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Using boat-towed radio-magnetotelluric and controlled-source audio-magnetotelluric data to resolve fracture zones at Äspö Hard Rock Laboratory site, Sweden

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SUMMARY

Boat-towed radio-magnetotelluric (RMT) measurements using signals between 14 and 250 kHz have attracted increasing attention in near-surface applications for shallow water and archipelago areas. Large-scale underground infrastructure projects, such as the Stockholm bypass in Sweden, are sometimes planned to pass underneath such water zones. However, in cases with high water salinity, RMT signals have a penetration depth of a few metres and do not reach the underlying geological structures of interest in archipelagos. To overcome this problem, controlled-source signals in the range of 1 to 12.5 kHz can be utilized to improve the penetration depth and to enhance the resolution for modelling deeper underwater structures. Joint utilization of boat-towed RMT and boat-towed controlled-source audio-magnetotellurics (CSAMT) was tested for the first time at the Äspö Hard Rock Laboratory (HRL) site in south-eastern Sweden to demonstrate acquisition efficiency and improved resolution to model fracture zones along a 600-m-long profile. Pronounced galvanic distortion effects observed in one-dimensional (1D) inversion models of the CSAMT data as well as the predominantly two-dimensional (2D) geological structures at this site motivated usage of 2D inversion. Two
standard academic inversion codes, EMILIA and MARE2DEM, were used to invert the RMT and
CSAMT data. EMILIA was used to invert the RMT and CSAMT data separately and
jointly with the plane-wave approximation. MARE2DEM, a controlled-source
electromagnetic (CSEM) 2.5D inversion code, was modified to allow for inversions of RMT
and CSAMT data accounting for source effects. Results of EMILIA and MARE2DEM reveal
the previously known fracture zones in the models. The 2D joint inversions of RMT and
CSAMT data carried out with EMILIA and MARE2DEM show clear improvement compared
with 2D single inversions, especially in imaging uncertain fracture zones analysed in our
previous study. Our results show that boat-towed RMT and CSAMT data acquisition systems
can be utilized for detailed 2D or 3D surveys to characterize near-surface structures
underneath shallow water areas. Potential future applications may include geo-engineering,
geohazard investigations, and underwater mineral exploration.

Key words: Radio-magnetotellurics; Controlled source audio-magnetotellurics; Marine
electromagnetics; Joint inversion; Fractures, faults, and high strain deformation zones

1 INTRODUCTION

The magnetotelluric (MT) method was first introduced to the geophysical community by
Cagniard (1953) and Tikhonov (1950). The MT method utilizes measurements of two
horizontal components of electrical fields and three components of magnetic fields generated
by natural sources, such as magnetospheric and ionospheric currents and thunderstorms. The
MT transfer functions, relating the measured electric and magnetic fields in the frequency
domain, are sensitive to vertical and lateral changes of electrical resistivity in the earth. The
MT method is widely used in groundwater monitoring (Aizawa et al. 2009), hydrocarbon
exploration (Vozoff 1972; Constable et al. 1998), and fracture zone mapping (Unsworth and
Bedrosian 2004). Using natural sources has, however, disadvantages, such as low signal strength in the “dead” bands (around 1 Hz and 1 kHz) and low signal-to-noise (S/N) ratios in areas subject to cultural noises. In order to overcome these problems, Goldstein and Strangway (1975) proposed use of the controlled source audio-magnetotelluric (CSAMT) method. However, near-field effects often arise due to the limited distance between the transmitter and the receiver sites employed for a higher S/N ratio preventing the use of a plane-wave approximation (Wannamaker 1997a, b; Routh and Oldenburg 1999; Kalscheuer et al. 2015).

The radio-magnetotelluric (RMT) method was first proposed by Turberg et al. (1994). Transmitters operating at very low frequency (VLF) used for communication with submarines and radio transmitters at low frequency (LF) are signal sources for the RMT method. These transmitters generate relatively stronger signals at receiver sites than the natural sources (Tezkan et al. 2000; Bastani 2001) at these frequencies. Pedersen et al. (2006) showed that in the frequency band of 14 - 250 kHz, generally there is a sufficient number of transmitters available to estimate MT transfer functions in most parts of Europe. Furthermore, RMT signals are usually free from near-field effects and the signals can be considered as plane waves. Thus, RMT has been widely used in different near-surface studies, such as: mineral exploration (Bastani et al. 2009; Malehmir et al. 2015), hydrogeological applications (Turberg et al. 1994; Linde and Pedersen 2004a; Pedersen et al. 2005; Perttu et al. 2012), geohazard investigation (Bastani et al. 2012; Kalscheuer et al. 2013; Shan et al. 2014, 2016; Wang et al. 2016; Malehmir et al. 2016), fracture zone mapping (Candansayar and Tezkan, 2008; Bastani et al. 2011; Wang et al. 2018), and environmental issues (Tezkan 1999; Tezkan et al. 2000; Bastani and Pedersen 2001; Yogeshwar et al. 2012; Shan et al. 2017). CSAMT measurements have also successfully been used to delineate ore deposits (Irvine and Smith 1990; Boerner et
al., 1993; Basokur et al. 1997; Bastani et al. 2009; McMillan and Oldenburg 2014), to characterize fault zones (Suzuki et al. 2000; Troiano et al 2009; Bastani et al. 2011), to study volcanoes and geothermal reservoirs (Wannamaker et al. 1997a,b; Gonzalez et al. 2014), and to investigate potential landslide sites (Kalscheuer et al. 2013; Shan et al. 2016).

Most of the previous investigations with RMT were traditionally carried out on land. After Bastani et al. (2015) introduced a new technique, the so-called boat-towed RMT, the application of RMT has been extended to the studies of targets underneath shallow water bodies, such as lakes, rivers, and archipelagos. The technique has successfully been used to conduct RMT measurements over three water passages of lake Mälaren (Bastani et al. 2015; Mehta et al. 2017) and at Äspö Hard Rock Laboratory (HRL) in Sweden (Wang et al. 2018). When RMT measurements are conducted over saline water with resistivities as low as 1.5 ohm-m, the penetration depth is limited to a few metres (e.g. Wang et al. 2018). In such circumstances, use of complementary controlled-source techniques together with boat-towed RMT leads to an increase in the exploration depth and, accordingly, a better resolution for deeper targets is gained.

In this study, the boat-towed controlled-source RMT (CSRMT) method was implemented by combining the RMT and CSAMT data and tested for resolving fracture zones at the Äspö HRL site, south-eastern Sweden. The study is a continuation of our previous research which successfully used joint inversion of boat-towed RMT and lake-floor ERT data to resolve fracture zones (Wang et al. 2018). The implementation of the boat-towed CSRMT method was initiated because of the limited penetration depth observed in the individual 2D inversions of boat-towed RMT data. The objectives of this study are: (1) to demonstrate the new concept of boat-towed CSRMT data acquisition; (2) to show the improved model
resolution by inverting CSRMT data with proper tools; and (3) to further study fracture systems under the lake at the Äspö HRL. The acquisition instrument used is the modified Enviro-MT system (Bastani et al. 2015). It took two days to measure a 400-m-long boat-towed CSRMT profile with approximately 10 m station spacing. Moreover, eight on-land RMT stations expanded the whole profile to 600 m length. In this work, we give details on the CSRMT data acquisition procedure, one-dimensional (1D) inversion of CSAMT data accounting for source effects and distortion parameters, and two-dimensional (2D) single and joint inversions of RMT and CSAMT data with and without regard to source effects.

2 BOAT-TOWED CONTROLLED SOURCE RMT

In the boat-towed RMT method operating at frequencies of 14 to 250 kHz, the magnetic and electric sensors are mounted on a wooden frame and towed behind a boat, and the measurements are conducted while the boat moves ahead slowly and smoothly. A detailed description of the method is given in Bastani et al. (2015). The CSRMT (a combination of RMT and CSAMT) method is necessary when lower frequency signals and a high S/N ratio are required to resolve targets in saline and deep fresh water environments. In a boat-towed CSRMT data acquisition, the setup at the receiver site is the same as for the boat-towed RMT method (Bastani et al. 2015; Mehta et al. 2017; Wang et al. 2017, 2018); the transmitter can be set up either on land or on a frame floating on the water surface. The transmitter used here for boat-towed CSAMT acquisition is a pair of mutually perpendicular horizontal magnetic dipoles and emits signals at frequencies of 1, 1.25, 2, 2.25, 4, 6, 6.25, 8, 10, 12.5 kHz. A pair of perpendicular dipoles is required to generate two independent source polarisations for estimation of tensor transfer functions. The transmitter is remotely controlled from the receiver site using a radio modem. Time is accurately synchronized by GPS-controlled crystal
clocks at both transmitter and receiver sites. More details about the data processing and the
transmitter are given in Bastani (2001).

Since the transmitter is designed for MT use, the current generated by the transmitter is not
recorded by the system. So, it was not possible to invert individual EM field components for
resistivity models, as is common practice in controlled-source electromagnetic (CSEM)
surveys. Thus, we use either scalar or tensor CSAMT transfer functions (Zonge and Hughes,
1991) as data for inversion. In the more traditionally employed scalar CSAMT, the data of a
single transmitter dipole are employed to compute scalar impedances $Z_{xy} = E_y/H_y$ or $Z_{yx} =
E_x/H_x$ as appropriate to obtain a good S/N ratio for a given source-receiver geometry. Here, $E_x$
and $E_y$ denote the horizontal electric field components, and $H_x$ and $H_y$ denote the horizontal
magnetic field components. To retrieve tensor CSAMT transfer functions, the data of both
transmitter dipoles have to be used (Li and Pedersen, 1991). Hence, in tensor CSAMT, but
also in RMT, the horizontal electric and magnetic fields are related through the complex-valued impedance tensor $\mathbf{Z}$ given as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix},$$

(1)

and the vertical and horizontal magnetic field components are related through the complex-valued vertical magnetic transfer function (VMTF) $\mathbf{T}$ given as

$$H_z = \begin{bmatrix} T_x & T_y \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix},$$

(2)

where $x$, $y$ and $z$ represent directions in the measurement coordinate system.

For a homogeneous half space of resistivity $\rho$ and a signal frequency $f$, the plane-wave skin
depth is given as:

$$\delta_{pw} = \sqrt{\frac{2\rho}{\mu_0 \omega^2}},$$

(3)
Here, $\mu_0$ represents vacuum permeability, and $\omega$ represents angular frequency. At one skin depth, the amplitudes of the electric and magnetic fields decay to $1/e$ of their respective values at ground surface. The skin depth is typically used to evaluate the exploration depth at a given signal frequency as $1.5 \, \delta_{p\omega}$ (Spies 1989), however, in this paper $\delta_{p\omega}$ is used instead of $1.5 \, \delta_{p\omega}$ to guarantee a conservative estimation of exploration depth. In a layered medium, the resistivity $\rho$ is replaced by an effective resistivity $\tilde{\rho}$ (Spies 1989; Huang 2005). In the CSAMT method, the skin depth depends additionally on transmitter-receiver distance $r$ (Zonge and Hughes 1991). In the near-field zone of the source ($r << \delta_{p\omega}$), the skin depth is independent of frequency but depends on the transmitter-receiver distance $r$ and resistivity $\rho$, in the transition zone of the source ($r \sim \delta_{p\omega}$), the skin depth depends on resistivity $\rho$, signal frequency $f$, and transmitter-receiver distance $r$, and in the far-field zone of the source ($r >> \delta_{p\omega}$), the skin depth is that of plane waves, i.e. $\delta_{p\omega}$, and independent of transmitter-receiver distance $r$.

For a two-dimensional (2D) earth with $x$ in strike and $y$ in profile directions and in the far-field zone of a source, the diagonal elements of the impedance tensor are zero in the given coordinate system. The off-diagonal apparent resistivities ($\rho_{xy/yx}$) and phases ($\varphi_{xy/yx}$) defined as

$$\rho_{xy/yx} = \frac{1}{\mu_0 \omega} \left| Z_{xy/yx} \right|^2,$$  \hspace{1cm} (4)

$$\varphi_{xy/yx} = \tan^{-1} \left( \frac{\text{Im} \left( Z_{xy/yx} \right)}{\text{Re} \left( Z_{xy/yx} \right)} \right),$$  \hspace{1cm} (5)

are used to estimate the resistivity distribution of the earth. Here, $Z_{xy}$ corresponds to the transverse electric (TE) mode in which currents flow in the $x$ direction, and $Z_{yx}$ corresponds to the transverse magnetic (TM) mode in which currents flow in the $y$-$z$ plane.
3 DISTORTION OF TRANSFER FUNCTIONS

When the regional EM field is homogeneous across a shallow distorting body, a receiver will record a distorted impedance tensor $\mathbf{Z}$ and a distorted VMTF $\mathbf{T}$ that are related to the undistorted impedance tensor $\mathbf{Z}_0$ and undistorted VMTF $\mathbf{T}_0$ generated in the absence of the distorting body through (Wannamaker et al. 1984; Zhang et al. 1987; Groom and Bahr 1992; Zhang et al. 1993; Kalscheuer et al. 2012):

$$\mathbf{Z} = (\mathbf{I} + \mathbf{P}_h)\mathbf{Z}_0 (\mathbf{I} + \mathbf{Q}_h\mathbf{Z}_0)^{-1},$$  \hspace{1cm} (6)

$$\mathbf{T} = (\mathbf{T}_0 + \mathbf{Q}_v\mathbf{Z}_0)(\mathbf{I} + \mathbf{Q}_h\mathbf{Z}_0)^{-1}.$$  \hspace{1cm} (7)

Here, $\mathbf{I}$ is the identity matrix, the tensors $\mathbf{P}_h$ and $\mathbf{Q}_h$ contain the distortion parameters of the horizontal electric field and magnetic field, respectively. The tensor $\mathbf{Q}_v$ contains the distortion parameters of the vertical magnetic field.

The real-valued and frequency-independent tensors of $\mathbf{P}_h$, $\mathbf{Q}_h$, and $\mathbf{Q}_v$ have the following shapes

$$\mathbf{P}_h = \begin{pmatrix} P_{xx} & P_{xy} \\ P_{yx} & P_{yy} \end{pmatrix},$$  \hspace{1cm} (8)

$$\mathbf{Q}_h = \begin{pmatrix} Q_{xx} & Q_{xy} \\ Q_{yx} & Q_{yy} \end{pmatrix},$$  \hspace{1cm} (9)

$$\mathbf{Q}_v = \begin{pmatrix} Q_{zx} & Q_{zy} \end{pmatrix}.$$  \hspace{1cm} (10)

Owing to the post-multiplication with the regional impedance tensor in equations (6) and (7), the distortion effects of $\mathbf{Q}_h$, and $\mathbf{Q}_v$ show frequency dependency and are complex-valued (Kalscheuer et al. 2012).
4 INVERSION THEORY

Occam inversion is widely known for its geophysical applications (Constable et al. 1987; Menke 1989; Kalscheuer et al. 2010; Key 2016). It consists of two key steps: (1) A detailed and complex model is searched for to achieve the desired root-mean-square (RMS) misfit between modelled responses and field data; (2) A smooth model is searched for to provide the simplest model within a narrow range around the desired RMS misfit. In the Occam inversion, a model vector $\mathbf{m} = (m_1, \ldots, m_M)^T$ with $M$ entries is sought to minimize an objective function:

$$
\Phi(\mathbf{m}, \lambda) = (\mathbf{d} - \mathbf{F}[\mathbf{m}])^T \mathbf{W}_d (\mathbf{d} - \mathbf{F}[\mathbf{m}]) - Q_d^\ast + \lambda (\mathbf{m} - \mathbf{m}^r)^T \mathbf{W}_m^T \mathbf{W}_m (\mathbf{m} - \mathbf{m}^r). \tag{11}
$$

Here, the data vector $\mathbf{d} = (d_1, \ldots, d_N)^T$ contains $N$ observations, and the vector $\mathbf{F}[\mathbf{m}]$ contains $N$ forward responses computed for a given model $\mathbf{m}$. The superscript $T$ denotes matrix transposition. The vector $\mathbf{W}_d = \text{diag}(\sigma_1^{-1}, \ldots, \sigma_N^{-1})^T$ is a data weighting matrix, where $\sigma_i$ represents the standard deviations of the data $d_i$. The model regularization matrix $\mathbf{W}_m^T \mathbf{W}_m = \alpha_y \partial_y^T \partial_y + \alpha_z \partial_z^T \partial_z$ contains the horizontal and vertical smoothness matrices $\partial_y$ and $\partial_z$, respectively, which ensure the simplicity of the retrieved inversion model $\mathbf{m}$ (Constable et al. 1987; de Groot-Hedlin and Constable 1990). Both vertical and horizontal smoothness operators $\partial_y$ and $\partial_z$ have $M \times M$ elements. $\mathbf{m}^r$ is a reference model, which is constructed from a priori information and can also be omitted. The first term in equation (11) represents the data misfit of the forward responses (a $\chi^2$ function) and $Q_d^\ast$ represents a target data misfit that should be roughly close to the number of data points. The Lagrange multiplier $\lambda$ balances data misfit and model simplicity.
Minimization of the objective function $\Phi(m, \lambda)$ is performed iteratively by minimizing a series of approximate objective functions $\Phi^{\text{quad}}(m, \lambda)$ which are quadratic in $m_{k+1}$ (Menke 1989):

$$
\Phi^{\text{quad}}(m_{k+1}, \lambda) = (d - F[m_k] - J(m_{k+1} - m_k))^T W^T_d W_d (d - F[m_k] - J(m_{k+1} - m_k)) - Q_d^2 + \lambda(m_{k+1} - m')^T W^T_m W_m (m_{k+1} - m'),
$$

where $J = \left[ \frac{\partial F_i[m_k]}{\partial m_j} \right]_{m=m_k}$ is the Jacobian matrix of partial derivatives with $N \times M$ elements, and $i=1, \ldots, N$ and $j=1, \ldots, M$. $d$ and $F[m_k]$ may contain combinations of apparent resistivity, phase, and/or elements of the impedance and VMTF tensors. A logarithmic transformation can be applied to the apparent resistivity data with the purpose of fast convergence in inversion (e.g. Wheelock et al. 2015).

The RMS misfit of a single inversion is defined as

$$
\text{RMS} = \sqrt{\sum_{i=1}^{N_d} \left( \frac{d_i - F_i[m]}{\sigma_i} \right)^2 / N_d},
$$

and the RMS misfit of a joint inversion is defined as

$$
\text{RMS} = \sqrt{\sum_{j=1}^{N_{ds}} \sum_{i=1}^{N_j} \left( \frac{1}{w_{ji}} \frac{d_{ji} - F_{ji}[m]}{\sigma_{ji}} \right)^2 / \sum_{j=1}^{N_{ds}} \sum_{i=1}^{N_j} \left( \frac{1}{w_{ji}} \right)^2},
$$

where $N_d$ is the total number of data points, $N_{ds}$ is the number of datasets, $N_j$ is the number of data points in dataset $j$, $w_{ji}$ is data weighting factor (typically the same for all data points of a particular dataset), and $\sigma_{ji}$ is the standard deviation. In some of the subsequent plots, we show the misfit between individual forward responses and field measurements as a normalized residual of the form $\text{misfit} = (d_{ji} - F_{ji}[m]) / d_{ji}$. 

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5 GEOLOGICAL SETTING AND FIELD DATA

5.1 Geological setting

The research area, Äspö, is located about 30 km north of the city of Oskarshamn in an archipelago at the south-eastern coast of Sweden (Fig. 1a). The lake at the Äspö HRL site is connected to the Baltic Sea and the water resistivity is about 1.5 ohm-m (Ronczka et al. 2017; Wang et al. 2018). The Äspö HRL and nuclear power plant are located at the northern and the southern sides of the research area, respectively. Granitic rocks with diverse types of fracture zones dominate this area (Cosma et al. 2001). Most of the fracture zones are reactivated from older structures and depend on the nature of these structures (Stanfors et al. 1999). A known fracture zone NE-1 exists at the northern side of the area (Fig. 1a). It is a NE-SW running system about 60 m wide (Berglund et al. 2003; Rhén et al. 1997). NE-1 is highly fractured, hydraulically conductive, and composed of non-saline and brackish water, clay, diorite, fine-grained granites, and greenstone (Stanfors et al. 1999; Berglund et al. 2003). Three fracture zones, EW-7, NE-4, and NE-3, at the southern side of the profile, were indicated by refraction seismic and borehole data (Fig. 1a) (Wikberg et al. 1991; Stanfors et al. 1999; Rhén et al. 1997). The widths of fracture zones NE-3 and NE-4 are about 50 and 40 m based on borehole observations and low-resolution seismic data (the results are published but the data are unavailable), respectively. A fracture zone EW-5 was proposed by Wikberg et al. (1991) based on geological information. In our previous study (Wang et al. 2018), NE-1 was well resolved, while EW-5 and EW-7 were less well constrained by the data. All these complex fracture zones and their surrounding environment made this area a good case for the test and implementation of the boat-towed CSRMT method as well as the joint inversion of boat-towed RMT and CSAMT data.

5.2 Field data
The models computed from the RMT dataset in our previous study (Wang et al. 2018) motivated the use of the CSRMT (RMT and CSAMT) method to better resolve the fracture zones below the 3 - 6 m deep brackish water at the Åspö HRL site. The locations of the controlled source and the CSRMT profile crossing these fracture zones are shown in Fig. 1(a) by a red star and green stars, respectively. The setups of the boat-towed receiver platform and the horizontal magnetic dipoles at the transmitter site are shown in Figs 1(b) and (c), respectively. Each transmitter loop has an area of about 27 m² and a maximum dipole moment of 2700 Am² is reached by using 5 loop windings and a maximum current of 20 A. The source was laid out on an island 310 m away from the nearest receiver station and 430 m away from the farthest one (Fig. 1a), thus the source position in the coordinate system used by us is $x = -310$ m, $y = 0$ m, and $z = 2.5$ m (i.e., at 2.5 m above sea level). Transmitter frequencies of 1.25, 2, 4, 6.25, 8, 10, and 12.5 kHz were chosen to guarantee the desired penetration depth of 30 to 50 m (based on Wang et al. 2018). The boat was moved along a rope which was fixed at both ends on land (Fig. 1b). The duration of CSRMT measurements is about 8 minutes per station, and the measurements are conducted in a stand-still form at each station. Use of the rope secured a stable measurement platform especially in slightly windy conditions. In total, 40 CSRMT stations along a 400-m-long profile were collected within two days. Additionally, eight RMT stations were surveyed on land to estimate the resistivity of the granitic bedrock, which extended the whole profile to a length of 600 m. The $Z_{xy}$ and $Z_{yx}$ components of the impedance tensor field data are shown in Fig. 2. The location of the CSRMT profile does not coincide with the original RMT profile used by Wang et al. (2018), because we had to fix the rope to the island in the middle of the lake to achieve sufficient stability of the receiver system. Note that the $x$-direction coincides with the geological strike direction identified by Wang et al. (2018) and computed for our data (see below) to within 5 to 8 degrees. Hence, for the RMT data, the $Z_{xy}$ and $Z_{yx}$ impedances correspond to the TE and TM modes, respectively.
6 RESULTS

6.1 1D inversion

For the CSAMT data, both distortion and source effects should be investigated before we invert the data using a routine 2D inversion. We used the CSAMT and RMT 1D modules of EMILIA (a package for 1D and 2D inversions for different EM methods, Kalscheuer et al. 2008, 2010, 2012, 2015) that account for distortion and layer parameters and search for the simplest model. In joint inversions of CSAMT and RMT data, this code uses separate sets of distortion parameters for each dataset.

For 1D inversion of the CSRMT data, we used an initial model with thirty layers of fixed thicknesses. The first layer was 0.5 m thick and layer thicknesses increased by a geometric progression factor of 1.2. The model resistivities and the distortion parameters of the data were simultaneously inverted for. All four elements of the impedance tensor shown in equation (1) were used as inputs to the 1D inversion. We tried inversions incorporating the VMTF (equation 2) but the result generated high values of data misfits, and, so, they were excluded from further consideration. The error floors of the impedance tensor elements were set to 5%. Given that the complete impedance tensor was inverted, both the CSAMT and RMT responses show relatively reasonable data misfits at most stations in our 1D inversions (Fig. 3) yielding average RMS values of 2.38 to 2.82. At 200 – 280 m distance along the profile, the stitched resistivity model from the CSAMT 1D inversion models (Fig. 3a) resolves a resistor at about 20 – 40 m depth below the conductive water layer, whereas the stitched section assembled from the RMT 1D inversion models (Fig. 3b) does not show the same feature. This is because the CSAMT data have better resolution at greater depth than the RMT data. The 2D stitched resistivity section (Fig. 3c) from the joint inversion of the full
RMT and CSAMT impedance tensors combine the features from both single inversions. In Fig. 4, we show the impedance tensor elements of station 22 (marked in Fig. 3c) with the associated error bars and responses of the joint inversion model. The field data resemble a nearly 1D plane-wave case where $Z_{xx} = Z_{yy} = 0$ and $Z_{xy} = -Z_{yx}$ at about 35% of all the stations.

The estimated distortion parameters at station 22 are given in Table 1. The $P_{xx}$ and $P_{yy}$ values from the single inversion of CSAMT data and the joint inversion of RMT and CSAMT data have large absolute values, while the $P_{xx}$ and $P_{yy}$ values from the single inversion of RMT data show small values. Retrieving larger $P$ values for the RMT data in the joint inversion indicates that the RMT and CSAMT data are not fully compatible in a 1D sense and that 2D or 3D effects, that are not entirely obvious in the single inversions because of the disparate frequency ranges, are compensated for in the joint inversion by using larger $P$ values for the RMT data. The $Q$ parameters of the CSAMT data are rather high, suggesting that some 2D or 3D induction effects are transformed into frequency-dependent distortion or that a certain degree of transmitter overprint (Zonge and Hughes 1991) exists even for purely inductively coupled sources. However, since transmitter overprint is predominantly a problem for galvano-inductively coupled sources (e.g. horizontal electric dipoles or long grounded cables), the former possibility of 2D or 3D induction effects being accommodated for by frequency-dependent distortion seems the more likely one. Since part of the distortion observed in the 1D inversion seems to be caused by 2D or 3D geological structures at inductive scales, 2D inversion is needed to further interpret the CSRMT dataset.

6.2 Analysis of CSAMT data for source effects

In order to model CSAMT data using a plane-wave approximation (PWA), the data need to be analysed for source effects, and data that do not fulfil the PWA need to be excluded before the
inversion. The validity of the PWA depends on the transmitter-receiver distance relative to the
plane-wave skin depth at a given transmitter frequency. A transmitter-receiver distance of at
least five to ten times skin depth is needed to satisfy the PWA (Bartel and Jacobson, 1987;
Pedersen et al. 2005). Using the resistivity model shown by Wang et al. (2018), the skin depth
of the lowest transmission frequency (1.25 kHz) is about one tenth of the shortest transmitter-
receiver distance, 310 m. However, Wannamaker (1997a, b) showed that a clear increase of
resistivity at depth may require a distance between transmitter and receiver exceeding five to
ten times skin depth. Thus, care must be taken to use the PWA to invert the CSAMT data. In
order to investigate the impedance and tipper at different transmitter-receiver distances for
source effects, we resort to a comparative 1D modelling study of plane-wave responses and
CSAMT responses at different transmitter-receiver offsets using the 1D model of station 18,
which was recorded on shallow (< 4 m deep) water and, thus, can be expected to show strong
source effects. Fig. 5 clearly reveals that the phase of off-diagonal impedance and the
imaginary part of tipper data have strong source effects at 1.25 kHz at 310 m away from the
transmitter (corresponding to the closest receiver to the source in the field data). This
influence on the transfer functions is larger than the noise levels assumed for the field data
(deviations of 2.86 degrees on phase and of 0.1 on tipper) until the transmitter-receiver
distance increases to 400 m. Thus, the CSAMT data observed less than 400 m away from the
transmitter at the frequency of 1.25 kHz were excluded in the subsequently presented
inversions based on the PWA.

6.3 Dimensionality, distortion and strike analysis

During the field measurements, the sensors were oriented parallel and perpendicular to the
profile direction. Strike analysis of the RMT field data using the code by Zhang et al. (1987)
shows that the preferred strike direction is about 82-85°E with regard to the profile direction,
i.e. 74° East of geographic North, in a cumulative rose diagram (Fig. 6a). The estimated strike direction is approximately perpendicular to the profile direction. Swift (1967) skews of most of the RMT data (Fig. 6b) are lower than 0.2, and only at one third of the RMT sites and frequencies the Swift skews are larger than 0.2. These larger skew values were mostly observed at measurements that were performed close to a small island. Therefore, the RMT data can approximately represent a 2-D structure. Since the angular deviation between the estimated strike direction and the $x$-direction of our coordinate system is small, we have not applied further rotation to the coordinate system.

Note that Zhang et al.'s (1987) dimensionality, distortion, and strike analysis cannot be applied to the CSAMT field data for two reasons. First, the analysis searches for a strike angle at which two real-valued distortion parameters relate the impedances in each column of the tensor to another, at least over a certain frequency band. However, in the transition and near-field zones of the source, $Z_{xx}$ and $Z_{xy}$ may differ from zero even in the undistorted 2D case and, thus, may not be related to $Z_{yx}$ and $Z_{yy}$, respectively, through simple real-valued distortion parameters. This holds even if the $x$ axis is oriented along the strike. In rare cases, when the source is located on the profile, the symmetry of the setup may suggest that MT strike analysis was applicable, but in our case this does not apply. Second, one may argue that MT strike analyses should be applicable at least for those CSAMT data which are recorded in the far-field zone of the source. Our 1D inversion results (see above) contain relatively high values of $Q_h$ for the distortion of the magnetic field components. From the 1D inversion results, it is not clear whether these high $Q_h$ are caused by 2D or 3D induction or are related to source overprint. Since the latter is not accounted for in Zhang et al.'s (1987) method and in most other dimensionality, distortion, and strike analyses (e.g. Groom and Bailey 1989; McNeice and Jones 2001), we decided not to apply Zhang et al.’s (1987) analysis to the
CSAMT data. For future strike analyses of far-field CSAMT data, it would be appropriate to use the method proposed by Chave and Torquil-Smith (1994), which takes distortion of both electric and magnetic fields into account.

6.4 2D inversion based on plane-wave approximation

The first code we used to carry out 2D inversion of the field data is EMILIA (Kalscheuer et al. 2008, 2010) which inverts plane-wave data such as MT and RMT data. Also, using a plane-wave approximation is a traditional way to interpret CSRMT data (Pedersen et al. 2005; Bastani et al. 2011; Shan et al. 2016). For the 2D inversion, EMILIA uses a finite-difference (FD) algorithm for forward modelling on a rectangular mesh. A Gauss-Newton (GN) algorithm is implemented with smoothness constraints. Thread-based parallelization of the numerical solver of the system of linear equations in the inverse problem and OpenMP parallelization over frequency of the forward response and sensitivity computations reduces the runtimes.

The field data analysis and the mesh generation for inverse modelling were carefully done to gain reasonable inversion results. Outliers of RMT and CSAMT data were removed, because they are in violation of the diffusive nature of EM fields (Ward and Hohmann 1988). Whether a data point can be considered an outlier also depends on the error levels of the measurements. We excluded CSAMT data with near-field effects as described above. The same error floor as in 1D inversion was applied in the 2D inversion (10% in apparent resistivity and 2.86 degrees for phase both corresponding to 5% relative error on the impedance tensor elements). The weights on horizontal and vertical smoothing were equal. A two-step inversion scheme was carried out: (1) Occam inversion using regular smoothness constraints; (2) Occam inversion with additional Marquardt-Levenberg damping, with the Lagrange multiplier for the Occam
term selected as the one that gave the preferred model in step 1. The initial model in step 1 is
a 100 ohm-m half-space model, and the initial model in step 2 is the preferred model from
step 1. The model mesh is finer at the station locations and the cell size gradually increases
towards the edges of the mesh, until the mesh reaches an appropriate size for the Dirichlet
boundary condition applied. Figs 7(a) and (b) show models from individual inversions of
RMT and CSAMT TM-mode data, where the input data were apparent resistivity and phase in
either case. The white dashed line in the models presents the estimated depth of investigation
(DOI) following Spies’ (1989) method for 1D models with the layer parameters extracted
from the vertical resistivity sections of the 2D model at each station. We interpret the high-
resistivity features in Figs 7(a) and (b) at both ends of the profile to correspond to the granitic
bedrock. In Fig. 7(a), the conductive zone at 300 to 350 m distance and 5 to 50 m depth
corresponds to the fracture zone NE-1 which is well documented and has also been delineated
in our previous study (Wang et al. 2018). At -240 to -150 m distance along the profile, two
shallow (at 3-10 m depth) and moderately conductive (about 100 ohm-m) anomalies are
observed. A warning for a high-voltage cable is visible at the site, but it is unclear whether
there is any connection between the anomalies and the cable. The inversion of the CSAMT
data resolves a rather vague conductive zone at 250 to 300 m distance and from 0 to about 50
m depth (Fig. 7b), which may correspond to the fracture zone EW-5 (Wikberg et al. 1991;
Wang et al. 2018). However, the CSAMT single inversion model does not contain a
conductive structure that would be interpreted as NE-1 due to the lack of data above the
fracture zone. The RMT model cannot resolve EW-5 due to the limited DOI. The inverted
model using integrated RMT and CSAMT data (Fig. 7c) shows the combined features from
both single inversions. Most notably, it indicates the presence of both NE-1 and EW-5.
Although one does not normally observe galvanic distortions in marine EM data, because of the uniform resistivity of water. Here we have an island and shallow bathymetry along parts of the profile. Thus, a static shift correction was also applied in the inversion to improve ability to fit data. The method of subtracting static shift parameters was as follows. An inversion was done with a 90% error floor on apparent resistivity and 2.86 degrees of phase error floor. Then, constant factors between the apparent resistivities of the inverted model and field data at each station were calculated from the two and were defined as static shift parameters (Fig. 8). Afterwards, the static shift parameters were fixed in the inversion to remove their influence (Siripunvaraporn and Egbert 2000). Fig. 7(d) shows the inversion results for CSRMT TM-mode data with the static shift correction. The bedrock resistivity seems to be better determined, because it is known from Linde and Pedersen’s (2004b) study that the granitic rock has a resistivity larger than 10000 ohm-m at this site (Fig. 7d). Also, the transition between the north-western part of the lake and land at around 300 m distance along the profile is modelled more sharply. All the inversions have acceptable data misfits (RMS = 2.45 or less, Fig. 9). The crosses in Fig. (9) indicate which data points were excluded in the inversions due to the lack of observations, insufficient quality, or the near-field effect. The observation that the inversion models contain pronounced conductive zones in regions with known fractures seems to suggest that the distortion parameters obtained in the 1D inversion are at least partly caused by the improper dimensionality. Single inversions of TE mode data and joint inversions of TE and TM-mode data were also carried out to delineate resistivity structures, and are shown in the Appendix.

The bedrock below the conductive water layer is not resolved at -100 to 50 m distance along the profile (Figs 7b-d) due to the exclusion of the data at the lowest frequency. Therefore, an
inversion code which incorporates source effects as well as the data at the lowest frequency is utilized to further study the CSAMT data.

6.5 2D inversion incorporating source effects

6.5.1 Inversion code MARE2DEM

The second code used to conduct 2D inversion of the boat-towed RMT and CSAMT data is MARE2DEM, which incorporates source effects to accurately model the CSAMT data. MARE2DEM is a publically available code for 2D inversion of MT and CSEM data for onshore and offshore surveys (Key 2016). Unstructured grid parameterization in both forward and inverse modelling provides significantly better geometric flexibility and better computational efficiency than the structured rectangular grid used, for example, by EMILIA. A goal-oriented adaptive finite element method is implemented for the forward modelling (Li and Key 2007; Key and Ovall 2011; Key 2016). A dual-grid approach is used in MARE2DEM: a locally fine mesh at the receiver and source positions is generated automatically and refined by the error estimators in the forward modelling; a coarser mesh, generated by the code Mamba2D.m (Key 2016), is used for the inversion domain. The code is highly parallelized by partitioning the data into independent subsets consisting of a certain number of frequencies, transmitters, and receivers (Key 2016). Each subset is separately modelled by an assigned computational unit under the coordination of message passing interface (MPI) commands. The forward responses and sensitivities of all groups are then combined together in the iterative inversion which employs a Gauss-Newton method (de Groot-Hedlin and Constable 1990; Key 2016).

6.5.2 CSAMT modification of MARE2DEM
MARE2DEM uses different types of input data for 2D inversions of MT and CSEM data. For example, the data may be linear or logarithmic apparent resistivities and phases for the MT method, and real and imaginary parts or amplitudes and phases of the electric and magnetic field components for the CSEM method. Neither CSAMT impedance tensors, as used in the previously presented 1D and 2D inversions of our field data, nor scalar CSAMT impedances are valid input data types in the current implementation of MARE2DEM. However, since the current of the transmitter was not recorded during our CSAMT data acquisition due to instrument limitations, the only data types of our field campaign suitable for inversion are the impedances (or VMTFs). In order to invert at least scalar CSAMT transfer function field data, a modification of MARE2DEM was required by implementing these data types in the input routines, output routines, and the forward and sensitivity calculations. More specifically, in our modification, scalar transfer functions of type $Z_{xy} = E_x/H_y$ and $Z_{yx} = E_y/H_x$ are calculated from the EM signals of a single source as appropriate for a given source-receiver configuration. Moreover, in order to use MARE2DEM in the radio-frequency band (>1 kHz), 50 wavenumbers equally distributed from $10^{-5}$ to $10^1$ m$^{-1}$ in logarithmic space are used to reduce the source singularity based on a scope and number tests for wavenumbers employed in the Fourier transformation along the strike direction. The tests are done with a total scope of $10^{-7}$ to $10^2$ m$^{-1}$ varying the number from 30 to 60. A source added at the right-hand side of the finite element equations results in an inaccurate solution for receiver positions close to the source. This is a disadvantage of modelling CSEM data using a total field approach (Mitsuhata 2002) which is adopted in MARE2DEM. A magnetic dipole instead of a loop source is used for the CSAMT modelling, because the EM fields are measured at a distance of more than fifty loop diameters (around 5 m), which satisfies the condition for approximating a vertical transmitter loop by a horizontal magnetic dipole (Ward and Hohmann 1988).
A comparison between the semi-analytical solution calculated via CSAMT 1D modelling and the numerical solution calculated via CSAMT 2D modelling was done to verify our modification with a two-layered model. The top layer is 10 m thick and with 1.5 ohm-m resistivity underlain by a layer with 0.5 ohm-m resistivity. A horizontal magnetic dipole parallel to the $x$ direction is used in the comparison. The signal frequencies and the positions of transmitter and receivers are the same as in the field campaign in order to better understand the field data. The semi-analytical and the numerical amplitudes and phases of the scalar impedances $Z_{xy}$ and $Z_{yx}$ as well as their relative errors ($errors = (F_{1D} - F_{2D}) / F_{1D}$, $F$ represents either impedance amplitude or phase) are shown in Fig. 10. Both amplitude and phase of $Z_{xy}$ modelled by MARE2DEM show data differences in excess of 5% for receivers at distance -70 to 70 m along profile direction (Figs 10a and b). Additionally, the impedance component $Z_{yx}$ shows a singularity at large distance at $y \sim 220$ m (Figs 10c and d). According to Weitemeyer and Constable (2014) this additional singularity occurs within a certain azimuthal angle. Since these singularities affect the results from modelling the total field by MARE2DEM, we can only exclude CSAMT stations in the corresponding profile ranges with inaccurate 2D solutions from further consideration in the subsequently presented 2D inversion.

### 6.5.3 Synthetic test for inversion

A synthetic test was designed to show how well MARE2DEM can perform after the modification. A layered model shown in Fig. 11(a) was used for generating synthetic data. The top layer represents 10 m thick saline water with 1 ohm-m resistivity. It overlies a 20 m thick layer with 10 ohm-m resistivity. The third layer represents the bedrock with 1000 ohm-m resistivity. All of the receiver and transmitter positions as well as the frequencies are the same as in the field experiment (Fig. 1a). A magnetic dipole oriented in the $x$ direction is used as a source, and it is located at 2.5 m above the surface to simulate the setup used in the field.
Due to the singularity of the source, receiver stations in the ranges of $y = -70$ to $70$ m and at the distance of $y \sim 220$ m were excluded from the simulations. The grids employed for forward modelling and inversion are very fine at the station and projected source locations, and coarser at the areas away from these locations. 5% Gaussian noise was added to the synthetic impedance data. A 100 ohm-m half-space model was used as an initial model in the subsequent inversions. The inversion results for the amplitude and phase data of the scalar impedances $Z_{xy}$ and $Z_{yx}$, are shown in Figs 11(b) and (c), respectively. The inversions resolve the top two layers of the true model underneath the parts of the profile that are covered by receivers (Figs 11b and c). The areas where we have no stations show very limited resolution. Therefore, these model regions should not be considered in the interpretation of the field data. Also, the result of the impedance $Z_{xy}$ shows slightly better resolution than the one for the impedance $Z_{yx}$. This example demonstrates that the modification of MARE2DEM works sufficiently for the inversion of scalar CSAMT impedance data, and that the CSAMT signals can penetrate 30 m deep even in such an extreme case. The DOI evaluated by Spies’s (1989) method (not shown here) approximately verifies that the top two layers in the synthetic model can be resolved.

6.5.4 Inversion of field data

In accordance with the scalar CSAMT modelling approach implemented in MARE2DEM, we computed scalar CSAMT transfer functions from our field data. A 5% error floor was used on the impedance data. A 100 ohm-m half-space model is used as an initial model. Note, that derivation of an initial model from the inversion model computed using EMILIA would require substantial effort in regridding the regular rectangular finite-difference mesh to an unstructured triangular finite-element mesh. Hence, we have not tested this approach. The mesh of the initial model is presented in Fig. 12. In the part of the mesh containing the
receivers, the grid is very fine. Towards the edges, the cell size increases to ascertain the
validity of the employed Dirichlet boundary conditions and to avoid an unnecessarily high
number of elements. In the forward modelling, the mesh was automatically refined based on
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towards edges. In the forward modelling, the mesh was automatically refined based on error estimators (Key 2016). Twelve receivers (i.e., all receivers after removal of those with inaccuracy forward responses), one transmitter, and all frequencies were grouped as one subset, meaning there were two subsets for CSAMT data, and four subsets for RMT data.

For convenience, we use the term CSRMT TM-mode data to indicate a combination of RMT TM-mode data and CSAMT $Z_{yx}$ data, even though the latter do not correspond to a pure TM-mode signal when near-field effects are present. Both individual and joint inversions were used to mainly interpret the boat-towed RMT TM-mode data and CSAMT $Z_{yx}$ data, because TM-mode data show better resolution for the delineation of fracture zones than TE-mode data (Figs 7 and A1). In our particular case, 2D inversion of TM-mode data seems preferable, because the TE-mode data are more sensitive to 3D structure and they are more affected by a finite-water depth than TM-mode data (Andreis and MacGregor 2007). Note that a joint inversion of CSRMT TM-mode and TE-mode data resulted in poor convergence. Hence, it is not shown here. Bathymetry data from the old profile, close to the CSRMT one, in a previous study (Wang et al. 2018) were used to decouple the smoothness constraints along the lake floor in the RMT inversion. In order to reduce the potential artefacts caused by smoothing in the vertical direction in our model, three times more smoothing weight in the horizontal direction was applied in all inversion models. Note that the differences in gridding in the 2D inversion codes used by us (regular finite-difference grid in EMILIA vs. unstructured finite-element grid in MARE2DEM) require largely different weights on horizontal and vertical smoothing to be used. The inverse model for logarithmic apparent resistivities and phases of the RMT TM-mode data is shown in Fig. 13(a). The conductive zone, corresponding to the
fracture zone NE-1, is resolved at around 300 to 350 m distance along the profile. The lake bottom obtained from the bathymetry data is visible as a boundary. Below the lake bottom, conductive zones along the profile may be artefacts due to the limited penetration depth of the RMT signals. The inverse model for the CSAMT $Z_{yx}$ impedance data is shown in Fig. 13(b).

The data are logarithmic amplitudes of the CSAMT impedance $Z_{yx}$ generated via the loop which is parallel to the profile (the phase data are hard to use probably due to an insufficient number of measurement stacks). The data from the perpendicular loop have low quality due to the faster decay of the fields, so we excluded them. Due to the source singularity in the code, the closest stations to the transmitter as well as the ones at a distance of about 220 m along the profile were excluded in the inversion. The bathymetry data are not included in the inversion due to higher sensitivity of CSAMT data to the inaccurate bathymetry data compared with RMT data (essentially a result of the smaller footprint of the CSAMT system, e.g. Boschetto and Hohmann, 1991). One conductive zone is shown in Fig. 13(b) at distances of 300 to 350 m along the profile, which may be NE-1. For the other speculative conductive fracture zones, no supportive evidence is available in Fig. 13(b).

Joint inversion of RMT and CSAMT with the static shift correction is shown in Fig. 13(c). Five times more weight on the CSAMT dataset than on the RMT dataset was used for the inversion, because there are less CSAMT stations than RMT stations and the CSAMT data have better resolution at depth (Figs 13a and b). In the joint inversion model (Fig. 13c), the conductive zones are obviously better resolved than in any single inversions (Figs 13a and b). Based on a comparison to the existing geological, limited borehole, and low-resolution geophysical information marked by arrows above the surface (cf. Figs. 1a and 7d), we interpret the fracture zones NE-1, EW-5, and EW-7 to be partly resolved. However, the conductive zones NE-3 and NE-4 in the model need to be further studied, even though their
positions match well with the prior information. The conductive zone at around -150 to -100 m distance along the profile (Figs 13b and c) may be caused by a 3D effect or infrastructure of the tunnel which only possibly can be detected by the signal at 1.25 kHz at this south-eastern CSAMT site. Note that the pronounced spread of this conductor towards the southeast may be caused by a shadow-zone effect of the source (Boschetto and Hohmann, 1991; Zonge and Hughes, 1991). The single and joint inversion models of the RMT TE-mode data and the CSAMT $Z_{yx}$ impedance data are shown in the Appendix.

6.6 Evaluation of inversions

Further evaluation of the reliability of our inversion results is required. Particularly, the resolution in some parts of the inversion models may be limited by the conductive water. Looking at the data misfit is a way to evaluate the inversions. In our inversions, reasonable RMS values and well-distributed misfits are obtained (Figs 9 and 14). Furthermore, we carried out a synthetic test based on the joint inversion results to evaluate the resolution of the boat-towed CSRMT data. The single inversion models were not used, since the joint inversion model shows all the important information. Fracture zones and other structures that are in agreement with previous geological knowledge together with other speculated fracture zones in the joint inversion model (Fig. 13c) were introduced into a synthetic model (Fig. 15a). The model has resistivities of water, fracture zones, and bedrock set to 1.5, 10, and 10000 ohm-m, respectively. Synthetic RMT and CSAMT data were then generated using the same acquisition parameters as in the edited field datasets in Fig. 13. To simulate the noise level of the field data, 5% Gaussian noise on the impedances was added to the synthetic data. Single and joint inversions of logarithmic apparent resistivities and phases of the RMT TM-mode data and logarithmic amplitudes of the CSAMT impedance $Z_{yx}$ data were carried out. The single inversion of the RMT data (Fig. 15b) shows poorer resolution at depth than the single
inversion of the CSAMT data (Fig. 15c) due to the limited DOI of the RMT signals. Joint
inversion of RMT and CSAMT data resolves some of the hypothetical fracture zones
underneath those parts of the profile covered by both datasets, especially for the presumed
fracture zones NE-1, EW-5, and EW-7 in the upper 20 m (Fig. 15d). However, the fracture
zones NE3 and NE4 are not distinguished in the model. The synthetic test indicates that the
interpretation of the field datasets is to a certain degree reasonable. The structure at the
bottom of and underneath the conductive sea water is uncertain for two reasons: (1) lack of
sensitivity that is basically due to the limited DOI; and (2) EM methods are known to perform
poorly at resolving structures at the bottom of or immediately below low-resistivity features
(Bedrosian 2007; Kalscheuer et al. 2018). Despite of this, the true resistivity of the bedrock in
the synthetic test is resolved in the joint inversion, mostly owing to the use of RMT stations
on land and the greater penetration depth of the CSAMT signal underneath the lake floor.

7 DISCUSSIONS

7.1 High efficiency in data acquisition

We employed a boat-towed CSRMT method for the first time for resolving conductive
fracture zones below a lake at the Åspö HRL site as a continuation of our previous study
(Wang et al. 2018), following the earlier successful use of boat-towed RMT (Bastani et al.
2015; Mehta et al. 2017). The field data acquisition follows a highly efficient workflow. A
400-m-long boat-towed CSRMT profile with 10 m station spacing was easily surveyed within
two days, eradicating the need for instrument transportation in the field which is usually the
heaviest work in the MT and RMT data acquisition. Also, this method has better penetration
depth than the boat-towed RMT method due to the utilization of the controlled source for
lower frequency signals (Bastani 2001; Wang et al. 2017). Thus, the boat-towed CSRMT
method guarantees that the data acquisition is suitable for detailed 2D and 3D surveys and to
resolve relatively deep and complex subsurface structures up to very roughly 50 m and 20 m depth underneath shallow fresh water and saline water bodies, respectively. This ability is important for underwater infrastructure planning, since other resistivity-based methods, such as ERT and boat-towed RMT, hardly show comparable acquisition efficiency, resolution, and deployment efficiency simultaneously. Particularly, once the transmitter deployment is done, multiple profiles can be easily surveyed. Note that boat-towed transient electromagnetic methods (Barrett et al. 2005; Hatch et al. 2010; Mollidor et al. 2013; Bekesi et al. 2014) have similar acquisition efficiency and penetration depth, but do not offer multi-component measurements and dual source polarisations.

7.2 1D and 2D inversions of CSRMT data

Two available tools, EMILIA and MARE2DEM, were used to invert the boat-towed CSAMT and RMT data. The distortion parameters resolved by the 1D inversion in EMILIA suggest using 2D inversion to model the data, which is also compatible with what we observed in the previous study (Wang et al. 2018). The approximate inversion of the CSAMT data based on the PWA shows better resolution at depth than the inversion of the RMT data due to the enhanced DOI (Figs 7a and b). Since single inversions of RMT and CSAMT data resolve the fracture zones NE-1 and EW-5, respectively, the inversion of the integrated datasets simultaneously resolves them (Fig. 7). This strongly demonstrates the advantage of the boat-towed CSRMT method compared to the boat-towed RMT method. The traditional way of inverting CSRMT data using a PWA should be considered with care, even though the approximation seems reasonable when the transmitter-receiver distance is 5-10 times larger than the skin depth (Bartel and Jacobson 1987; Pedersen et al. 2005). A careful analysis shown in Fig. 5 based on 1D CSAMT forward modelling also proves this. Thus, the signals at the lowest frequency in our dataset were excluded in the inversion using the PWA to avoid
any misleading results. One should remember that simply using the ratio of a source-receiver
distance to skin depth based on certain information is not enough to indicate the existence of
the near-field effect, especially when the underground geology is complicated.

Since the source current is not recorded by our CSAMT system, inversion of individual field
components, as supported by MARE2DEM, was not possible. Hence, we modified
MARE2DEM to invert CSAMT impedances, adding the relevant modifications to the forward
modelling and sensitivity calculations. Both forward and inverse modelling based on a
conceptual layered model show that our modification for MARE2DEM is reasonable and
accurate. This is the first time that MARE2DEM has been used to invert radio-frequency
signals. The inversion of the scalar CSAMT field data using the modified MARE2DEM code
shows reasonable resolution (Fig. 13b). Moreover, the CSAMT data contain more information
on underwater structures but have fewer data points than the RMT data, so that using five
times more weight on the CSAMT dataset in the joint inversion was needed to delineate
structure at depth. The resulting joint inversion model in Fig. 13(c) seems to indicate the
conductive fracture zones NE-1, EW-5, and EW-7. Owing to the pronounced source
singularity and the ensuing numeric difficulties in modelling the source, almost half of the
CSAMT station had to be excluded from the 2D inversions using MARE2DEM.

7.3 Resolution evaluation
Resolution analysis is an important step to know how reliable inversion results are. In our
case, the model resolution provided by the field data is limited by the saline water at the
surface. Two steps were taken for evaluation. In the first step, data misfits are evaluated (Figs
9 and 14). Reasonable misfits could be obtained in the inversions. In the second step, a
synthetic test based on the resolved structures was done, which indicates which structure in
the model is reliable (e.g. Fig. 15). The synthetic test with a layered structure in Fig. 11 shows that the CSAMT method can resolve structure at up to 30 m depth, even though 10 m thick saline water with 1 ohm-m resistivity was located at the top part of the model. Thus, the presumed fracture zones NE-1, EW-5, and EW-7 are well constrained at shallow depth by the CSAMT data. In particular, both the RMT and CSAMT observations could effectively cover those targets. The conductive zones marked as NE-3 and NE-4 in Fig. 13(c) are not reliable based on the synthetic test and need further study, even though they match the geological and borehole information and the data misfits are also reasonable.

7.4 Future improvements

Both modelling and instrumental aspects of the CSAMT method need improvement. Firstly, in the field example presented here, almost half of the CSAMT stations had to be excluded from the inversions using MARE2DEM because of the inaccurate modelling results in a range of -70 to 70 m along the profile. This suggests that further improvement to MARE2DEM for land CSEM surveys is highly desirable when the source and receivers are not along the same profile. Secondly, we would want to implement fully tensorial transfer functions in MARE2DEM. This would enable better comparability to our 1D and 2D inversion results from EMILIA which use a full tensor description and the off-diagonal elements of the impedance tensor, respectively. As compared to the first point, this improvement may be of lower importance. Thirdly, the current generated by the source during the data acquisition should be recorded, and then the controlled-source EM fields could be inverted directly. Inverting for a resistivity model using EM field components as input data rather than transfer functions may provide more detailed information on the subsurface. However, modelling studies are required for verification. These three modifications can further improve the resolution capability of CSRMT data for targets underneath shallow water bodies and land.
8 CONCLUSIONS

The implementation of the boat-towed CSRMT method is a new achievement after the boat-towed RMT method was successfully utilized for modelling structures below water bodies and specifically in the delineation of fracture zones. The new approach, used in fracture zone mapping at Äspö HRL, demonstrates high efficiency in data acquisition. An inversion code tuned to the dimensionality of the problem can be expected to provide more reasonable details in the resulting inversion models. Using 2D inversions of the RMT and CSAMT data, we can resolve fracture zones at depth. Especially, the 2D joint inversion of boat-towed RMT and CSAMT, which was implemented here for the first time, shows better resolution for the fracture zones than single inversions. For further improvements, the present boat-towed CSAMT system needs to be upgraded to record the source current.

The 2D inversion of CSAMT data using MARE2DEM carries the promise of improved utilization of CSAMT data for mapping fracture zones compared with using a plane-wave approximation. Proper modelling of CSAMT data with due regard for the source allows inclusion of low-frequency data which otherwise have to be excluded in a plane-wave approach. However, the numerical inaccuracies in the MARE2DEM forward modelling results close to the source suggest that the modelling scheme needs improvement when the source and receivers are not along the same profile. With the current implementation of MARE2DEM and for our field dataset, almost half of the CSAMT stations had to be excluded from the inversion.

The boat-towed CSRMT method can play an effective role in geo-engineering studies. The improved acquisition efficiency can reduce the planning costs of underwater constructions.
Moreover, the improved resolution of subsurface models provided by boat-towed CSRMT can help geo-engineers to identify the fracture or weak zones in bedrock under shallow water. The new method is cost-effective and can be successfully applied in countries such as Sweden, Norway, and Finland that are largely covered by shallow waterbodies. This extends the application field for the traditional CSRMT method. Certainly, the method is not restricted to geo-engineering applications, and it can also be introduced in geohazard investigations and underwater mineral explorations.

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References


Figures

Figure 1 (a) Arial map of Äspö HRL area (Image © Google). Green dots are the CSRMT stations, and the transmitter to the east of the profile is indicated by a red star. A small island in the middle of the profile resulted in a gap in data acquisition. (b) Boat-towed receiver system. The electric and magnetic field sensors were mounted on a floating platform together with a differential global positioning system (DGPS) antenna. The processing units, including the digitizer and computer system, and a palm computer for the DGPS, were inside the boat. (c) Double horizontal magnetic dipoles used as the source to generate EM signals on an island.
Figure 2 (a) CSRMT TE-mode data, (b) CSRMT TM-mode data. Left and right panels are apparent resistivity and phase, respectively. Low frequency data (<13 kHz) are collected using the controlled source. Crosses mark stations on land for which no controlled source data were acquired. Other removals, marked by crosses, indicate boat towed-data that had noise problems.
Figure 3 (a) Stitched resistivity model of CSAMT 1D inversion results, average RMS of forty individual inversions is 2.38. (b) Stitched resistivity model of RMT 1D inversion results, average RMS of forty-eight individual inversions is 2.82. (c) Stitched resistivity model of the joint 1D inversion results for the CSAMT and RMT data, average RMS of forty individual inversions is 2.76 (land RMT stations were not used in the joint inversion). Empty station positions represent removed stations. The CSAMT data were inverted accounting for the source (Kalscheuer et al. 2012). The white dashed lines in the models approximately represent the exploration depth estimated with the method proposed by Spies (1989). The land RMT stations are able to resolve the bedrock resistivity.
Figure 4 Measured and inversely modelled CSAMT and RMT impedances of station 22 indicated in Fig. 3(c): (a) $Z_{xx}$, (b) $Z_{xy}$, (c) $Z_{yx}$, and (d) $Z_{yy}$. CSAMT data were inverted accounting for source (Kalscheuer et al. 2012). RMS of CSAMT data is 1.53, and RMS of RMT data is 1.89. The diagonal elements of the impedance tensor are much smaller than the off-diagonal elements.
Figure 5 Comparison between the responses at different transmitter-receiver distances of 310, 400, and 2000 m and the plane-wave response, to study the near field effects: (a) $\rho_{xy}$ (lines) and $\phi_{xy}$ (symbols), (b) real part of $T_y$ (lines) and its imaginary part (symbols), and (c) resistivity model from station 18 of the 1D inversion (location in Fig. 3) used for the calculations. At the lowest frequencies, non-negligible near-field effects are observed both in the impedance phase and the imaginary part of $T_y$ until the transmitter-receiver distance reaches 400 m. The other transfer function components are not shown since the model is 1D.
Figure 6. (a) Strike directions calculated with the method proposed by Zhang et al. (1987). The structure underneath the profile is 2D with a preferred strike direction of 82° East with regard to the profile direction used in the field (corresponding to 74° East of geographic North). (b) Swift skews (Swift, 1967). The underground structures along the profile are not perfectly 2D, because the profile crossed an island in order to install a rope that enabled stable measurements on the water surface.
Figure 7 2D inversion models for (a) RMT TM-mode data, (b) CSAMT $Z_{xy}$ data, (c) CSRMT TM-mode data, and (d) CSRMT TM-mode data with static shift (SS) correction. Black triangles on top of the models represent the receiver stations. All models were inverted using EMILIA with a plane-wave assumption (Kalscheuer et al. 2008, 2010). Known information on fracture zones is marked on top of the model by arrows in Fig. 7(d).
Figure 8  TM-mode apparent resistivities of field data (blue) and of inverse model responses used for static-shift correction (black) at stations (a) 2, (b) 35, (c) 43, and (d) 46. The inversion was run with an error floor of 90% on apparent resistivity to identify stations with static shift. The stations on land (e.g. Figs. 8a, c, and d) and a few stations on water (e.g. Fig. 8b) have obvious distortion, especially the stations on land. At station 35, a rock at roughly 1 m depth seems to have caused the distortion. The selected stations are also marked in Fig. 7(a). The 2D inversion model of the static shift corrected data is shown in Fig. 7(d).
Figure 9 Normalised data misfits for the inversions, shown in Fig. 7, of (a) RMT TM-mode data, (b) CSAMT TM-mode data, (c) CSRMT TM-mode data, and (d) CSRMT TM-mode data with static shift correction. The misfits of apparent resistivity and phase are shown in the left and right panels, respectively. Crosses indicate data points that were not acquired or removed prior to inversion. The gap at 100 m distance corresponds to the position of the island.
Figure 10 1D semi-analytical and 2D numerical solutions as well as their differences of (a) amplitudes of impedance $Z_{xy}$, (b) phases of impedance $Z_{xy}$, (c) amplitudes of impedance $Z_{yx}$, and (d) phases of impedance $Z_{yx}$. Different frequencies are marked with different symbols. 2D1.25kHz represents the response at a signal frequency of 1.25 kHz calculated by MARE2DEM in 2D. 1D1.25k represents the response at a signal frequency of 1.25 kHz calculated by EMILIA in 1D. The source is located at (-310, 0, 2.5) m and the profile direction is $y$ with $x = 0$ m and $z = 0$ m. Strong deviations between 1D and 2D solutions at $y = -70$ m to 70 m led to exclusion of these field data in the subsequent 2D inversions.
Figure 11 (a) Synthetic model, (b) 2D inversion model for the data of CSAMT impedance $Z_{xy}$, and (c) 2D inversion model for the data of CSAMT impedance $Z_{yx}$. Dashed lines represent the boundaries between different layers. Seven frequencies, 1.25, 2, 4, 6.25, 8, 10, 12.5 kHz, were used in this synthetic test. Receivers are marked with triangles. A magnetic dipole oriented in the $x$ direction is used as a source located at (-310, 0, 2.5) m and the profile direction is $y$. Synthetic data and inversion models were computed using MARE2DEM.
Figure 12 Finite-element mesh used in MARE2DEM for simulations (a) whole inversion domain and (b) the zoom-in part of inversion domain covered with receiver stations. The mesh is triangular and generated by Mamba2D.m (Key 2016). Dirichlet boundary conditions require a large model domain as shown in (a) to accurately model EM responses. A fine grid in the observation area as shown in (b) is required to model the EM responses accurately.
Figure 13 2D inversion models computed using MARE2DEM and the finite-element mesh shown in Fig. 12. (a) single inversion model for RMT TM-mode data, (b) single inversion model for CSAMT impedance $Z_{yx}$ data, and (c) joint inversion model for both datasets with five times more weight on CSAMT dataset and with static shift correction. Triangles mark receiver positions. Geological and borehole information is marked with arrows at the top of the model in (c).
Figure 14 (a) Field and modelled data and (b) the normalised data misfits of the RMT TM-mode apparent resistivity, RMT TM-mode phase, and amplitude of CSAMT impedance $Z_{yx}$ from left to right panel for single inversion models in Figs 13(a) and (b). (c) Field and modelled data and (d) the data misfits of RMT TM-mode apparent resistivity, RMT TM-mode phase, and amplitude of CSAMT impedance $Z_{yx}$ from left to right panel for joint inversion model in Fig. 13(c). F14kHz and M14kHz represent the field and the modelled data at a frequency of 14 kHz.
Figure 15 (a) 2D model deduced from the 2D joint inversion model shown in Fig. 13(c), (b) 2D inversion model for RMT synthetic data, (c) 2D inversion model for CSAMT synthetic data, (d) 2D joint inversion model for both datasets with five times more weight on CSAMT dataset. Dashed lines mark the positions of fracture zones. Inverse triangles are receiver positions, and the source position of (-310, 0, 2.5) m is not marked, because the profile direction is y. Targets which are not covered by both datasets are not well reconstructed, such as NE-3 and NE-4.
Table 1 Distortion parameters for impedance tensor of station 22 from 1D inversion: four elements for electrical field ($P$, no units) and four elements for magnetic field ($Q$ in $\text{A/V}$). The layered model is shown in Fig. 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$P_{xx}$</th>
<th>$P_{yx}$</th>
<th>$P_{yx}$</th>
<th>$P_{yy}$</th>
<th>$Q_{xx}$</th>
<th>$Q_{xy}$</th>
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<td>0.048</td>
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<td>0.060</td>
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<tr>
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<td>0.230</td>
<td>-0.502</td>
<td>-0.724</td>
<td>0.465</td>
<td>0.661</td>
<td>0.213</td>
</tr>
<tr>
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<td>-0.395</td>
<td>0.029</td>
<td>-0.008</td>
<td>-0.030</td>
<td>0.038</td>
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</table>
Appendix

Inversions of the CSRMT TE-mode data were also carried out using EMILIA. All the inversion settings such as the initial model, the finite-difference mesh, and the weights on horizontal and vertical smoothing are the same as those for the TM mode shown in the main text. The inversions in Fig. A1 show limited information about the conductive zones compared with the inversions for CSRMT TM-mode data (Fig. 7), except for an anomaly at -240 to -200 m distance along the profile. CSRMT TE-mode data have poorer lateral resolution compared with CSRMT TM-mode data. This is due to potential incompatibility of the TE-mode data to the 2D preferred structures caused by the data being more sensitive to 3D structure (Berdichevsky et al., 1998). The joint inversion results for CSRMT TE and TM-mode data are shown in Fig. A2. They contain fewer distinct structures than observed in the inversions of CSRMT TM-mode data, and the data misfits are also larger than for inversions of single mode data (Fig. A2). This is probably because the data of the two modes are sensitive to the different aspects of the subsurface structures. However, the inversion models of the TM-mode data show higher resolution than the TE-mode data.

The single inversion of the RMT TE-mode data and the joint inversion of the RMT TE-mode and CSAMT $Z_{xy}$ data were also carried out using MARE2DEM. All the inversion settings are the same as those for the RMT TM-mode data in the main text, such as the initial model, the mesh used for forward and inverse modelling, weighting of datasets, and weighting of model smoothness in different directions. The inversion model of the RMT TE-mode dataset is shown in Fig. A3(a). The fracture zone NE-1 is unclear at around 300 m distance along the profile. The lake bottom constrained from the bathymetry data is visible as a boundary. The inversion for CSAMT $Z_{xy}$ impedance data did not converge, thus the CSAMT $Z_{yx}$ impedance data is shown again (Fig. A3b) and used for the joint inversion. Joint inversion with five times
more weight on CSAMT data than on RMT data with static shift correction was used to compute inversion models (Figs A3c). The subsurface structures in the joint inversion models are obviously better resolved at fracture zones NE-1, EW-5, and EW-7 than in the single inversions (Figs A3a and b). However, other conductive zones, such as the one marked as NE-3, are not well covered by the receiver stations, thus, further information is needed for verification.
**Figures for Appendix**

**Figure A1** 2D inversion models for (a) RMT TE-mode data, (b) CSAMT $Z_{xy}$ data, and (c) CSRMT TE-mode data with static shift correction. Black triangles at the surface represent station positions. All models were computed using EMILIA and a plane-wave assumption is used for CSAMT data.
Figure A2 2D inversion models for (a) RMT TE-mode and TM-mode data, (b) CSAMT $Z_{xy}$ and $Z_{yx}$ data, and (c) CSRMT TE-mode and TM-mode data with static shift correction. Black triangles at the surface represent station positions. All models were computed using EMILIA and a plane-wave assumption is used for CSAMT data.
Figure A3 (a) 2D inversion model for RMT TE-mode data, (b) 2D inversion model for CSAMT impedance $Z_{yx}$ data, (c) 2D joint inversion model for both datasets with five times more weight on CSAMT data with static shift correction. Inverse triangles mark receiver positions. The source is at (-310, 0, 2.5) m position and the profile direction is $y$. All models were computed using MARE2DEM. Geological and borehole information is marked with arrows at the top of the model in (c).