Electromagnetic images of the Earth from near-surface to deep within the mantle

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The natural-source magnetotelluric (MT) technique has one major advantage over all other electrical or electromagnetic (EM) methods: namely that the skin depth phenomenon ensures that all depths can be probed using MT data, albeit with decreasing resolution with depth due to the intrinsic spatially-averaging filter of the method. Thus, one can tune MT for the depth of interest and use the same processing, analysis, modelling and inversion approaches; one must only use different magnetic sensors and different input boards and higher digitizing rates.

Although the MT method is an integrating method, like potential field methods, it does not suffer from intrinsic non-uniqueness. Two uniqueness theorems were presented in the early 1970s (Bailey, 1970; Weidelt, 1972) for the case of perfect data from an Earth in which the conductivity varies with depth alone (the 1D case). Equivalent uniqueness theorems for conductivity varying with depth and in one lateral direction (the 2D case) have recently been shown to exist (Weidelt, 2000, pers. comm.). Accordingly, non-uniqueness in MT is associated with data error, insufficiency and sparseness. One can therefore address all of these issues and thus increase resolution and reduce non-uniqueness.

This paper will present resolution and uniqueness aspects of the MT method, demonstrating that *a priori* data or joint inversion can constraint otherwise poorly-posed problems. Examples will be shown, taken from the recent literature, of the MT method in action at all depths, from near-surface to crustal to mantle. In particular, the correlation of conductivity structures with information derived from other geophysical, geochemical and geological data will be highlighted.

Resolution and uniqueness in MT

An example taken to demonstrate the resolving power and non-uniqueness properties of MT data is the three-layer 1D case with a conducting middle layer sandwiched between two resistive layers, the so-called H-type model in D.C. resistivity sounding. This model is one of particular interest to those who wish to understand the reason for the enhanced conductivity of the continental lower crust: a resistive (10,000 Ω.m) 20-km-thick upper crust overlying a conductive (100 Ω.m) 20-km-thick lower crust on top of a resistive (1,000 Ω.m) mantle. The response of this model over the frequency range 10^{-2} - 10^{4} s is shown in Fig. 1, (red lines). Inversion of these data, with a very low noise and scatter level added (0.1%), shows that all of the parameters are resolved to within 1%.

Generating synthetic data over a restricted bandwidth (10^{-1} - 10^{3} s) with only 5 estimates per decade and noise and scatter at a much higher level (20%), demonstrates the problems of non-uniqueness due to data error, insufficiency and sparseness. The best-fitting model to these noisy synthetic data displays a thin, more conducting lower crust (Fig. 2, blue model). Singular Value Decomposition (SVD) analysis (Jones 1982) shows that the eigenparameters of this model for this frequency range are not the layer thicknesses and resistivities independently, but their combinations. For these data the best-resolved parameter is the integrated conductivity of the second layer, $S_2 = s_2 h_2$, with a standard error of 3.5%. The true model has an integrated conductivity of 200 Siemens, whereas the model derived from the noisy synthetic data has an integrated conductance of 203.9 Siemens. Parker's D^+ analysis (Parker and Whaler, 1981), which finds the best-fitting model possible (consisting of delta-like spikes in conductance), yields a conductance spike of 15 Siemens at 19.6 km, and a second one of 255 Siemens at 24.4 km. These values are consistent with the existence of a conducting layer of 200 Siemens at a depth starting at around 20 km.

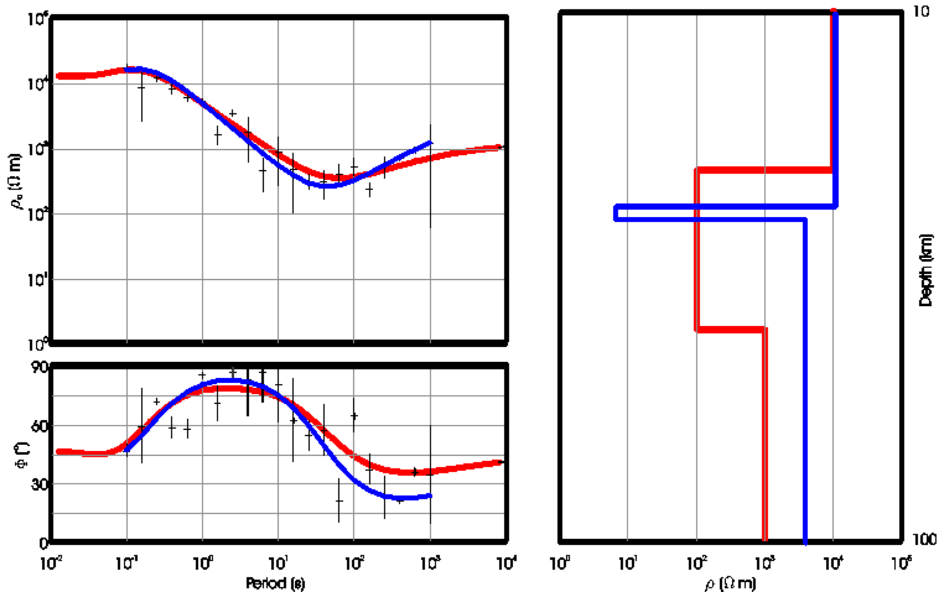

Figure 1: Theoretical responses of the true model (red) and inversion of synthetic data (blue).

The next best resolved parameter is the combination of the basal conductivity and the top layer thickness ($s_3 h_1$) followed by the basal resistivity and the top layer thickness ($r_3 h_1$). Marginally resolved is the top layer resistivity (h_1), and totally unresolved is the integrated resistivity of the second layer, $T_2 = r_2 h_2$. The true model has an integrated resistivity of $2\text{x}10^6$ Ω, whereas the derived model has an integrated resistivity of 9,100 Ω. Consequently, the thickness of the top layer and the resistivity of the basal layer are well-resolved, but the conductivity and thickness of the second layer are not independently resolved, only their combination. Thus, the existence, conductance and depth of the conducting lower crust can be ascertained, but not its actual resistivity and thickness (Jones, 1987, 1992; Zhang and Pedersen, 1991).

This poor resolution of the conducting layer can be significantly improved with *a priori* information. For example, if we have seismic information that gives us the depth to the top of the lower crust and the depth to the Moho, then we can constrain these two parameters in the inversion. With these constraints, then all remaining model parameters can be resolved, in the order r_2, r_3, r_1, and with standard error bounds of 78 - 128 Ω.m, 590 - 1,690 Ω.m and 2,400 - 41,500 Ω.m respectively. (Note the implicit assumption made here that seismic velocity and electrical conductivity can be directly related in a functional manner.)

This analysis demonstrates the need for obtaining the highest quality estimates of the MT impedance tensor elements possible, and also for the implementation of joint inversion of MT data with other data, or at the very least of constrained inversion using information provided by other methods.

Application of MT at all depth levels

The magnetotelluric method is currently being applied in Canada to solve real-world industry problems at both extreme ends of its depth imaging capability. It has a number of advantages over controlled-source EM methods (CSEM):

1. The logistics of MT are far simpler than CSEM methods given that there is no need for a source.

2. Sophisticated robust data processing methods have been developed for MT time series over the last decade.
3. Full tensor information is obtained, from which one can determine directionality and dimensionality.
4. Methods to remove the effects of surficial distorting features have been advance in the 1990s.
5. The mathematics of dealing with a uniform source field are far more tractable than for CSEM methods. This has resulted in 2D inversion and 3D modelling of MT data being now standard and routine, and 3D inversion is being developed.

Recording high frequency (10 Hz - 20,000 Hz) variations in the audio-range, the AMT (audio-MT) method is being applied for geothermal and mineral exploration around the globe. AMT is a very effective tool for detecting conducting mineralization at depths greater than conventionally probed using CSEM methods, but which are still economic (>500 m) (e.g. Livelybrooks et al., 1996; Chouteau et al., 1997). Over the last few years AMT data have been recorded at over 3,000 sites in Canada for mineral exploration purposes, predominantly for nickel in Voisey's Bay and Sudbury. The results of most of these recent surveys remain confidential, but some have been presented to the public (Balch et al., 1998; Stevens and McNeice, 1998; Zhang et al., 1998).

At long periods, the LMT (long period MT) method is being applied for determining properties and geometries of the continental mantle lithosphere and its underlying asthenosphere. Electrical conductivity is very sensitive to the onset of partial melt, and it increases by two or more orders of magnitude with only a fraction of one percent of an interconnected melt phase. Thus MT can resolve the lithosphere-asthenosphere boundary (LAB) as a step change from 100s - 1000s Ω.m to 10-25 Ω.m with high precision (Jones, 1999). Comparison of electrical parameters of the mantle lithosphere with seismic ones may provide significant information about the tectonic history and development of the mantle lithosphere (e.g., Ji et al., 1996).

At even deeper depths in the mantle, laboratory studies have shown that there should be a significant conductivity increase at the 410-km boundary as olivine undergoes a pressure phase transformation to wadsleyite (Xu et al., 1998). Whilst surface MT measurements cannot resolve step changes in conductivity, if the boundary is known to exist then hypothesis testing can show whether the data support a step change (Jones, 1999). The only study to date that obtained responses of sufficiently high quality for mantle resolution was that of Schultz et al. (1993) on the Superior craton.

References

Bailey, R.C., 1970. Inversion of the geomagnetic induction problem. *Proc. Roy. Soc. London*, **Ser. A 315**: 185-194.

Balch, S., T.J. Crebs, A. King and M. Verbiski, 1998. Geophysics of the Voisey's Bay Ni-Cu-Co deposits. SEG Annual Meeting Expanded Technical Program Abstracts with Biographies. 68.

Chouteau, M. P. Zhang, D.J. Dion, B. Giroux, R. Morin and S. Krivochieva, 1997. Delineating mineralization and imaging the regional structure with magnetotellurics in the region of Chibougamau (Canada). *Geophysics*, **62**, 730-748.

Ji, S., S. Rondenay, M. Mareschal and G. Senechal, 1996. Obliquity between seismic and electrical anisotropies as a potential indicator of movement sense for ductile mantle shear zones. *Geology*, **24**: 1033-1036.

Jones, A.G., 1982. On the electrical crust-mantle structure in Fennoscandia: no Moho and the asthenosphere revealed? *Geophys. J.R. Astron. Soc.*, **68**: 371-388.

Jones, A.G., 1987. MT and reflection: an essential combination. *Geophys. J.R. Astron. Soc.*, **89**: 7-18.

Jones, A.G., 1992. Electrical conductivity of the continental lower crust. In: *Continental Lower Crust*, eds., D.M. Fountain, R.J. Arculus and R.W. Kay. Elsevier, Amsterdam, Chapter **3**: pp. 81-143.

Jones, A.G., 1998. Waves of the future: Superior inferences from collocated seismic and electromagnetic experiments. Tectonophys., **286**, 273-298.

Jones, A.G., 1999. Imaging the continental upper mantle using electromagnetic methods. Lithos, **48**, 57-80.

Livelybrooks, D.W., M. Mareschal, E. Blais and J.T. Smith, 1996. Magnetotelluric delineation of the Trillabelle massive sulfide body in Sudbury, Ontario. *Geophysics*, **61**, 971-986.

Parker, R.L. and Whaler, K.A., 1981. Numerical methods for establishing solutions to the inverse problem of electromagnetic induction. *J. Geophys. Res.*, **86**: 9574-9584.

Schultz, A., Kurtz, R.D., Chave, A.D. and Jones, A.G., 1993. Conductivity discontinuities in the upper mantle beneath a stable craton. *Geophys. Res. Lett.*, **20**: 2941-2944.

Stevens, K.M. and G. McNeice, 1998. On the detection of Ni-Cu ore hosting structures in the Sudbury Igneous Complex using the magnetotelluric method. SEG Annual Meeting Expanded Technical Program Abstracts with Biographies. 68.

Xu, Y. B.T. Poe, T.J. Shankland and D.C. Rubie, 1998. Electrical conductivity of olivine, wadsleyite and ringwoodite under upper-mantle conditions. *Science*, **280**, 1415-1418.

Weidelt, P., 1972. The inverse problem of geomagnetic induction. *Z. Geophys*, **38**: 257-289.

Zhang, P. and L.B. Pedersen, 1991. Can magnetotelluric data resolve lower-crustal conductors? *Phys. Earth Planet. Inter.*, **65**, 248-254.

Zhang, P., A. King and D. Watts, 1998. Using magnetotellurics for mineral exploration. SEG Annual Meeting Expanded Technical Program Abstracts with Biographies. 68.

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