

**Radio-magnetotelluric and controlled-source magnetotelluric surveys on a frozen lake: opportunities for urban applications in Nordic countries**

**running title: RMT and CSAMT surveys on a frozen lake**

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## Abstract

In a novel approach, we have carried out controlled-source and radio-magnetotelluric measurements in the frequency range of 2-250 kHz on a frozen lake located over a planned major multi-lane underground road tunnel near the city of Stockholm. The aim was to gain a better understanding of the resistivity variations above and potentially within the crystalline bedrock. Previous studies on the lake water using the boat-towed RMT technique at higher end of frequency band lacked resolution at depth and could not provide conclusive information about bedrock level and potential fracture systems in the bedrock. Taking advantage of Nordic winters, we measured four profiles on the frozen lake complementing the previously acquired boat-towed radio-magnetotelluric data utilizing a double horizontal magnetic dipole transmitter that generated signals down to 1 kHz. The new resistivity models, incorporating the lower frequency data, show improvements and deeper penetrations based on a combined analyses of penetration depth, data misfits, and sensitivity studies. The resistivity models also show better correlation with the

available high-resolution shallow water reflection seismic data and the geological observations. A potential fracture system within the bedrock can also better be inferred in the new models. The idea of running similar surveys on frozen lakes can be further exploited in similar conditions such as in Sweden where approximately seven percent of the land is covered by freshwater bodies and poorly explored for infrastructure planning projects.

Keywords: frozen lake, controlled-source, electromagnetics, tunnel, radio magnetotelluric

Data Availability Statement: The CSRMT data collected in this study are available for further research and can be collected by contacting the customer service at the Geological Survey of Sweden (SGU) at: kundservice@sgu.se.

## **Introduction**

It is a common practice that high resolution surface geophysical measurements are planned at areas suggested by either interpretation of airborne data or other disciplines involved in a project, for example geo-technicians or mine engineers. One of the challenges in planning such surveys is sometimes presence of waterbodies such as lakes and rivers, which may cross or cover the target structures. One such example is the 21-km-long Stockholm Bypass in Sweden where 18 km is below the ground surface planned as two separate tunnels each having three lanes. The tunnels at three locations pass underwater passages of the Lake Mälaren (Figure 1). Luckily, in such areas the cold winters furnishes the possibility of running geophysical measurements on frozen

waterbodies. Geophysical measurements on frozen lakes and seas have been carried out over the past decades for various purposes. Gravity measurements on the surface of frozen lakes in northern parts of Europe (mainly Scandinavia) and North America is routinely conducted over the winter periods. Ugalde et al. (2006) collect gravity data at 98 stations over the frozen Wanapitei Lake in Sudbury, northern Ontario, Canada. Inclusion of the collected data into the existing database improved the Bouguer anomaly map in resolving the extent of a known meteorite crater below the central parts of the lake. Andersson and Malehmir (2018) conducted a similar survey in Sweden to find lateral extent of a carbonatite system into the Baltic Sea. Dugan et al. (2016) report the use of ground penetrating radar (GPR) to study small-scale structures within the ice covering two lakes in McMurdo Dry Valleys, Antarctica. Their findings confirmed the results from an earlier study carried out in Lake Vida where airborne transient electromagnetic (ATEM) data were also collected and modelled (Dugan et al., 2015 and reference therein). Schwamborn et al. (2002) collected high-resolution reflection seismic and GPR data over Lake Nikolay in the western Lena Delta to study the uppermost basin fill and the bordering of frozen margins. Their results showed that combination of the two profiling systems provides detailed information about stratigraphy along the profiles in both frozen and unfrozen parts of the lake.

Radio-magnetotelluric (RMT) is an established electromagnetic (EM) method for mapping near-surface resistivity variations (Tuberg et al., 1994; Tezkan et al., 2000; Bastani 2001; Persson, 2001; Bastani et al., 2012). The passive sources such as very low frequency (VLF) and LF transmitters as well as a portable data acquisition system make the RMT method efficient and practical tool for near-surface geophysical surveys. However, acquiring RMT data over shallow waterbodies pose a challenge in many conditions and in particular in the Scandinavia where a considerable portion of the land is covered by waterbodies such as rivers and lakes. To overcome some of these



challenges, a new acquisition technique called boat-towed RMT was introduced by Bastani et al. (2015) with an example to acquire data over freshwater body of Lake Mälaren in the outskirts of the city of Stockholm in Sweden over the water passages where the tunnels of Stockholm Bypass cross. The EnviroMT instrument (Bastani, 2001) was modified to carry out the waterborne RMT survey. The analog sensors were made to float on a wooden platform and towed by a boat at low speeds (0.5-1 m/s). The boat-towed acquisition system works effectively and is highly cost-effective. Mehta et al. (2017) examined and provided a detailed analysis of the resolution of boat-towed RMT data. Given the frequency range of the RMT data (10-250 kHz), it was evident that the RMT data acquired over Lake Mälaren provided better resolution at shallow depths compared to very low frequency (VLF) data in the range of 10-30 kHz. However, a major drawback of the RMT system is that it works in a narrow frequency band, which limits the depth penetration. This limitation becomes more problematic at the presence of conductive water column or sediments, which can for example hinder delineation of bedrock level and potential weakness zones within it both of which have great implications for planning of underground infrastructures, reinforcements used and excavation methods (Malehmir et al., 2015; Dehghannejad et al., 2017).

In a recent study by Wang et al. (2018), the boat-towed RMT data and lake-floor electrical resistivity tomography (ERT) are jointly inverted to model the structures below the waterbody at the Äspö Hard Rock Laboratory (HRL) site in southeastern Sweden. The resistivity models from the 2D inversions delineated subsurface structures such as a major northeasterly directed fracture system that is highly saturated with saline water. The presence of fracture zone is observed in the HRL underground facility and also confirmed by boreholes. The limited depth penetration of the

RMT data is somehow compensated for in the inversion process by incorporation of the ERT data that are acquired with a reasonably long array extent (Ronczka et al., 2017).

Employing controlled-source audio magnetotelluric (CSAMT) at lower frequencies in the range 1 to 10 kHz is a proper solution to increase the depth penetration and for a reasonably fast data acquisition. The concept of controlled sources in magnetotelluric studies was originally developed to improve the signal strength (Goldstein and Strangway, 1975), especially in areas close to manmade infrastructures where the background noise level is considerably high. In the controlled-source measurements, in order to meet the plane wave approximation, the source, which is either an electric or magnetic dipole, should be sufficiently far enough from the measuring site. Zong and Hughes (1991) give a detailed account on the CSAMT method and discuss the conditions for near- and far-field electromagnetic data acquisition and interpretations. Wannamaker (1997) provides prerequisites for source-receiver separation to be 5 times the skin depth in order to avoid near-field effects (NFE). Pedersen et al. (2005) and Bastani et al. (2009 and 2011) present the results of RMT and CSAMT measurements for a number of near-surface investigations. Sterich and Becken (2010) provide a detailed account on the EM fields from a finite-length wire source and compare it with a point dipole solution. They discuss the issues caused by point source approximation where the long wires of hundreds of meters are used to generate the EM signals. Use of controlled source EM approaches for hydrocarbon exploration is discussed in detail by Streich (2016). Saraev et al. (2017) present the use of controlled source radio-magnetotellurics (CSRMT) for near surface investigations in remote regions. They demonstrate use of grounded electric dipole as a source where they could measure the signal in a wide frequency range by utilizing the odd harmonics of the base frequency. Shlykov and Saraev (2015) discuss and present

the possibilities of estimating the macro-anisotropy of the earth material from the RMT sounding and using a controlled source that transmits the signals up to 1000 kHz. They also provide a forward modelling solution that takes into account the displacement currents. Tezkan et al. (2019) show an application of the CSRMT survey to detect and model the buried faults in 2D in Vuoska region close to the city of St. Petersburg. The study included the CSRMT measurements using a horizontal electrical dipole using the frequencies of 0.5, 11.5, 30, and 105 kHz and their odd harmonics. They could successfully resolve and map the buried faults by using resistivity model from the 2D inversion of the acquired CSRMT data. Synthetic analysis carried out by Mehta et al. (2017) suggests that EM frequencies as low as 2.5 kHz should provide the desired penetration depth in the case of Lake Mälaren site to gain better understanding of the fracture systems in the underlying resistive bedrock. The logistical requirement to acquire CSAMT data on shallow waterbodies with a floating platform is possible but challenging and can be time-consuming since the measurement time at each station can take a few minutes. To keep the towed platform with sensors stable at a location can also be difficult and impractical at places where ships and boats can pass often and frequently. Wang et al. (2019) present the results of their study at HRL site made in June 2017. They acquire boat-towed RMT and CSAMT data along a 600-m-long profile to showcase the increased depth penetration when the lower frequency data in the range 1.25-12.5 kHz are included in the 2D inversions. The resulting resistivity models resolve the deeper parts of the underlying fractured granite when compared to the inversion of just the RMT data. However, in the presented case, the measurement platform is stationary and stabilized during the data acquisition using a rope that is fixed to an island located in the middle of the profile. Such a procedure slows the production rate and might not even be possible at many locations. Recently, Shlykov et al. (2020) present an interesting application of the CSRMT method to map and model

permafrost in an area located at northern part of Siberia. By using the same data frequency range presented in Tezkan et al. (2019) they could successfully delineate loam and sand horizons using the resistivity models from the 2D inversion of the CSRMT where they also compared the results with the existing borehole data. Yavich et al. (2020) present a new fast 3D parallel simulation code applied to the CSRMT data acquired in Aleksandrovka study area in Kaluga Region, Russia. Their results reveal that the developed method can be applied in the very complex geological structures. In our case study, after a number of careful inspections, we took advantage of the Nordic winters and carried out the simultaneous RMT and CSAMT measurements on the frozen lake of Mälaren during February 2017. Hereafter we use the term CSRMT wherever the results from the combination of both methods are presented to make the text more compact and easier to follow, unless the RMT and CSAMT should separately be discussed.

The present study provides detailed information about the field procedures, source setup and data processing of the CSRMT measurements made for the first time on a frozen lake along four parallel profiles. 2D inversion results of the acquired CSRMT data demonstrates deeper penetrations down to approximately 40-80 m depth, leading to a better delineation of the level and possible weakness zones within the resistive granitic bedrock where the underwater planned tunnels will be running through. The resistivity models from 2D inversion also better correspond with the existing marine high-resolution reflection seismic data from the same site illustrating the accuracy and effectiveness of the approach.

## **Study area and survey setup**

The study area is located close to the city of Stockholm, Sweden. The measurements were carried out over one of the three water passages (Figure 1) reported by Bastani et al. (2015). A

detailed account of the geology in the area is given in Mehta et al. (2017). The selected water passage, number 2, is between the Lovön and Kungshatt islands (Figure 1). The bedrock at the tunnel location is of granitic and partly metasedimentary rock types. Geological observations indicate fractures in the crystalline bedrock that vary in width (1-5 m) and are partly filled with clay, graphite, and chlorite. The CSRMT data were collected along four profiles (Figure 2) on the frozen Lake Mälaren. All the four profiles are nearly parallel to each other and run in a SW-NE direction. The distance between the profiles is approximately 50 m with station interval of 25 m and 24 stations per profile (a total length of ca 580 m). The frozen ice crust was about 10-15 cm at the time of the survey. Five holes were drilled to allow electrodes in contact with the lake water (one for grounding and four for two electric components). These holes (in total 500) were drilled using a handheld auger prior to the survey in order to allow faster station deployment.

#### **Data processing and quality**

The EnviroMT (Bastani, 2001) acquisition system was used to measure the EM signal. The setup of the EnviroMT field equipment is similar to a typical MT set up as shown in Figure 3. The magnetic sensor is composed of three induction coils and is placed in a way that the two horizontal sensors measure the magnetic field components along and perpendicular to the profile and the third one measures the vertical component. Two pairs of electric field sensors and the horizontal magnetic field sensors are aligned either parallel or perpendicular to the profile direction. The system acquires data in two modes, namely RMT and CSAMT. At each station, the RMT data in the frequency range 14-250 kHz are acquired and stored first. Seven frequencies are used after the processing and the transmitters during the acquisition are typically more than 20. Then the controlled-source signals, generated in the frequency range of 2.5-12.5 kHz are recorded. In each measurement mode the data quality can be checked and if necessary, the data

at given mode/frequencies are repeated. The recorded data are the components of the EM field that are processed to estimate the complex-valued EM transfer functions, namely impedance tensor,  $\mathbf{Z}$ , defined as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} = \mathbf{Z} \begin{bmatrix} H_x \\ H_y \end{bmatrix} \quad (1)$$

and tipper vector (also referred to as vertical magnetic transfer function),  $\mathbf{T}$ , given by

$$\begin{bmatrix} H_z \\ H_x \\ H_y \end{bmatrix} = \begin{bmatrix} T_x & T_y \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} = \mathbf{T} \begin{bmatrix} H_x \\ H_y \end{bmatrix} \quad (2)$$

where  $E$  and  $H$  are the electric and magnetic field components, respectively. The subscripts  $x$  and  $y$  refer to directions of the sensors' setup in the field. In our case  $x$  was perpendicular and  $y$  in the profile direction. In the routine MT data interpretation, the input data for forward modelling and inversion are the tipper data calculated as in equation (2), apparent resistivity and the impedance phase at a given target frequency,  $f$ , in measurement directions,  $xy$  or  $yx$ , calculated as

$$\rho_{xy/yx}(f) = \frac{|Z_{xy/yx}|^2}{2\pi\mu_0 f} \quad (3)$$

$$\varphi_{xy/yx}(f) = \text{Arg}(Z_{xy/yx}) \quad (4)$$

where  $xy$  refers to the electric field in  $x$  direction and the magnetic field in  $y$  direction, vice versa for  $yx$ .

The field data processing schemes integrated into the EnviroMT is detailed in Bastani (2001). In the RMT mode, at every station the number of selected transmitters depends on the site location and a predefined signal to noise ratio (S/N) of the total horizontal magnetic field power. For the

Lake Mälaren survey, we used a threshold of 10 dB and on an average 24 radio transmitters were selected. The stored raw data are mean stacked auto and cross powers of five components of the measured EM fields at selected transmitter frequencies. The RMT transfer functions (**Z** and **T**) are then estimated using the band averaging technique (Bastani, 2001). The uneven distribution and lack of radio transmitters in certain frequency bands affect the quality of the estimated transfer functions. Pederson et al. (2006) reports gaps in the spectrum of radio transmitters in Europe. At the Lake Mälaren site we could observe these gaps. Two such gaps are visible in the data (Figure 4).

The signal source for the CSAMT measurements consists of two orthogonal horizontal magnetic dipoles. The source can remotely be controlled from the recording point. The location of the source is shown in Figure 2 with a yellow square mark. Based on the results of previous studies (Mehta et al., 2017), we selected 5 source frequencies of 2.5, 3.2, 5, 8 and 10 kHz. The source, when triggered, activates one of the magnetic dipoles and the signal is transmitted according to the given list of frequencies. The second dipole is then activated, and the same procedure is repeated (Bastani, 2001). Eventually, the tensor transfer functions and their corresponding errors are estimated with a method given by Li and Pedersen (1991). As it is also discussed by Li and Pedersen (1991), at certain distances from the transmitter site the data might contain EM signals that are not only dependent on the induced currents in the earth electrical resistivity structure but also depend on the type of the transmitter/source used. At large distances where the depth penetration of EM signal is considerably smaller (5-10 times) than the distance to the source, the wave can be considered as plane and the source effects are negligible. In the RMT case the EM waves are certainly plane, and the data can be inverted using the standard 2D/3D MT programs. However, for the inversion of

combined RMT and CSAMT data one must ascertain that the later are measured at distances long enough from the source where the plane-wave assumption is met. At closer distances/lower frequencies, the source effects might be either considered (using the code that take the source effects into account, for example see Wang et al., 2019) or the source contaminated data, namely near field data, must be rejected prior to the inversion.

The collected data in our study show a smooth transition between the RMT and CSAMT frequencies in both apparent resistivity and phase data. This provides an indication of CSAMT data being in the far field. The typical signature of the near-field effect for a magnetic dipole source in case of homogeneous half space is that with decreasing frequency the phase rises above 45 degrees and apparent resistivity decreases. In this study, the closest and farthest stations to the source were at distances 477 m and 625 m, respectively, and the second closest station is 516 m away from the source. At few stations on the northwestern part of the area, some signs of the near-field effects (NFE) were observed in the raw data at lower frequencies. Most of the measuring stations located at a distance greater than 500 m from the source did not show any NFE. An example of raw data quality along profile C1 is shown in Figure 5. A smooth transition from the RMT to CSAMT frequencies provides confidence to combine both datasets for further modeling and interpretation. The controlled source data in YX direction show more sensitivity in detecting a resistive structure at the deepest parts of the profile as compared to data in YX direction. Especially, a decreasing phase in YX direction from values  $> 55$  degrees to values below 45 nearly along the entire profile indicates the presence of a resistive structure at depth. The phase in XY direction shows nearly the same trend at the starting stations (1-10) and no sensitivity along the



rest of profile. The apparent resistivity data do not show clear indication of a resistive feature at the lowest frequencies.

## **2D inversion of combined RMT and CSAMT data**

As mentioned earlier, the most important objective to acquire the CSAMT data in the area (Figure 1) was to increase the depth of penetration using lower frequencies to the level where the planned tunnels would be excavated. The CSRMT profiles are perpendicular to the boat-towed RMT profiles (Bastani et al., 2015 and Mehta et al., 2017) and cover the area with the deepest water column where the RMT signal may not reach the crystalline bedrock. This means that the measured CSAMT data can be included in the inversion of the boat-towed RMT data to improve sensitivity to the resistivity variations within the bedrock. We used EMILIA program (Kalscheuer et al., 2008; Siripunvaraporn and Egbert, 2000) for the 2D inversion of the CSRMT data, which uses the finite difference method for forward solver and Gauss-Newton method for the inversion. Mehta et al. (2017) carried out strike and dimensionality analysis for the previously acquired RMT data and showed that the geological strike is along the water passage, nearly perpendicular to the RMT profiles. Thus, no rotation of the data collected in both campaigns was required. Joint transverse electric (TE) and transverse magnetic (TM) mode inversions, namely TE+TM, were carried out on the CSRMT dataset to obtain a better constraint on the deeper parts of the models (Pedersen and Engels, 2005). In the TE mode, electric current flows along the strike direction. In the TM mode, the electric current flows in the plane perpendicular to the strike direction. An error floor of 10% on the apparent resistivity and 5% ( $\sim 2.86^\circ$ ) on the phase was used in the inversion. The design of the model mesh was such that the shallowest block size was 0.5 m thick and the subsequent cell thickness increased with geometrical progression factor of 1.12. The deepest cell thickness was 2500 m. We considered two blocks per measuring point for the horizontal dimensions of cells. We

used a homogeneous half space of 1000  $\Omega\text{m}$  as the starting model. Regularization is used for smoothness constraint in the inversion (Constable et al., 1987). The horizontal smoothness weighting factor is equal to the vertical one, so that no preferred smoothness was given in any direction.

The selected boat-towed RMT profile L9 (marked with an arrow in Figure 2) coincides with four controlled-source stations. These two datasets were combined and inverted together. The inversion was carried out with two steps: (1) the Occam inversion with the maximal data inclusion unless the data point is too noisy to be accepted and (2) the damped Occam inversion with the data points which have reasonable misfits. In the second step, the starting model is the best fitted model in the first inversion. More details can be found in Wang et al. (2018). Besides, two lowest frequencies (2.5 & 3.2 kHz) at the station closest to the source were omitted to eliminate the near-field effects. For a conservative consideration, the distance between the source and receivers is required to be 12 times larger than the skin depth to avoid the near-field effect. Figure 6a shows the resistivity model from joint inversion of TE+TM mode of only RMT data (boat-towed) along L9 (see Figure 2 for the location) with an RMS of 1.74. Figure 6b shows the results from the combined RMT and CSAMT datasets with an RMS of 1.62. The detailed data misfits are also shown in Figure 7. TE-mode apparent resistivities have relatively high misfit at 28.31 kHz in the middle of the profile. TM-mode apparent resistivities have relatively high misfit at 226.50, 160.03, and 28.31 kHz in the middle of the profile. However, the phase data in both modes have low misfits. The inverse model has shallow structures well constrained by RMT data and deeper structures constrained by CSAMT data (Figure 6). The major difference in the two models is in the middle of the profile where a resistive feature below the conductive layer can be more clearly observed when CSAMT data are included. The controlled-source data at stations located in the middle of the profile, where

the conductive marine sediments overlying the more resistive and partly fractured crystalline have likely the greatest thickness, show considerable improvement in the model resolution at depth thanks to the increased penetration depth. The penetration depth, white dashed lines in Figure 6, was calculated as 1.5 times skin depth based on Spies (1989) and Huang (2005). The feature in the model below the penetration depth is not reliable for interpretation.

### **Reflection seismic data**

The reflection seismic data were acquired in a separate project and by another party (Nilsson, 2008). However, data in the form of raw shot gathers were made available to us for comparative studies and supporting the current studies. The dataset covers the two water passages and was acquired over the planned tunnels using a 12-channel hydrophone-streamer system positioned 0.5 m in the water. Hydrophones were separated 1 m. Boomer was used as the seismic source. A sampling rate of 0.125 ms was used for the acquisition. The reflection data processing involved mainly marine geometry setup, velocity analysis and stacking. No migration was attempted since the dataset is quite shallow and that diffractions likely from undulated bedrock or fractured bedrocks were intended to be kept for interpretations. Multiples while strong from both the lake floor (sediments) and bedrock, they did not make trouble for this study as the target depths were only a few meters in the bedrock and that multiples arrived much later in the dataset. The water bottom and sediments bottom can clearly be seen in the reflection seismic section (Figure 6c). Only two sections (S4 and S6) are presented together with CSRMT results in this study since the main objective is to investigate the CSRMT survey results.

## Interpretation and discussion

The resistivity model obtained from 2D inversion of only RMT dataset shows some distinct resistive features (Figure 6a). The shallowest part of the model, mainly in the form of a 10-12 thick layer with a resistivity of ca 200  $\Omega\text{m}$ , represents the freshwater. The large contrast between the freshwater resistivity and the underlying lake sediments with considerably lower resistivity yields the best-case scenario for the inversion to resolve the boundaries between the two, especially with the inclusion of CSAMT data (Figure 6b). The water-sediment boundary also well correspond with the strong reflection seen in the reflection seismic data (Figure 6c). The underlying more conductive lake sediments layer has a varying thickness along the profile that seems to be generally thinner on the NW and SE ends and thicker in the central part of the water passage. This limits the depth penetration of the RMT signal and leads to the ambiguities to analyze the bedrock resistivity variations by just using RMT resistivity models. However, the CSAMT data has less limit of resolving the features in the bedrock.

Information available from a few cored boreholes in the area suggests the presence of fracture systems with a varying width of a few centimeters to tens of centimeters within the bedrock, and the total width of the fracture systems can reach up to 1-5 m (Ignea 2015; Mehta et al., 2017). The dominating minerals within the fracture system are graphite, chlorite, and calcite. The resistivity model in Figure 6a does not show any indication of such a lower-resistivity fracture system, which is mainly because of poor data sensitivity (limited depth penetration, see in Figure 8a-b) and partly smoothing imposed by the smoothness constraint used in the inversion. The new controlled-source stations can make it possible to resolve the depth to bedrock at the middle of the profile where thick lake sediment is present (Figure 8c-d). The near surface features interpreted in the RMT model can be observed in the new CSRMT model as well (Figure 6b). The locations of controlled-

351 source stations are marked along the x-axis with stars. The resistivity model differs from the RMT  
352 model mainly at the depth in the distance 100-200 m along the profile where a more resistive  
353 feature can be observed. Clearly, the sediments lower boundary is focused, and the fractured zone  
354 in the bedrock is detected when the controlled source data are added. According to the borehole  
355 information, the depth to the fractured bedrock (or the bottom of lake sediments) is expected to be  
356 about 30-50 m which seems to be better resolved with control source lower frequencies. Noticeably,  
357 the resistivity of the fractured bedrock appears to be relatively low. This can be probably caused  
358 by the presence of infilling of conductive materials and clays in the fracture system.

359 The acquired reflection seismic data closest to the RMT profile L9 is presented in Figure 6c. A  
360 major undulation in the seismic section (S4) can be observed (distances 150-200 m) that likely  
361 marks the location where the bedrock might be eroded and can be inferred to be fractured. The  
362 CSRMT model is superimposed on the seismic section and shown in Figure 6d. The undulations  
363 in the bedrock can be easier compared and show a clear correlation between the two datasets that  
364 are independently processed and modelled. Based on the estimate of skin depth and the distance  
365 between the transmitter and receivers, the first controlled-source station towards the NW part of  
366 the profile might be influenced by near-field effect (transmitter-reciever distance less than 12 times  
367 of skin depth). Since the near-field effect is more dominant at lower frequencies, the two lowest  
368 frequencies (2.5 and 3.2 kHz) were omitted from the dataset prior to the inversion to eliminate  
369 effect. Sensitivities for the boundary of sediments and bedrock (anomaly A in Figure 8) and the  
370 potential fracture zone (anomaly B in Figure 8) are studied by model perturbation. This means that  
371 we have changed the resistivity of the model bounded in the region of anomaly A and calculated  
372 the forward response of the model and compared the data fits with the resistivity model from the  
373 inversion shown in Figure 6b. The resistivity of the anomalies is increased to 1000  $\Omega\text{m}$  from the

inverted values. The RMS increase is the original and perturbed RMS difference normalized by the original RMS. For both anomalies, the RMS increases of combined inversions are nearly 2-3 times larger than the ones of RMT inversions, which indicates the increase of sensitivity at depths due to the inclusion of four CSAMT stations. Clearly, the sensitivity tests not only show the low frequency CSAMT signals increase the investigation depth of the inverse models, but also illustrate that observed data have sensitivities to the bedrock surface and potential fracture zone filled with conductive materials (Figure 8). One should note that the most conductive deepest zone in Figure 6b at distances 150-200 m lies below depth of investigation and therefore our interpretation of the possible fracture zone (marked by white lines in Figure 6d) are limited to depths dictated by the depth of investigation.

To further scrutinize the effectiveness of the CSRMT survey on the frozen lake we show a comparison between the resistivity model along profile L13 and the available reflection seismic data along S6 (Figure 9). Even though this profile is away from our most interested region, it can repeatedly demonstrate the improvements obtained by including the CSAMT data in the inversion. The corresponding data misfits for the inversion are shown in Figure (10). Again, phase data have lower misfits than the apparent resistivity data, and apparent resistivity data only have relatively high misfits at certain frequencies. In both RMT and CSRMT models, water column is perfectly resolved; However, bedrock undulation is only resolved in the CSRMT model. Resistivity of the fracture system is relatively low due to the filling of conductive materials. Penetration depth, white dashed lines in Figure 9, also shows that the discussed features are well constrained by the observed CSRMT data. We must emphasize that the smoothing regularization applied in the inversion, and the diffusive nature of EM fields in the earth, generate smoother nearly vertical low

resistivity zones compared to the observed fractures in the drillholes (reported by Ignea, 2015) that are much narrower and have varying dips. But, comparing to the reflection seismic section, the CSRMT data still have good vertical resolution.

## **Conclusions**

To the best of our knowledge, for the first time, CSRMT data over a frozen lake were successfully acquired in an area close to Stockholm and in connection to the planned bypass multi-lane underground road tunnel project. The goal was to map the depth to bedrock and investigate the presence of any fracture system particularly in the middle of the surveyed profiles where the previously acquired boat-towed RMT dataset was incapable of resolving such details. Variation of the modelled resistivity well correlates with the results reported in the previous studies, available drillholes and reflection seismic data. This is also testified by the penetration depth evaluation, inversion misfit analysis, and the model sensitivity by model perturbation method. Quality of the CSRMT data collected are in general good although at some stations closer to the transmitter near-field effect was speculated. In a broader perspective, the idea of CSRMT study on frozen lake can be used on shallow waterbodies in similar climatic conditions where only RMT dataset is not sufficient in terms of penetration depth. A more detailed analysis can be made by 3D modelling/inversion of all densely collected RMT and CSRMT data in this survey area for future studies. We anticipate this approach to open new opportunities in the northern countries for infrastructure planning projects where these structures are expected to cross waterbodies and for mineral exploration where little is known about subsurface structures and bedrock. However, the Bayesian inversion could be used in the further along the full CSRMT profiles for quantitative model uncertainty studies, which is hard to achieve with deterministic inversions, such as the one we used.

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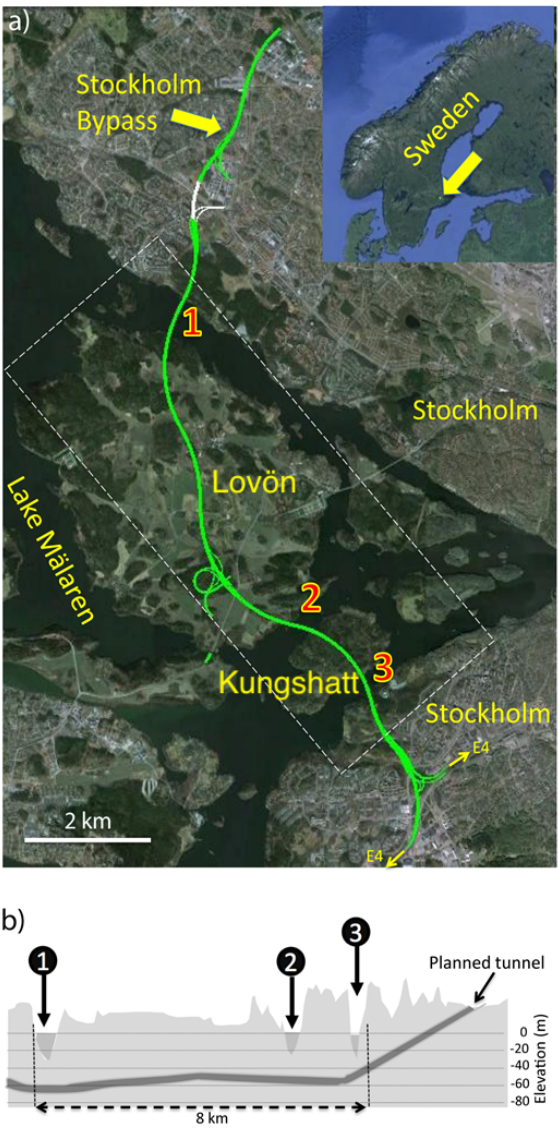
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524 **Figures**

525 **Figure 1**



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Figure 2

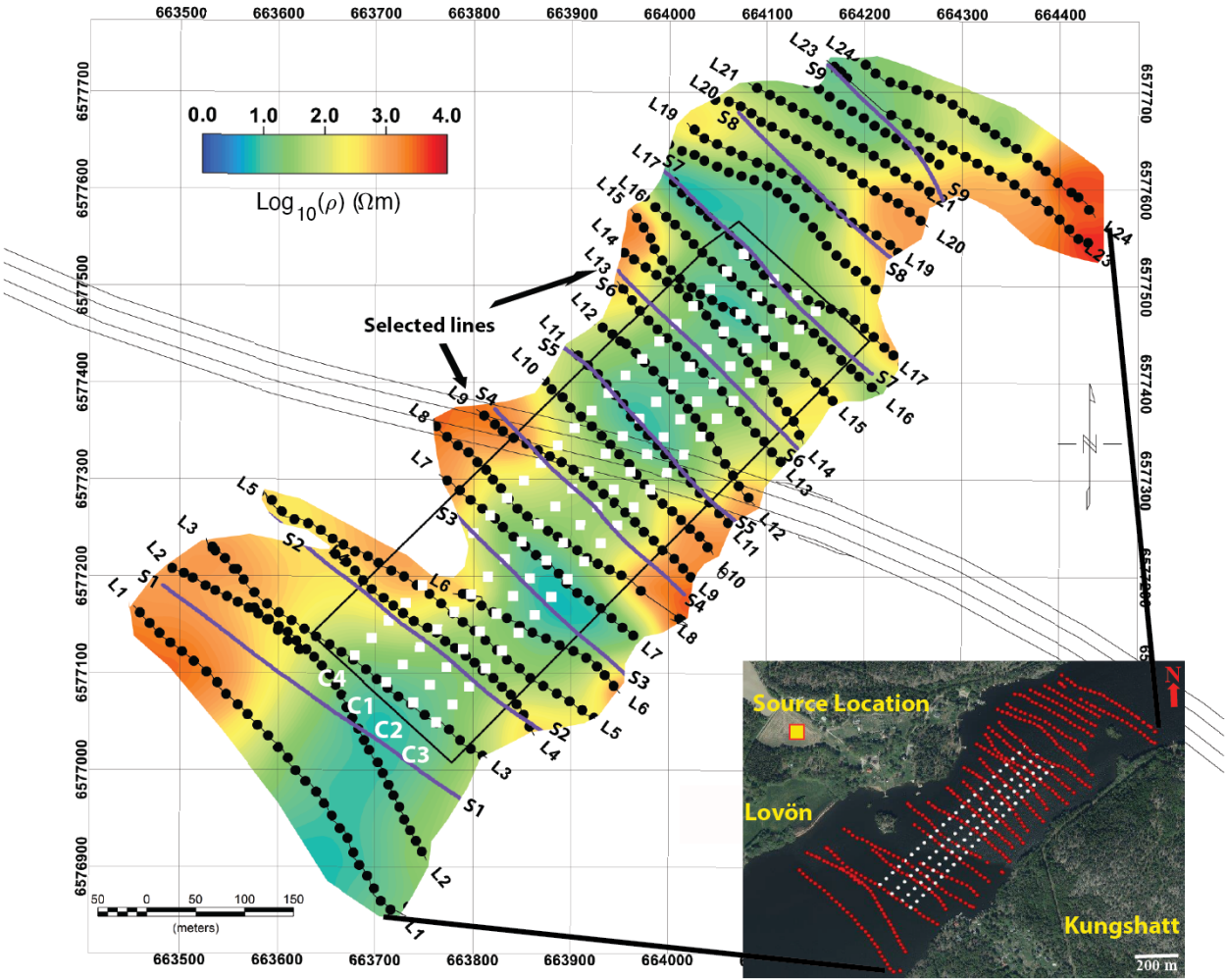




Figure 3

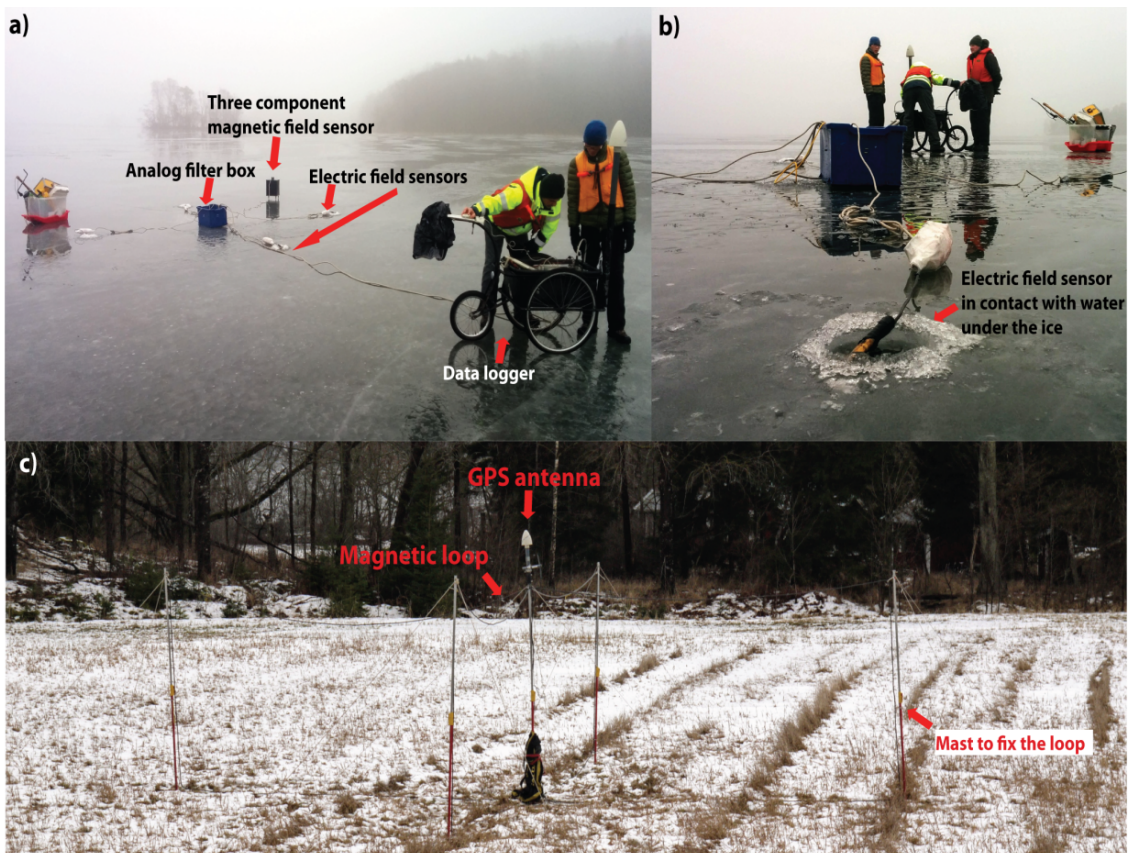
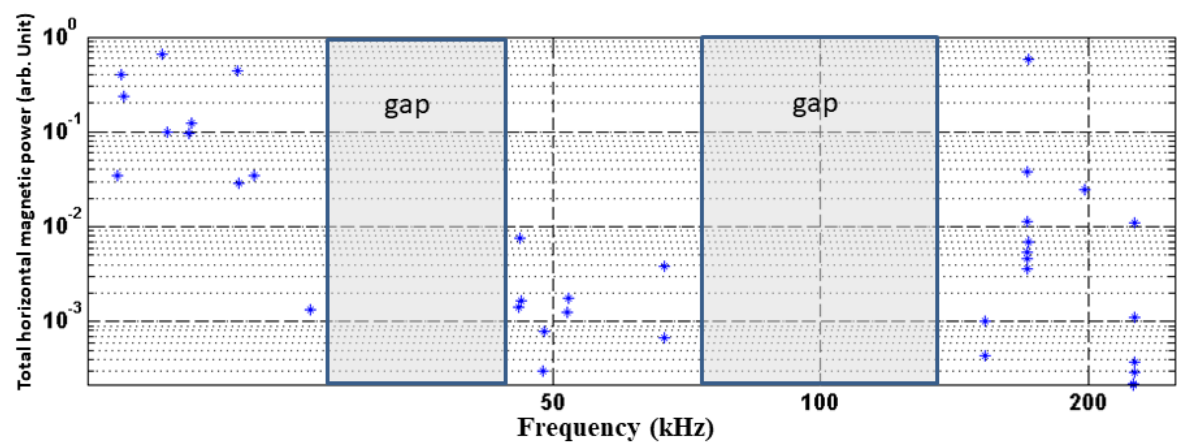


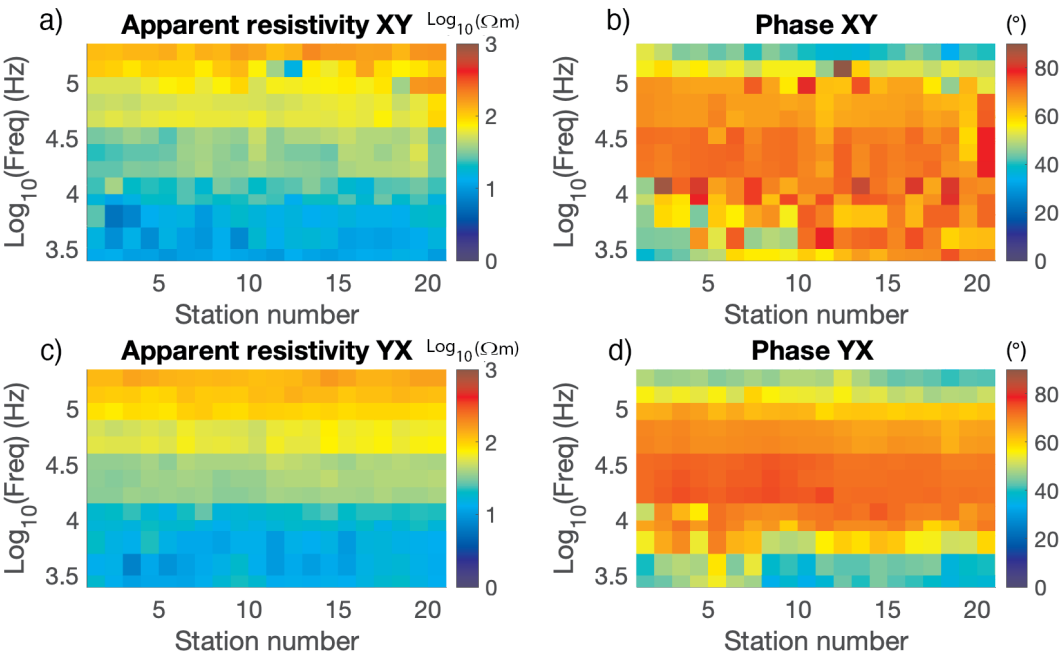
Figure 4





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570 Figure 5



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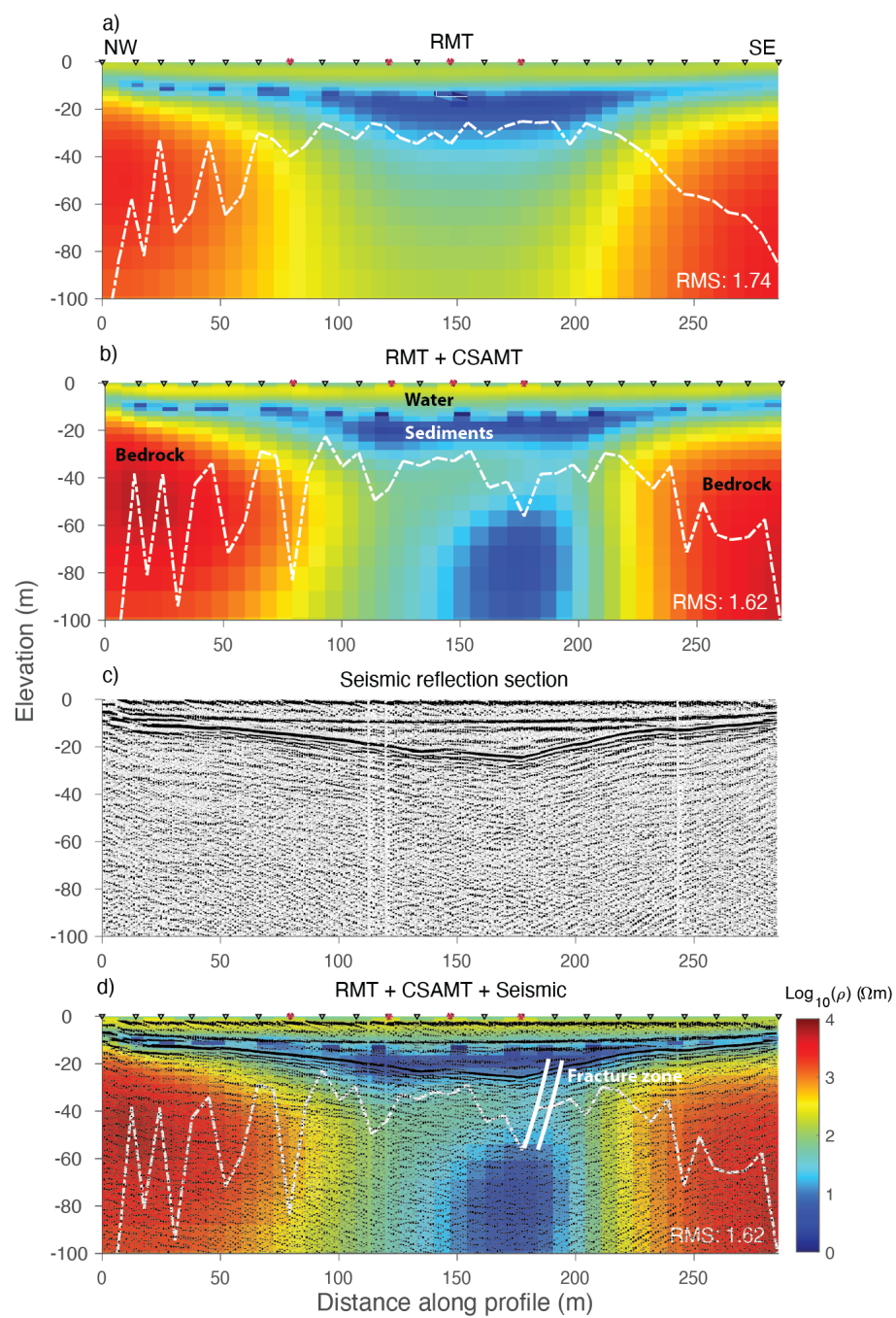
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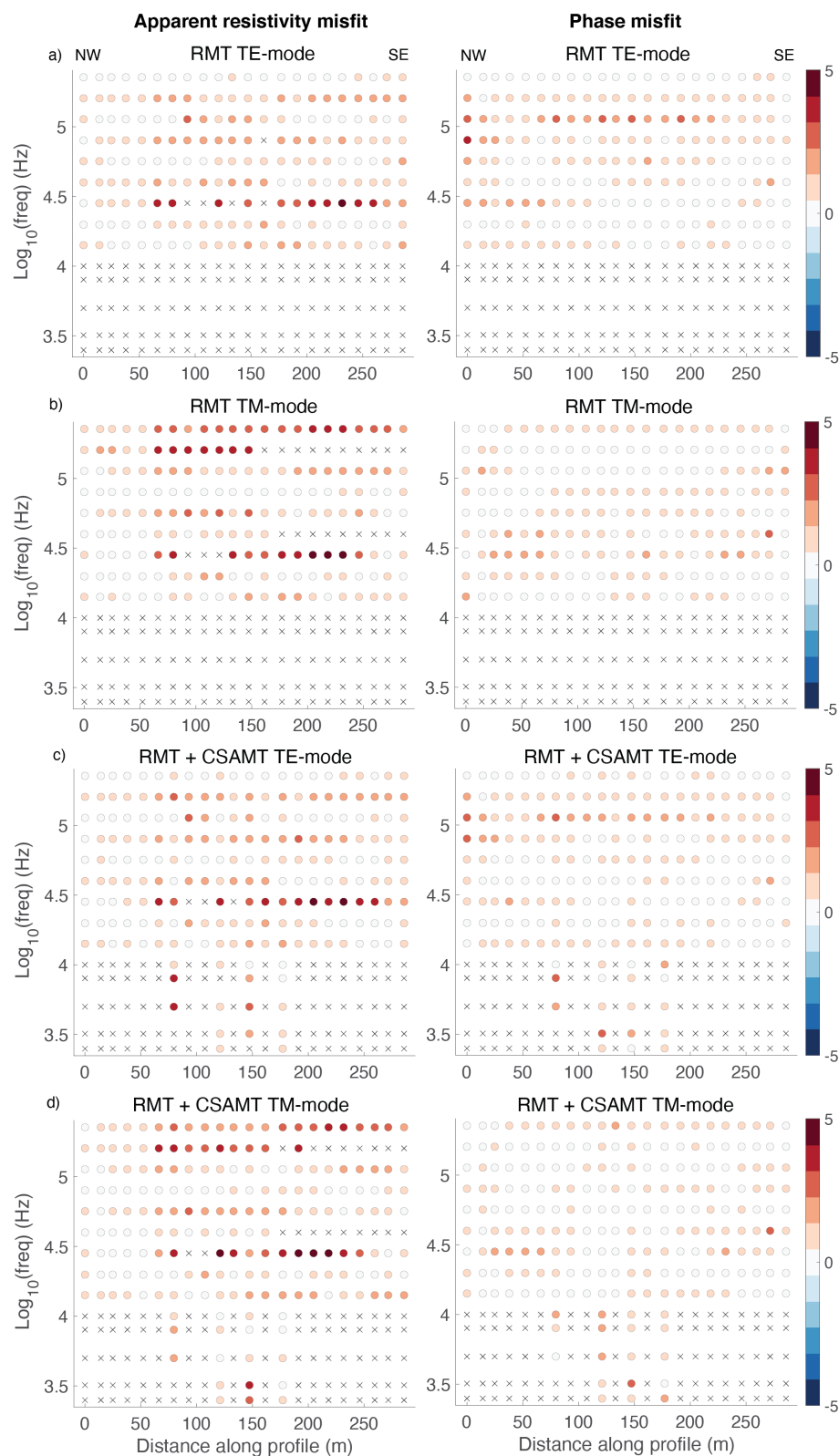
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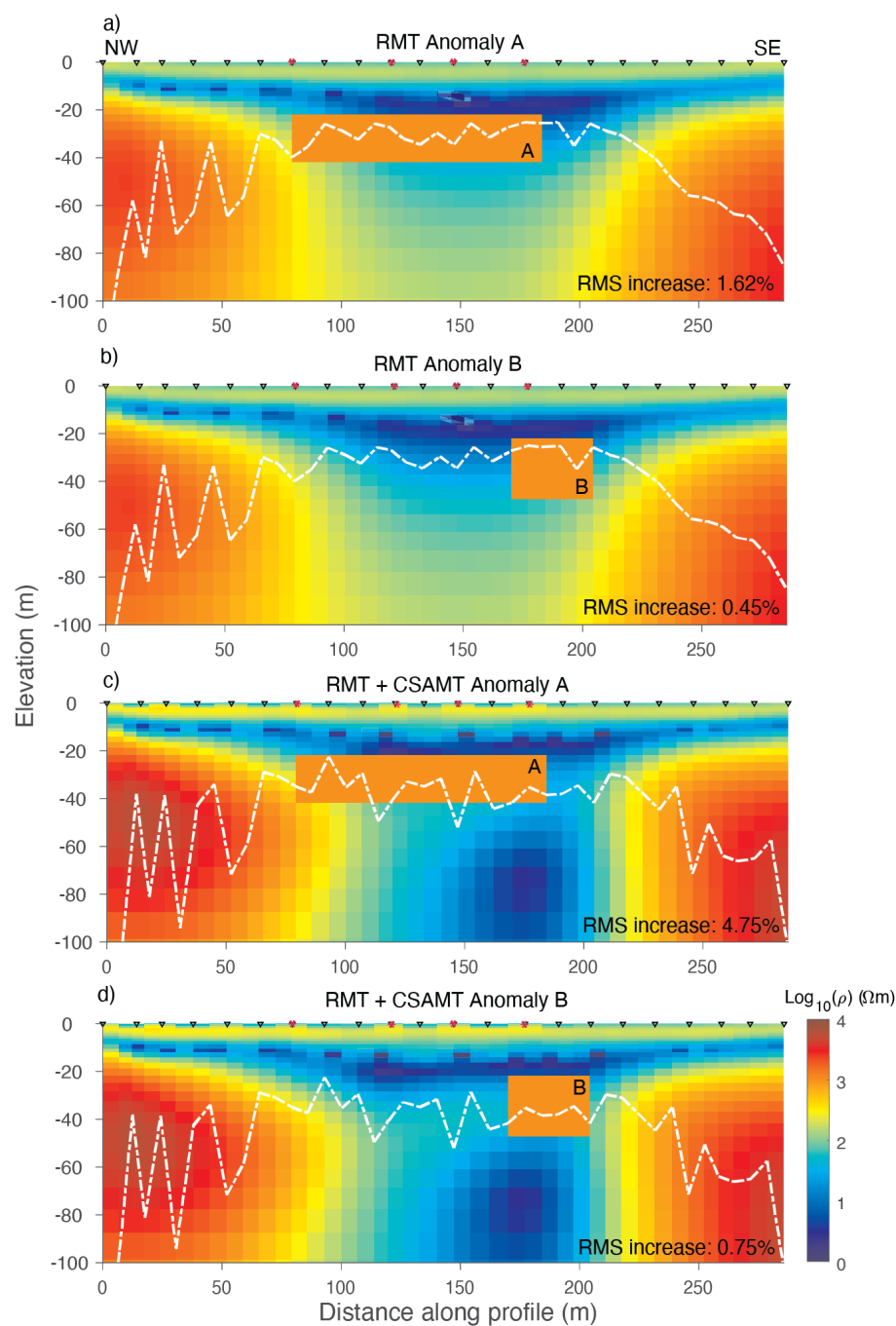
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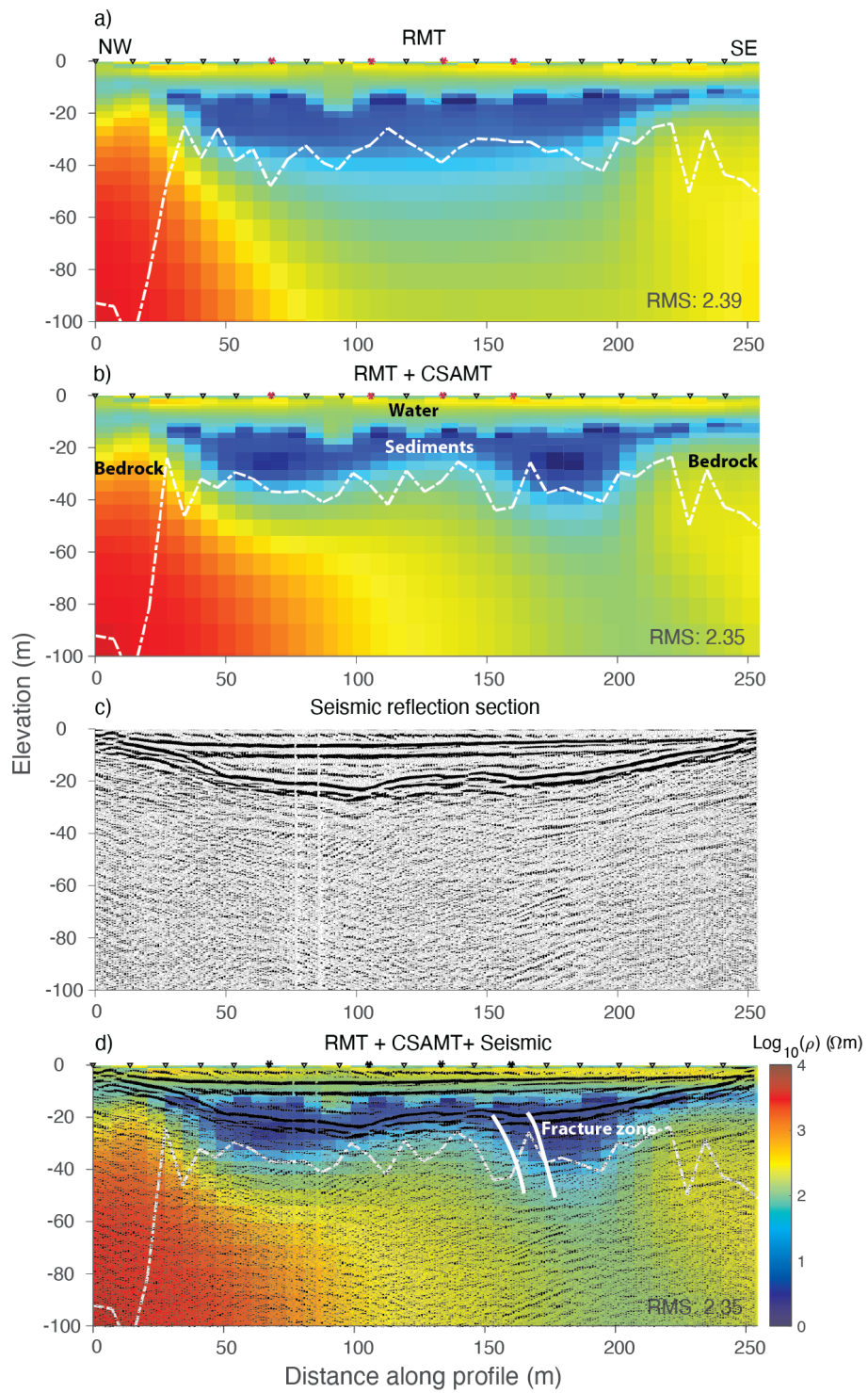
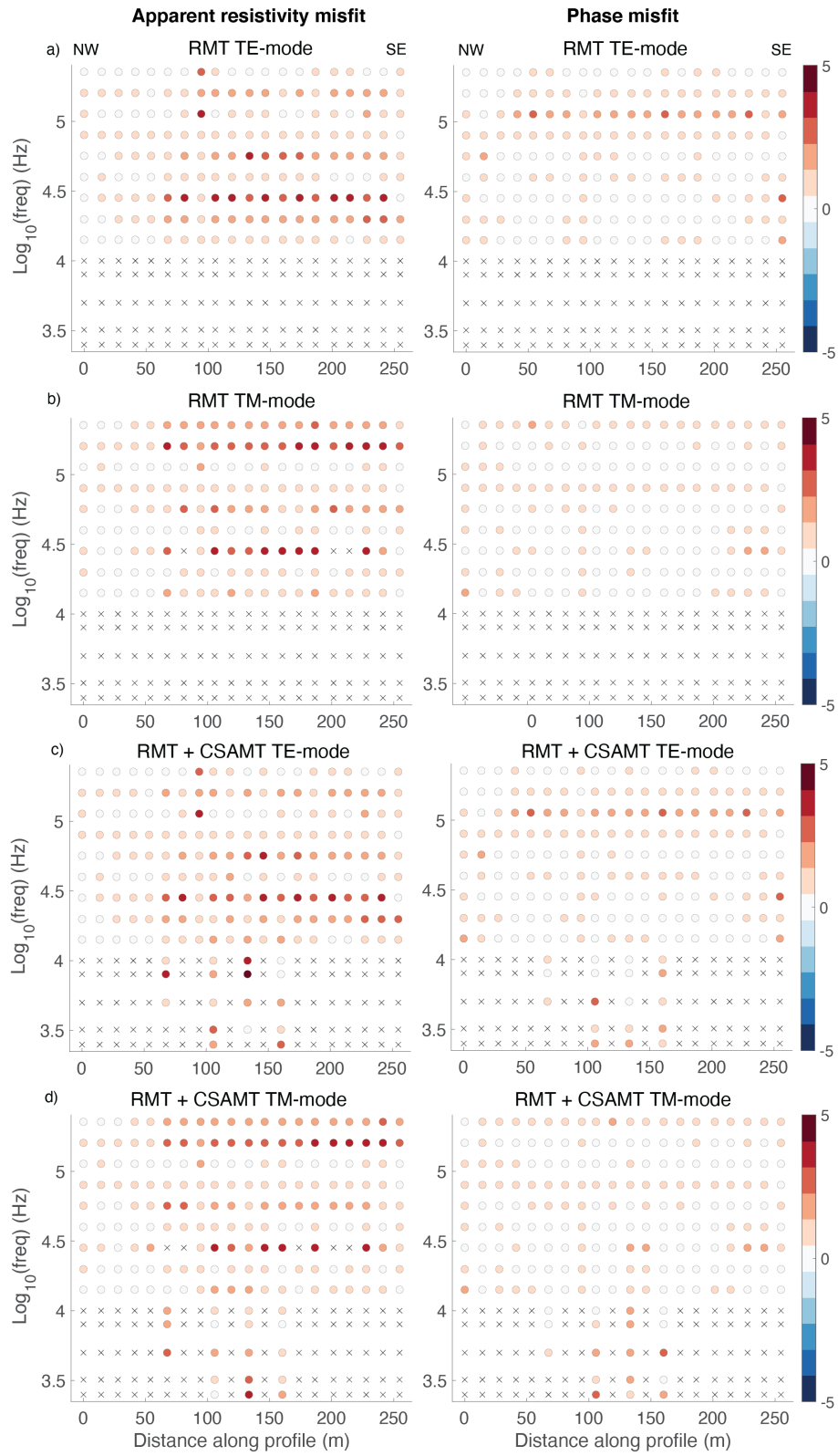


Figure 10



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**Figure legends:**

Figure 1: Location of study area. (a) The Stockholm Bypass (Förbifart) project. The planned bypass is shown with the green track. (b) Profile section of water passages, marked by numbers 1 to 3, showing the location and depths to the top of the tunnel. The inset map in (a) shows the location of study area in Sweden.

Figure 2: Location of the boat-towed RMT profiles (marked from L1 to L24 with black circles and lines) and the new CSRMT profiles (marked from C1 to C4 with white rhombus). In the background the resistivity slice at 38 m depth from the 2D inversion of boat-towed RMT data are shown (Mehta et al., 2017). In the present study and to showcase the improvements, we used L9 RMT profile (marked with arrow) along with the four controlled-source stations that located along it. The location of the CSRMT source is shown in the inset figure (bottom right) with respect to the previously acquired RMT and the newly acquired CSRMT stations.

Figure 3: (a) Photo showing the EnviroMT CSRMT field setup while measuring on the Lake Mälaren near the city of Stockholm, Sweden. Different components of the setup are also shown. (b) A close look at the drill hole made in the ice crust for proper electric electrode contact with water. (c) The setup of the double magnetic dipole transmitter used as source.

Figure 4: Amplitude of the power spectra (unit is arbitrary) of radio transmitters at station 6 profile 1. The grey boxes show the gaps in the RMT frequency range.

Figure 5: Measured apparent resistivity and phase of CSRMT data at stations along profile C1. (a) Apparent resistivity in XY direction, (b) phase in XY direction, (c) apparent resistivity in YX direction, (b) phase in YX direction. At most stations the transition between RMT and controlled-source data is smooth.

Figure 6: 2D inversion models of (a) RMT and (b) combined RMT and CSAMT dataset from L9 line shown in Figure 1. The location of the controlled-source stations along the profile is marked by red ‘\*’ in (b), and the location of RMT station is marked by inverse triangles. (c) For comparison a nearly collocated reflection seismic section along the resistivity profile is superimposed (d) into the model shown in (b). The improvement is significant especially in better delineating bedrock level and its undulation on the middle part of the profile. Penetration depth of data is marked in white dashed line, and the potential fracture zone is marked in white line.

Figure 7: Data misfits corresponding the inversion in Figure 6, which are the observed and modelled data difference normalized by the data errors. In general, phase data have lower misfits than the apparent resistivity data. The crosses mean the exclusion of data points in the corresponding inversions.

Figure 8: Sensitivity test of anomaly A and anomaly B. The resistivity of the anomalies is increased to 1000  $\Omega\text{m}$  from the inverted values for model perturbation. The RMS increase is the original and perturbed RMS difference normalized by the original RMS. (a) Anomaly A for RMT inversion, (b) anomaly B for RMT inversion, (c) anomaly A for RMT plus CSAMT inversion, and (d) anomaly B for RMT plus CSAMT inversion. The RMS increases of RMT plus



CSAMT inversions are about 2-3 times larger than the ones of RMT inversions, which indicates the increase of sensitivity at depths due to the inclusion of four CSAMT stations.

Figure 9: 2D inversion models of (a) RMT and (b) combined RMT and CSRMT dataset from L13 line shown (see Figure 2 for locations) and the location of the controlled-source stations along the profile is marked by red ‘\*’. (c) Reflection seismic data along the same profile. (d) For comparison the nearly collocated reflection seismic section along the resistivity profile is superimposed on the resistivity model shown in (b). Penetration depth of data is marked in white dashed line.

Figure 10: Data misfits corresponding the inversion in Figure 9, which are the observed and modelled data difference normalized by the data errors. In general, phase data have lower misfits than the apparent resistivity data. The crosses mean the exclusion of data points in the corresponding inversions.