Integrated use of Radio-Magnetotelluric and High-Resolution Reflection Seismic data to delineate near surface structures – two case studies from Sweden

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SUMMARY

Radio-MagnetoTelluric (RMT) and high-resolution reflection seismic data were jointly used to investigate subsurface geological structures. For this, two case studies in Sweden were designed and implemented. The first one is located in the Göta River valley at a quick-clay landslide site and the second one is located at a mineral exploration site in northern Sweden, each site with own overall objectives. Joint investigations provided detailed images of the bedrock fluctuations and provided complementary information about the structures that controls the formation and possibly the generation of landslides as well as structures potentially hosting mineral deposits. These studies demonstrate the potential for integrating reflection seismic and RMT data especially for near surface applications.

Keywords: RMT, reflection seismics, integration, landslide, mineral exploration

INTRODUCTION

Magnetotelluric and reflection seismic methods are routinely used for studying deep structures of the earth crust. However, with the recent technical and instrumental developments, the Radio-Magnetotelluric (RMT) method has been able to record the electromagnetic (EM) signal from distant radio transmitters at frequencies up to 1 MHz for near-surface investigations (Tezkan and Saraev, 2008; Bastani, 2001). Malehmir et al. (2013a) have recently reported a review of combined geophysical methods for near surface studies especially using combined high-resolution reflection seismic data with other common geophysical methods, such as Electrical Resistivity Tomography (ERT) and RMT. In this work we present two case studies in Sweden where integrated use of RMT and high-resolution reflection seismics was adopted to study near-surface structures.

Landslides are not uncommon in Sweden and mostly related to the presence of sensitive materials, the so-called "quick clays" (Nadim et al. 2008; Malehmir et al. 2013a). In the first case study both methods were utilized to image geometry and to model electrical properties of structures controlling quick-clay landslides in the area. Quick clays are formed after the last glacial period during a slow process (that continues even today) where the salt in the marine clays is leached by fresh water infiltration and/or circulation (Rankka et al. 2004; Malehmir et al. 2013a). Therefore quick clays usually have higher electrical resistivity than their host marine clays. In our study site, Lilla Edet (Figure 1), quick clays are often found on the top of a coarse-grained (sandy-silty) layer that has varying thickness (Löfroth et al. 2011) and which may control the leaching process and may also act as a slip landslide surface (Malehmir et al. 2013a). The main targets were depth to and thickness of the coarse-grained layer, zones containing quick clays, and surface of undulating crystalline bedrock.

The use of seismic methods in mineral, geothermal and groundwater exploration is increasing considerably. This is also particularly useful at shallow depths where it is greatly desired to link shallow and deeper structures especially where the detailed surface geological observations and shallow boreholes are present and at where highly conductive materials are present. In the second case study, we present the results from a pilot three-component (3C) reflection seismic landstreamer survey together with the RMT measurements carried out to better understand the surface morphology of a crystalline basement and its internal structures that may be important for mineralization in the study area.

METHODS

RMT

RMT is a passive source EM method where the signal sources are distant radio transmitters operating in the frequency range from 14 to 250 kHz. At such distances the EM signals are considered as a plane-wave and can be used to estimate electrical resistivity of the near-surface structures. (Bastani 2001; Bastani et al. 2012). RMT data comprise of three components of the magnetic field (H_x, H_y, H_z) and two horizontal components of the electric field (E_x, E_y). In the frequency domain the electric and magnetic field components are related through the impedance tensor **Z** given as:

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

where x and y represent the measurement directions in

Cartesian coordinate system.

The determinant of impedance tensor is defined as:

$$Z_{det} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}} \quad (2)$$

Pedersen and Engels (2005) showed that 2D inversion of the determinant data is more robust than TE and TM inversions in a 3D environment. So determinant data were used in this study to carry out 2D inversions.

Reflection seismics

Malehmir et al. (2013b) provided a detailed account on the reflection seismic instrument and data acquisition parameters used in the quick-clay study. For the second case a 3C seismic landstreamer system recently developed at Uppsala University was utilized. The current landstreamer configuration is a prototype broadband (0-800 Hz), which is based on digital sensors. It consists of three segments with twenty 3C-sensors (2 m apart) and an additional segment with twenty 3C-sensors (4 m apart). This provides a total streamer length of 200 m. These segments can be towed in parallel or in series. The system is especially geared for noisy environments and areas where high-resolution images of the subsurface are needed. The streamer and explosives (20 gram fired at every 10 m) were used in the second study area for the seismic data acquisition.

RESULTS

The station spacing of the RMT measurements was 10 m in both cases. We used EMILIA software (Kalscheuer et al. 2013) to run 2D inversions of the RMT data. Noisy data with high RMS values were removed to improve the inversion results.

The Lilla Edet data set presented here is composed of two profiles shown in Figure 1 as yellow and orange lines. They are 30 m apart from each other in the EW direction (Figure 1). We used a damped Occam inversion method (Kalscheuer et al. 2013) with a horizontal to vertical smoothing of three and an error floor of 0.09 and 0.03 for the apparent resistivity and phase, respectively. After 9 iterations the inversion reached an RMS data-misfit of 1.8 and the final model shown in Figure 2a was achieved. The model suggests bedrock as a high resistivity structure with undulations at distances 800-1150 m along the profile. The bedrock outcrops 50 m west of the profile in the 850 m position (Figure 1, yellow line).

Noticeable in the model is a layer with 50-80 Ωm resistivity that lies above the interpreted bedrock at about 20 m depth, which maybe an indication for the presence of quick clay (leached clays) and/or coarse-grained materials. Migrated and time-to-depth converted stacked section from vertical component data at the quick-clay site (Figure 2b) suggests a depression zone with its deepest point at the location of the landslide scar (Figure 1). Reflectors labeled as S1 and S2 are interpreted to originate from the coarse-grained layers and onlap the reflector B1 from the bedrock. Blue and orange boxes represent the intersection of the geotechnical boreholes with the interpreted coarse-grained layer and quick-clay formations, respectively (Malehmir et al. 2013b).

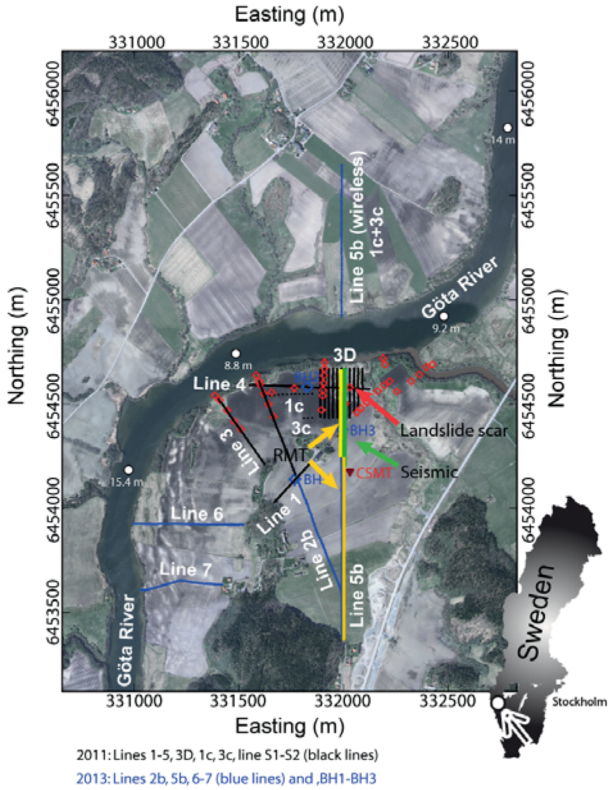

Figure 1. Aerial photo showing the first study site and the locations of the RMT and seismic profiles available at the site. RMT data shown in this paper are from the profiles marked by the yellow and orange lines. Seismic data are from the green line. The blue circles labeled by BH1, BH2, BH3 show the locations of newly drilled boreholes. The landslide scar (meshed area, marked by the red arrow) is located in the southern part of the river.

For the second case study, an error floor of 0.09 and 0.045 was used for apparent resistivity and phase, respectively. The regularization type was again damped Occam with a horizontal to vertical smoothing of three. With fewer number of radio transmitters, the data were collected on the frozen and snowy ground, thus, more number of iterations were required (10 times), and a higher overall misfit was achieved (4.6). Final inversion model (Figure 3a) shows a noticeable 100 Ωm resistivity structure at the top of the model. Results from processing of SH-wave seismic (crossline) data from the exploration site show a strong sub-horizontal reflector at about 25 m depth (Figure 3b). The reflector is likely generated from a contact between shale and sandstone and not from the crystalline basement. Vertical component data (P-wave) better image the basement and is interpreted to be at about 50-80 m depth (Malehmir et al. 2014).

Integration of RMT and reflection seismic data

Both case studies utilized RMT and reflection seismic data. Combination of the electrical resistivity models and reflection seismic sections demonstrates a strong correlation between the two images, even though they have been processed and imaged independently. It not only allows a better interpretation of the near-surface geological structures but also offers a high-level of confidence on the models and images obtained. For example, the RMT model and seismic profile from the quick-clay site (Figure 2c) clearly show an about 50-80 Ωm resistivity layer above the reflector S1 which might be an indication of quick-clay materials that overlie the reflector S1 (coarse-grained materials). The electrical resistivity model and reflection seismic section (Figure 3c) from the exploration site show a remarkable correlation even at where the contact boundary is fluctuated or faulted.

CONCLUSIONS

Geophysical methods have their own advantages and limitations. When combined and effectively integrated, the complementary results are superior for a more realistic and effective interpretation. We have illustrated examples from near-surface case studies at two different locations in Sweden combining RMT and high-resolution reflection seismic data. RMT data provide resistivity information of near-surface structures, especially the lateral variations. Reflection seismic data have considerably high vertical resolution, however they do require a large contrast and this may not be always the case. Thus a combination of both methods can be used to gain a more accurate understanding about the geometry and physical properties of near-surface structures. The resistivity of quick clay ranges from 10–90 Ωm; materials showing this resistivity range maybe considered as sensitive clays. Their delineation is possible using RMT method and difficult by reflection seismic method. However, structures controlling their formation and locations can be better imaged using reflection seismic data. The two case studies shown here illustrate the need for joint and constrained inversion of these data sets that will/should be attempted in the near future studies.

ACKNOWLEDGEMENTS

This study was conducted through Trust-GeoInfra project sponsored by several organizations but in particular Formas, Boliden Mineral AB, and SGU. SEG through its Geoscientists Without Borders (GWB) program and SGU sponsored the quick-clay study. Several PhD students contributed in the field data acquisition; T. Kalscheuer provided EMILIA software and together with L.B. Pedersen provided technical advice for optimizing the RMT inversion parameters. China Scholarship Council and National Natural Science Foundation of China (No. 41227803) and Formas are also thanked to fund S. Wang's PhD study.

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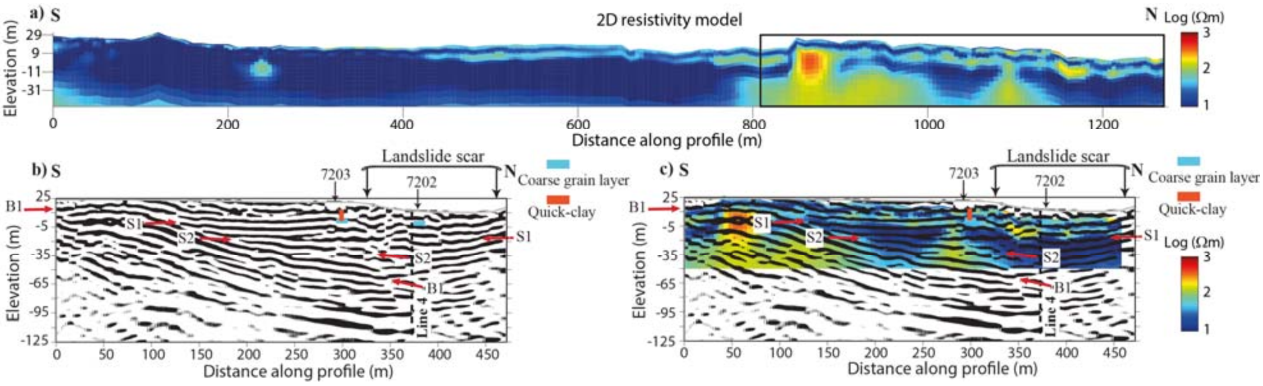

Figure 2. (a) RMT resistivity model, black box represents the position where reflection seismic data are acquired. (b) P-wave migrated reflection seismic section; reflectors S1 and S2 are probably originated from coarse-grained layers; B1 indicates the bedrock; labeled 7203 and 7202 are available geotechnical boreholes. (c) Superimposed image of the two data sets suggesting a possible quick-clay layer above/at the reflector S1. See Figure 1 for the locations of the profiles.

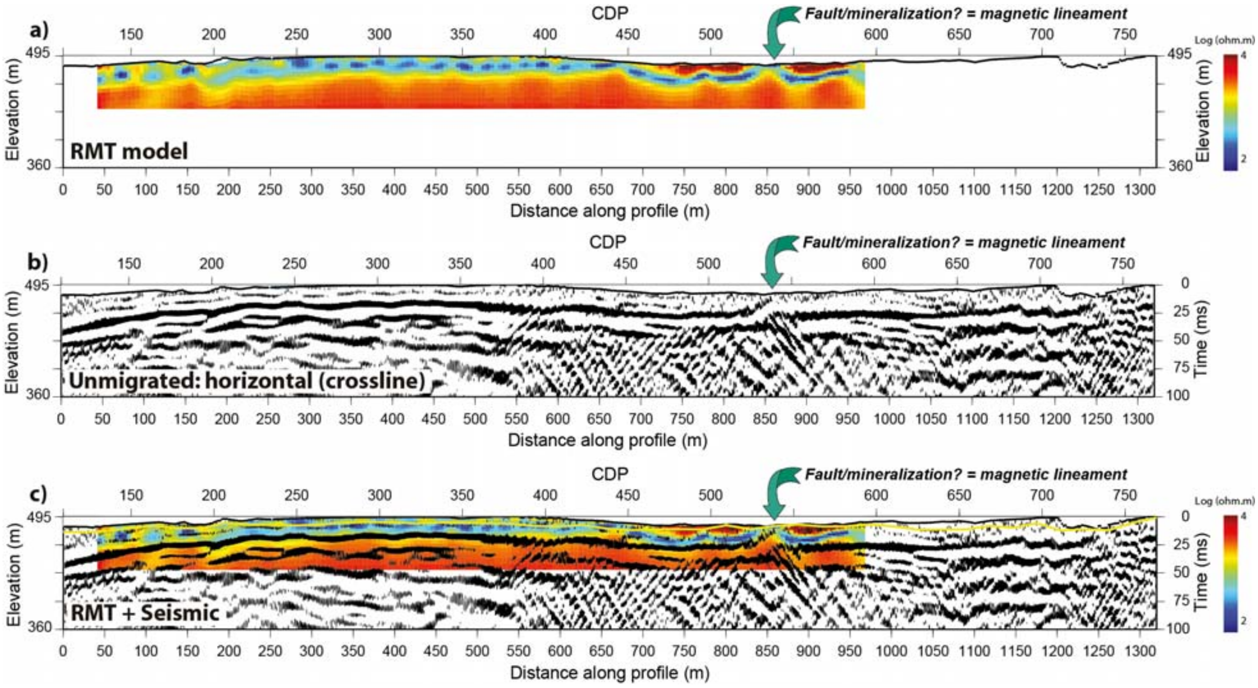

Figure 3. (a) RMT resistivity model, (b) processed SH-component of the reflection seismic data and (c) superimposed image of RMT model and the seismic section suggesting a lithological boundary at about 25 m depth and a potential fault, associated with a magnetic lineament, at about 850 m distance from the start of the profile. Yellow line in (c) is the estimated depth to the bedrock from the refraction component of the data.