% when R_w = 1 ohmm. This lens is therefore of no interest in any further groundwater prospecting as the porosity is estimated to be insufficient for any significant groundwater extraction.

5.3.1 SkyTEM and RMT

A large contrast in the depth to a modeled conductive layer is present in area C. Below the high resistive lens the depth is -80 and -90 m.a.s.l to layers with a maximum resistivity of 100 and 40 ohmm respectively. In the neighboring area at a distance of 1500 meters north, the first conductive layer is modeled to be at -15 and -20 m.a.s.l. respectively. Such a huge contrast in depth at a relative small distance suggests that the modeled conductor below the high resistive lens does not conform to the boundary between the saline and fresh groundwater. The conductor below the high resistive anomaly is thought to represent a bedrock boundary between a highly consolidated and massive bedrock lens overlying marl and marlstone. A viable scenario is that the lens has such a low effective porosity that the transition between fresh and saline groundwater yields no clearly visible result in the SkyTEM data within the lens.

In the area south of Marpes nature reserve (Fig. 28) where the modeled conductor is situated at a shallow depth of -15 to -20 m.a.s.l. several variables could give rise to such an anomaly:

1. A shallow boundary between fresh and saline groundwater.
2. Low resistive bedrock such as marl or marlstone.
3. A low formation factor resulting from high porosity and low consolidation.

The initial two scenarios would yield a geological model with a low possibility of extraction of any high quantitative and qualitative groundwater. The last scenario would yield a geological model with a large estimation of potential groundwater extraction. Further investigations would be required to accurately determine the hydrogeological properties of this area, but some speculation can be done. Two profiles, RMT-A and RMT-B, from the radiomagnetictelluric survey overlap with the shallow conductor south of Marpes nature reserve. Both sections of the profiles show coherent results with a high resistive layer of 10-20 meter thickness lying on top of bedrock with lower electrical resistivity. The top surface of the marl/marlstone layer in the northern half of profile RMT-C (Fig. 19) is situated at the same elevation as the top surface of the shallow low resistive anomaly south of Marpes. This indicates that the marl/marlstone layer possibly continues into the area of the shallow anomaly which would strengthen the probability of the second scenario. Electrical conductivity measurements were performed in two wells (Fig. 18) within the shallow conductor anomaly. Neither of the wells had elevated electrical conductivities which excludes scenario 1 as a likely explanation. Further, if scenario three, with exceptionally high bedrock porosity and low consolidation should be true, there should be a secondary boundary in the resistivity data. This second boundary between saline and fresh groundwater would be expected as ion concentrations would further decrease the formation resistivity. This is not visible in the data. Contrary, the SkyTEM data in profile C-01 displays a quite sharp boundary between the high and low resistive layers which would fortify one of scenario 1 or 2 with a small possibility of extraction of any high quantitative and qualitative groundwater. RMT data and conductivity measurements both suggest that low resistive bedrock such as marl/marlstone and not saline groundwater is the reason for a shallow first good conductor in the area south of Marpes.

5.3.2 Groundwater extraction potential

Area C is interpreted to have the least potential out of the four areas, for any significant groundwater extraction. The high resistive lens is interpreted to have a porosity which is so low that it is mapped as an aquitard. The area south of Marpes nature reserve is considered to have a small potential for any large fresh groundwater extraction, as the most likely scenarios are interpreted to yield a low potential for quantitative and qualitative groundwater.

5.4 Area D: Southeastern peninsula

Area D deviates in its geology due to its coarser limestone and large extent of marlstone. The eastern half of the peninsula has been mapped as coarse crystalline limestone and argillaceous medium crystalline limestone (calcarenite). The western half of the peninsula has been mapped as marl and marlstone by Erlström *et al*. (2009), see Fig. 4. The area mapped as calcarenite show a conductive layer, 100-120 ohmm, at a depth of between 0 and -10 m.a.s.l in the SkyTEM data, clearly visible in the mean resistivity layer 8 and also in profiles D-02 and RMT-B, see Fig. 33 and Fig. 19. This strong conductor is interpreted as a layer of marl and/or marlstone. Beneath the conductive layer is a 30-40 meter thick layer with a higher resistivity, 150-250 ohmm, though SkyTEM does not have a high accuracy in determination of the absolute resistivity of resistive layers between conductive layers due to resistivity equivalence, its thickness can still be accurately determined, see Fig. 10 and Christiansen *et al*. (2009). The resistive layer is also present in SkyTEM data in the area mapped as marl and marlstone (Erlström *et al*. 2009). Both these layers are below the measured groundwater table and interpreted to be saturated by fresh groundwater. Therefore according to Archie’s law the resistive layer should have a higher porosity and/or lower consolidation. Based on this the layer is interpreted as bedrock, most likely limestone, with promising potential regarding hydrogeological properties. This yield a large possible groundwater aquifer, with a thickness of up to 30-40 meters and an area of approximately 20 km^2, delimited upwards by the layer of marl and marlstone and downwards by saline groundwater.

By using Archie´s law and the results from geophysical borehole logging (appendix D), a rude calculation of the porosity can be made. Measured electrical conductivities of the borehole fluid in well 914610436 range between 70 and 90 mS/m. The formation resistivity in the geophysical logging data, at the top of the interpreted boundary between saline and fresh groundwater at -37 meters above sea level is approximately 250 ohmm. These values of borehole fluid electrical conductivity and formation resistivity would yield a formation factor of 18 by using Eq. IV. Depending on the consolidation factor, Eq. V would yield bedrock porosity values between 11 and 24 % where the higher porosity values would be achieved in a well consoli-

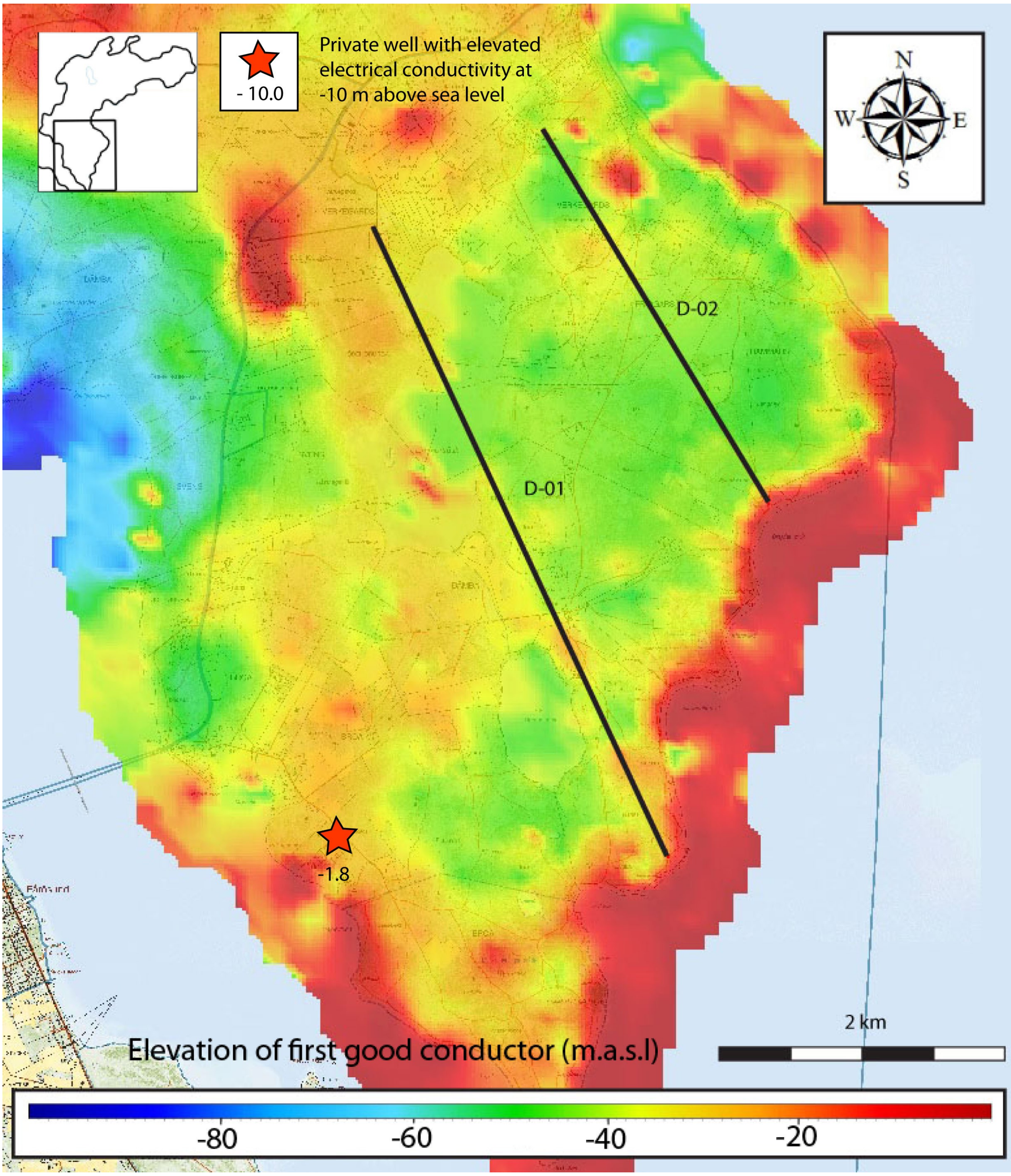

Figure 31. Positions of profiles D-01 and D-02 plotted on top of a raster containing the elevation of the first good conductor. Area D is defined by its relatively large depth towards the first good conductor.

dated environment. As consolidated limestone is expected to be the dominating lithology at these depths (Varadi 1982), the porosity is likely approaching 24 % rather than 11 %. By using resistivity data from SkyTEM for the area around well 914610436, a formation resistivity of 150 ohmm was measured at the top of the interpreted boundary between fresh and saline groundwater. By using the same methodology, Eq. IV and V would yield a formation factor of 10 and a porosity approaching 31 % by using data from the SkyTEM survey. This rude calculation indicates that bedrock porosity in this area is in the vicinity of 20-30%.

The National Food Agency of Sweden has defined suitable drinking water to have an upper limit in its electrical conductivity of 250 mS/m in order to prevent corrosion of water pipes. In a geological setting with a formation factor of 10, this is equal to a formation resistivity of approximately 40 ohmm. As the formation factor is a site-specific quantity and geophysical logging data yield a formation factor of 18 compared to 10 when using SkyTEM data, a value of 100 ohmm can be used in order not to overestimate the aquifer. As a result, when estimating the extraction potential of fresh groundwater, the elevation of the first conductor with a maximum resistivity of 100 ohmm, Fig. 31, can be used in order to delimit the aquifer downwards.

5.4.1 Boundary between saline and fresh groundwater

Results from the SkyTEM survey show a modeled conductive layer with a gentle dip of approximately 0.2° towards the southeast. The depth to the modeled conductor with a maximum resistivity of 40 ohmm ranges from -40 and -60 m.a.s.l. The depth to the corresponding conductor with a maximum resistivity of 100 ohmm ranges from -30 and -50 m.a.s.l. In both profile D-01 and D-02 (Fig. 32 & Fig. 33) the transi-

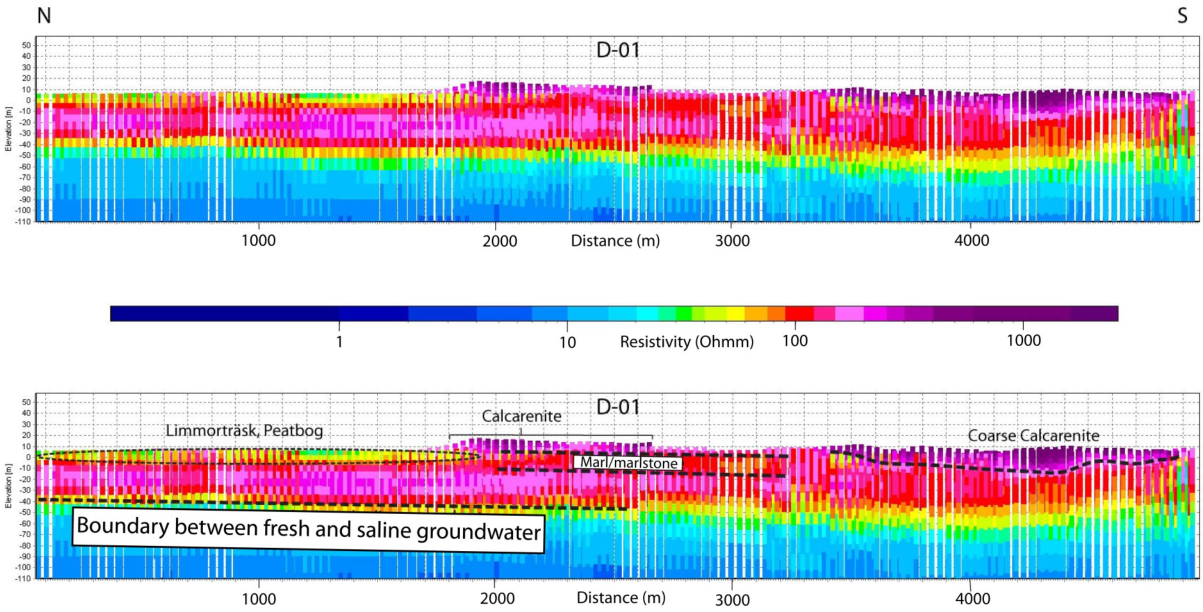

Figure 32. SkyTEM data from profile D-01, the upper transect is presented without interpretation and the lower transect is the same data presented with interpretations. The eastern part beneath the coarse calcarenite displays a diffuse transition zone, which makes it harder to accurately interpret the boundary between fresh and saline groundwater in this area.

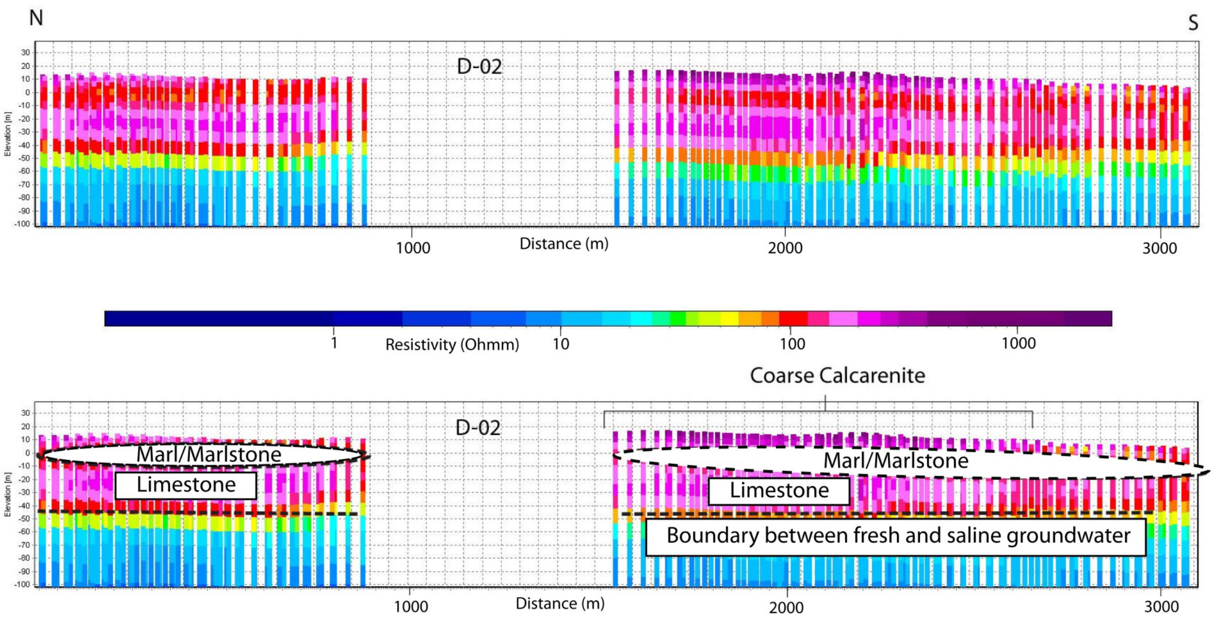

Figure 33. SkyTEM resistivity data from profile D-02, presented without (upper) and with (lower) interpretation. The interpreted limestone unit is estimated to have a thickness of 30-40 meters and is mapped to have the highest potential for any substantial groundwater extraction on Fårö.

tion zone between high and low electrical resistivity is thicker than in the other areas, especially in the southern part of D-01. This indicates that the transition zone has a weak gradient and as a result the determination of the displacement of the boundary between fresh and saline groundwater is accompanied by a larger uncertainty (Poulsen *et al*. 2006). Calibration of the interpreted boundary by onsite measurements, such as a borehole logging and salinity measurements, would strengthen the reliability of this interpretation greatly. The data from the well drillings and geophysical logging of well 914610436 is currently under processing by SGU but a preliminary interpretation indicates that the top of the transition zone between fresh and saline groundwater is situated at – 37 m.a.s.l. (appendix D). The corresponding formation resistivity from the SkyTEM survey at this depth is between 100 and 200 ohmm, values that can be used as a foundation to interpolate the position of the top of the boundary in area D, see Fig 34.

During the Temperature Level Conductivity measurements (TLC), one out of five sampled wells had an

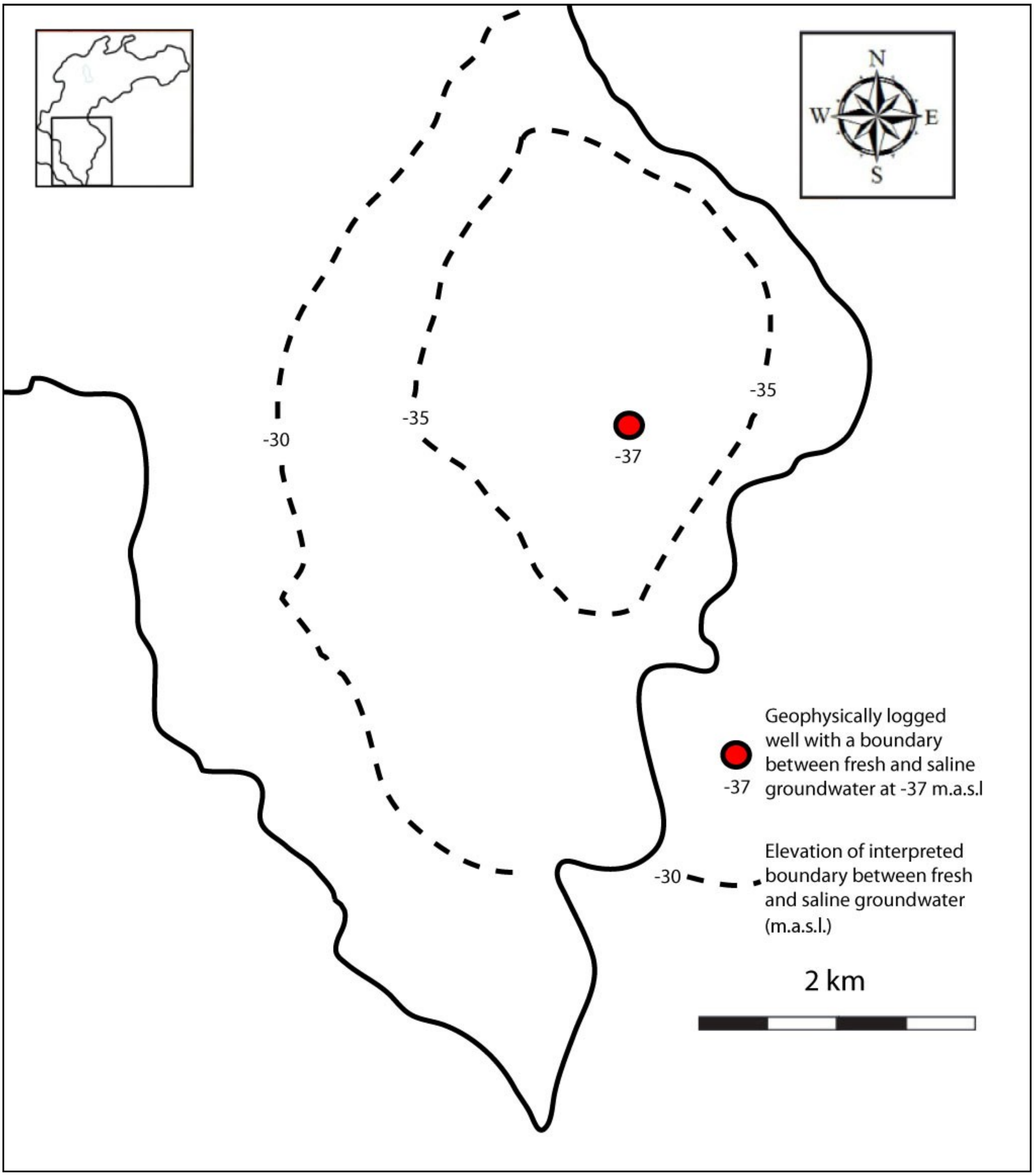

Figure 34. Interpretation of boundary between saline and fresh groundwater in area D. Resistivity data from the geophysical logging of well 914610436 was used to interpret and extrapolate the boundary in combination with RMT and SkyTEM data.

elevated electrical conductivity within area D. That well is situated in a near coastal environment on the southwestern peninsula (Fig. 18) and had an electrical conductivity of 240 mS/m at the water table level at -1.8 meters above sea level, which indicates intrusion of saline water. When interpreted in combination with the increased thickness of the transition zone towards the southern part of the peninsula, larger uncertainties in the determination of the saline boundary are present along coastal parts of area D compared to the central part due to coastal intrusion of marine water and also due to a weaker gradient of the transition zone.

5.4.2 Groundwater extraction potential

Due to the 30-40 meter thick zone that is interpreted to be limestone saturated with fresh groundwater, area D is interpreted to have the largest potential out of the four areas for groundwater extraction. Results from the SkyTEM survey indicate a continuous layer of low resistive bedrock, most likely marl/marlstone, overlying a bedrock unit with higher electrical resistances. In the western parts of area D the marl/marlstone is exposed and in the eastern areas it is covered by calcarenite and coarse crystalline limestone, see Fig. 4. Marl and marlstone generally has lower hydraulic conductivities than limestone and could act as a natural barrier, an aquitard, and separate the two limestone lithologies into two aquifers, thus the lower aquifer is interpreted as a confined aquifer. In order to determine the absolute quantity of available fresh groundwater and if the lower aquifer is truly confined, one or more aquifer tests are required. As all available boreholes are estimated to be open boreholes, jointing the two aquifers, a suggestion is to establish a new borehole where the well is sealed down to beneath the confining marl/marlstone layer and then testing each aquifer separately by pumping and monitoring the response.

5.4.3 Risk Assessment

According to the previous survey by Region Gotland (2014), the central parts of area D belongs to vulnerability category 3 and 4 out of 5, see Fig. 14. No areas of Fårö are mapped to belong in any higher category, i.e. groundwater in area D is relatively well protected as compared to the rest of Fårö. The extensive marl/marlstone layer, which was identified by interpreting resistivity data, see Fig. 19, 32 & 33, could act as a confining layer and would therefore most likely decrease the vulnerability of underlying aquifers further.

Intrusion of saline water along the coastline is a possible threat towards groundwater quality in area D. As seen in Fig. 18, one privately owned well close to the establishment of Broa had elevated electrical conductivity values of 240 mS/m^2. Similar values could be expected, especially along the western coast during periods of overuse, as indicated by resistivity data.

Another threat towards groundwater quality of area D is the large fen peat, Limmorträsk, situated in the central parts of area D, see Fig. 12. As population density in this area is low and the number of wells is also sparse (Fig. 11), the amount of information about Limmorträsk is in comparison to the peat deposits on the densely populated Avanäs low. Even though the size of the impact is unknown it would be safe to say that the peat has a negative effect on local groundwater quality due to an increased amount of dissolved organic content.

One site with potentially contaminated soil is situated on the southern most tip of Ryssnäset (Fig. 15). The site is a former military shooting range and potential threats towards groundwater quality is mainly elevated levels of lead (Wanhatalo 2011).

5.5 Summary

Based on the results and the discussion for each separate area, Fig. 35 summarizes the pontential for groundwater extraction for entire Fårö. The map is divied into zones from low potential (category 1), where problems even with individual water supply can be expected, to areas with high potential (category 6), where water quantity and quality is expected to be sufficiently high to be used by municipal supply.

6 Conclusions

- Aquifers have been delimited and their relative potential for groundwater extraction has been interpreted according to Fig. 35.
- The highest probability to find large quantities of fresh groundwater is mapped in a 20.6 km^2 large area on the southern peninsula of Fårö.
- A 2.1 km^2 large area on southeastern Avanäs is mapped as the second most suitable area to find any significant quantity of fresh groundwater.
- The majority of Fårö is highly vulnerable to potential groundwater contamination

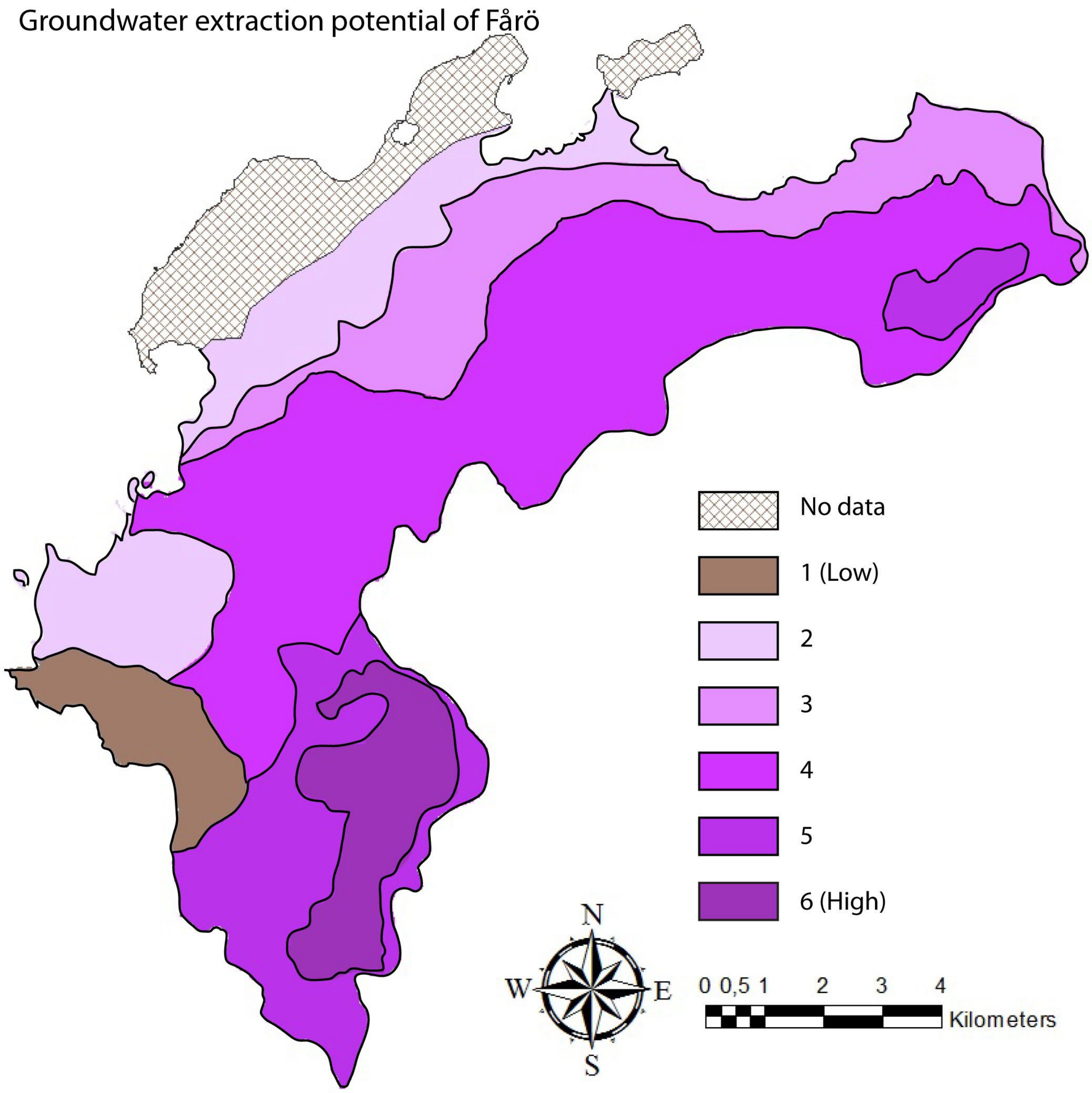

Figure 35. Map of relative groundwater extraction potential with extraction potential running from 1 (low) to 6 (high). Crosshatched areas are outside the study area and lack assessment.

7 Acknowledgements

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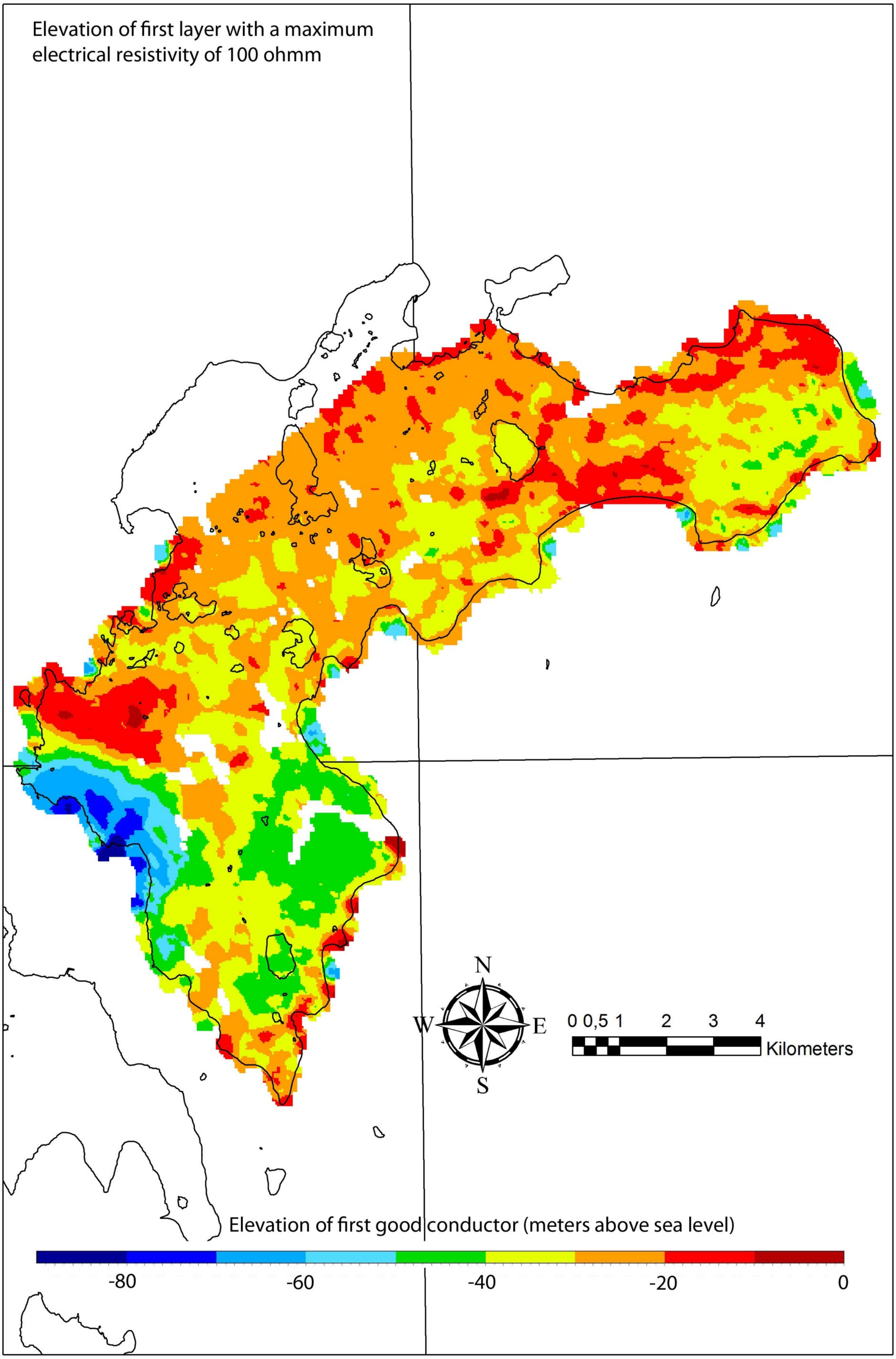
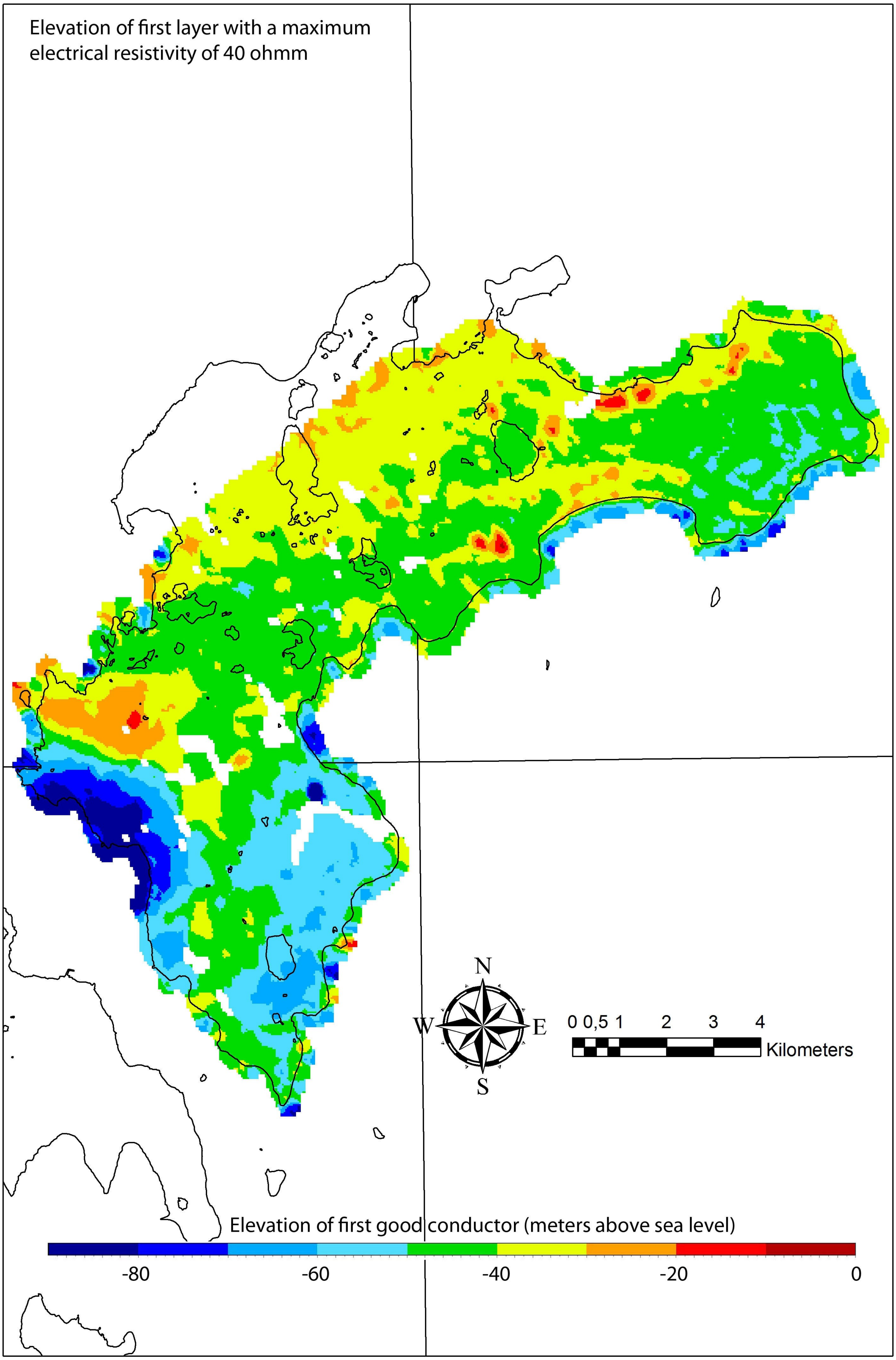
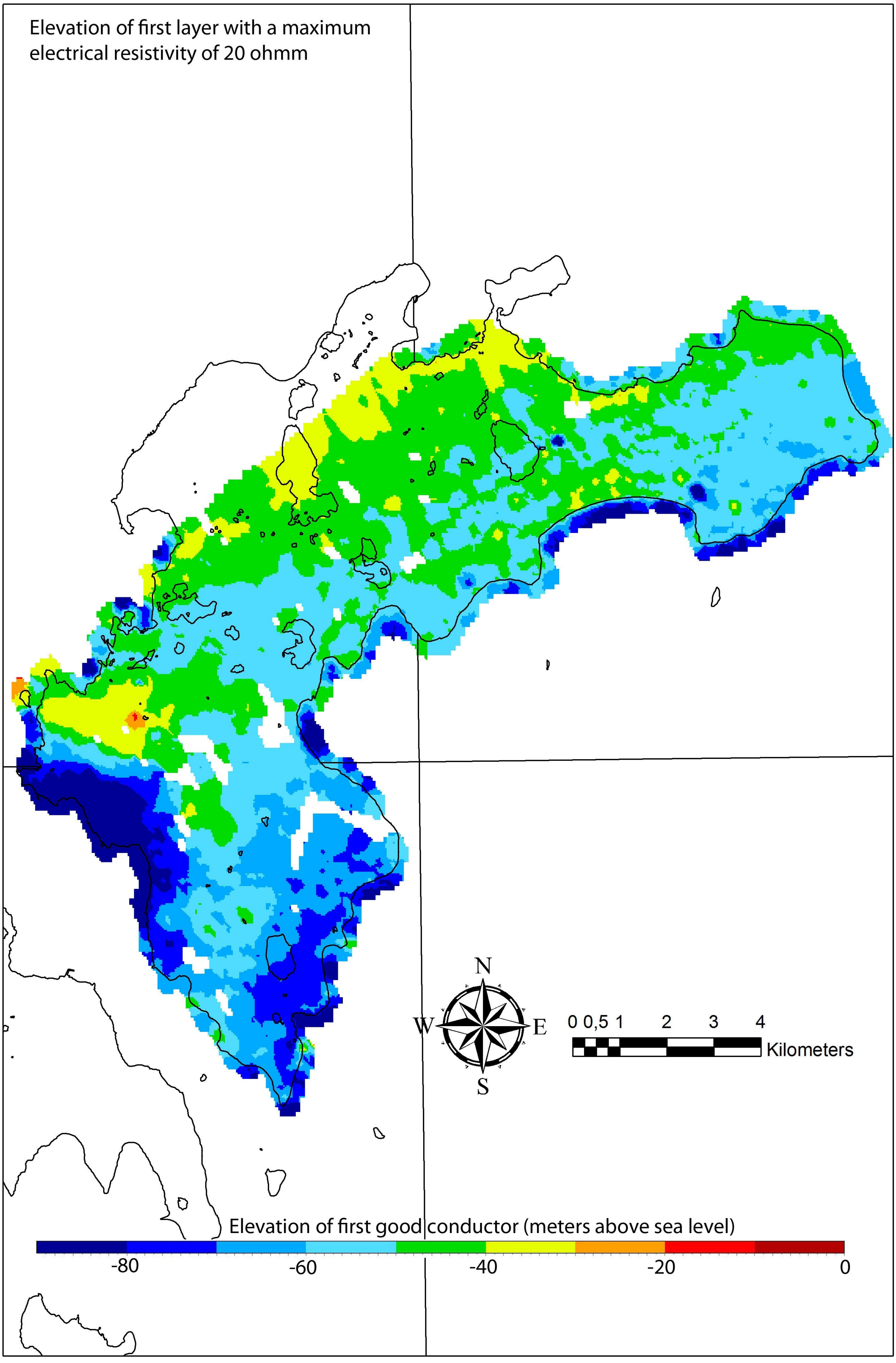
9 Appendix


Elevation of first layer with a maximum
electrical resistivity of 100 ohmm
N
W
E
S
0 0,5 1 2 3 4
Kilometers
Elevation of first good conductor (meters above sea level)
-80
-60
-40
-20
0


Elevation of first layer with a maximum
electrical resistivity of 40 ohmm
N
W
E
S
0 0,5 1 2 3 4
Kilometers
Elevation of first good conductor (meters above sea level)
-80
-60
-40
-20
0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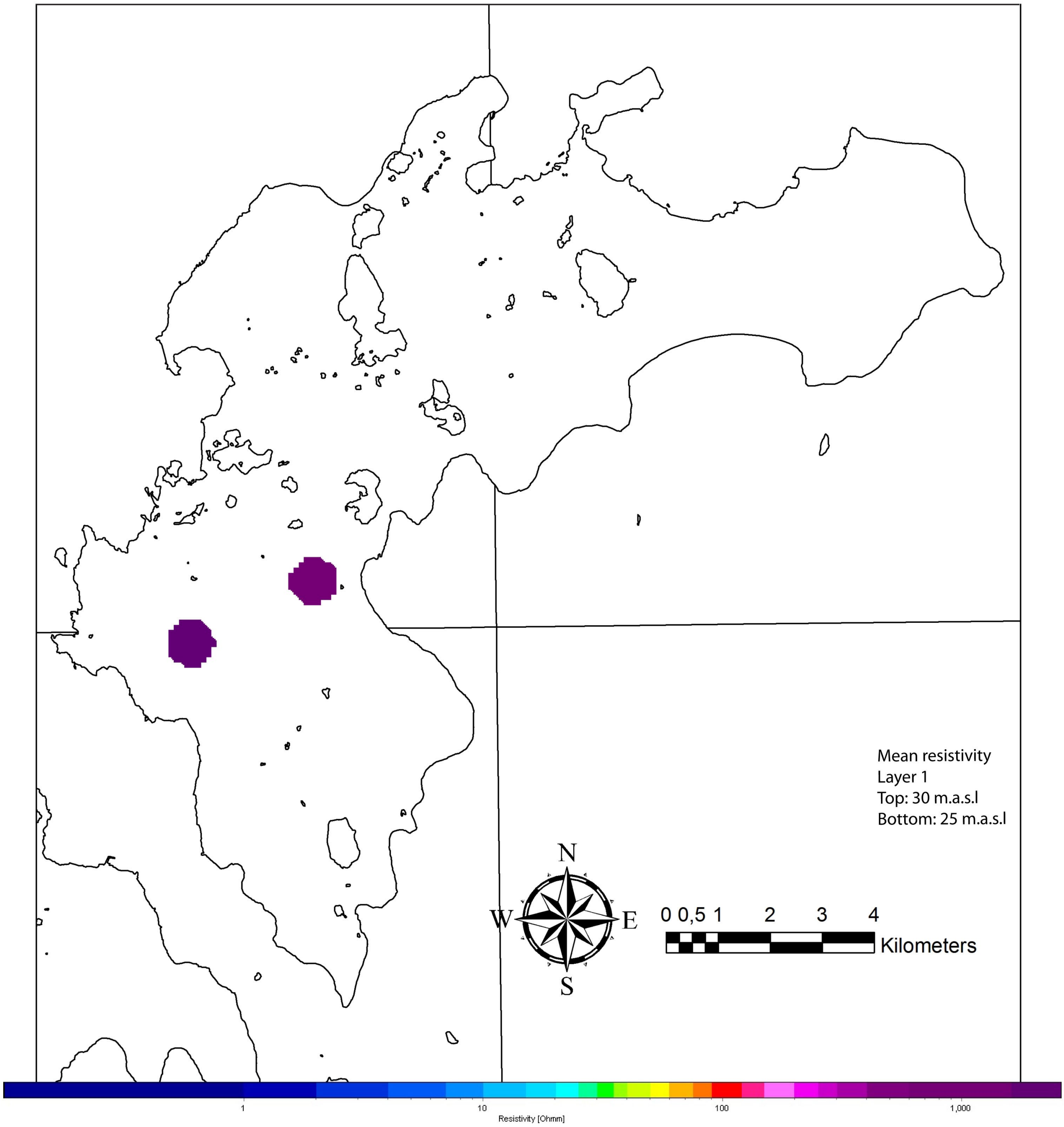
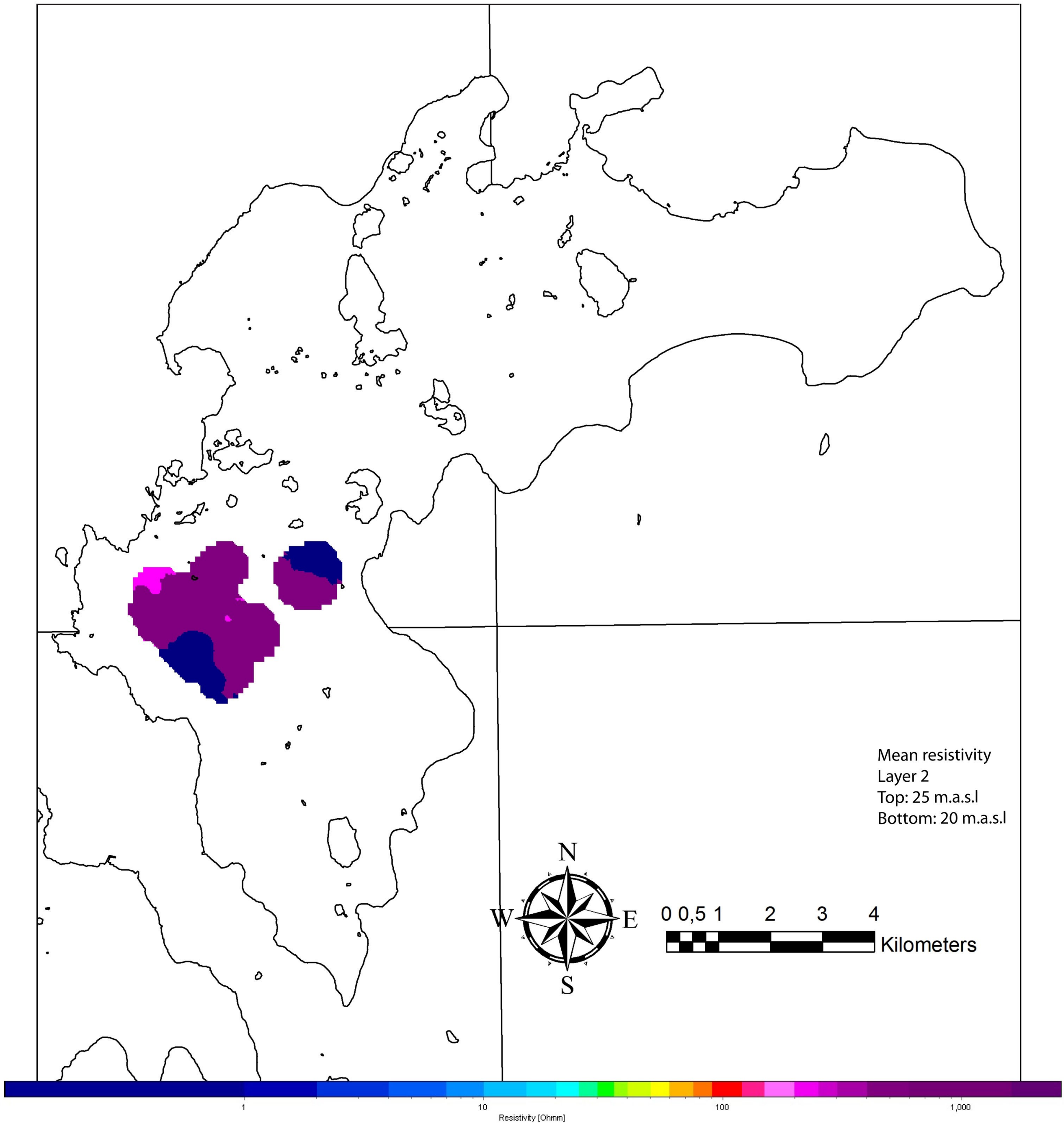
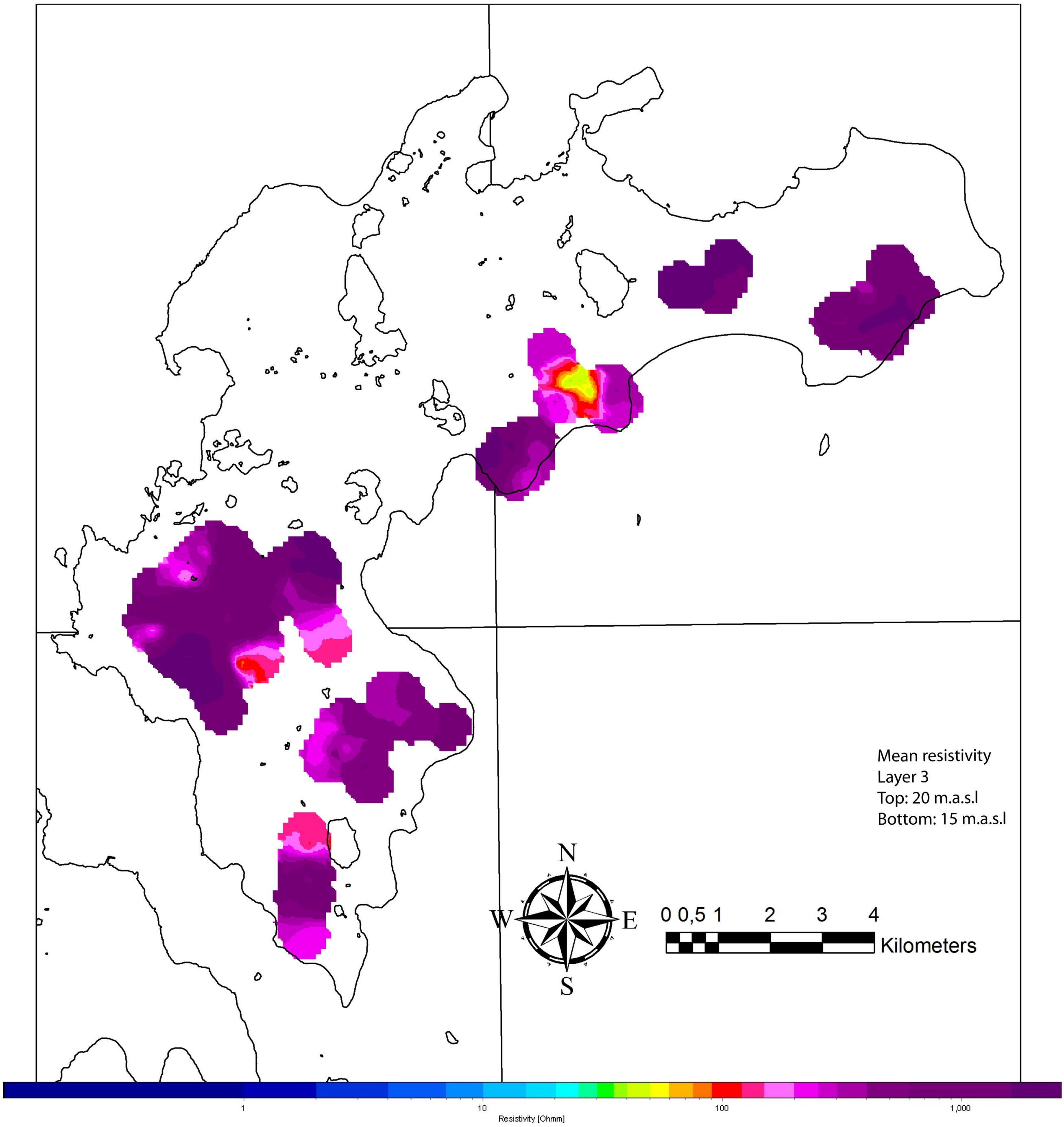
electrical resistivity of 20 ohmm
N
W
E
S
0 0,5 1 2 3 4
Kilometers
Elevation of first good conductor (meters above sea level)
-80
-60
-40
-20
0


Mean resistivity
Layer 1
Top: 30 m.a.s.l
Bottom: 25 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 2
Top: 25 m.a.s.l
Bottom: 20 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]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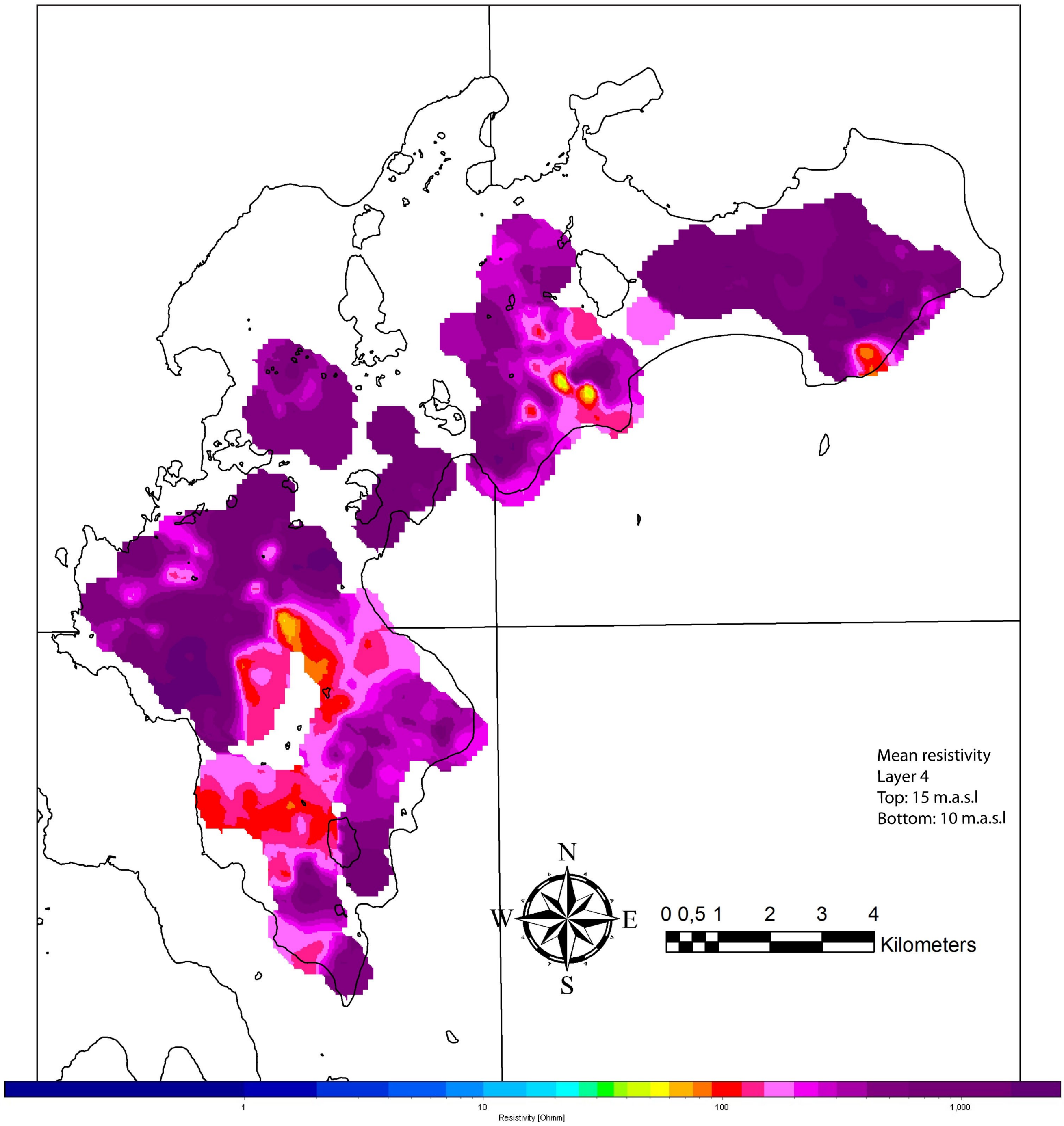
Layer 3
Top: 20 m.a.s.l
Bottom: 15 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]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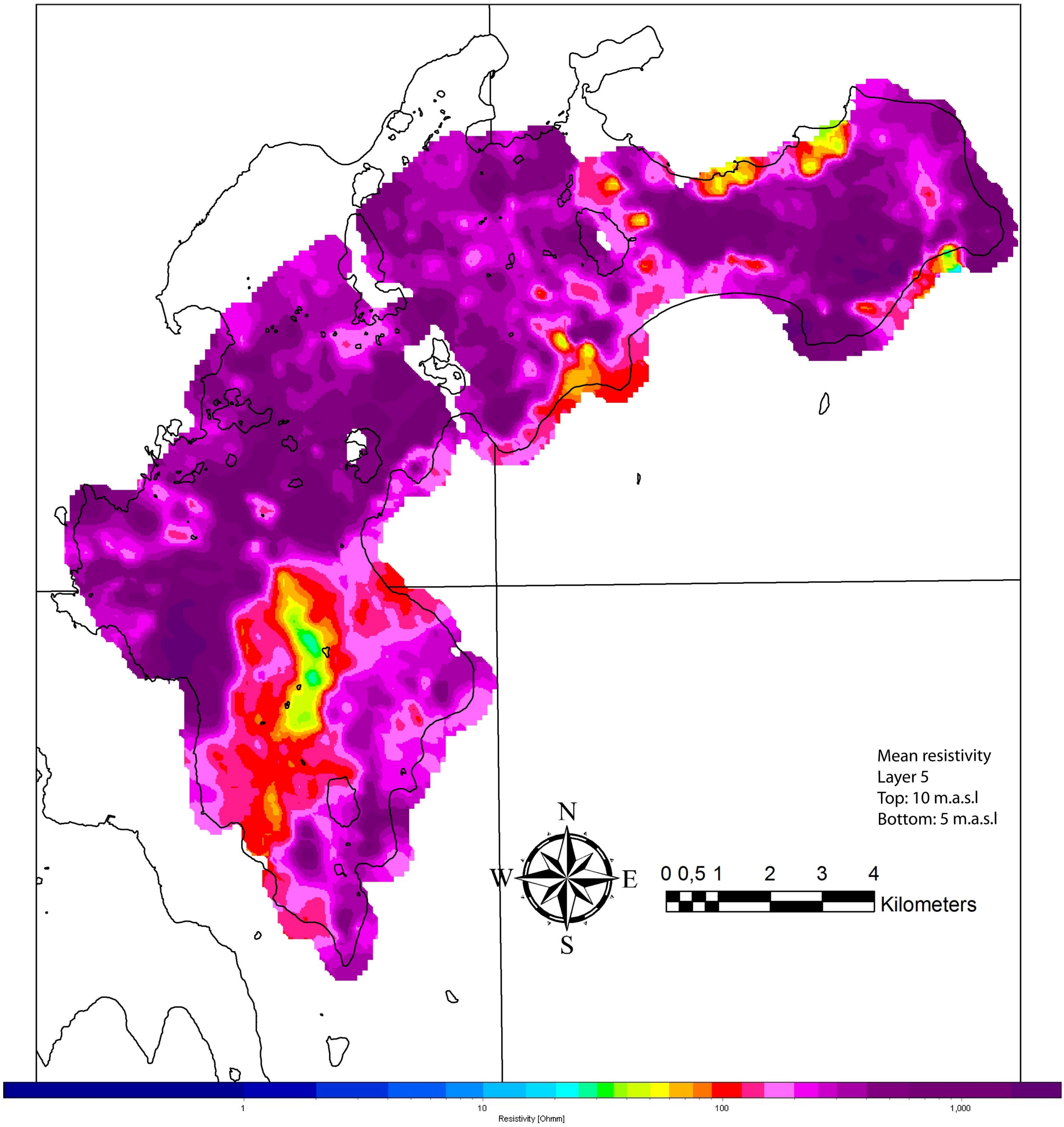
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]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Layer 5
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Bottom: 5 m.a.s.l
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W
E
S
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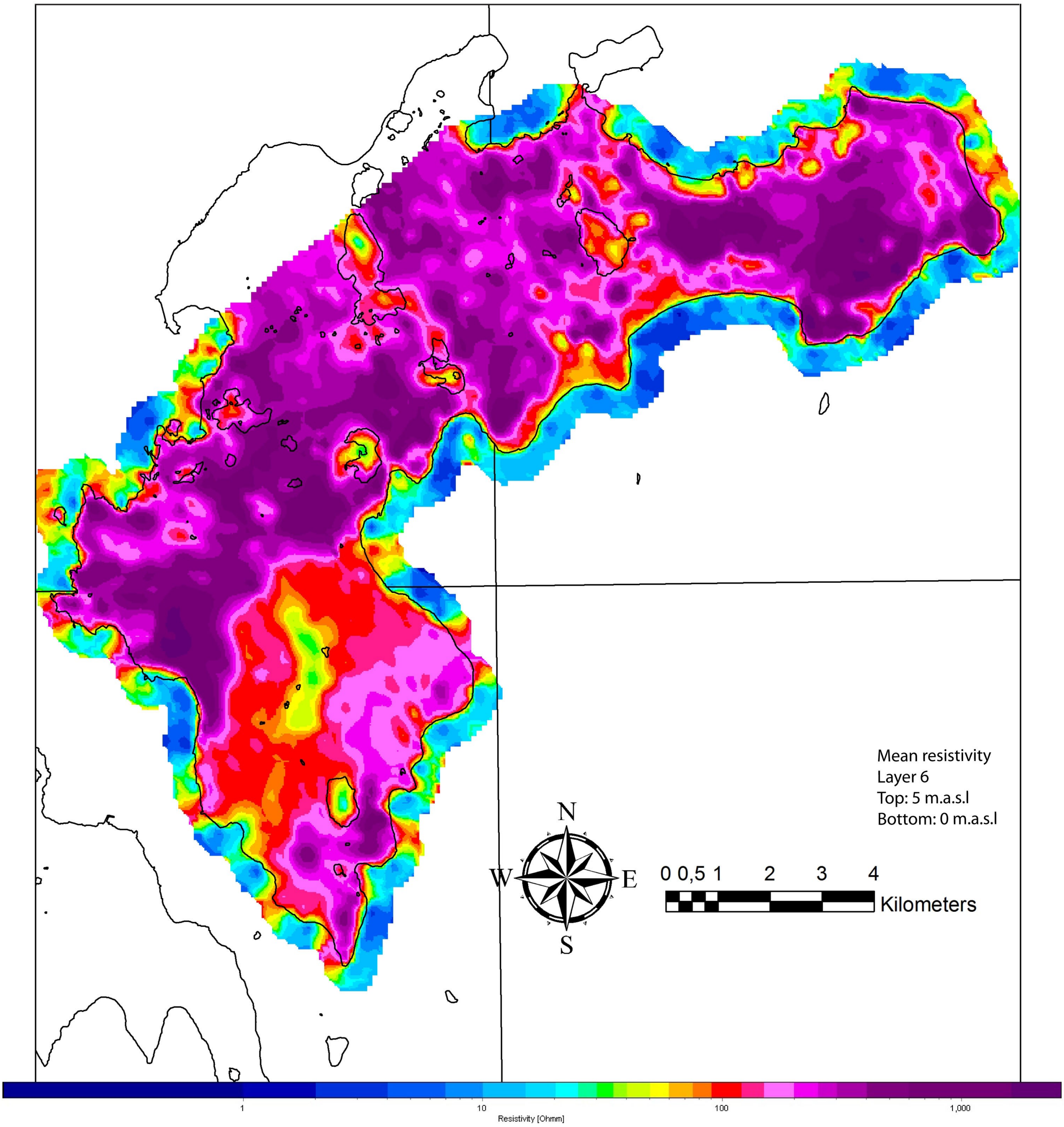
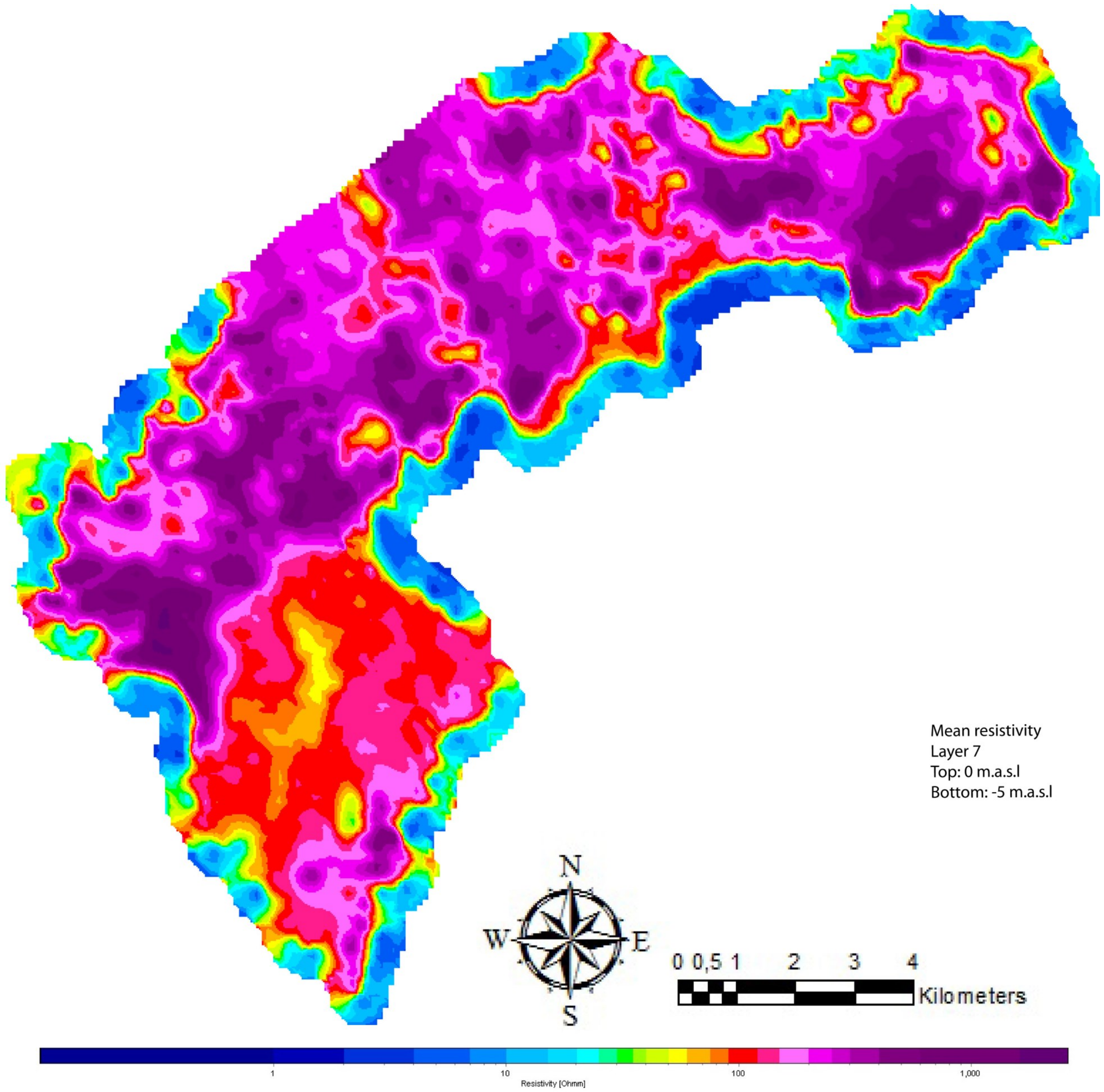
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 6
Top: 5 m.a.s.l
Bottom: 0 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]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Layer 7
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Bottom: -5 m.a.s.l
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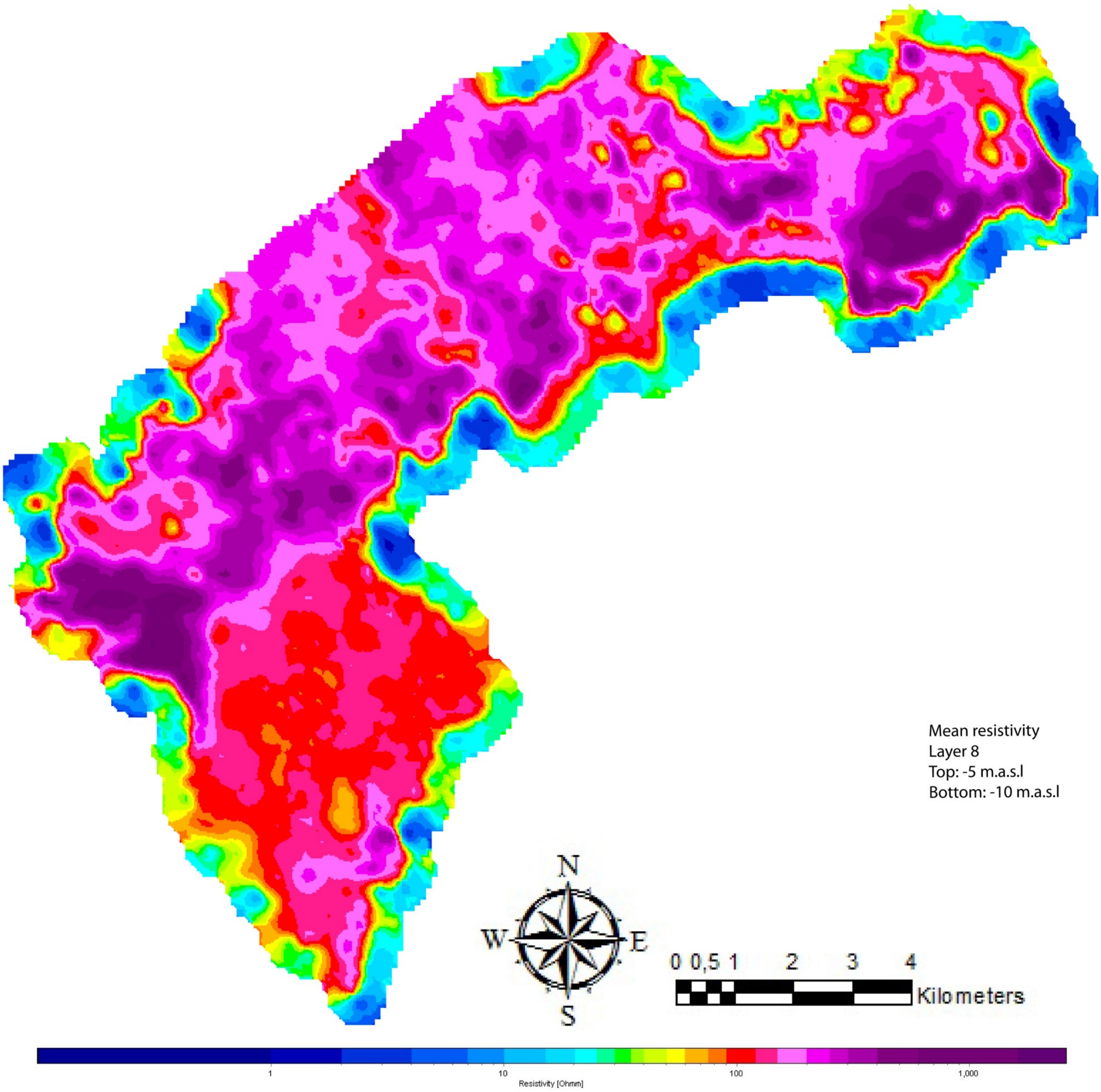
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]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Layer 8
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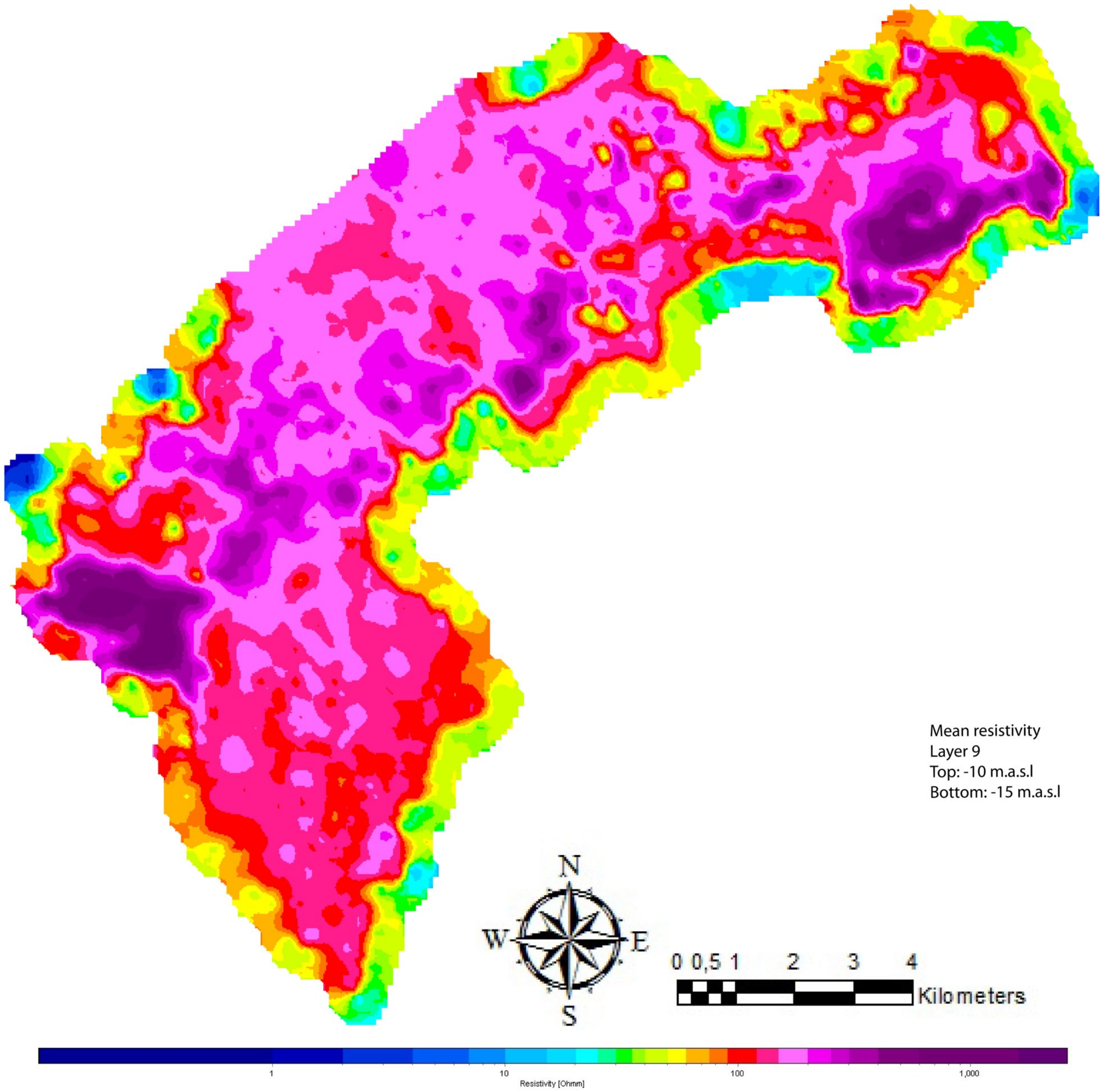
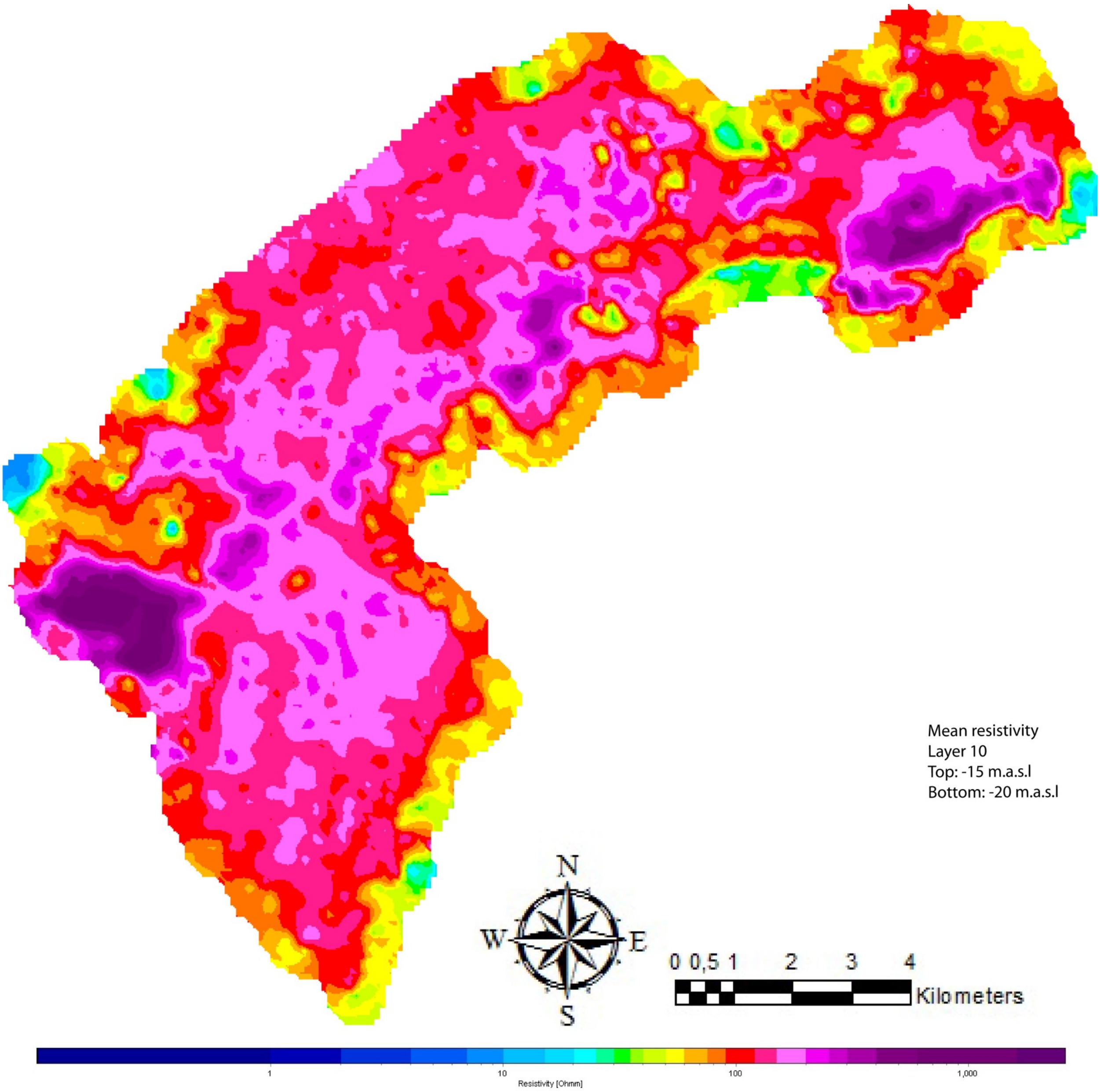
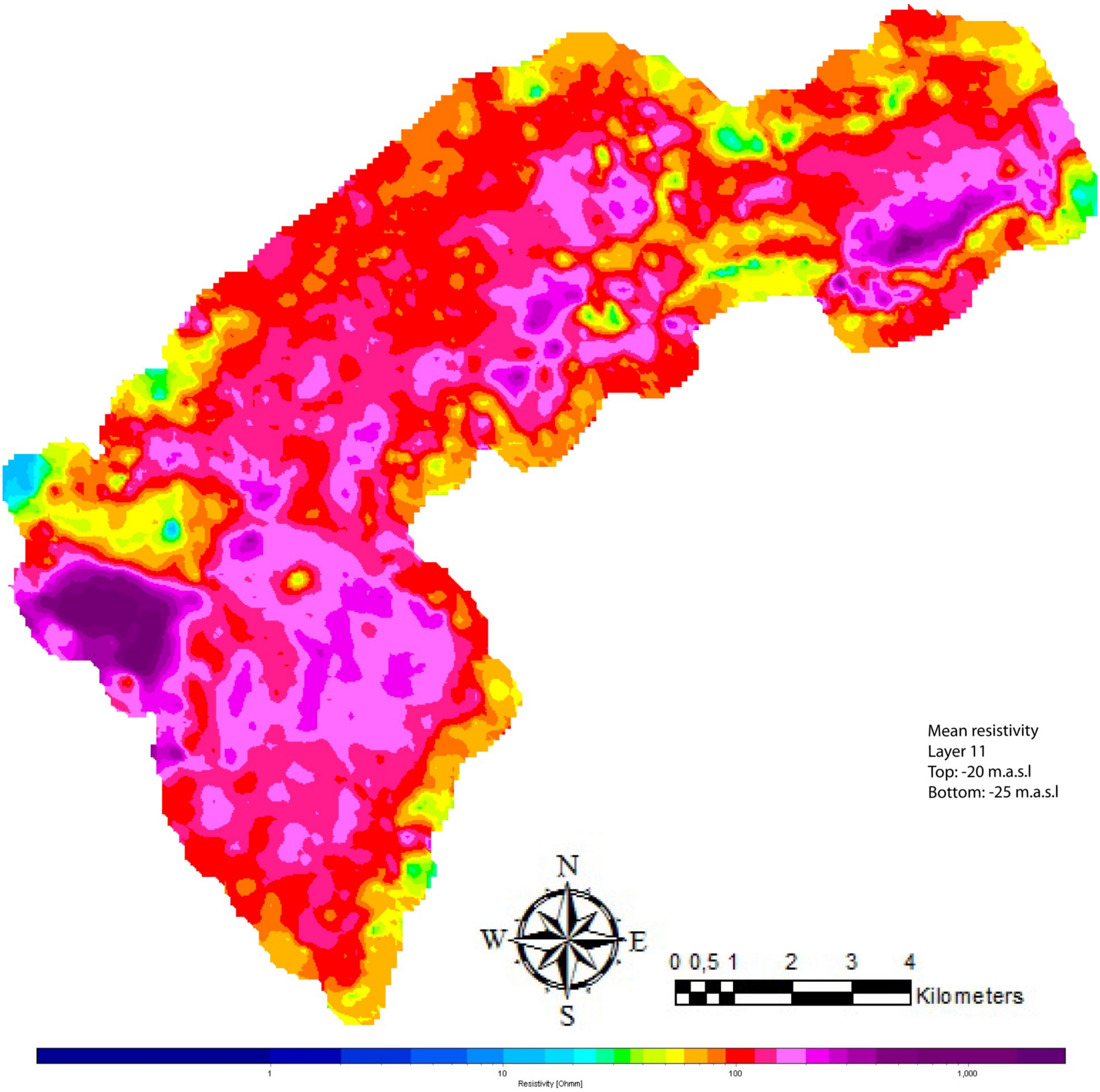
Bottom: -10 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 9
Top: -10 m.a.s.l
Bottom: -15 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 10
Top: -15 m.a.s.l
Bottom: -20 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 11
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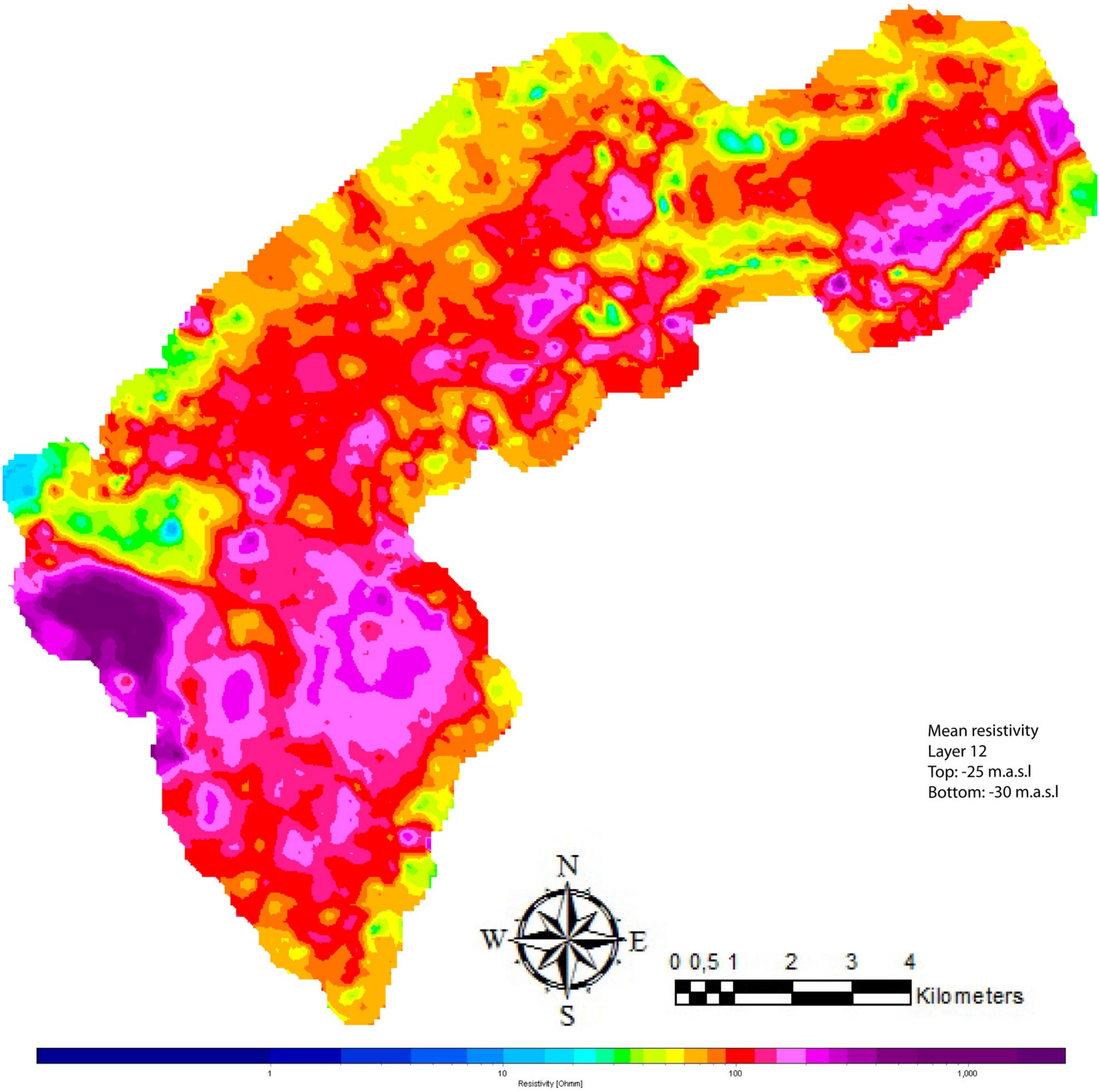
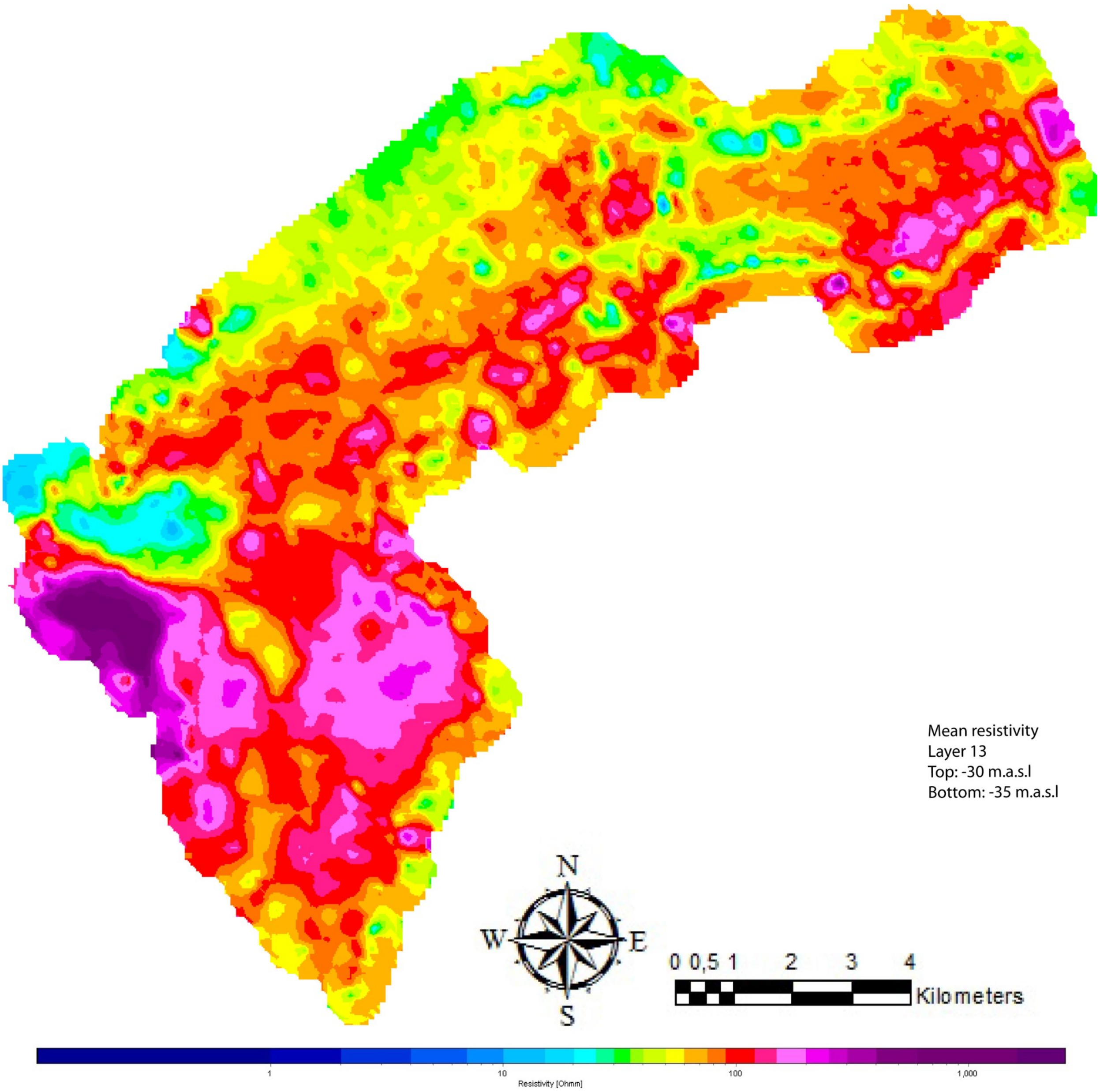
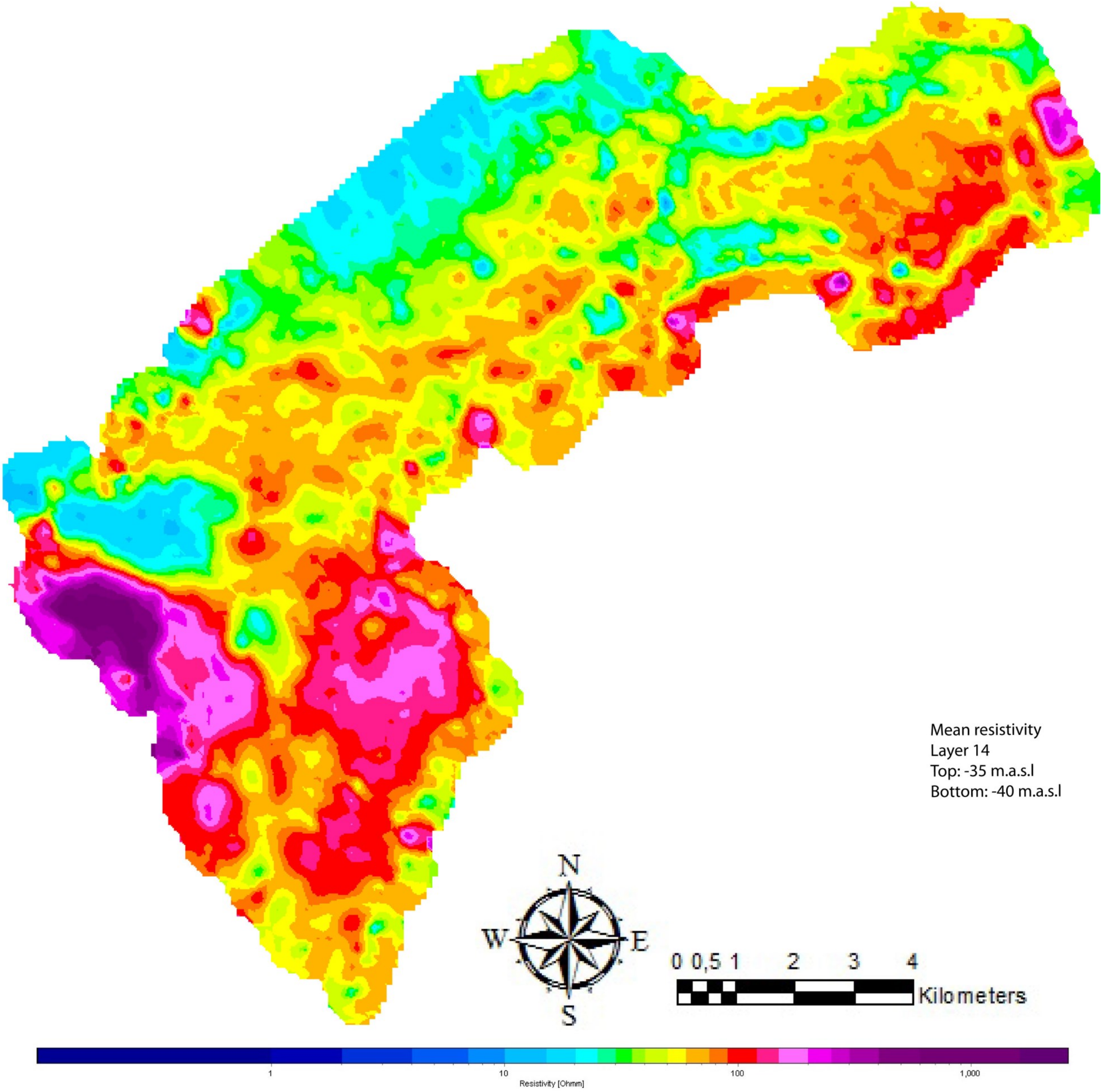
Bottom: -25 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 12
Top: -25 m.a.s.l
Bottom: -30 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 13
Top: -30 m.a.s.l
Bottom: -35 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]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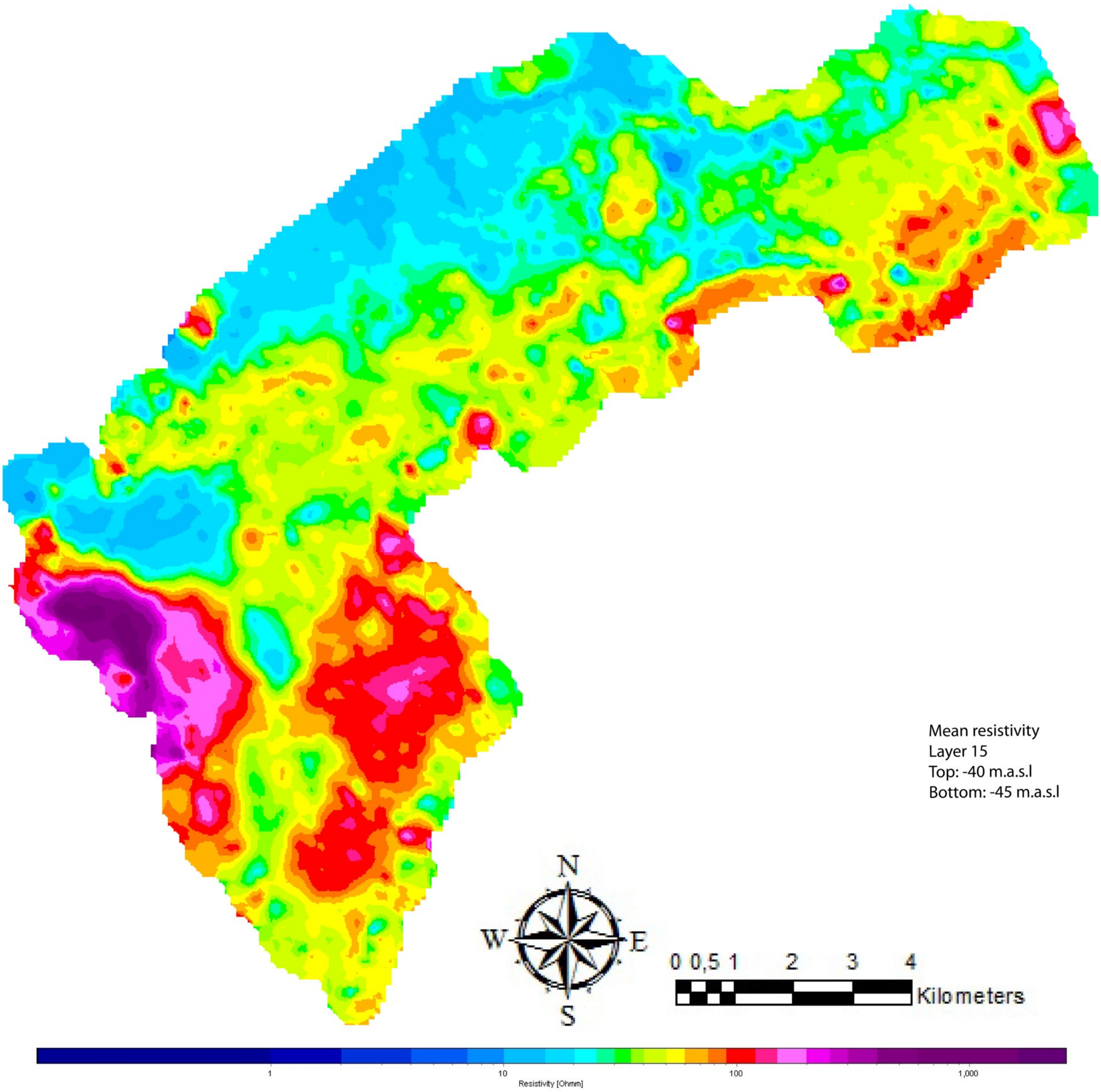
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
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Bottom: -45 m.a.s.l
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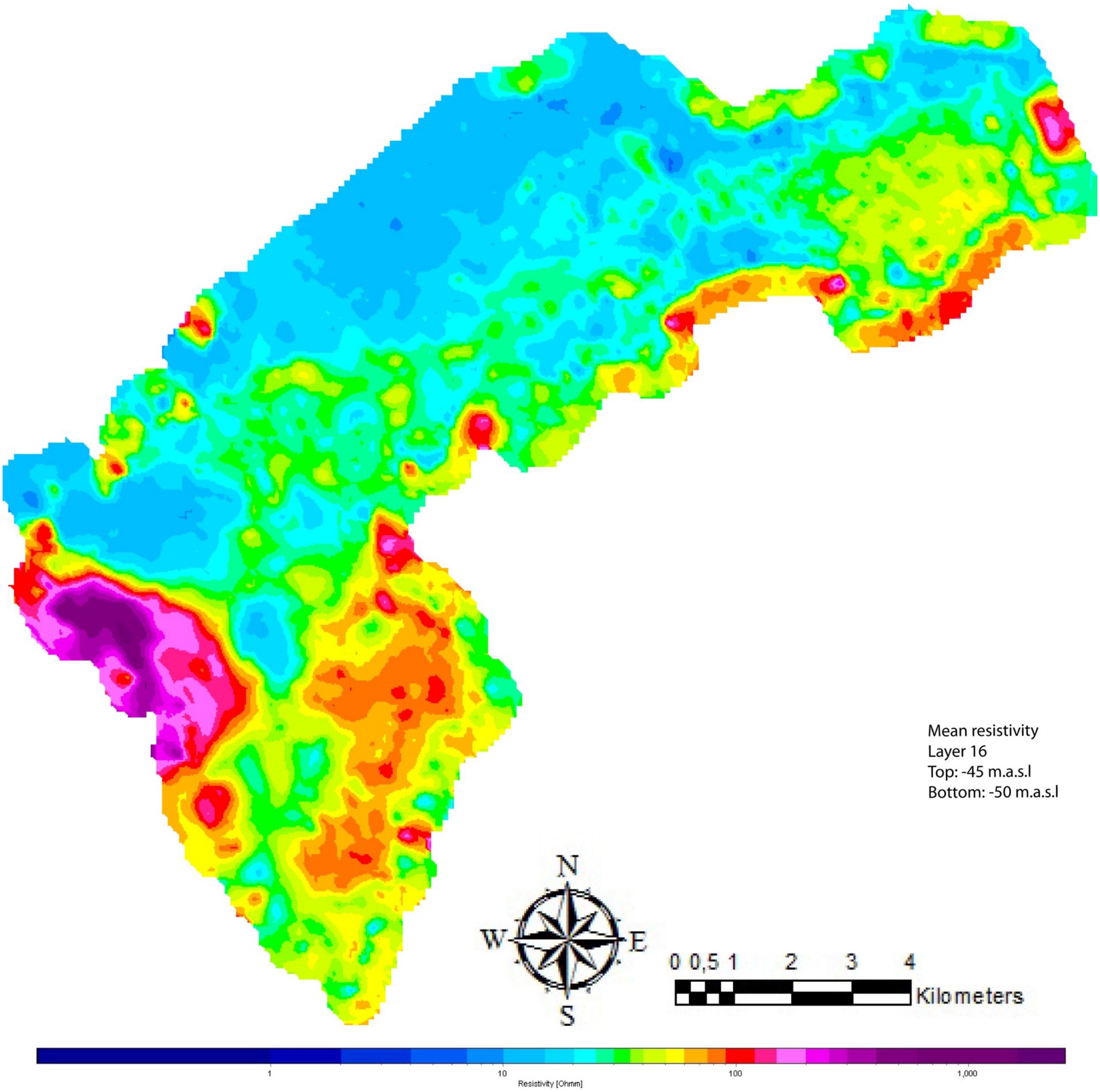
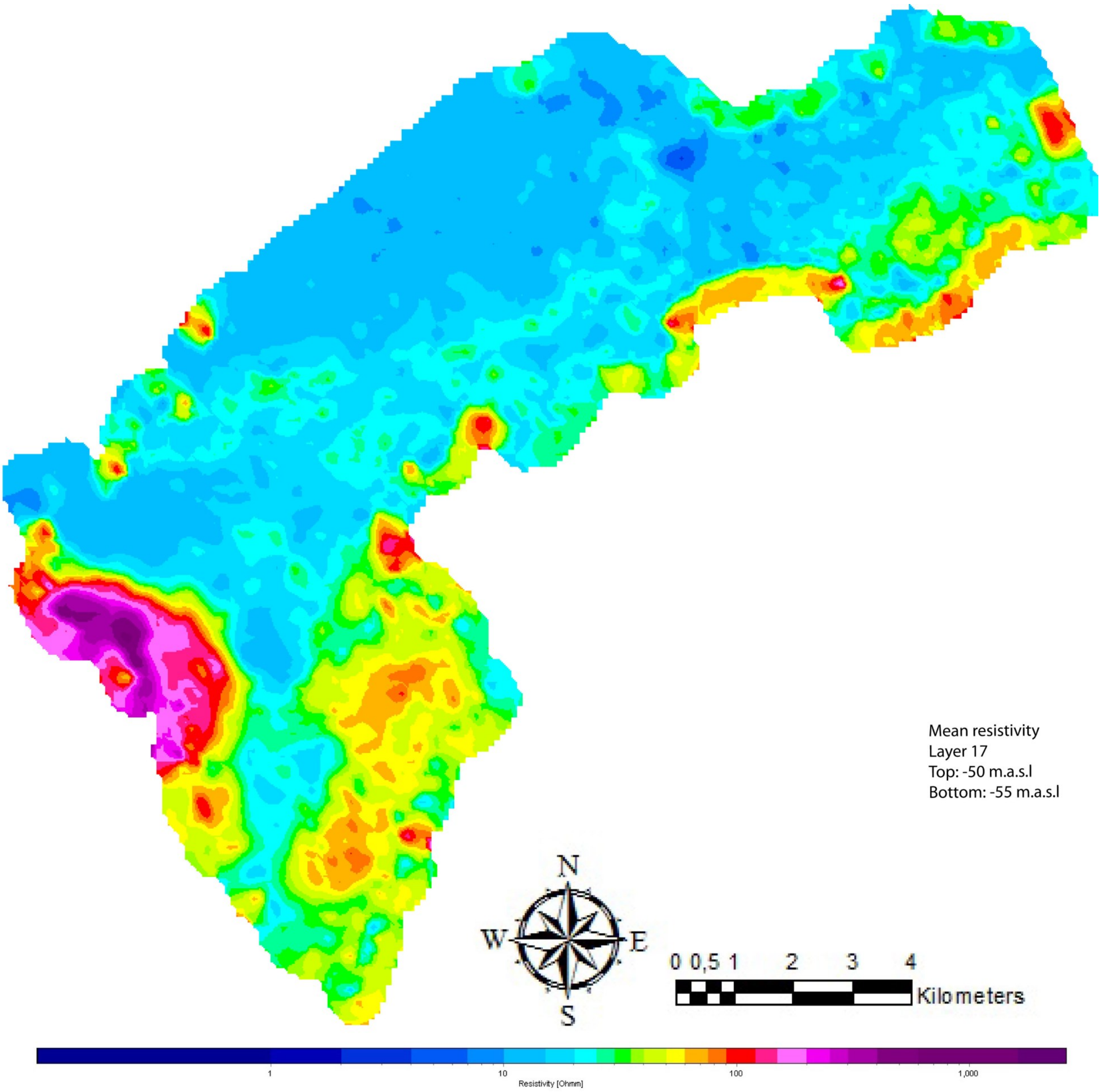
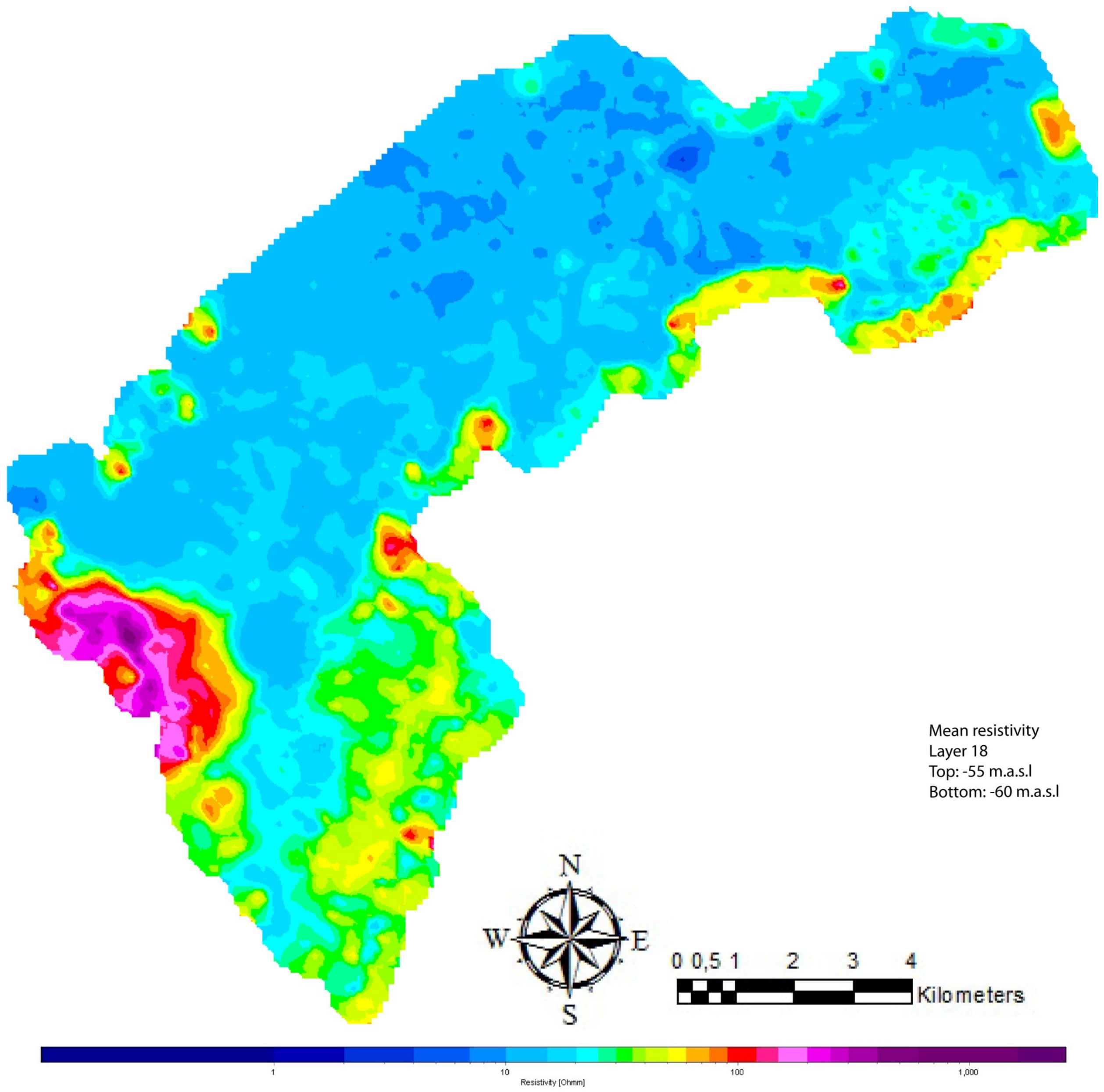
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 16
Top: -45 m.a.s.l
Bottom: -50 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]



Mean resistivity
Layer 17
Top: -50 m.a.s.l
Bottom: -55 m.a.s.l
N
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 18
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W
E
S
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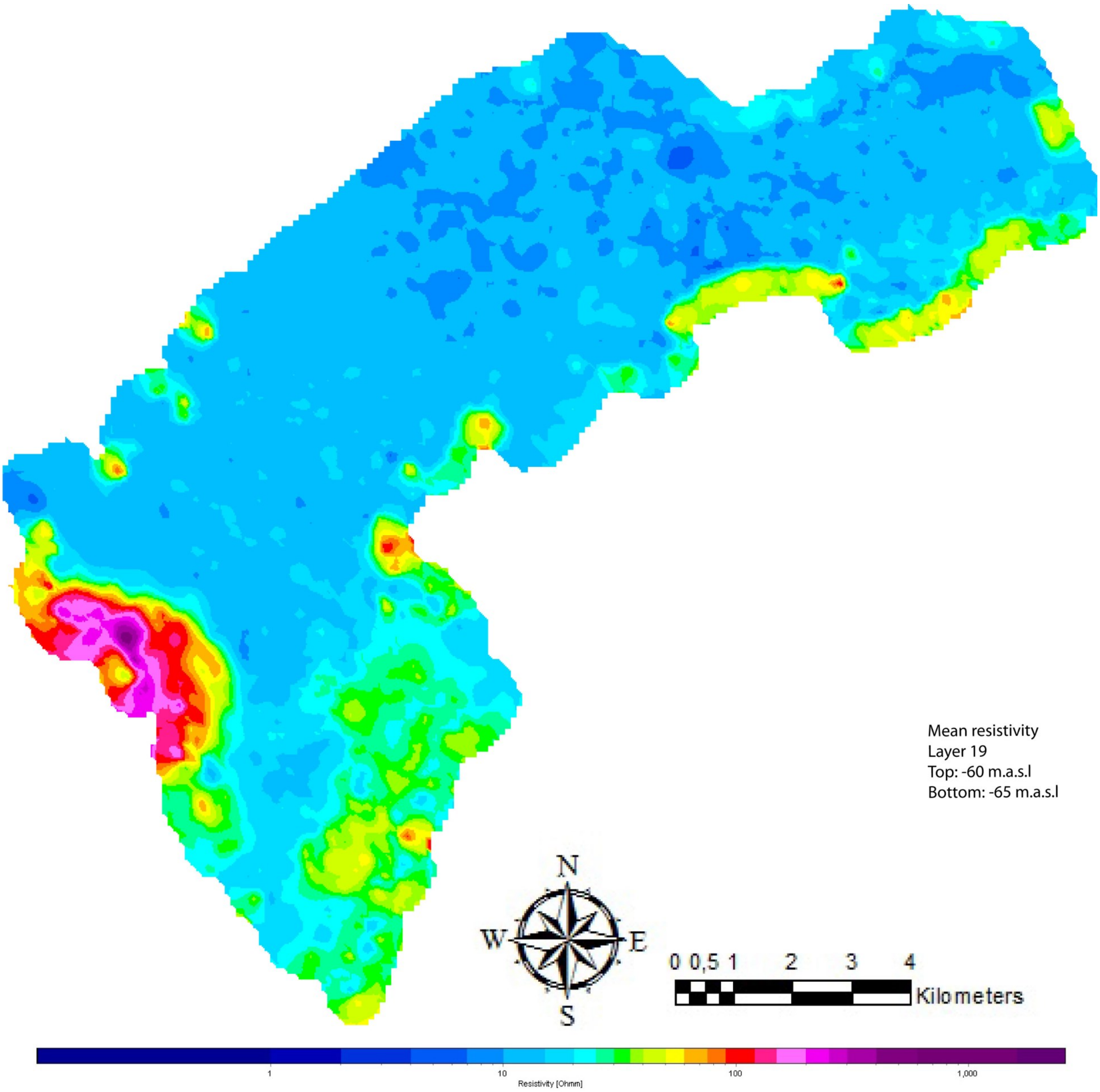
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 19
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W
E
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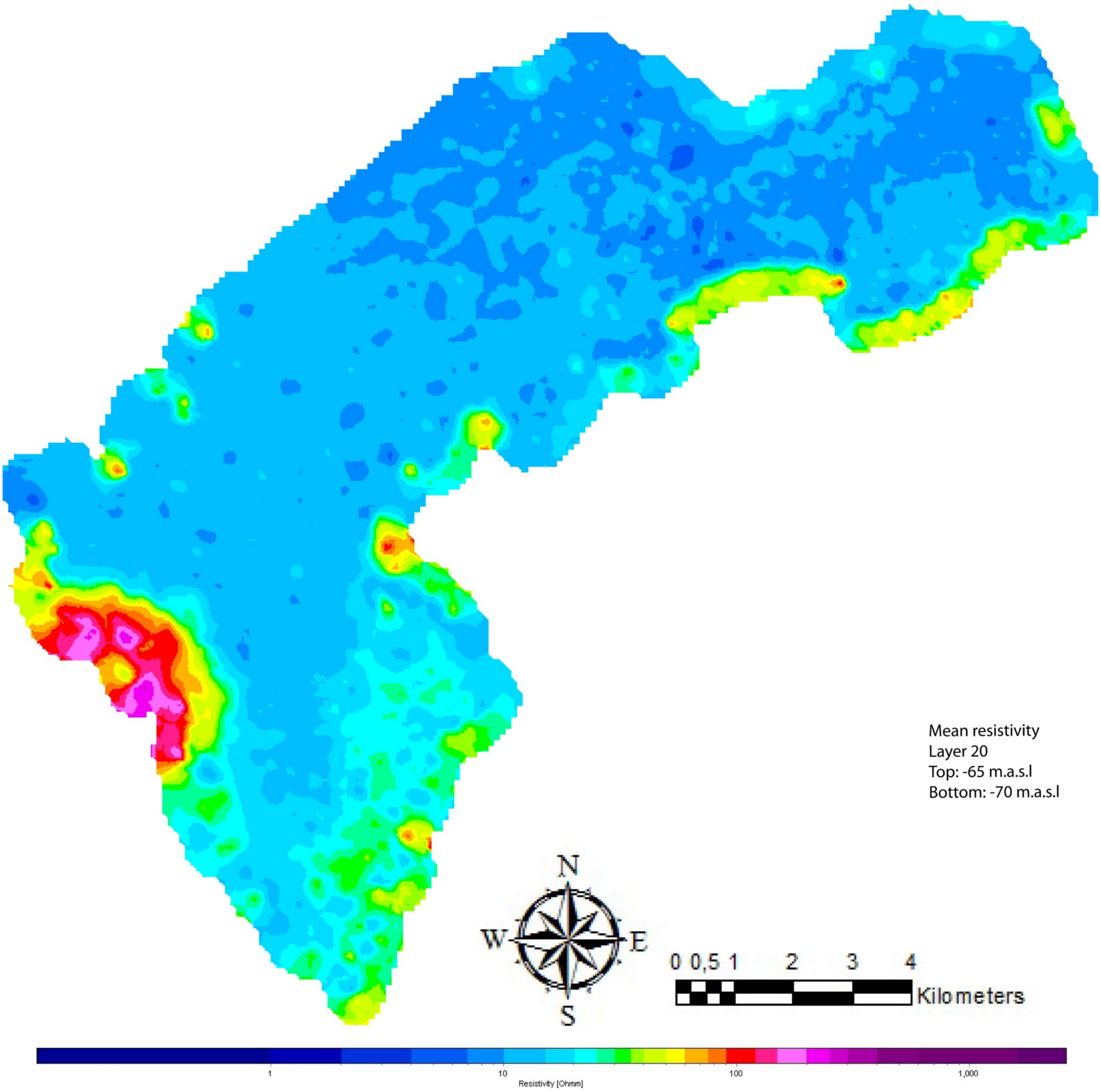
Kilometers
1
10
100
1,000
Resistivity [Ohmm]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W
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S
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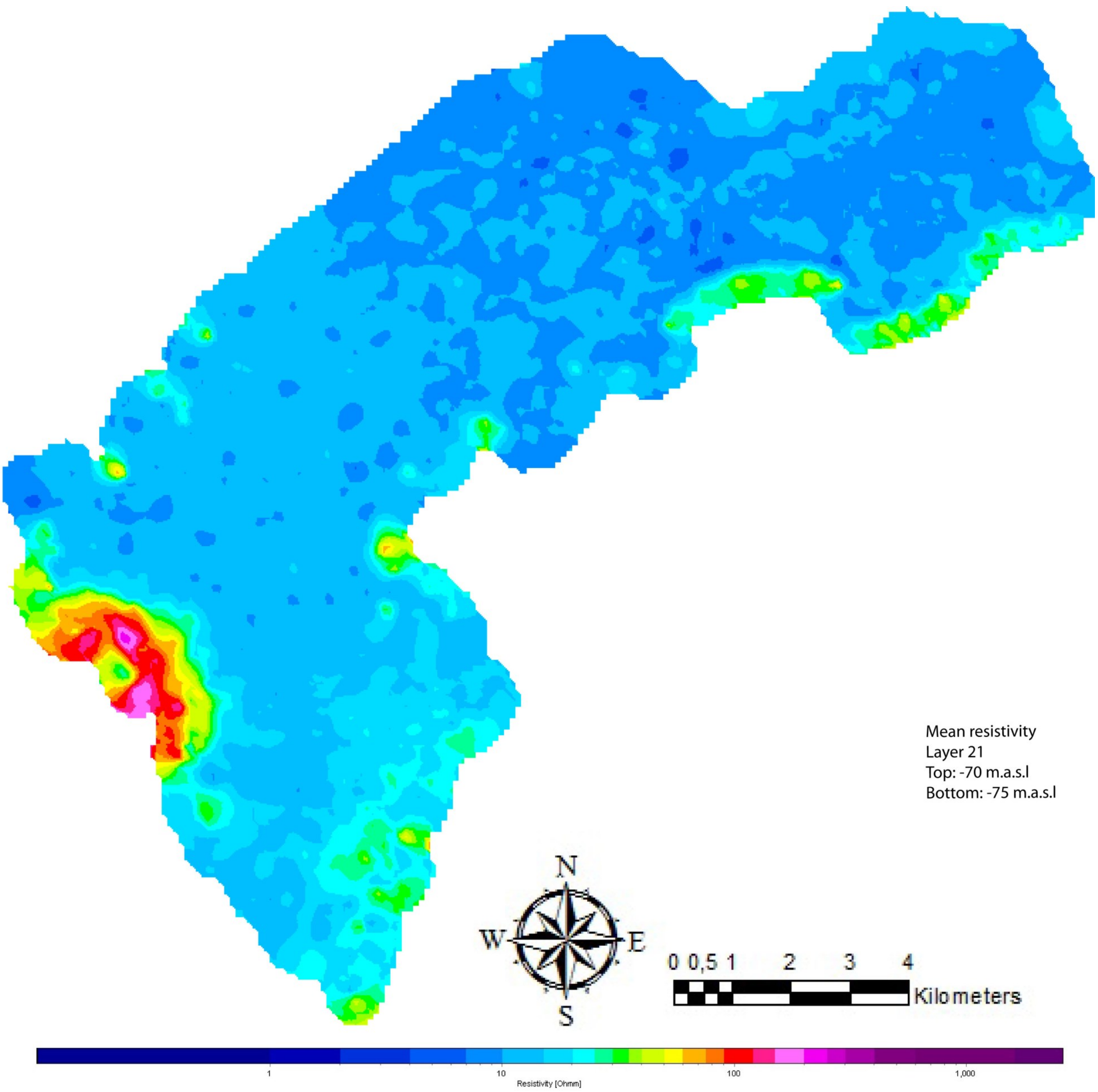
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 21
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W
E
S
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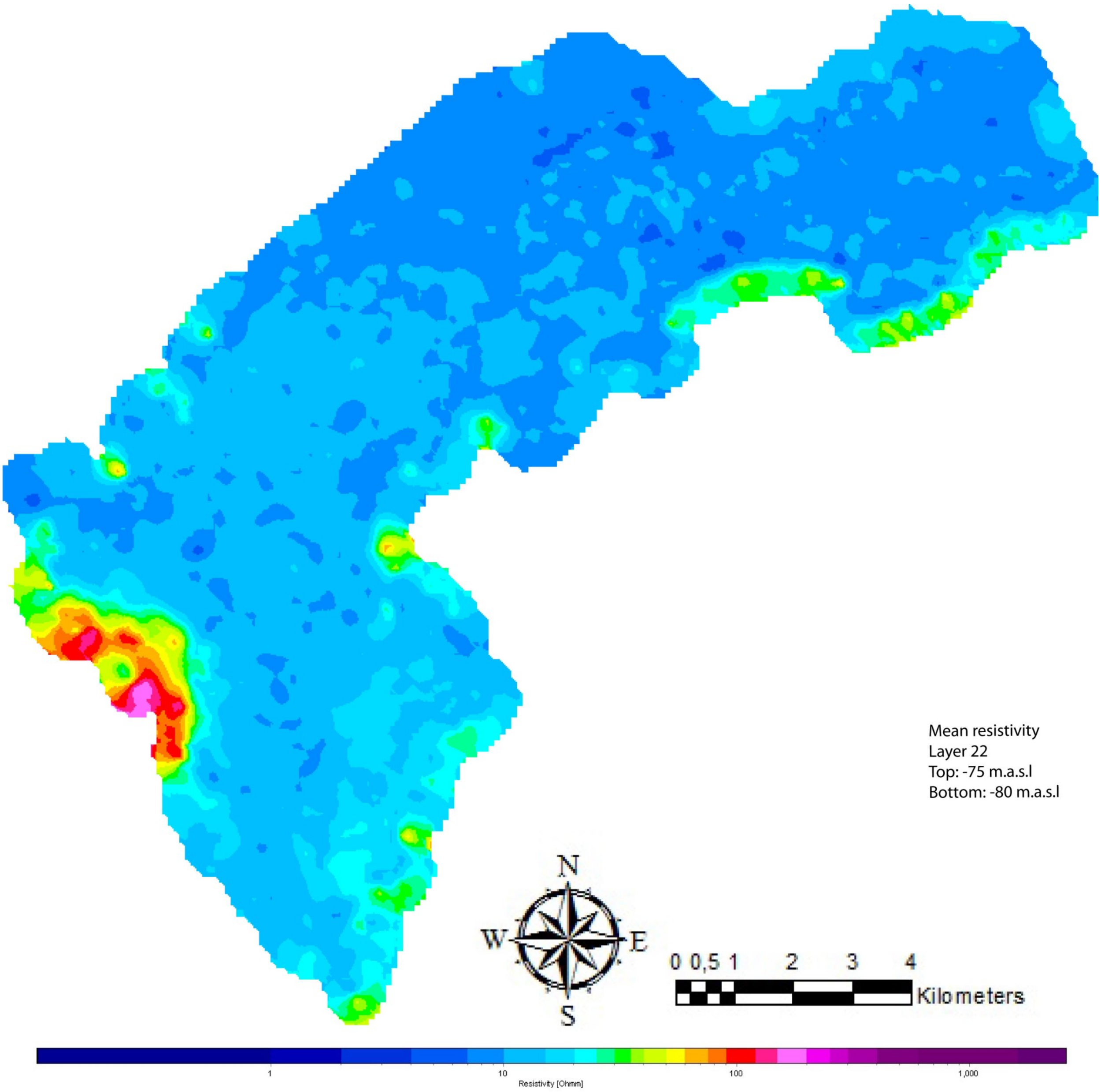
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 22
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W
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S
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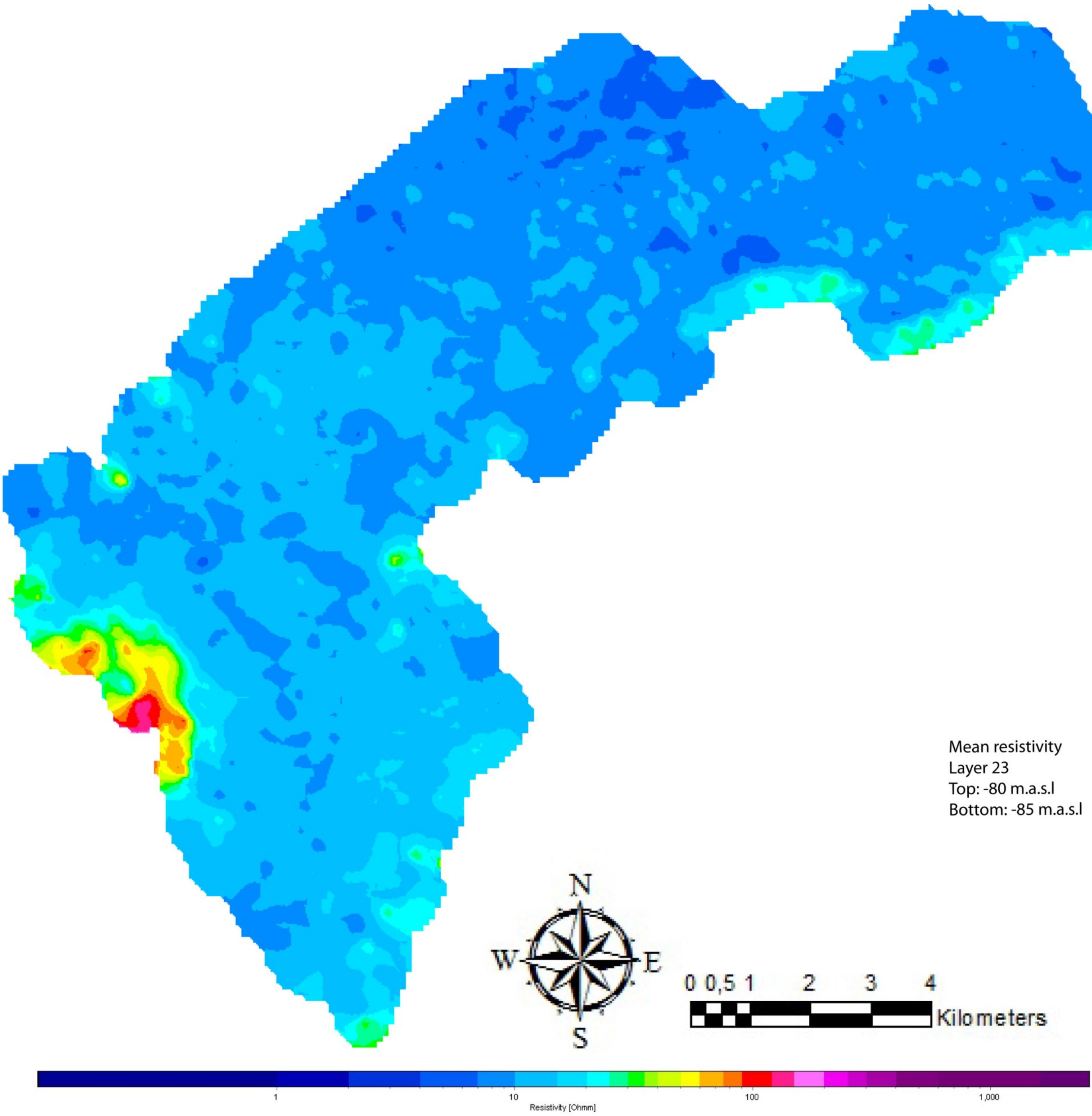
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
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Bottom: -85 m.a.s.l
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W
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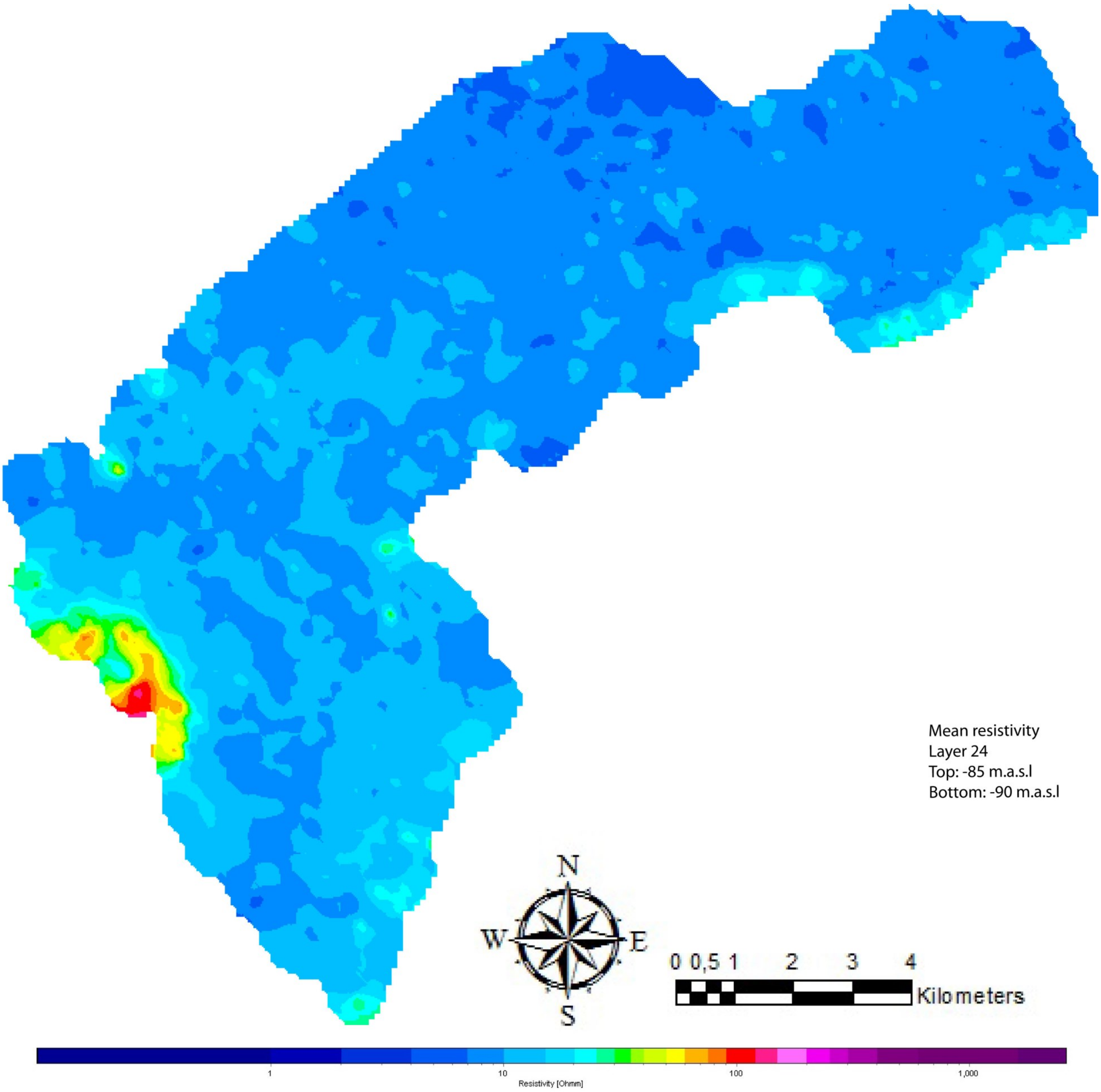
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
Layer 24
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Bottom: -90 m.a.s.l
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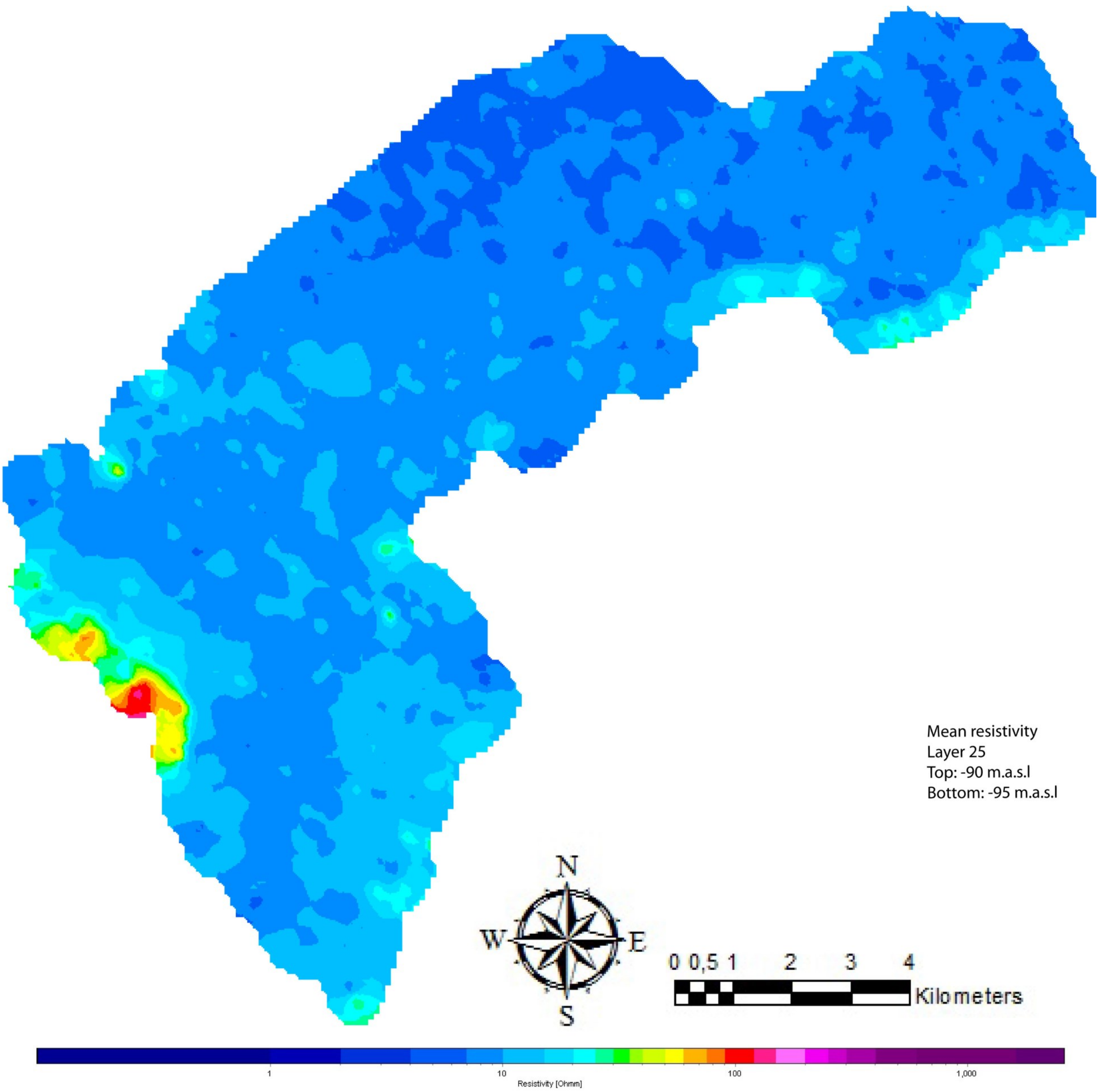
W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
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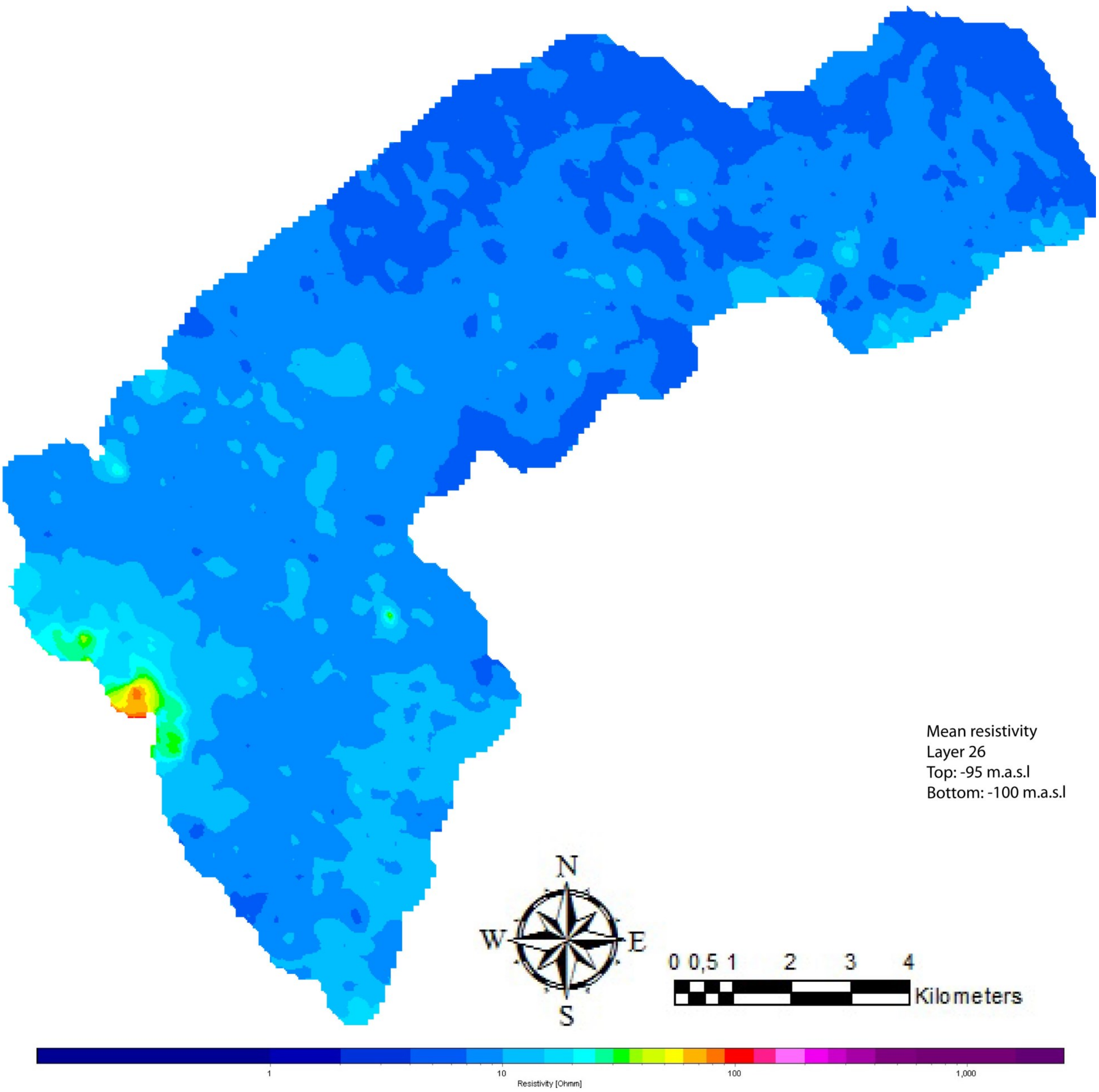
1
10
100
1,000
Resistivity [Ohmm]


Mean resistivity
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Bottom: -100 m.a.s.l
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W
E
S
0 0,5 1 2 3 4
Kilometers
1
10
100
1,000
Resistivity [Ohmm]

Table C1. Described stratigraphies from OPAB´s hydrocarbon exploration on Fårö. (Varadi 1982)

Nystugu-1	
Depth below ground level (meters)	**Stratigraphy, as originally described**
36.3 – 157.3	“White, hard limestone at top. Predominantly clay-stone becoming soft with depth”
157.3 – 187.3	“Red and grey marlstone”
187.3 – 201.3	“Limestone, light grey, clayey intercalated with marl-stone”

Limmorträsk-1	
Depth below ground level (meters)	**Stratigraphy, as originally described**
48.3 – 163.3	“Grey marlstone, underlying white hard limestone”
163.3 – 206.3	“Red and grey marlstone, from [199.3] m exclusively grey marlstone”
206.3 – 217.3	“Grey marlstone interbedded with light grey, brittle limestone”

Alnäsa-1	
Depth below ground level (meters)	**Stratigraphy, as originally described**
36.3 - 146.3	“Grey marlstone. At top white, hard limestone”
146.3 – 185.3	“Predominantly red marlstone.”
185.3 – 195.3	“Light grey, argillaceous limestone and grey marl-stone”

Verkegards-1	
Depth below ground level (meters)	**Stratigraphy, as originally described**
54.3 – 140.3	“Hard, slightly clayey limestone at the upper portion. Grey marlstone at the lower portion”
140.3 – 177.3	“Red marlstone, becoming grey at bottom”
177.3 – 188.3	“Grey marlstone interbedded with limestone, light grey, friable to soft, argillaceous”

Friggars-1	
Depth below ground level (meters)	**Stratigraphy, as originally described**
48.15 – 160.15	“Grey marlstone-limestone”
160.15 – 193.15	“Red marlstone”
193.15 – 205.15	“Grey marlstone”
205.15 – 213.15	“Grey marlstone with increasing amount of limestone (argillaceous)”

Myrhaga-1	
Depth below ground level (meters)	**Stratigraphy, as originally described**
40.1 – 141.1	“Grey marlstone and some interbedded limestone”
141.1 – 178.1	“Red marlstone”
178.1 – 193.1	“Mainly grey marlstone and interbedded, clayey lime-stone”

Ajketräsk-1	
Depth below ground level (meters)	**Stratigraphy, as originally described**
40.1 – 150.1	“Grey marlstone interbedded with limestone”
150.1 – 186.1	“Red marlstone”
186.1 – 193.1	“Mainly grey marlstone”
193.1 – 206.1	“Marlstone interbedded with limestone, from [203.1] m increasing to 70% limestone.”

Table C2. Coordinates for OPAB´s wells on Fårö (Varadi 1982).

Borehole name	**Nystugu-1**	**Limmorträsk-1**	**Alnäsa-1**	**Verkegards-1**	**Ajketräsk-1**	**Myrhaga-1**	**Friggars-1**
N-cooridinate (SWEREF 99 TM)	6429767	6423455	6429200	6425244	6431654	6432226	64247686
E-cooridinate (SWEREF 99 TM)	748801	745145	747649	742964	749411	748650	745979

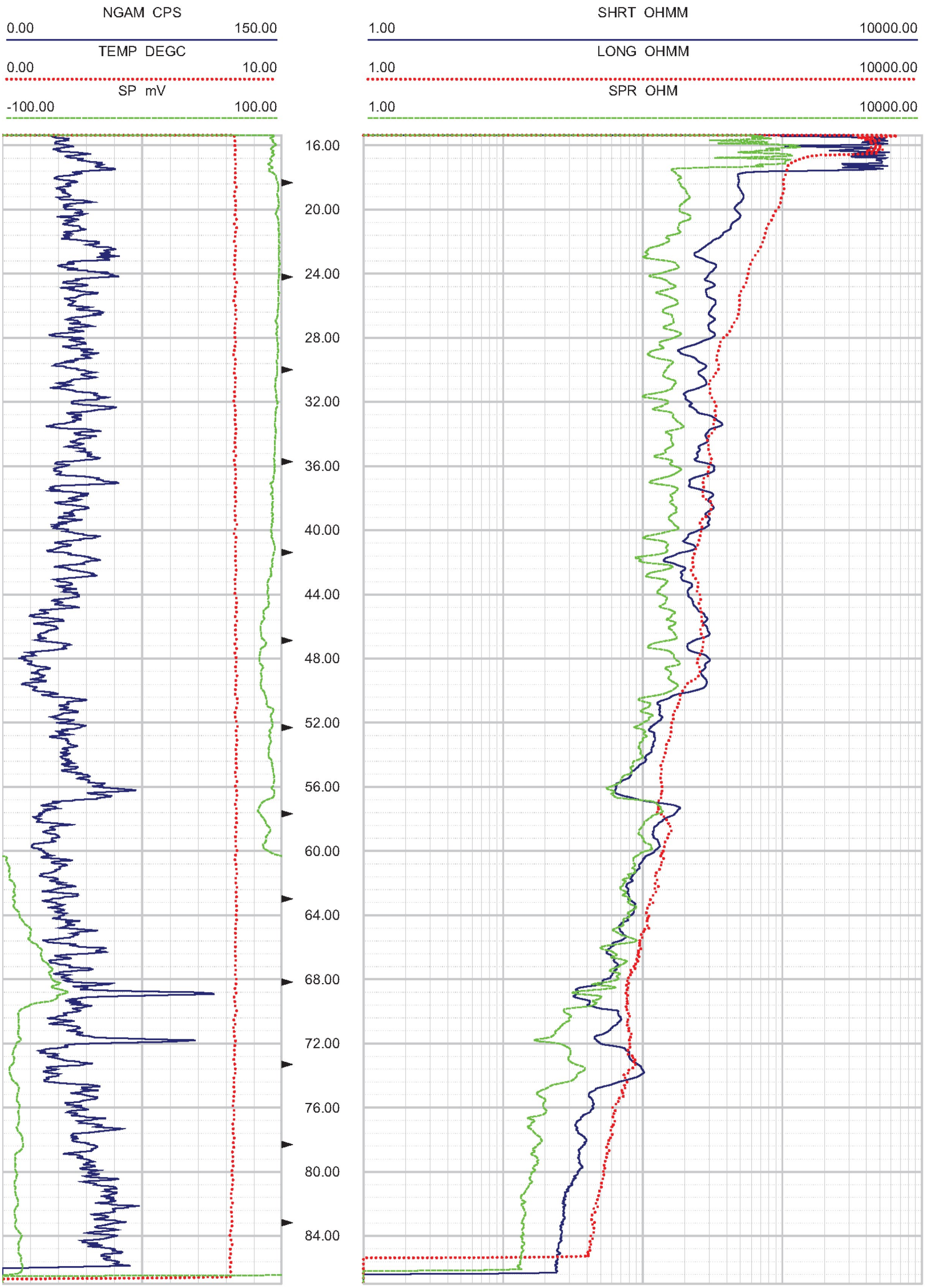

Figure D1. Geophysical borehole logging data from well 914610436, see Fig. 13 for orientation. The logging was carried out by Engineering Geology at Lund University using equipment from Roberston Geologging. The right graph contains resistivity data of the surrounding bedrock formation. At approximately 50 meters below surface the resistivity initiates a drop, which is interpreted as a progressively increasing amount of chloride ions.

SGU diarienr: 914610426

Borrföretag

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BRUNNS- OCH BORR-PROTOKOLL

Utskriftsdatum 2014-11-28

Borrningen avslutad datum 2014-11-15

Protnr: 200225

Borrplatsens läge

Fastighetsbeteckning (namn och nummer): Fårö Hammars 1:10	Ort: Fårö
Församling: Fårö	Kommun: Gotland
Borrplatsens läge	Borrplatsens GPS-koordinater i system: X SWEREF 99 TM ☐ SWEREF 99 (WGS 84) X RT90 2,5 gon V N: 6432005 E: 754322 X: 6431195 Y: 1706803
Borrplatsens adress	Telefon (även riktnummer)

Ägare/Beställare

Ägares/beställares namn: Sveriges geologiska undersökning (SGU)	Telefon (även riktnummer): 046-311784
Utdelningsadress, om annan än borrplatsens adress ovan: Killiansgatan 10	Ortsadress (postnummer och ortsnamn): 223 50 Lund

Jordarter/bergarter m.m.

Djup under markytan från	till	Jordart/bergart	Färg	Anmärkningar (vattenförekomst, sprickor m.m.)
0.0	0.1	Jord		
0.1	1.8	Sand		
1.8	2.8	Grus		
2.8	81.0	Kalkberg		

Tekniskt utförande

Borrmaskinstyp: X sänkhammare ☐ annan:

Tätning mellan foderrör och berg har skett med: X cementering ☐ extra plaströrsfodring ☐ annan:

Borrhål fodrat: X stålrör Ytterdiameter 139.7 x Godstjocklek 5.0 mm djup från 0.0 — till 6.0 m

☐ annan rörtyp: Ytterdiameter x Godstjocklek mm djup från — till m

Totaldjup från markytan: 81.0 m

Jorddjup från markytan (djup till berg): 0.1 m

Borrhålets bottendiameter: 115.0 mm

Brunnens användning: ☐ hushållsvatten ☐ energi värme/kyla ☐ kommunalt vatten X övrigt: Annan användning

Vattenanalys utförd: ☐ fys. kemisk ☐ bakteriologisk ☐ radon

Vattenflaska lämnad: ☐ ja ☐ nej

Analysresultat: ☐ bifogas ☐ insändes senare

Provpumpning m.m.

Typ av kapacitetsmätning: X blåsning ☐ flottörmätning ☐ pumpning

Pumpens maxkapacitet: liter/tim

Pump- eller blåsdjup under markytan	Pump- eller blåstid	Vattenmängd		Vid kapacitetsmätningen sjönk vattenytan (räknat från markytan)
81.0 m	0.5 tim	12000 liter/tim	X före tryckning	djup från — till m
m	tim	liter/tim	☐ efter tryckning	djup från — till m

Gv-nivå

Stabil grundvattennivå under markytan: m

Datum vid mätningstillfället:

Mätning av grundvattennivån har skett: ☐ före vattenuttag ☐ efter vattenuttag antal timmar

Anmärkningar

Anmärkningar: ☐ tryckning ☐ sprängning ☐ gradborrning, riktning:

Annan anmärkning:

Borrhål 8 av 10. Vatten på 4 m ca 5 lit/min ökande vid 38 m
till ca 80 lit/min ökande vid 51 m till ca 200 lit/min,
salt!

Uppmätt kloridhalt	konduktivitet	m under markytan
mg/l	mS/m	
mg/l	mS/m	
mg/l	mS/m	
mg/l	mS/m	

Konduktivitet anges i milliSiemens per meter, mS/m

Underskrift

Namnförtydligande Certifierad borrare nr

GEOTEC Svenska Borrentreprenörers Branschorganisation

Figure D2. Borehole logging performed by the drilling entrepreneur of well 914610426.

SGU diarienr: 914610436

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www.ahlqvistsbrunnsborrning.se Borrad enligt Normbrunn-07

BRUNNS- OCH BORR-PROTOKOLL
Utskriftsdatum 2014-11-28
Borrningen avslutad datum 2014-11-14
Protnr: 200225

Borrplatsens läge

Fastighetsbeteckning (namn och nummer): Fårö Hammars 1:35	Ort: Fårö
Församling: Fårö	Kommun: Gotland
Borrplatsens läge:	Borrplatsens GPS-koordinater i system: X SWEREF 99 TM ☐ SWEREF 99 (WGS 84) X RT90 2,5 gon V N: 6423489 E: 745445 X: 6422784 Y: 1697824
Borrplatsens adress:	Telefon (även riktnummer):

Ägare/Beställare

Ägares/beställares namn: Sveriges geologiska undersökning (SGU)	Telefon (även riktnummer): 046-311784
Utdelningsadress, om annan än borrplatsens adress ovan: Killiansgatan 10	Ortsadress (postnummer och ortsnamn): 223 50 Lund

Jordarter/bergarter m.m.

Djup under markytan från	till	Jordart/bergart	Färg	Anmärkningar (vattenförekomst, sprickor m.m.)
0.0	0.1	Jord		
0.1	90.0	Kalkberg		

Tekniskt utförande

Borrmaskinstyp: X sänkhammare ☐ annan:

Tätning mellan foderrör och berg har skett med: X cementering ☐ extra plaströrsfodring ☐ annan:

Borrhål fodrat: X stålrör Ytterdiameter 139.7 x Godstjocklek 5.0 mm, djup från 0.0 till 6.0 m

☐ annan rörtyp: Ytterdiameter x Godstjocklek mm, djup från till m

Totaldjup från markytan: 90.0 m — Jorddjup från markytan (djup till berg): 0.1 m — Borrhålets bottendiameter: 115.0 mm

Brunnens användning: ☐ hushållsvatten ☐ energi värme/kyla ☐ kommunalt vatten X övrigt: Annan användning

Vattenanalys utförd: ☐ fys. kemisk ☐ bakteriologisk ☐ radon

Vattenflaska lämnad: ☐ ja ☐ nej

Analysresultat: ☐ bifogas ☐ insändes senare

Provpumpning m.m.

Typ av kapacitetsmätning: X blåsning ☐ flottörmätning ☐ pumpning

Pumpens maxkapacitet: liter/tim

Pump- eller blåsdjup under markytan	Pump- eller blåstid	Vattenmängd		Vid kapacitetsmätningen sjönk vattenytan (räknat från markytan)
90.0 m	0.5 tim	15000 liter/tim	X före tryckning	djup från — till m
m	tim	liter/tim	☐ efter tryckning	djup från — till m

Gv-nivå

Stabil grundvattennivå under markytan: m — Datum vid mätningstillfället: — Mätning av grundvattennivån har skett: ☐ före vattenuttag ☐ efter vattenuttag — antal timmar

Anmärkningar

Anmärkningar: ☐ tryckning ☐ sprängning ☐ gradborrning, riktning:

Annan anmärkning:
Borrhål 9 av 10. Vatten på 18 m ca 1 lit/min ökande vid 23 m till ca 50 lit/min, salt och ökande vid 71 m till ca 250 lit/min.

Uppmätt kloridhalt	konduktivitet	m under markytan
mg/l	mS/m	
mg/l	mS/m	
mg/l	mS/m	
mg/l	mS/m	

Konduktivitet anges i milliSiemens per meter, mS/m

Underskrift

Namnförtydligande — Certifierad borrare nr

GEOTEC
Svenska Borrentreprenörers Branschorganisation

Figure D3. Borehole logging performed by the drilling entrepreneur of well 914610436.

SGU diarienr: 914610468

Borrföretag

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Borrad enligt Normbrunn-07

BRUNNS- OCH BORR-PROTOKOLL

Utskriftsdatum: 2014-11-28

Borrningen avslutad datum: 2014-11-15

Protnr: 200225

Borrplatsens läge

Fastighetsbeteckning (namn och nummer): Fårö Lansa 7:1	Ort: Fårö
Församling: Fårö	Kommun: Gotland
Borrplatsens läge	Borrplatsens GPS-koordinater i system: X SWEREF 99 TM ☐ SWEREF 99 (WGS 84) X RT90 2,5 gon V N: 6425313 E: 740785 X: 6424664 Y: 1693185
Borrplatsens adress	Telefon (även riktnummer)

Ägare/Beställare

Ägares/beställares namn: Sveriges geologiska undersökning (SGU)	Telefon (även riktnummer): 046-311784
Utdelningsadress, om annan än borrplatsens adress ovan: Killiansgatan 10	Ortsadress (postnummer och ortsnamn): 223 50 Lund

Jordarter/bergarter m.m.

Djup under markytan från	till	Jordart/bergart	Färg	Anmärkningar (vattenförekomst, sprickor m.m.)
0.0	0.1	Jord		
0.1	105.0	Kalkberg		

Tekniskt utförande

Borrmaskinstyp: X sänkhammare ☐ annan:

Tätning mellan foderrör och berg har skett med: X cementering ☐ extra plaströrsfodring ☐ annan:

Borrhål fodrat: X stålrör — Ytterdiameter 139.7 x Godstjocklek 5.0 mm — djup från 0.0 till 6.0 m

☐ annan rörtyp: Ytterdiameter x Godstjocklek mm — djup från till m

Totaldjup från markytan: 105.0 m — Jorddjup från markytan (djup till berg): 0.1 m — Borrhålets bottendiameter: 115.0 mm

Brunnens användning: ☐ hushållsvatten ☐ energi värme/kyla ☐ kommunalt vatten X övrigt: Annan användning

Vattenanalys utförd: ☐ fys. kemisk ☐ bakteriologisk ☐ radon

Vattenflaska lämnad: ☐ ja ☐ nej

Analysresultat: ☐ bifogas ☐ insändes senare

Provpumpning m.m.

Typ av kapacitetsmätning: X blåsning ☐ flottörmätning ☐ pumpning

Pumpens maxkapacitet: liter/tim

Pump- eller blåsdjup under markytan	Pump- eller blåstid	Vattenmängd		Vid kapacitetsmätningen sjönk vattenytan (räknat från markytan)
105.0 m	0.5 tim	6000 liter/tim	X före tryckning	djup från — till m
m	tim	liter/tim	☐ efter tryckning	djup från — till m

Gv-nivå

Stabil grundvattennivå under markytan: m — Datum vid mätningstillfället: — Mätning av grundvattennivån har skett: ☐ före vattenuttag ☐ efter vattenuttag — antal timmar

Anmärkningar

Anmärkningar: ☐ tryckning ☐ sprängning ☐ gradborrning, riktning:

Annan anmärkning:

Borrhål 10 av 10. Vatten på 15 m ca 0,5 lit/min ökande vid 25 m till ca 1 lit/min ökande vid 54 m till ca 100 lit/min, mycket salt.

Uppmätt kloridhalt	konduktivitet	m under markytan
mg/l	mS/m	
mg/l	mS/m	
mg/l	mS/m	
mg/l	mS/m	

Konduktivitet anges i milliSiemens per meter, mS/m

Underskrift

Namnförtydligande — Certifierad borrare nr

GEOTEC Svenska Borrentreprenörers Branschorganisation

Figure D4. Borehole logging performed by the drilling entrepreneur of well 914610468.

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