Groundwater exploration using combined controlled-source and radiomagnetotelluric techniques

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ABSTRACT
Radiomagnetotelluric (RMT) (14–250 kHz) combined with controlled-source magnetotelluric (CSMT) (1–12 kHz) measurements were applied to the exploration of groundwater located in sandy formations at depths as great as 20 m below thick clay lenses. A combination of approximately 30 radio frequencies and controlled-source frequencies is essential for penetrating the thick clay layers. The electromagnetic transfer functions of impedance tensor and tipper vectors point toward a structure that is largely two-dimensional, although clear three-dimensional effects can be observed where the sandy formation is close to the surface. The determinant of the impedance tensor was chosen for inversion using two-dimensional models. The final two-dimensional model fits the data to within twice the estimated standard errors, which is considered quite satisfactory, given that typical errors are on the level of 1% on the impedance elements. Comparison with bore-hole results and shallow-reflection seismic sections show that the information delivered by the electromagnetic data largely agrees with the former and provides useful information for interpreting the latter by identifying lithological boundaries between the clay and sand and between the sand and crystalline basement.

INTRODUCTION
A new full-tensor radiomagnetotelluric (RMT) technique integrated with controlled-source magnetotelluric (CSMT) measurements, in short CSRMT, has been employed in a variety of conditions to study its capacity to map in detail the uppermost tens of meters of the vulnerable part of unconsolidated sedimentary structures. One such study of unconsolidated sediments is reported here. The objective is rather simple: determine the geometry of a glacio-fluvial aquifer system composed of a sand/gravel formation overlying crystalline basement, and overlain by a formation dominated by clay lenses. Well-penetration tests available at a few points along the profile can be used for calibration of the measurements.

Fractured Precambrian crystalline rocks are the dominating aquifers in the rural part of Sweden. However, municipal water supply must resort to groundwater resources in large sand/gravel deposits with typical yields of 50 000–500 000 l/h. If relatively thick clay layers cover the sand/gravel formations, it is difficult to determine their geometry with many geophysical methods. Refraction seismic methods demand very large spreads to penetrate the formations, the well-conducting clay will heavily attenuate ground-penetrating radar signals, and electrical resistivity methods also require very large arrays to penetrate the conducting clay layer.

In contrast, the seismic reflection method has shown great potential for detailed mapping of shallow deposits of clay and sand/gravel formations (Juhlin et al., 2000). High-frequency energy generated by employing small, 50-g dynamite charges and the seismic waves were recorded with sufficient density, 1 m between geophones, to avoid spatial aliasing.

Müller and his group at Neufchatel pioneered the RMT technique in its original and scalar form. It was used in hydrogeological applications in Switzerland (Turberg et al., 1994; Stiefelhagen and Müller, 1997; Bosch et al., 1999) and in environmental applications in general by Tezkan and his group at Cologne (Tezkan, 1999; Tezkan et al., 2000).

The new tensor RMT technique has additional high-resolution capabilities because at every point along the profile, a detailed tensor sounding is performed. Although side effects can be important and can be estimated from profile measurements, often a rather clear image of the subsurface below the measuring point is realized. Furthermore, if the structure studied is 2D in character, very powerful techniques have been
developed by the basic research community to automatically invert the two polarizations of the MT data in terms of a complicated 2D structure (e.g., Smith and Booker, 1991; Smith et al., 1999; Siripunvaraporn and Egbert, 2000; Rodi and Mackie, 2001). Going from 1D to 2D models in this context can be compared well with the process of migration of reflection seismic data. For example, a line scatterer in the subsurface at a right angle to the measuring profile may have a wide-ranging effect on transfer functions far distant from the position of the source, so that when data from individual stations are interpreted with 1D models, the line scatterer appears as a conductor that gradually fades out and deepens away from the center of the source. Using a 2D model to interpret the same data will result in a model that is much more focused, both laterally and with depth.

GEOPHYSICAL EXPERIMENTS

Reflection seismics

Juhlin et al. (2000) reported on the details of the reflection seismic measurements along the profile sketched in Figure 1. Only the main result will be presented here. Small dynamite charges detonated in clayey material in shallow boreholes provided excellent sources for generating elastic waves with very little ground roll and air phases. The stacked section is shown in Figure 2, with the main reflections indicated by letters A, B, C, and D. Reflectors A and D probably represent thin sand layers in the clay formation bounded downward by reflector C, marking the transition to a sandy formation. Reflector B was interpreted as the transition from sand to crystalline basement.

Electromagnetics

The electromagnetic data were collected using a CSRMT system covering the frequency band 14–250 kHz using the RMT technique and 1–14 kHz using the CSMT technique. The data were combined into a total tensor description using a new parametric expansion of the electromagnetic transfer functions (Bastani and Pedersen, 2001).

The source field for RMT measurements are fixed transmitters used for communication and long-wavelength (LW) radio transmission. These transmitters are normally operated as vertical electric dipoles with transmitter powers of the order of 1 MW. The radio signals are transmitted either as ground waves or reflected waves in the waveguide made up by the solid earth and the conducting ionosphere. The wavelength of the electromagnetic field ranges from 20 km at 15 kHz to 1 km at 300 kHz. The corresponding skin depth in the ground for a resistivity as large as 10 kilo ohm-m varies from about 400 to 90 m in the same frequency range. Thus, to a very good approximation, the wavelength can be considered to be infinitely large compared with the penetration depth. From that, it follows that the electromagnetic field that would exist at a given position on the surface of the earth, in the absence of lateral variations in electrical conductivity, would closely

![Figure 1. Location map, surface geology, and geometry of field setup in glacial deposits, Sweden (courtesy of Geological Survey of Sweden). Reflection seismic and CSRMT profiles coincide.](image1)

![Figure 2. Migrated reflection seismic section. Reflector B was interpreted as a sand/gravel-crystalline basement interface. Reflectors C were interpreted taken to represent clay-sand/gravel interfaces, and reflectors A and D to represent thin sand layers within the clays.](image2)
Figure 3. CSRMT data from the profile. (a) RMT. Apparent resistivities (RHOA) and phases (PHASE) for XY: currents in the x-direction; YX: currents in the y-direction; and determinant: average for all current directions.

Figure 3b. CSMT. Apparent resistivities and phases, as (a).
resemble that of a vertically impinging plane wave with a horizontal electrical field directed along a line between the transmitter and the point of observation and a horizontal magnetic field that would be perpendicular to the horizontal electrical field. In the above approximation, the strong vertical electrical component of the field has been neglected because the vertical electrical field only couples to the ground by displacement currents. However, in the quasistatic approximation, displacement currents are neglected, and for frequencies less than 250 kHz, this is usually a good approximation.

Goldstein and Strangway (1975), in their classical paper on CSMT measurements, showed that for a homogeneous half-space, plane-wave conditions prevail if the distance between source and receiver is at least 3–5 times the depth of exploration. For structures involving highly resistive units, e.g., crystalline basement, the situation is more complicated. Wannamaker (1997) noted that conductive sediments over resistive basement seriously reduce the depth of exploration within the plane-wave regime (the so-called far-field) to about 1/20th of the transmitter-receiver distance. Hence, grounded transmitters of a 500-m dipole and a current of 10 A are used at an offset of up to 10 km.

For shallow studies, it is more advantageous to use horizontal magnetic dipoles, which are much easier to install than electric dipoles, and their range is sufficient to cover distances up to about 1 km. Also, the problem of coupling to nearby conductivity structures is reduced with magnetic dipoles because of smaller transmitter overprint (Qian and Pedersen, 1992). Therefore, better plane-wave conditions are expected from magnetic dipoles than from electric dipoles at a given distance between source and receiver. The resulting data are of very high quality with error bars of about 1–2% on the off-diagonal elements of the impedance tensor (error bars on the diagonal elements are of the same order, measured in absolute terms).

Figure 3a,b shows apparent resistivity and phases for (1) the XY mode, defined as currents parallel to presumed strike along the x-axis in the south-to-north direction; (2) the YX mode, defined as currents perpendicular to presumed strike; and (3) the determinant mode, the average of all current directions, invariant to rotation of the coordinate system (Weaver et al., 2000), along a profile oriented along the y-axis in the west-to-east direction. Note that the raw data already indicate a structure similar to that of the seismic image. 3D effects are small, with skew values generally less than 0.1, thereby justifying the use of 2D models.

Although integration of the results of several geophysical disciplines generally provide an improved image of the geologic reality, economic constraints often prevent the use of this approach. The CSRMT technique offers a relatively cheap, single discipline from which detailed 2D geoelectric models can be obtained in a fast way. For this data set with 23 RMT/CSMT stations, an average of 15 min was expended for each station, i.e., a total of approximately six hours for two persons to cover the entire profile, including setting up the transmitter pair. If only RMT data are needed, the average
time per station is reduced to only 3 min. Using an 800 MHz PC equipped with 284 Mbytes RAM, 2D inversion of the data takes a few tens of minutes when only the determinant data are considered.

RMT data

The apparent resistivity and phase data shown in Figure 3a can be qualitatively interpreted as conducting clay lenses separated by less conductive sand/gravel. Phases at the lowest frequencies, over the clay lenses, particularly at the eastern end of the line, are markedly higher than 45°, indicating that the layer thickness is significantly high such that response functions are only weakly influenced by the underlying resistive formations.

CSMT data

The frequency band from 1–16 kHz was covered by a double-dipole transmitter consisting of two mutually perpendicular, horizontal magnetic dipoles (vertical coils) tuned to preselected frequencies uniformly distributed along the logarithmic-frequency axis with approximately two frequencies per octave. Each dipole has a cross-sectional area of 27 m², 5 windings, and maximum current of 20 A, giving a maximum dipole moment of 2700 Am². Good timing accuracy is guaranteed by GPS-controlled crystal clocks on both transmitter and receiver sites. The selection and changing of source frequencies and polarizations is governed completely from the receiver. More details can be found in the Ph.D. thesis by Bastani (2001).

The apparent resistivity and phase data shown in Figure 3b support the RMT data in showing the two clay lenses. However, because of the lower frequencies and the resultant deeper penetration of the diffusing electromagnetic signal, the apparent resistivity and, especially, the phase data show values below 45° for frequencies close to 4000 (log scale 3.6) Hz along nearly the whole profile. This indicates that the EM signal is strongly influenced by the highly resistive crystalline basement below.

The transmitter pair used in this study is situated 350 m south of the midpoint of the profile. The high phases and corresponding low resistivities at frequencies lower than 2000 Hz are taken to represent near-field effects from the transmitter. Near-field effects come into play when the inductive scale length approaches the transmitter-receiver distance. Because of basement resistivities in the range 5000–10 000 ohm-m, the transition from far-field to near-field behavior of the transfer functions becomes very abrupt (Wannamaker, 1997). In our study, the impedance phase changes from 30° to 40° over one octave (2–4 kHz). Because the 2D modeling code used here operates in the far-field range (Siripunvaraporn and Egbert, 2000), we have selected only the frequencies above 4 kHz for inversion of the data. A 2.5D approach, where a dipole source is placed at any position of a 2D model, as developed, for example, by Lu et al. (1999), has not yet been attempted for interpreting the data because the basement depths are relatively shallow compared with the source-receiver distance.

Tipper data

Tipper data normally are not used quantitatively together with impedance data because they represent the effect of horizontal currents only, whereas the impedance includes effects of vertical currents as well (Vasseur and Weidelt, 1977). However, tipper data are useful for a qualitative identification of major lateral changes in electrical conductivity away from the profile. The real part of the tipper vector \( \text{Re}(A), \text{Re}(B) \) generally points away from conductors in the far-field, whereas in the near-field, it points away from the transmitter for magnetic-dipole sources as used here, and toward the transmitter for electric-dipole sources (Li and Pedersen, 1991). Thus, in the transition zone, the tippers originating from conductors and transmitters may add either constructively, if the conductor lies between the transmitter and receiver, or destructively, if the receiver lies between the transmitter and the conductor.

In the tipper data shown in Figure 3c, the two dominant clay lenses are indicated at the lowest RMT frequencies (about 20 kHz) in tipper \( \text{Re}(B) \), corresponding to current flow perpendicular to the profile along the presumed strike of the structure. The RMT tipper \( \text{Re}(A) \) is very small except in the middle of the profile, where it shows a strong positive peak, which is seen even on the controlled-source data for frequencies higher than 4 kHz. The positive peak indicates a shallow conductor located to the right of station 12. For lower CSMT frequencies, the effect of this conductor disappears, possibly because of the dominance of the near-field effect, in the limit of which the tipper decays to zero for horizontal magnetic-dipole transmitters.

The CSMT tipper element \( \text{Re}(B) \) has two strong, negative features coinciding with the edges of the clay lenses at the higher frequencies and broadening out at the lower frequencies, corresponding to increasing depth of the induced currents, as well as to near field-effects. Tipper element \( \text{Re}(A) \) behaves in much the same way but with a smaller amplitude, which can be generally explained as a 20° rotation of the dominant-strike direction away from the presumed strike direction, the x-axis.

The CSMT tipper element \( \text{Im}(A,B) \) are generally smaller than the corresponding real tipper elements, and \( \text{Im}(A) \) behaves much like a downscaled version of \( \text{Im}(B) \), in agreement with the real-part strike direction of the deeper structure, i.e., rotated about 20° from the x-axis. Whereas the real part for a given frequency typically changes sign when crossing a conductor, the imaginary part has a tendency to preserve its sign along the profile. For a given position, the imaginary part changes sign with decreasing frequency, from generally positive to generally negative, probably as a result of near-field effects that mimic deep conductors. Modeling and inversion with 2D geometry and magnetic-dipole sources has not yet been carried out to study these effects in more detail.

2D MODELING

In all inversions to be shown, we concentrate entirely on the determinant data. The integration of RMT and CSMT data was made using the parametric estimation procedure of Bastani and Pedersen (2001) on both data sets simultaneously.
Various attempts have been made to interpret the data using 2D models. We show only the result of inverting the determinant data because, in our experience, it shows better resolution than models based on the combined data set using TE and TM modes separately or together. Actually, it is generally difficult to fit TE and TM modes simultaneously (not to mention together with tipper data), probably because the real world is not 2D, but 3D. The inconsistencies of a 2D model become clearly visible, and with a degraded fit, the model becomes less resolved—or more smooth. When using the determinant mode, this inconsistency disappears because normally it is easy to explain the determinant data with a well-resolved 2D model, although the model should be looked upon with some care, because it incorporates some 3D effects in addition to 2D effects that clearly dominate for this data set. Compared with the traditional use of the TM mode only (Boerner et al., 1999) to suppress 3D effects, the determinant has the advantage of retaining the ability of the TE mode to couple well to isolated conductors, while at the same time retaining the property of the TM mode to model the boundaries at which major resistivity changes occur. The new, fast method of Siripunvaraporn and Egbert (2000) was modified slightly to invert for deterministic data.

A starting model of a homogeneous half-space of 50 ohm-m was used, together with an identical a priori model and an error floor of 1% on the impedance. We present the final model with all plane-wave data included in Figure 4. The rms data fit of 2.15 is very similar to that obtained for 1D inversion, and distribution of the residuals in apparent resistivity and phase shows a good balance between negative and positive values.

It should be noted that the images produced by over-parameterized models such as this one have wide transition zones between conducting and resistive features. While conductive zones are generally well constrained, interpretation of the transition zone is more problematic. As we shall see in the following section, there is good correlation between depth to basement at a few drill holes and the depth of the 300-ohm-m contour. The basement resistivity is probably at least one order of magnitude higher than that, but because of the large transition zone imposed by using smooth models, it is necessary to further interpret these models. This can be done by calibration with borehole information or by carrying out numerical experiments on models with distinct layer boundaries.

Another complication is the controlled magnetic-dipole source pair located 350 m south of the profile. We have employed models with plane-wave excitation, and the deeper part of the model (not shown here) includes an equivalent conductor produced by the source. Because the minimum frequency used in the inversion is 4 kHz, the whole CSMT data set probably is distorted somewhat, since there is no evidence that a deeper conductor should be present in the basement itself.

**THE 2D MODEL AND THE REFLECTION SEISMIC SECTION**

The 2D model of Figure 4 and the dominant reflectors from the migrated seismic-reflection section of Figure 2 have been superimposed and are shown in Figure 5. The lower boundaries of the clay lenses corresponding to the reflectors C seem to be well correlated with the 30-ohm-m contour to the west, but some horizontal displacement between the two can be observed to the east.
drill-hole located 50 m north of the profile at coordinate 105 gives a basement depth of about 35 m, which correlates very well with the basement reflector and the 300-ohm-m contour under the conducting clay lens to the west. The clay formations are expected to have resistivities less than 30 ohm-m. Resistivities below 10 ohm-m, seen here at depths below 6 m, are believed to represent marine clays with ion concentrations that have not been diluted since their formation some 10,000 years ago after the last glaciation. The sandy formations are expected to have resistivities greater than 30 ohm-m and less than 300 ohm-m, and basement resistivities are expected to be greater than 300 ohm-m. Reflector B, which is believed to represent the sand/basement interface, agrees well with this interpretation in the western half of the profile, where the basement is found at approximately 30-m depth. However, in the middle and toward the east, there is a strong disagreement between the two models. There is clear evidence that a resistive structure corresponding to sand or basement is found in the middle around coordinate 135, where the seismic section is somewhat blurry, possibly a result of bad surface coupling of the seismic energy. Two penetration tests met solid rock at a depth of approximately 32 and 25 m, thickness of clay of 12 and 23 m, and thickness of sand/gravel of 20 and 3 m at coordinates 150 and 200, respectively. The solid rock met at coordinate 200 was interpreted earlier by Juhlin et al. (2000) as a possible boulder; however, the EM interpretation supports the idea that the solid rock actually represents granites of the crystalline basement in the area. The penetration test at coordinate 150 meets sand/gravel at 12 m, supporting the interpretation of Juhlin et al. (2000) that reflector C represents the clay/sand interface; however, the EM model supports the hypothesis that C represents several interfaces from clay to sand in the western part to clay/basement in the eastern part.

The small red surface structure around coordinate 130 could represent the off-profile conductor identified from the tipper data at stations 11 and 12 located to the south of the profile.

DISCUSSION AND CONCLUSION

The combination of high-resolution reflection seismics with the new CSRMT approach has provided many useful details about a glacial deposit consisting of clay formations overlying sand formations making up the main aquifer. While the reflection seismic data are excellent in pinpointing the interfaces between the units, and in some cases even giving information about thin sand formations within the clay unit, the EM data provide unique information about the material properties of the various formations.

The EM data suggest a slightly improved interpretation of the seismic reflection section. Whereas the reflectors C, interpreted to represent the transition between clays and sands, correlate well with the lower boundary of the 30-ohm-m contour, the reflectors B, taken by Juhlin et al. (2000) to represent the transition from sands to crystalline basement, are more difficult to interpret. The western part of reflector B correlates well with the 300-ohm-m contour, but to the east of coordinate 100, the reflector, composed of several broken reflectors (as seen in Figure 2), probably represents an intrabasement reflector, e.g., a subhorizontal fracture zone.

The aquifer, imaged in the green to blue color range (Figure 5), is thus expected to be thicker toward the west. To the east, while the depth to the basement increases, so does the thickness of the clay formation, leaving less space for sandier formations that make up the aquifer. The average models constructed from the determinant will include largely unknown artifacts that may be generated by 3D structures and some distortion from 2D structures with a different strike, i.e., strong lateral conductivity changes along the presumed strike. However, it is quite simple to see directly from the data when strong 3D effects set in, thus warning that care must be exercised in interpreting the models in geologic terms. In our example, rather strong 3D effects in the middle of the structure can be seen on tipper element A. The resistive region at coordinate 130 therefore does not necessarily represent a basement high but could instead be an artifact produced by lateral variations away from the profile.

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