WHAT IS NEW IN MAGNETOTELLURICS?

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SUMMARY

The geophysical technique of magnetotellurics (MT) was first described over sixty years ago with seminal papers by Tikohnov (1950) and Cagniard (1953). Over the subsequent six decades, the method has developed steadily, finding application in both academic research and resource exploration. The MT method, along with seismics, is one of the few geophysical techniques to provide meaningful depth constraint, and to probe deep geology beyond the reach of a drill.

In the last two decades there have been significant developments and advancements, bringing the MT method into more routine use for mineral and energy resource exploration at all scales. Such developments have been driven by a combination of factors, which include: low-cost and large-data acquisition systems; advances in data processing; rapid 2D and more recently 3D/4D inversion that provides better geophysical models for geological interpretation; and greater insight into the geological factors that determine the electrical resistivity of Earth materials. Survey stations have increased from tens to hundreds of sites, and considerable resources are being devoted to continental grids of MT sites to provide a lithospheric-scale resistivity framework. Additionally, MT has also found application in monitoring changes in Earth resistivity associated with energy resource developments.

Some of the most significant opportunities into the future lie in the areas of instrumentation, modelling and petrophysics. Distributed acquisition systems that connect many sensors, potentially linked remotely by telecommunications networks will increase the efficiency, resolution and aperture of surveys. Drones offer the potential to deploy many sensors in difficult terrains and although there is significant challenge in remotely making grounded electrode measurements, capacititative electrodes could be equally effective. In modelling, the paradigm has moved from a single, optimal deterministic model, to suites of acceptable models that can be used to define probability and certainty. Additionally, joint inversion approaches that link different physical parameters to a common Earth model will eventually lead to better geological outputs. Finally, there is a gap in knowledge linking observed and modelled resistivities to mineral-scale thermal and fluid processes, particularly for deep parts of the crust and mantle. A stronger link between geophysical model and geological interpretation will further encourage the uptake of MT as a means of understanding the Earth.

Key words: Magnetotellurics, mineral exploration, petroleum exploration, tectonics

FIELD INSTRUMENTATION AND SURVEYS

An excellent review of the state of instrumentation is given by Ferguson (2012). For magnetic sensors, the MT bandwidth of approximately 10^4 Hz to 10^{-4} Hz is covered by either single-component induction coils for the higher frequencies, and three-component fluxgates for the lowest frequencies (Korepanov and Marusenkov, 2012). The quality of each type of sensor has considerably improved over the last two decades, and the overlap between fluxgates and induction coil bandwidths has increased. Electric fields, measured as voltage gradients over dipoles of lengths 50 m or more, are surprisingly difficult to achieve the same quality and typically display more sporadic and unidentified noise (Petiau, 2000). Moreover, long-dipoles are often subject to animal damage even when cables are buried. Ferguson (2012) discusses various types of electrodes and field deployments strategies, but there has been little substantive progress that has been published in the last decade.

Magnetotelluric sites are often employed in surveys over three distinct scale-lengths, with commensurate observed bandwidth, instrumentation and station spacing.

1. Long-period (10^0 – 104 s) measurements using fluxgate sensors can provide constraint on the resistivity to hundreds of kilometres depth, probing both the lithosphere and the asthenosphere. Stations are typically deployed in a wide-spread grid for two to three weeks to ensure good signal-to-noise ratios for MT estimates at the longest periods of several hours. The primary objective is to provide a lithospheric-scale framework of resistivity of the deep crust and upper mantle to define a broad regional mineral prospectivity. In the last decade a number of continental-scale 3D surveys have commenced, including the Australian Lithospheric Architecture Magnetotelluric Project AusLAMP (Roberston et al., 2016); US Array (Bedrosian and Feucht, 2014; Meqbel et al., 2014); Sinoprobe in China (Dong et al., 2014); and SAMTEX in southern Africa (Miensopust et al., 2011).
2. Broadband (10^3 – 10^{-3} Hz) transects and grids using induction coil sensors to image resistivity over crustal scales, often in conjunction with seismic reflection surveys. Instruments are left in the field for a few days, generally to capture sufficient signal for the dead-band (10^0-10^{-1} Hz) and longer periods, and are often leapfrogged along a survey. Some of the first broadband surveys were carried out in the Lithosprobe program in Canada (Jones et al., 2014). Such surveys link the deep

lower crust to potentially mineralised structures, or energy resources in sedimentary basins, and have become quite widespread in Australia over the last decade (eg. Thiel and Heinson, 2010; Thiel et al., 2016).

3. Finally, deposit-scale surveys (10^4 – 10^{-1} Hz) yield resource targets using the highest frequencies. At frequencies of order 10^4 Hz, the technique is often referred to as audio magnetotellurics (AMT) or controlled-source audio magnetotellurics (CSAMT) if a transmitter is used. However, the division between broadband and AMT systems has diminished as induction coil sensors have improved. Surveys are usually focused on the top one to two kilometres, and are used to identify anomalies. Data acquisition can be very rapid, and often the emphasis is on collecting numerous telluric dipoles (sometimes in a continuous line) with occasional magnetic sensors.

In addition to the use of MT for mapping in one, two or three dimensions the Earth's resistivity, a quite recent development has been in the use of MT for monitoring. In such cases, engineered changes in the Earth such as hydraulic stimulation for deep geothermal system (Peacock et al., 2012; 2013), shale gas (Rees et al., 2016a), and depressurisation of coal horizons in coal-seam gas development (Rees et al., 2016b) lead to observable changes in Earth resistivity. Such application provides potentially many new opportunity for MT, however there are many challenges in mapping observed changes at the surface to quantifiable models of change in the Earth. Moreover, it is not clear how the observations relate to the engineered hydrogeology (Peacock et al., 2013).

MODELLING

The most notable change in the MT community over the last decade has been the transition to the routine use of 3D inversion (Siripunvaraporn, 2011; Miensopust et al., 2013). Prior to this, 2D inversions were the most commonly used (deGroot-Hedlin and Constable, 1990; Rodi and Mackie 2001), as 3D inversions were largely seen as being unfeasible due to the very large computer requirements in terms of memory and time, and that models were often so blocky as to provide few geological insights.

In the research communities, there are two main 3D inversion codes, namely ModEM (Kelbert et al., 2014) and WSINV3DMT (Siripunvaraporn et al., 2005). Both have been successfully applied to large MT data sets (eg. ModEM by Robertson et al., 2016) to generate models that reproduce well the full impedance tensors. However, the model space is defined to be smooth, minimising gradients in resistivity, and resulting models can often appear to comprise isolated smooth regions of anomalous conductive regions, often of width commensurate with station spacing (Meqbel et al., 2014). There is scope for more geologically and geophysically constrained models that can better define target structures. Constable et al. (2015) provide a summary of the nuances of MT inversion in terms of resolution and inference.

There is a growing interest in defining not just the optimal model in a least squares manner (often known as the deterministic model), but rather the range of acceptable models that are comparable to data errors. The range of models can be used to quantify the uncertainty on model parameters. Such modelling is sometimes called stochastic, generally applying the Bayesian formulation of relationship between data and model probabilities. To date, such approaches are not routinely applied in higher-order MT inversions, partly because of the computational requirements of 2D and 3D forward models. There are a few published examples of 1D Bayesian inversion (eg. Guo et al., 2011), but only limited work in 2D (Chen et al., 2012; Schnaidt and Heinson, 2015). However, as massively parallel computational systems become more available, there will be progress in this field and eventually 3D will be tractable.

Limited progress has been in true joint inversion of different data sets for a common earth model over the last decade (Bedrosian, 2007). Joint inversion can be viewed from a petrophysical point of view, linking geophysical properties in a causal or correlated manner in each part of the Earth, and as a structural constraints assuming common orientation of gradients in different physical properties. Gallardo and Meju (2001) provide a review of the current practices, and multi-physics examples for the deep Earth are given by Afonso et al. (2013a,b). The difficulty of simultaneous joint inversion is often computational in solving two or more linked non-linear problems in a realistic time, and secondly in addressing differences in model resolution, sensitivity, data density and data error estimates. A more pragmatic approach is to use constraints from one technique (often seismics with highest resolution) to reduce ambiguity in a different technique (for example, MT). Lines et al. (1988) provide a good review of cooperative inversion, and a practical application is given by Jegen et al. (2009).

GEOLOGY

Geological interpretation of resistivity models requires knowledge of the physical properties that determine conduction; Pommier (2014) provides an excellent review of the conduction properties of Earth materials. Linking resistivity models directly to interpretable geological models is, however, not straightforward. Firstly, models are at best a low resolution image of the Earth's true resistivity and biased towards the sensitivity of the technique; and secondly the geochemical composition of the crust and upper mantle at depths below about 1 km are poorly known in any given geological setting. For deep crust and mantle interpretations Yang (2011) and Selway (2014) provide comprehensive reviews, but there is scope for a much greater petrophysical understanding to gain more geological insights from MT models.

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REFERENCES

Afonso, J. C., Fullea, J., Griffin, W.L., Yang, Y., Jones, A.G., Connolly, J.A.D., and O'Reilly, S.Y., 2013a, 3-D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. I: a priori petrological information and geophysical observables: Journal of Geophysical Research-Solid Earth, 118, 2586-2617.

Afonso, J. C., Fullea, J., Yang, Y., Connolly, J.A.D., and Jones, A.G., 2013b, 3-D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. II: General methodology and resolution analysis: Journal of Geophysical Research: Solid Earth, 118, 1650-1676.

Bedrosian, P.A., 2007, MT+, Integrating magnetotellurics to determine Earth structure, physical state, and processes: Surveys in Geophysics, 28, 121–167.

Bedrosian, P.A., and Feucht, D.W., 2014, Structure and tectonics of the northwestern United States from EarthScope USArray magnetotelluric data: Earth Planetary Science Letters, 402, 275–289.

Cagniard, L., 1953, Basic theory of the magnetotelluric method of geophysical prospecting: Geophysics, 18, 605-635.

Chen, J., Hoversten, G.M., Key, K., Nordquist, G., and Cumming, W., 2012, Stochastic inversion of magnetotelluric data using a sharp boundary parameterization and application to a geothermal site: Geophysics, 77, E265-E279.

Constable, S.C., Orange, A., and Key, K., 2015, And the geophysicist replied: “Which model do you want?”: Geophysics, 80, E197-E212.

deGroot-Hedlin, C., and Constable, S.C., 1990, Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data: Geophysics, 55, 1613-1624.

Dong, H., Wei, W., Ye, G., Jin, S., Jones, A.G., Jing, J., Zhang, L., Xie, C., Zhang, F., and Wang, H., 2014, Three-dimensional electrical structure of the crust and upper mantle in Ordos Block and adjacent area: Evidence of regional lithospheric modification: Geochemistry Geophysics Geosystems, 15, 2414–2425.

Ferguson, I.J., 2014, Instrumentation and field procedures: In: The Magnetotelluric Method: Theory and Practice, Editors: A.D. Chave, A.G. Jones, Cambridge University Press, pp.421-479.

Gallardo, L.A., and Meju, M.A. 2011, Structure-coupled multiphysics imaging in geophysical sciences: Reviews of Geophysics, 49, RG1003.

Guo, R., Dosso, S.E., Liu, J., Dettmer, J., and Tong, X., 2011, Non-linearity in Bayesian 1-D magnetotelluric inversion: Geophysical Journal International, 185, 663–675.

Jegen, M.D., Hobbs, R.W., Tarits,P., and Chave, A., 2009, Joint inversion of marine magnetotelluric and gravity data incorporating seismic constraints: Preliminary results of sub-basalt imaging off the Faroe Shelf: Earth Planetary Science Letters, 282, 47-55.

Jones, A. G., Ledo, J., Ferguson, I. J., Craven, J. A., Unsworth, M. J., Chouteau, M., and Spratt, J. E., 2014, The electrical resistivity of Canada's lithosphere and correlation with other parameters: Contributions from Lithoprobe and other programmes: Canadian Journal of Earth Sciences, 51, 573-617.

Kelbert, A., Meqbel, N., Egbert, G.D., and Tandon, K., 2014, ModEM: A modular system for inversion of electromagnetic geophysical data: Computers and Geosciences, 66, 40-53.

Korepanov, V., and Marusenkov, A., 2012, Flux-gate magnetometers design peculiarities: Surveys in Geophysics, 33, 1059-1079.

Lines, L., Schultz, A., and Treitel, S., 1988, Cooperative inversion of geophysical data: Geophysics, 53, 1, 8-20.

Meqbel, N.M., Egbert, G.D., Wannamaker, P.E., Kelbert, A., Schultz, A., 2014, Deep electrical resistivity structure of the northwestern U.S. derived from 3-D inversion of USArray magnetotelluric data: Earth Planetary Science Letters 402, 290–304.

Miensopust, M., Jones, A.G., Muller, M.R., Garcia, X., and Evans, R.L., 2011, Lithospheric structures and Precambrian terrane boundaries in northeastern Botswana revealed through magnetotelluric profiling as part of the Southern African Magnetotelluric Experiment. Journal of Geophysical Research - Solid Earth, 116, B02401.

Miensopust, M.P., Queralt, P., Jones, A.G., and the 3D MT modellers, 2013, Magnetotelluric 3-D inversion—a review of two successful work- shops on forward and inversion code testing and comparison: Geophysical Journal International, 193, 1216–1238.

Peacock, J., Thiel, S., Reid, P., and Heinson, G., 2012, Magnetotelluric monitoring of a fluid injection: example from an enhanced geothermal system: Geophysical Research Letters, 39, 1-5.

Peacock, J., Thiel, S., Heinson, G., and Reid, P., 2013, Time-lapse magnetotelluric monitoring of an enhanced geothermal system: Geophysics, 78, 121-130.

Petiau, G., 2000, Second generation Lead-Lead Chloride electrodes for geophysical applications: Pure and Applied Geophysics, 157, 357-382.

Pommier, A., 2014, Interpretation of magnetotelluric results using laboratory measurements: Surveys in Geophysics, 35, 41-84.

Rees, N., Carter, S., Heinson, G., and Krieger, L., 2016, Monitoring shale gas resources in the Cooper Basin using magnetotellurics: Geophysics, 81, A13-A16.

Rees, N., Heinson, G., and Krieger, L., 2016, Magnetotelluric monitoring of coal seam gas depressurization: Geophysics, 81, E423-E432.

Robertson, K., Heinson, G., and Thiel, S., 2016, Lithospheric reworking at the Proterozoic-Phanerozoic transition of Australia imaged using AusLAMP magnetotelluric data: Earth and Planetary Science Letters, 452, 27-35.

Rodi, W., and Mackie, R.L., 2001, Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion: Geophysics, 66, 174-187.

Schnaidt, S., and Heinson, G., 2015, Bootstrap resampling as a tool for uncertainty analysis in 2-D magnetotelluric inversion modelling: Geophysical Journal International, 203, 92-106.

Siripunvaraporn, W., 2011, Three-dimensional magnetotelluric inversion: An introductory guide for developers and users: Surveys in Geophysics, 33, 5–27.

Siripunvaraporn, W., Egbert, G., Lenbury, Y., and Uyeshima, M., 2005. Three-dimensional magnetotelluric inversion: data-space method: Physics of the Earth and Planetary Interior, 150, 3–14.

Selway, K., 2014, On the causes of electrical conductivity anomalies in tectonically stable lithosphere: Surveys in Geophysics, 35, 219-257.

Thiel, S., Soeffky, P., Krieger, L., Regenauer-Lieb, K., Peacock, J., and Heinson, G., 2016, Conductivity response to intraplate deformation: evidence for metamorphic devolatilization and crustal-scale fluid focusing: Geophysical Research Letters, 43, 11-244.

Thiel, S., and Heinson, G., 2010, Crustal imaging of a mobile belt using magnetotellurics: An example of the Fowler Domain in South Australia: Journal of Geophysical Research – Solid Earth, 115, 06102-1-06102-18.

Tikhonov, A.N., 1950, On determining electrical characteristics of the deep layers of the Earth's crust: Doklady, 73, 295-297.

Yang, X., 2011, Origin of high electrical conductivity in the lower continental crust: a review: Surveys in Geophysics, 32, 875–903.