Boat-towed RMT for urban underground infrastructure planning

Stockholm Bypass (Förbifart) case study

Suman Mehta

Abstract

The tensor radio magnetotelluric (RMT) method has extensively been used in near surface investigations for imaging resistivity structures of the subsurface. In this research, for the first time a data acquisition system called boat-towed RMT is introduced that has the capability to measure tensor RMT data on still or moderately wavy fresh water bodies like lakes, rivers and streams. One of the main objectives of this thesis is to demonstrate the operational capability and feasibility of using boat-towed RMT for near surface applications. Three days of RMT data acquisition was carried out on Lake Mälaren near the city of Stockholm and in total fifty-two lines including 1160 stations with an average spacing of 15 m were surveyed. In spite of being in an urban environment, the acquired data were of reasonably good quality within an acceptable error level of 2-3%. The second half of this thesis examines the resolution and sensitivity of the boat-towed RMT data for delineating the presence of fracture zones in crystalline bedrock. 2D models were obtained by inversion of determinant and joint transverse electric and transverse magnetic modes resistivity and phase data. The models are consistent from one line to another and in general show good correlation with the existing drilling information from the site. Overall, a three-layer resistivity model was obtained that had a conductive layer interpreted as lake sediments, which is sandwiched between high resistive bedrock and resistive water layer. A consistently low resistivity discontinuity was observed in the bedrock across all the lines. It was interpreted to be from a fracture zone striking in the perpendicular direction of lines. However, due to lack of penetration, RMT method itself was insufficient to provide a conclusive interpretation of fracture zone. Through various synthetic modelling it was evident that lower frequencies are required to better resolve the geometry and properties of the bedrock that lies below the conductive lake sediments. However, the Lake Mälaren case study illustrates that boat-towed RMT is capable of acquiring high quality data over water bodies and can be expected to be useful in many different applications on fresh water bodies.

Dedicated to my parents

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Bastani M., Persson L., Mehta S. and Malehmir A., 2015, Boat-Towed radio-magnetotellurics (RMT) – A new technique and case study from the city of Stockholm: Geophysics, 80, B193–B202.

II Mehta S., Bastani M., Pedersen L., and Malehmir A., 2015, Analysis of resolution and sensitivity of boat-towed RMT data over Lake Mälaren, Stockholm: Submitted to Interpretation

In the second part of this printed version of the thesis papers I and II are included in full text.

The following publications are not included in this thesis:

Malehmir A., Andersson M., Mehta S., Maries M., Brodic B., Munier R., Place J., Smith C., Kamm J., Bastani M., Mikko H. and Lund B., 2015, Post-glacial reactivations of the Bollnäs fault, central Sweden: Solid Earth Discuss, 7, 2833–2874.

Contributions

The papers included in this thesis are the result of collaboration with several authors. The individual contributions of the author of this thesis are summarized below.

Paper I: *Boat-towed radio-magnetotellurics (RMT) – A new technique and case study from the city of Stockholm:*

My primary responsibility in this article was to process the acquired data and to correct the coordinate locations of all the stations. Further, I carried out inversions to obtain the 2D models presented in the paper. Finally I was also involved in discussion and writing of relevant sections of the manuscript.

Paper II: *Analysis of resolution and sensitivity of boat-towed RMT data over Lake Mälaren, Stockholm:*

In this paper, I was responsible for all the strike analysis, 2D modeling of the RMT data in different modes, synthetic analysis, constrained inversion and comparative study with seismic results. With the help of critical comments and suggestions from the co-authors, I was responsible to prepare the first draft of manuscript and completed until its submission.

Contents

Abbreviations

RMT: Radio magnetotelluric
MT: Magnetotelluric
VLF: Very low frequency
LF: Low frequency
2D: Two dimensional
Hz: Hertz
kHz: kilo Hertz
TE: Transverse electric
TM: Transverse magnetic
TEM: Transient electromagnetic
EM: Electromagnetic
S/N: Signal to noise ratio

1. Introduction

Magnetotelluric (MT) method for geophysical exploration has been established since early 1950s (Tikhonov 1950 and Cagniard 1953). For over half a century MT, which is an electrical resistivity imaging methods, has evolved significantly and its applications have been illustrated for mineral and hydrocarbon exploration (Orange, 1989; Hoversten, 1996; Pandey et al. 2008 and Mansoori et al. 2015) and study of deep crust and upper and lower mantle of the earth (Lizarralde et al. 1995; Xu et al. 2000; Ichiki et al. 2001 and Dasgupta et al. 2013). MT is essentially a plane wave, natural source electromagnetic method that measures in the frequency band range from 10^{-4} Hz to a few hundreds of Hz. With the development in instrumentation and formulation in the last few decades, it is possible to implement the theory of MT method in shallow investigations using radio magnetotelluric (RMT) method. RMT method uses radio frequencies in a band range of 10 KHz to 250 KHz from distant radio transmitter as electromagnetic sources that can be well approximated as a plane wave. For practical purpose, Goldstein and Strangway (1975) showed that the plane wave criteria can be satisfied if the distance between source and receiver is at least three to five times of the skin depth in case of homogeneous half space. Pedersen et al. (2006) showed the stability of the transfer functions obtained from RMT data collected at different sites in Europe. Application of RMT technique in scalar form, where only one horizontal electric field and the perpendicular magnetic horizontal component is measured, has been explored in numerous studies (Turberg et al. 1994, Bosch et al. 1999, Tezkan 1999 and Tezkan et al. 2000). The tensor RMT technique in which all electrical and magnetic components are measured simultaneously (Pedersen et al. 2005, 2006, Bastani 2001, Bastani and Pedersen 2001) have significant advantages over scalar measurements in case of complex geological conditions. There are numerous publications showing wide applications of RMT method in near surface hydrological, environmental and engineering problems (Bastani et al. 2013, Malehmir et al. 2015; Newman et al. 2002 and Tezkan et al. 2000). Further, Oskooi and Pedersen (2005) discussed the importance of broader range multi-frequency VLF/LF system in better resolving the very shallow as well as relatively deeper subsurface. Persson (2001) analyzed the resolution of RMT and VLF data using field VLF and RMT and synthetic modeling.

Recently, there has been a wide range of successful experiments to carry out electrical resistivity and electromagnetic surveys on shallow water bodies like lakes and rivers. Some of the water borne electrical resistivity studies related to near surface geological and engineering problems was reported by Day-Lewis et al. (2006), Danielsen and Dahlin (2009) and Chang Ping-Yu et al. (2015). Tassi et al. (2015) carried out electrical resistivity tomography in a marine environment for delineating fracture zones for an underwater tunnel project in Norway. A persistent issue with electrical resistivity survey on lakes is the lack of penetration depth and in a comparative study of floating electrode array and bottom array, Loke and Lane (2004) concluded that in case of a floating array, water depth should not be more than 25% of the depth of investigations.

Several transient electromagnetic (TEM) studies over lakes have been reported. TEM data acquired on the Sea of Galilee by Goldman et al. (1996 and 2005) show the results for mapping of saline groundwater. With an objective to resolve the thickness of lake sediments, Mollidor et al. (2013) acquired floating in loop transient EM data on Lake Holzmaar.

This thesis, for the first time introduces tensor radio magnetotelluric measurements on lakes in an urban environment. The main objective of this thesis is to study the adaptability, feasibility and analysis of resolution and sensitivity of tensor RMT data acquired on Lake Mälaren in the city of Stockholm.

In paper I, details about the method and required modification in the setup and field procedures are provided. It presents the effectiveness, challenges and shortcomings of the waterborne RMT data acquisition set up. It also illustrates the quality of raw data and the efficiency of the system compared with similar type land RMT surveys.

In paper II, the studies are extended to focus on the interpretation and securitization of the data to analyze the resolving capacity and sensitivity of the method in delineating weak zones in crystalline bedrock with the help of synthetic data and modeling. A comparative study with existing seismic results and available bathymetry data from the lake were performed to better constrain the interpretations. The study shows the necessity for controlled source low frequencies to obtain desired depth of penetrations for verification of the interpreted weak zones in the bedrock. This is likely the focus of the future studies towards the completion of the PhD work.

1.1 Study area

Stockholm bypass (known as Förbifart Stockholm) is a planned underground motorway project by the Swedish road administration (Trafikverket) that aims to reduce the increasing traffic pressure from Stockholm. It is a 21-km long motorway of which 18 km will be in forms of tunnel that will bypass the city and connect the southern and northern parts of Stockholm (see http://www.trafikverket.se/). The proposed path of the tunnel will pass under the Lake Mälaren at three locations. These water passages and path of the tunnel is shown in Figure 1 (Bastani et al. 2015). Boat-towed RMT setup was tested and data were collected over these water passages with an objective to resolve the crystalline bedrock and identify if any weak zones are present. Sweden has 7-8% of its land covered by fresh water bodies (rivers and lakes) hence the developed boat-towed RMT equipment would significantly be relevant for major underground infrastructure planning projects.

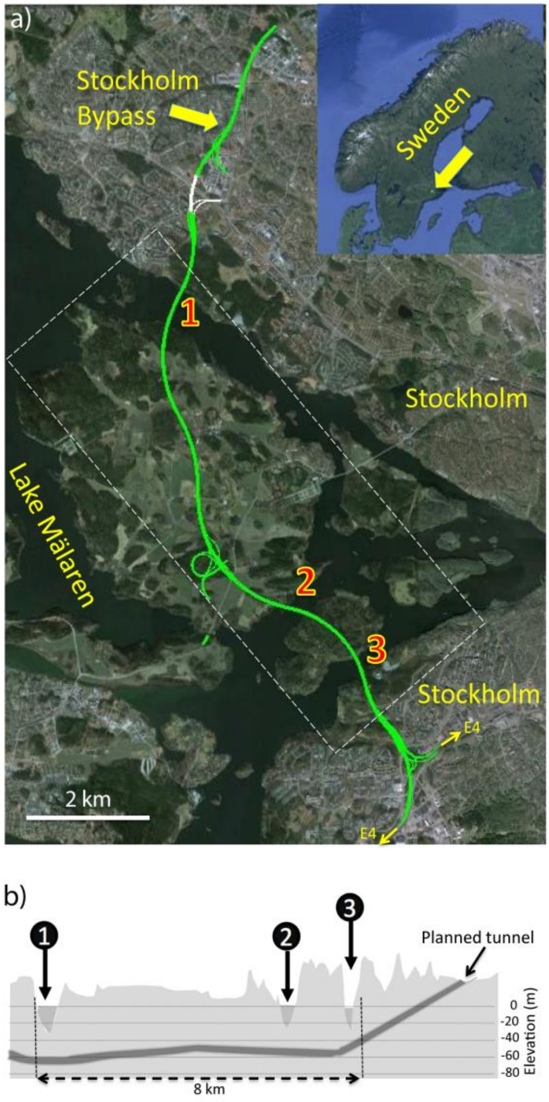

Figure 1. (a) The Stockholm Bypass project plan. The green line is the planned track, and the frame on the top-right corner shows the location of the study area in Sweden. (b) Cross section of part of the planned tunnels (marked with the dashed white box in panel [a]) below Lake Mälaren. Sites 1, 2, and 3 are where the case study was conducted (Figure is modified from Bastani et al. 2015).

2. Theoretical background

2.1. Radio magnetotelluric method

The RMT method uses electromagnetic signals from distant radio transmitters in the frequency band of 15 kHz to 250 kHz and has in general sufficient penetration depth of penetration in Scandinavian conditions for shallow investigation. Turberg et al. (1994) was the first to use RMT method for hydrogeological studies. Since then there has been a vast number of publication covering wide range of hydrological, environmental and geotechnical applications (Bastani et al. 2009 and 2011; Shan et al. 2014, Tezkan et.al 1996, Tezkan et al. 2000, Bastani and Pedersen 2001).

Pedersen et al. (2006) carried out a comprehensive analysis of RMT data acquired at different sites in Europe. Their study showed that depending on the site, a reliable signal with a horizontal magnetic field signal to noise ratio ≥12dB can observed in RMT frequency range. At a remote observation point, the transmitted electromagnetic waves from radio transmitters can be well approximated as plane wave. The ground acquisition procedure is similar to ordinary MT survey. Two horizontal components of electric field and three components (2 horizontal and 1 vertical) of the magnetic field are measured simultaneously. Fourier transformation of these time series gives linear relationship in frequency domain to estimate of earth EM transfer functions, namely, the impedance tensor **Z** and tipper vector **T** (Pedersen 1982). For a given angular frequency ω, transfer function can be defined as:

$$\begin{bmatrix} E_x(\omega) \\ E_y(\omega) \end{bmatrix} = \begin{bmatrix} Z_{xx}(\omega) & Z_{xy}(\omega) \\ Z_{yx}(\omega) & Z_{yy}(\omega) \end{bmatrix} \begin{bmatrix} H_x(\omega) \\ H_y(\omega) \end{bmatrix}, \quad (2.1)$$

and

$$H_z(\omega) = T(\omega) \begin{bmatrix} H_x(\omega) \\ H_y(\omega) \end{bmatrix}, \quad (2.2)$$

where *E* and *H* are the electric and magnetic fields and subscripts *x*, *y*, and *z* represent the two horizontal and vertical measurement directions, respectively.

The diagonal elements are zero in case of a two dimensional case and Z_{xy} represents transverse electric (TE) mode and Z_{yx}_corresponds to transverse magnetic ™ mode. TE mode refers to a case when current is flowing in the strike direction where as in TM mode, current flows perpendicular to the strike (Berdichevsky et al. 1998, Tuncer et al. 2006). The determinant of the impedance tensor is defined as

$$Z_{det} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}} \quad (2.3)$$

Zdet is commonly used in modeling because of its rotationally invariant characteristic (Pedersen and Engels, 2005, Smirnov and Pedersen, 2009, Bastani et al. 2011). Pedersen and Engels (2005) showed that TE mode couples well with conductors and TM mode couples well with resistive features and joint TE and TM mode modeling give superior models. The apparent resistivity (ρ_a) and phase (φ) of impedance corresponding to different modes described above can be obtained by the following expressions:

$$\rho_a(\omega) = \frac{1}{\omega\mu_0}|Z(\omega)|^2 , \quad (2.4)$$

$$\varphi(\omega) = arctan\frac{Im(Z(\omega))}{Real(Z(\omega))} . \quad (2.5)$$

2.2. Dimensionality analysis

The impedance tensor provides an estimate of dimensionality of the subsurface structures. Swift (1967) defined a parameter skew as:

$$S(\omega) = \frac{|Z_{xx}(\omega)+Z_{yy}(\omega)|}{|Z_{xy}(\omega)-Z_{yx}(\omega)|}. \quad (2.6)$$

The value of skew is an indicator of the dimensionality. If the value is small and lies below 0.3 then it can be assessed that data can be expressed in a simpler model, 1D or 2D. However, this parameter does not take into account the 3D effects caused by near surface heterogeneity and it is also sensitive to galvanic distortions. A more precise approach to estimate regional strike was suggested by Zhang et al. (1987). It is based on least square minimization of Q value which is defined as:

$$Q_{ij} = \frac{|Z_{xx}(\omega_i)-\beta_j^{est}Z_{yx}(\omega_i)|^2}{\sigma_{xx}^2(\omega_i)} + \frac{|Z_{yy}(\omega_i)-\gamma_j^{est}Z_{xy}(\omega_i)|^2}{\sigma_{yy}^2(\omega_i)}, i = 1, N; j = 1, M \quad (2.7)$$

$\sigma_{yy}(\omega)$ and $\sigma_{xx}(\omega)$are standard deviation of Z_{yx} and Z_{xy}respectively. *N* is the number of frequencies used and *M* is the number of stations. β_j^{est} and γ_j^{est}

are the estimated distortion parameter at station j. The Q value is calculated for each for different rotational angles and it obtains its minimum value at the regional strike direction. This approach of estimating regional strike direction takes the galvanic distortion into account and provides more reliable estimate.

3. Data acquisition and analysis

3.1. RMT data processing

The raw data used in this thesis were acquired by the EnviroMT acquisition system (Bastani, 2001) developed at Uppsala University for land surveys. Since the relation between the measured EM components are much simpler in frequency domain than in time domain, therefore each time series is Fourier transformed and data are stacked as the auto and cross powers in the form of spectral matrix. For detecting a suitable transmitter, an adjustable total horizontal magnetic S/N threshold ratio is defined (see Bastani 2001 for details). The magnetic field is preferred for this purpose because it is usually less noisy than the electric field.

Further, the RMT frequency band of 15-250 kHz is split into nine overlapping sub-bands of one octave width (Bastani, 2001). A reliable estimate of transfer functions is obtained by band averaging technique (Bastani, 2001). The raw data might be contaminated by cultural noises or by uneven distributions of available transmitters within a given band of one octave. In such cases a post processing using a parametric representation of each impedance tensor element combined with truncated singular value decomposition (TSVD) regularization (Bastani and Pedersen, 2001) can be utilized.

3.2. Boat-towed RMT

With an objective to carry out RMT survey on lakes and other fresh water bodies, the existing acquisition EnviroMT system (Bastani, 2001) was upgraded and improvised. The new set up referred to as boat-towed RMT (Bastani et al. 2015) was developed at the Geological Survey of Sweden (SGU). The basic setup remains the same as land measurement except that the analog part of the setup was made to float and towed by a boat. The analog components like 3 component magnetic field sensor (MFS), analog filter (AF) box and other electronics were set up on a platform made of wood and Styrofoam to float on the water. Two pairs of steel electrodes along with buffer amplifiers (used to minimize capacitive leakage in the cables) were fixed on a pair of five-meter-long arms in perpendicular direction attached to the platform, acted as electric dipoles. The floating platform was towed at a constant distance of 10 m from the boat. The digital part of the set up was placed in the box and received analog signal with the help of a 10 m long cable from the floating analog part. The boat-towed RMT survey is carried out while the boat is moving, which makes the data acquisition more efficient and faster than the on land survey. Figure 2 shows the schematic diagram of the floating acquisition system.

3.3. Position correction

The boat-towed RMT system currently lacks in-built GPS system for simultaneously geodetic surveying of the RMT measuring points. A handheld GPS located in the boat was used for the positioning of the stations, which were 10 m away from the correct location of the sensors on the floating platform (Figure 2). This may have some effects on the interpretation of subsurface structures. Thus, to correct this constant offset between the central measuring point and the boat, the registered coordinates has to be corrected to remove the 10 m shift. The correction can be done by estimating the heading angle of the boat and the known offset. The heading angle can be estimated using geodetic position of consecutive measuring points. With subsequent improvement in the acquisition setup, a DGPS device is now installed that gives more accurate positioning.

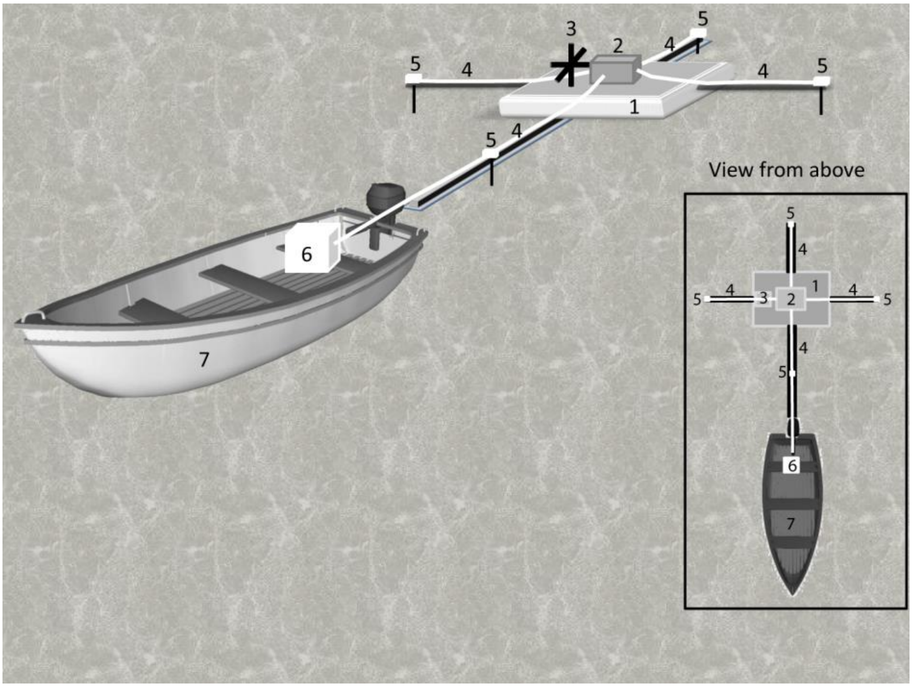

Figure 2. Sketch of the boat-towed RMT setup. (1) Floating platform, (2) central AF box (3) 3C MFS, (4) arms and cables for electric field measurements, (5) electric buffer amplifiers connected to the steel electrodes floating in water, (6) central processing unit, and (7) motorboat used for towing. Figure from Bastani et al. (2015).

4. Modeling

4.1. 2D inversion

In estimating the earth resistivity model representing the subsurface structures from the observed geophysical data, mathematical inversion methods play a crucial role. In this thesis, for 2D modeling of the RMT data, a modified version of the REBOCC program (Siripunvaraporn and Egbert 2000; Kalscheuer et al. 2008) has been used. The advantage of the modified inversion algorithm is that it accounts for displacement currents and also allows the inversion of determinant mode (Kalscheuer et al. 2008). Further, the inversion algorithm is performed in data space, which helps to significantly reduce the computational cost and makes it a portable inversion module for ordinary desktop computers.

Mathematically, the inverse problem can be described as a process of deriving a model vector *m* from a set of measured data *d*. It can be expressed as *d* = F(*m*) which is a nonlinear problem and needs to be linearized. If we can consider the earth as a discretized **M** number of blocks of constant resistivity, **m**= [$m_1, m_2, \ldots, m_M$], N observed data **d**=[$d_1, d_2, \ldots, d_N$] then the fitness of the model response **F[m]** to the observational data can be expressed as

$$X_d^2 = (\boldsymbol{d} - \boldsymbol{F}[\boldsymbol{m}])^T \mathbf{C}_d^{-1} (\boldsymbol{d} - \boldsymbol{F}[\boldsymbol{m}]) \qquad \textbf{(4.1)}$$

where the superscript T denotes matrix transpose and $\mathbf{C}_d^{-1}$ is the inverse of data covariance matrix. The inversion problem is ill-posed and in order to prevent over fitting, additional information should be introduced and a regularization method is employed for model selection. The model norm X_m is minimized towards *a priori* information. A general model norm is expressed as

$$X_m^2 = (\boldsymbol{m} - \boldsymbol{m_0})^T \boldsymbol{C}_m^{-1} (\boldsymbol{m} - \boldsymbol{m_0}) \qquad \textbf{(4.2)}$$

where $\boldsymbol{m_0}$ is *a priori* model and $\boldsymbol{C}_m^{-1}$ is an inverse of a model covariance matrix which acts as a smoothness operator. The objective function defined for minimization of the problem is a combination of equation 4.1 and 4.2 and can be expressed as

$$\begin{aligned} \Phi = (\boldsymbol{m} - \boldsymbol{m_0})^T \boldsymbol{C}_m^{-1} (\boldsymbol{m} - \boldsymbol{m_0}) \\ +\boldsymbol{\lambda}^{-\mathbf{1}} \{ (\boldsymbol{d} - \boldsymbol{F}[\boldsymbol{m}])^T \mathbf{C}_d^{-1} (\boldsymbol{d} - \boldsymbol{F}[\boldsymbol{m}]) - X_*^2 \} \end{aligned} \qquad \textbf{(4.3)}$$

Here λ is a Lagrange multiplier that acts as a trade-off between minimizing the norm of data misfit and the norm of the model (Tikhonov and Arsenin, 1977; Parker, 1994). X_*^2 is the desired level of misfit.

The inversion algorithm uses finite difference approach to discretize the model space with rectangular cells. In the modeling shown in papers I and II, the shallowest block was 1 m thick and an increasing vertical cell size with geometrical progression of ratio 1.12 with the deepest cell being 1200 m was constructed. The boat speed was variable and thus the spacing between the stations was not the same. So width of the blocks was of variable size and defined by the station spacing. The modified REBOCC module allows employing different inversion schemes like Occam, mean square error (MSE) inversion and Marquardt-Levenberg inversion (Kalscheuer et al. 2008). Models in this thesis were generated using the Occam type regularization to obtain smooth models.

4.2. Constrained inversion

A priori knowledge derived from other independent studies such as geological or geophysical can be of great importance and aid to constrain the inversion process and overcome the problem of non-uniqueness (de los Ángeles García Juanatey 2013; Park and Mackie 2000). This *a priori* knowledge can also be introduced in the inversion process that guides the algorithm to better resolve structural units. The modified REBOCC program (Kalscheuer et al. 2008) allows the introduction of a priori model that helps to obtain better geological model and a better fit to the data. In paper II, the known bathymetry data were used as a-priori information to constrain the 2D resistivity models from inversion of RMT data.

4.3. Synthetic modeling

MT inversion problem is known to be nonlinear. The inversion results are also non-unique hence to validate and investigate important features suggested in models synthetic analysis can be done. This can be done by analyzing the sensitivity of the data with respect to changes in model parameters. Further that the depth penetration was limited and it was not sure that the conductive features seen along all the line were inversion artefacts or fractured bedrock. In order to investigate the limitations of the method and study the extension of the penetration depth (by using CSMT) frequencies synthetic modeling were carried out. In paper II a set of synthetic analysis was carried out to investigate the sensitivity of the RMT method/data in detecting fracture zone in the crystalline bedrock that lies under lake. Synthetic analysis also helped in the design of optimum frequencies for control source measurements that would give the desired depth of penetration.

5. Summary of papers

5.1. Paper I: Boat-towed radio-magnetotellurics — A new technique and case study from the city of Stockholm

5.1.1 Summary

The main objective of this paper is to further illustrate the potential of the boat-towed RMT system and to analyze its resolution power and sensitivity in delineating major geological structures. This was conducted as a complementary study to what presented in paper I. Analysis of the data acquired over two water passages were carried out and 2D inversions of determinant and joint TE+TM mode data of all the lines were performed. The results were compared with existing seismic refraction results of the corresponding lines. Furthermore, the known bathymetry information of the lake was used to carry out constraint inversions. Through various synthetic modeling and inversions, the sensitivity and resolving capability of the method in resolving conductive fracture zones in crystalline bedrocks were assessed. The synthetic studies proved to be useful in designing optimum frequencies that can be used in the controlled source magnetotelluric (CSMT) measurements to achieve the desired penetration depth.

5.1.2 Boat towed RMT setup

The boat-towed RMT setup is nearly the same as the EnviroMT system introduced by Bastani (2001) that is used for RMT surveys on land. The setup and configuration for water borne measurement is described in detail in section 3.2. Before the main acquisition, several feasibility tests were performed at the test site near Lake Mälaren. These tests showed the availability of 20-27 radio-transmitters for measurement that had S/N >10 dB. A motorboat was used to tow the floating platform and was moving at a speed of 0.5 m/s. A total of 15 km long RMT data with an average spacing of 15 m between the stations was acquired during the three days of data acquisition.

5.1.3 Data processing and position correction

The city related cultural noise was processed using the procedure described by Bastani and Pedersen (2001) to obtain reliable estimates of impedance tensor. The boat-towed RMT system lacks inbuilt GPS system and position was registered with a handheld GPS, which was in the boat at an offset of

10 m from the central measuring point. Thus this error in positioning was corrected for by estimating boat heading using positions of two consecutive measuring points and the known offset.

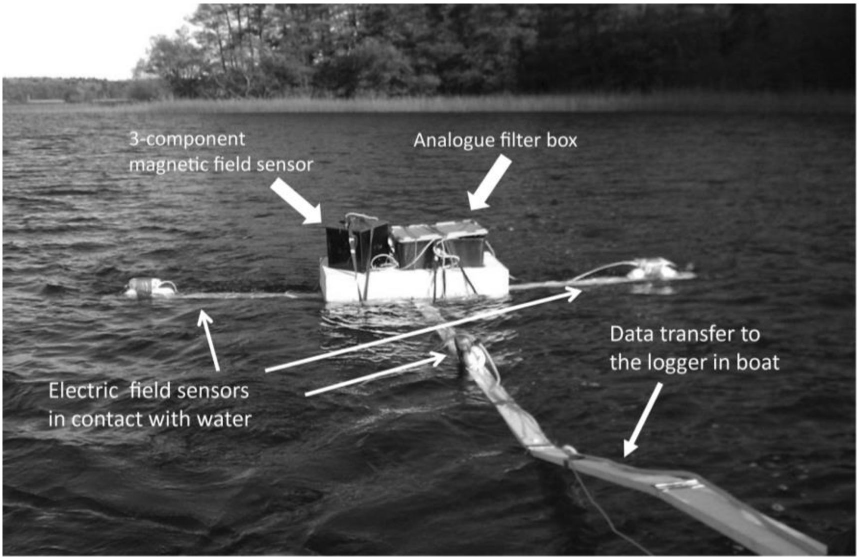

Figure 3. A photo showing the boat-towed RMT setup while measuring on the Lake Mälaren close to Stockholm, Sweden. Different components of the setup are also shown (see also Figure 2) (After Bastani et al. 2015).

5.1.4 2D inversion results

2D inversion of tensor RMT data of all the lines in Kungshatt-Lovön water passage was performed using modified REBOCC program (Siripunvaraporn and Egbert, 2000; Kalscheuer et al. 2008). The determinant RMT data were used in the inversions because of their rotationally invariant property, which is useful in case when regional strike is unknown (Pedersen and Engels 2005). Occam-type regularization was used for the inversion and 4% error floor on apparent resistivity and 1.2 degree on phase were used to avoid data overweighting. 2D models of some selected lines are shown in Figure 4. The distinct features that can be observed are the water column (W), conductive lake sediments (LS), highly resistive crystalline bedrock (B) and possibility of fracture zones (FB?).

5.1.5 Conclusions

The experiment of the boat-towed RMT measurement has been illustrated, and its capability is proved by the Lake Mälaren case study. The data acquired using this newly developed system were of reasonably good quality at an efficient speed rate. Resistivity models obtained from the acquired dataset showed consistent results from one line to another and in good correlation with the existing geological field observations. Distinct features in the models like highly resistive bedrock, conductive lake sediments, moderately resistive water layer and a possible fracture zone were identified along all the lines. It is expected that this system should be of high potential use in near future for other near-surface applications.

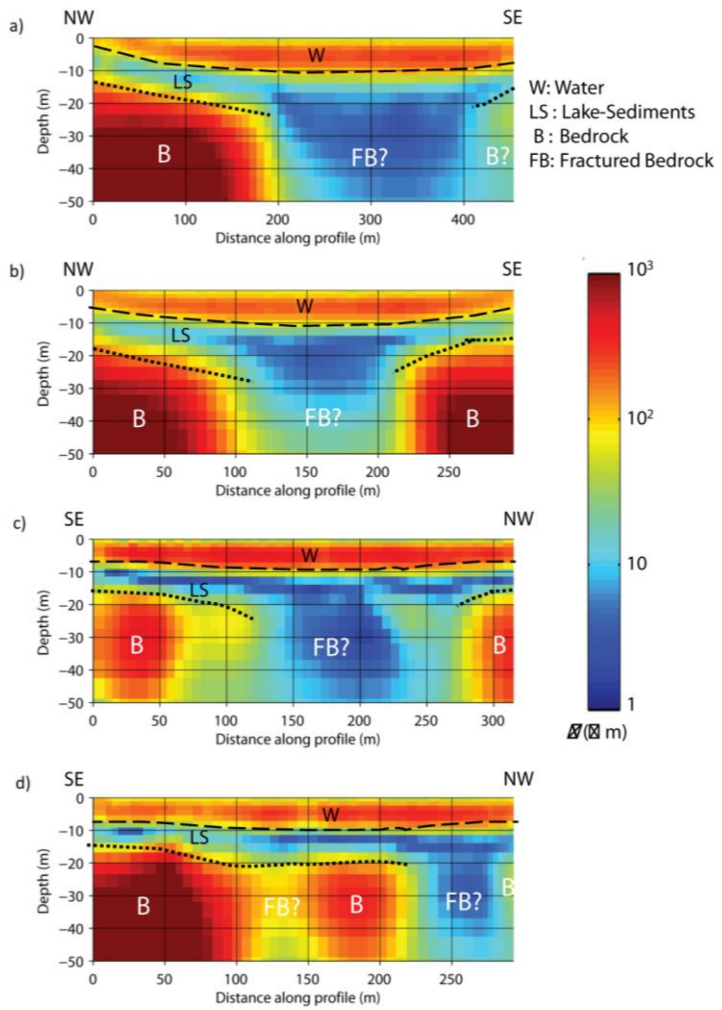

Figure 4. Selected 2D resistivity models along four lines located on the water passage between Lovön and Kungshatt: (a) line 1, (b) line 9, (c) line 16, and (d) line 24. The resistive bedrock is marked by B, possible low-resistivity-fractured bedrock by FB, water by W, and lake sediments by LS (modified from Bastani et al. 2015).

5.2. Paper II: Analysis of resolution and sensitivity of boat-towed RMT data from Lake Mälaren, Stockholm

5.2.1. Summary

The main objective of this paper is to further illustrate the potentials of the boat-towed RMT system and analysis its resolution power and sensitivity in delineating major geological structures. This was conducted as a complimentary study to what presented in paper I. Analysis of the data acquired over two water passages were carried out and 2D inversions of determinant and joint TE+TM mode data of all the lines were performed. The results were compared with existing seismic refraction results of the corresponding lines. Furthermore, the known bathymetry information of the lake was used to carry out constraint inversions. Through various synthetic modeling and inversions, the sensitivity and resolving capability of the method in resolving conductive fracture zones in crystalline bedrocks were assessed. The synthetic studies proved to be useful in designing optimum frequencies that can be used in the controlled source magnetotelluric (CSMT) measurements to achieve the desired penetration depth.

5.2.2 Analysis of boat-towed RMT data and other available data

The boat-towed RMT data were processed to reduce the cultural noise associated with the city-related environment using a parametric representation of each impedance tensor element combined with a truncated singular value decomposition (TSVD) regularization (Bastani and Pedersen 2001). After strike analysis using different approaches, it was quite evident that 2D models can express the RMT data. 2D inversions of determinant and joint TE+TM mode data of all the lines (38 lines) acquired across two water passages were carried out. Distinct structural features in 2D RMT models in paper I were also clearly observed in other water passages (e.g., Kungshatt-Sätra) as well. The interpreted layers from available refraction seismic data superimposed on the RMT models ate shown in Figure 5 (shown in black lines) for comparison. Subsurface features observed in the RMT models are in a good agreement with the seismic results. The interpreted structural features of two data sets correlate well. Velocities obtained, for example 1480 and 1750 m/s, well match those obtained for water and post-glacial sediments (e.g., Salas-Romero et al. 2015). A low resistivity zone that runs perpendicular to all the lines can be interpreted from the models and considered as weak zone.

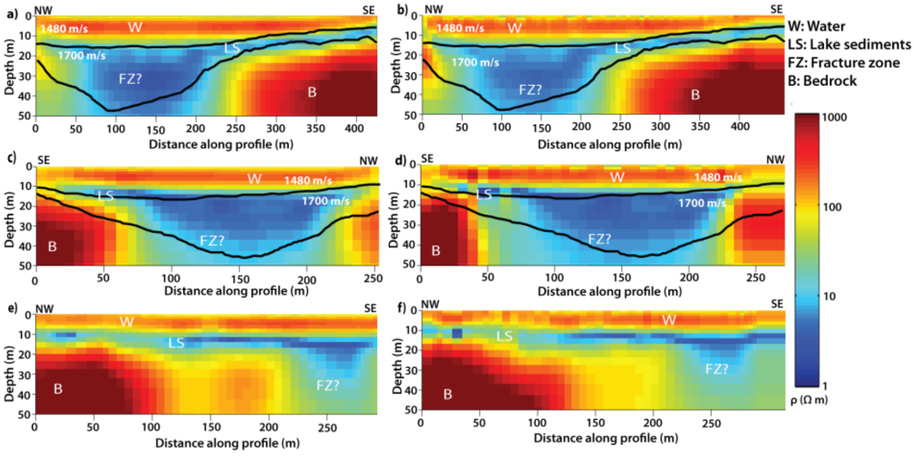

Figure 5. (a, c and e) 2D resistivity models (determinant data) of lines 2, 12 and 24, respectively from Kungshatt-Lovön region. (b, d and f) 2D resistivity models of the same lines but obtained using joint inversion of TE and TE mode data. The interpreted layers from refraction seismic data are superimposed on the RMT models for comparison (shown in black lines). The interpreted structural features of two data sets co related well. Velocities obtained, for example 1480 and 1750 m/s, well match those obtained for water and post-glacial sediments (e.g., Salas-Romero et al. 2015). W stands for water, LS glacial sediments, FZ fracture bedrock and B fresh bedrock.

5.2.3. Synthetic analysis

The synthetic analysis was carried out to validate the structural features that were expressed by RMT dataset in 2D models. Further, analysis of the sensitivity of the method with changes in model parameters were studied. The synthetic model considered closely mimics the RMT models obtained from the observed data. Overall it is a three-layered electrical resistivity model with top layer of resistivity 300 ohm-m that mimics the water followed by a layer of lake-sediments of 10 ohm-m and then the crystalline bedrock of 1000 ohm-m with a thin vertical fracture zone. Figure 6 shows the true model and the *a priori* model used for synthetic analysis. The data generated by forward modelling were contaminated by 4% Gaussian noise and inverted using an initial model of half space (1000 ohm-m) with different frequency ranges. Further an *a-priori* model was introduced to the inversion with an additional fracture zone located at some distance from the one in the forward model. The synthetic data were inverted for both determinant and joint TE+TM modes (see Figure 7). It was evident from the analysis that RMT method is capable of resolving fracture zone but lower frequencies are required to achieve desired depth of penetration for more conclusive results regarding the location of the fractures. Moreover, the analysis showed that the joint TE+TM mode inversion provides better constraint to conductive fracture zone as compared to determinant mode.

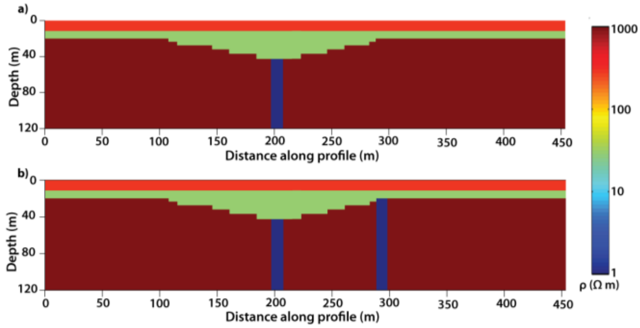

Figure 6. (a) Synthetic model (with one major fracture zone in the bedrock) used to generate synthetic RMT data; it replicates the general features observed in real RMT models. (b) An a priori model (with two major fracture systems in the model), which was introduced in the inversion process later. The idea with this model was to study the sensitivity of the RMT data to arbitrary a priori information in the inversion.

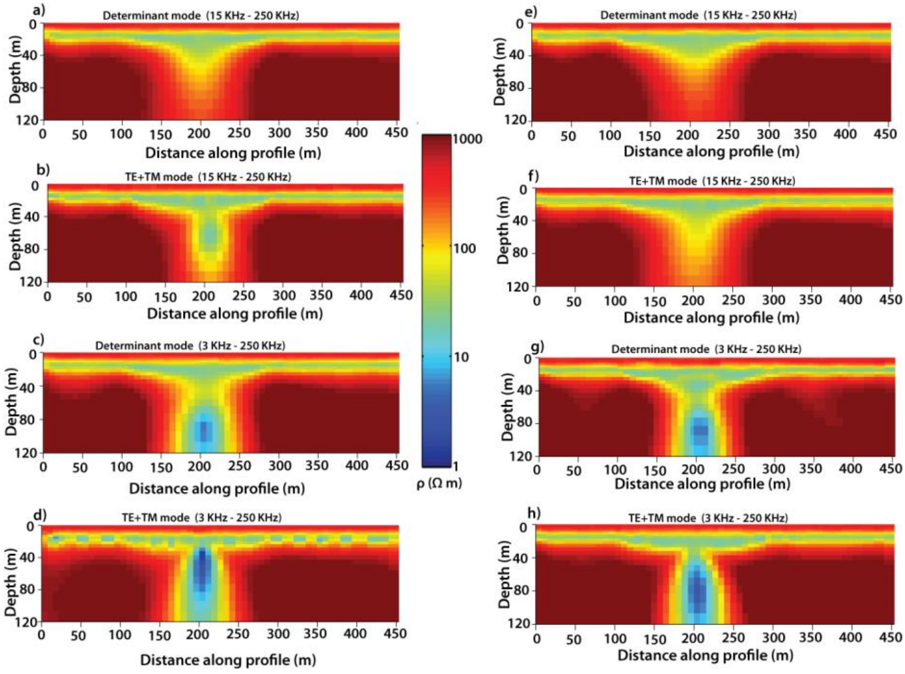

Figure 7. (a) Synthetic model (with one major fracture zone in the bedrock) used to generate synthetic RMT data; it replicates the general features observed in real RMT models. (b) An a priori model (with two major fracture systems in the model), which was introduced in the inversion process later. The idea with this model was to study the sensitivity of the RMT data to arbitrary a priori information in the inversion.

5.2.4. Conclusions

The data acquired using the boat-towed RMT method has the resolution power and sensitivity to detect the presence of thin conductive fracture zones in a resistive crystalline bedrock if they are located within its penetration depth limit (for example, about 50 m in Scandinavian conditions). The drawback is that due to the limited frequency band of radio transmitters only a limited depth of penetration can be achieved. Thus It is difficult to achieve conclusive results. RMT is an inductive method and presence of conductive lake sediments acts as a shield that further hampers the penetration depth. Synthetic analysis showed that using lower frequencies this problem can be overcome. Thus, in future controlled-source boat-towed RMT method can be employed to have greater penetration depths for more conclusive interpretations. The study also shows the advantage of having a water layer that acts as a near surface homogeneous medium that eliminates near-surface distortions. Figure 7 shows the 3D visualization of all the 2D RMT models across the two water passages. It shows a consistent low resistivity zone (possible fracture zone) in all models but certainly more penetration depth is required to better these structures.

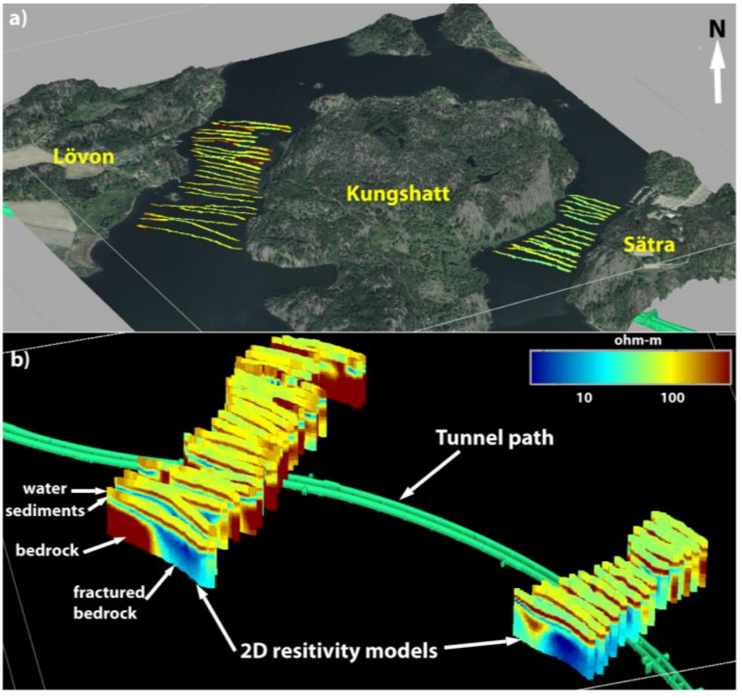

Figure 7. 3D visualization of all the 2D resistivity lines; (a) the two water passages and the locations of all the RMT lines and (b) the planned tunnel model (in green) visualized together with the RMT resistivity models.

6. Conclusions

This thesis presents the development of the boat-towed RMT acquisition system that extends the capacity to measure tensor radio magnetotelluric over fresh water lakes, rivers and streams. Paper I, illustrates the operational capability of the newly developed acquisition system over still to moderately wavy water. The test site was over three water passages of the Lake Mälaren close to the city of Stockholm where a three-day measurement was carried out. A total of 15 km long survey that consisted of fifty-two lines including 1160 stations with an average spacing of 15 m were covered. Data acquisition with a production rate of 1 km/h proved to be significantly efficient compared to traditional surveys on land. The Lake Mälaren case study also shows certain aspect of the system that can be further improved. At present, the boat-towed RMT system is not equipped with inbuilt GPS system. In future, a DGPS receiver can be incorporated in the data acquisition system for more accurate positioning.

Paper II lays emphasis on comprehensive analysis of the boat-towed RMT data to examine the resolution and sensitivity of the system over the Lake Mälaren. 2D resistivity models were obtained from the inversion of joint TE+TM modes as well as determinant resistivity and phase data. These resistivity models were consistent from survey line to survey line and correlated well with existing available geological knowledge and results of a refraction seismic survey in the same area. The main distinctive features were easily interpreted and in general all models had a conductive sediment layer of varying thickness along the line that was sandwiched between two resistive layers of water column and bedrocks. However, a discontinuity in the bedrock was clearly indicated in all the models and was interpreted as a possible fracture zone present in the bedrock striking in the direction of the water passages. The lack of penetration depth of the acquired RMT data made it difficult to conclude the presence of fracture zone just by this method itself. To validate the obtained models and to analyze the resolving capacity and the sensitivity of RMT method in detecting a fracture zone in crystalline bedrock, several synthetic analysis were carried out with different sets of model parameters. The synthetic analysis showed that lower frequencies will be required to enable us to better interpret the geometry and properties of the bedrock overlain by a layer of conductive lake sediments. However, the resistive fresh water layer proved to have certain advantages as it acts as a homogeneous medium and eliminates any near surface 3D effects.

Future works

The case study of Lake Mälaren showed there is great potential for improvements of the boat-RMT data and data acquisition for near surface applications. Inbuilt DGPS will be incorporated with the acquisition system to acquire accurate positioning of measuring points. Further, lower frequencies will be employed to increase the penetration depths. The same data acquisition system will be used to measure controlled-source audiomagnetotellurics data at frequencies as low as 1000 Hz. However, there are certain challenges associated with controlled-source measurements over water bodies since it slows down the production rate. Also in case of controlled-source measurements, special attention needs to be given to overcome the near field effects that violate the plane-wave approximation. The success of the boat-towed RMT system encourages and motivates to further improve and upgrade the acquisition system to extend its potentials in future for near surface investigations.

8. Summary in Swedish

Radiomagnetotelluriska (RMT) metoder har använts i en omfattande utsträckning och vid en rad olika tillämpningar där det funnits behov att göra avbildningar av variationer i resisitiveten vid grunda djup. Metoden använder redan befintliga elektromagnetiska signaler från avlägsna radiosändare i frekvensbandet 10-250 kHz. Eftersom källan befinner sig på långt avstånd från mätområdet kan signaler approximeras med en plan vågform. När metoden först introducerades av Turberg et al. (1994) var det i skalär form och användes då för hydrogeologiska undersökningar. Vid skalär RMT används endast ett fält som är horisontellt och vinkelrät mot den horisontella magnetiska komponenten vid mätningen. Vid mer komplex geologi används med fördel vektorbaserad RMT istället för skalära mätningar (Pedersen et al. 2005, 2006, Bastani 2001, Bastani and Pedersen 2001). Tekniken gör det möjligt att mäta samtliga tre magnetiska komponenter och samtidigt, via två överföringsfunktioner i frekvensdomänen, även se hur de är linjärt kopplade till varandra. De två överföringsföringsfunktionerna kallas impedansvektor och tipper och ger information om hur den elektriska resisitiviteten varierar nära ytan. Bastani (2001) introducerade ett instrument EnviroMT för vektor-RMT mätningar på land (Pedersen et al. 2006; Pedersen 2001; Bastani et al. 2009).

I denna avhandling introduceras en nytt vektor-RMT baserat system; båt-bogserad RMT, för mätningar på grunda söt-vattensamlingar och -vattendrag. Den första publikationen illustrerar detaljerna för hur systemet sätts upp och fältmetodik. För att testa anpassningsbarhet och kapacitet för det båt-dragna RMT–systemet sjösattes en fältkampanj på en sträcka av 15 km i Mälaren, nära Stockholm, under 3 dagar. Datainsamlingen visade sig mycket effektiv med en produktionshastighet av 1 km/h där stationerna i genomsnitt låg på ett avstånd av 15 m. Insamlat data höll god kvalitet, inom en acceptabel felmarginal av 2-3%.

Den andra publikationen fokuserar på analys av upplösning och sensitivitet i det RMT-data som samlats in med metoden med båt-bogserad RMT. Modeller i 2D från 40 profiler togs fram genom sammankopplad inversion av TE+TM och determinant resistitivitet och fas. Generellt har modellen tolkats som konduktiva lager; sjösediment, mellan berggrund och ett vattenskikt med hög resivititet. Ett genomgående diskontiunerligt skikt i berggrunden tolkades som en sprickzon med vinkelrät utsträckning mot samtliga profiler. De tolkade

RMT modellerna var samstämmiga och stämde väl överens med den geologiska information och resultat givna från annan tillgänglig geofysisk data. En serie av modeller med syntetisk data skapades för att validera RMT-modellerna och ge en uppskattning om dess kapacitet och sensitiviteten för att upptäcka sprickzoner i kristallint berg. Det är tydligt att lågfrekventa signaler skulle underlätta för att nå större djup, och ge bättre förståelse för geometri och egenskaper hos berget.

Den aktuella avhandligen ger en omfattande överblick av båt-bogserad RMT och hur metoden kan appliceras samt dess potential för att insamla RMT-data från vattenytan. I framtiden kan systemet vidareutvecklas för att användas vid mätningar med en kontrollerad källa med frekvenser ner till 1000 Hz och därmed märkbart kunna öka penetrationsdjupet. Då landmassan i Skandinavien till 7% är täckt av sötvatten kan båt-bogserad RMT i framtiden komma att användas vid flera olika tillämpningar.

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