Magnetotelluric monitoring of unconventional energy resource development: Disruptive technology or damp squib?

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SUMMARY

A significant scientific and engineering challenge for the energy resources industry is to monitor injected or produced fluid at depths of hundreds or thousands of metres, and over time-scales of hours to years. A new approach using surface magnetotelluric (MT) methods has been developed over the last five years to map deep-fluid pathways by virtue of their electrical resistivity changes, both spatially and temporally. This is a cheap technology as it uses natural electromagnetic source-fields and does not require drilling. However, is this method really effective for industry for economic reasons and for social and environmental compliance? In other words, is it a disruptive technology or a damp squib?

This paper reviews the physics of the approach, and demonstrates the feasibility of the MT method for monitoring unconventional energy resource development. A number of case studies will be shown, including shallow coal seam gas de-pressurisation, deep hydraulic stimulation of a shale gas reservoir, and enhanced geothermal system development.

Key words: Magnetotellurics, monitoring, unconventional energy resource.

INTRODUCTION

Unconventional energy resources have become a major global industry over the last decade, driven by technological developments and increasing demand. A key factor is in establishing sufficient permeability in otherwise low-porosity and low-permeability formations. Permeability can be established through hydraulic stimulation of deep formations, either through existing fracture networks or by creating new pathways for fluids, and though de-pressurisation of shallower coal beds by extracting existing sub-surface fluids.

Surface geophysical monitoring can be used to determine lateral and vertical constraints on the fluid movements in the target lithologies. Such constraints optimise production and well placement. Independent verification is also critical for social and environmental regulation, to ensure that hydraulic stimulations and de-pressurisation do not interact with overlying aquifers. To date, microseismic monitoring has been the primary and most successful geophysical technique, widely used for many types of unconventional energy resource development.

In contrast to the microseismic method that delineates the locations of a rock failure, MT monitoring is sensitive directly to the presence of connected fluid, which in turn is dependent on the permeability. Additionally, MT is sensitive to the direction of fluid connection, so may yield important information on how fluids migrate with time. As sub-surface fluids conduct electrical current dependent on the porosity, connectivity and ionic saturation of the fluid, it follows that the introduction or removal of fluids will change the electrical resistivity of the formation.

METHOD

Electromagnetic fields propagate by diffusion and thus resolution of the physical properties of any particular lithology is not possible. Most modelling approaches involve generating smooth resistivity responses that reflect the intrinsic resolution of the MT method. However, the advantage of MT monitoring is that the zone of altered resistivity is well constrained given the depth, volume and timing of injected fluid are known in an otherwise unchanging Earth (Rosas-Carbajal *et al.*, 2015; Rees *et al.*, 2016).

The bulk electrical resistivity of any sub-surface lithology is dependent on the matrix and the pore fluids. Silica-dominated clastic sediments and crystalline basement are typically resistive (>1000 Ω.m) and thus contribute little to the overall conduction. However, clay-rich lithology can have significantly lower resistivity (1-10 Ω.m) with conduction dominated by surface mobility of ions. On the other hand, interstitial fluids generally have a more significant role. Ionic conduction through dissolved salts typically have low resistivity (0.1-10 Ω.m) depending on ionic concentration. For deep formations, high temperatures of >100 ºC will reduce fluid resistivity by about an order of magnitude (Nesbitt, 1993).

The final factor in determining bulk resistivity is in how fluids are connected. Such connectivity depends on total porosity and the interconnection of pores, which is clearly linked with the permeability. For primary porosity in clastic sediments, porosity and permeability are relatively isotropic meaning that the properties do not vary in any specific orientation. However secondary porosity due to fractures, faults, bedding planes and solution channels in carbonates may result in highly anisotropic permeability and hence anisotropic resistivity properties (Macfarlane *et al.*, 2014; Kirkby *et al.*, 2015; 2016).

The effect of hydraulic stimulation on the bulk resistivity at depth depends on a number of factors (Rees *et al.*, 2016). These include the salinity of the injected fluids; the total volume of fluid and the rate of injection; temperature of the target formation; regional stress field and presence of existing fracture networks; and presence of over-pressured interstitial fluids. Peacock *et al.* (2012; 2013) showed a significant change of more than 5% in the MT responses for a stimulation of a geothermal target with 3.1 million litres of fluid of resistivity 0.3 Ω.m at 20 °C injected at 3.8 km depth. On the other hand, Didana *et al.* (2016) reported a much smaller MT response change for 36.5 million litres of fluid of resistivity of 13 Ω.m at 20 °C injected at 4 km depth.

Although the total volumes of stimulation fluids are relatively small, opening existing and new fracture networks may connect significantly larger volumes of pre-existing fluids. Didana *et al.* (2016) noted that naturally occurring over-pressured fluids in the granites had resistivities of < 0.3 Ω.m. Microseismic events spanned a much larger volume (approximately 1.25 km^3) than might be expected for 36.5 million litres of injected fluid suggesting that the bulk resistivity may be more affected by connecting existing fluids than through the stimulation fluid alone.

Figure 1 shows a simple feasibility study of a shale stimulation at a depth of 2900 m using 1D MT forward-modelling (Rees *et al.*, 2016). Although the model is clearly unrealistic in that a finite 3D volume is actually stimulated rather than a layer of infinite lateral extent, such models indicate the magnitude and bandwidth of the MT response change. Wireline logs were used to generate a background resistivity model over the length of the log and extrapolated for depths above and below based on simple trends. An analytic 1D forward model generated MT responses at 50 frequencies over a range of 10^{-3} to 10^2 Hz. Two additional models were then constructed to simulate the resistivity structure after hydraulic stimulation with a 100 m-thick layer of either 1 Ω.m or 10 Ω.m below 2900 m.

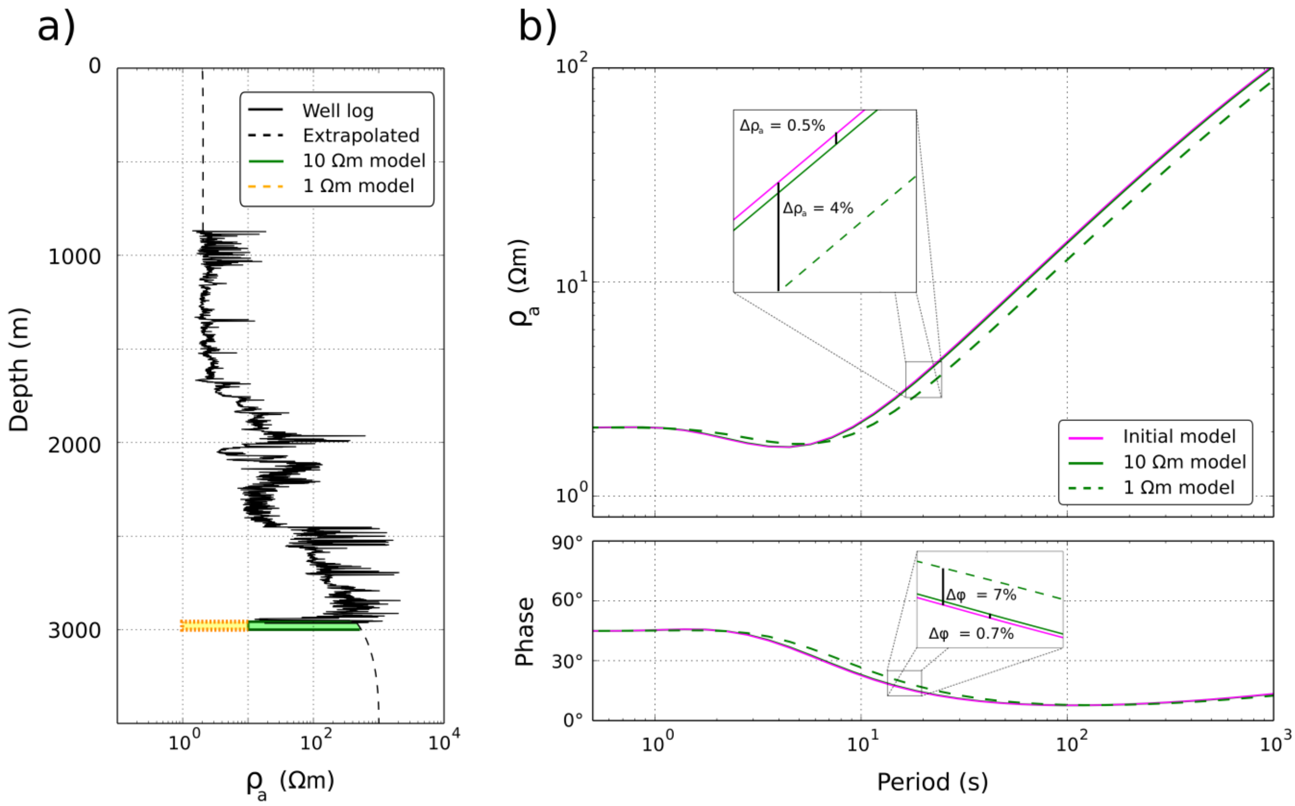

Figure 1: (a) A wireline log resistivity plot extrapolated to the surface and to greater depth (dashed line). The dashed green and solid green regions indicate two scenarios of injected fluid that reduces the resistivity to 1 Ω.m and 10 Ω.m. (b) Forward modelled apparent resistivity and phase for a typical bandwidth of 1–1000 s. The black curve shows the response prior to stimulation, and the dashed green and solid green curves indicate the change in response to the two scenarios.

For the 10 Ω.m layer, MT responses change by less than 1 %, but the 1 Ω.m layer yields an MT response change of up to 7% which are detectable (Peacock *et al.*, 2013). Apparent resistivity data show most difference at frequencies lower than 0.1 Hz, whereas the phase has maximum difference between 1 and 0.1 Hz. This is the MT dead-band of low signal, which introduces noise issues, but such problems can generally be reduced by using long time windows (often 2-3 days) to improve the signal-to-noise response.

CONCLUSIONS

The utility of MT monitoring of unconventional resource development is at an early stage. Results from a handful of surveys undertaken to date demonstrate that the MT method has promise, but as a new technology will require time to improve outcomes. There is scope for major innovation in modelling the resistivity of fluid stimulations and de-pressurisation. In particular, it is important to incorporate all known constraints in space (such as resistivity logs as a priori background, and depth of fluid stimulation), time (the commencement and rate of fluid injection) and fluid characteristics (fluid resistivity, formation temperature and fluid volume). A significantly constrained model will be much more successful in defining regions of fluid injection or de-pressurisation than a smooth unconstrained model.

ACKNOWLEDGMENTS

Magnetotelluric equipment was made available through AuScope and the Australian Geophysical Observing System (AGOS) through the Australian Department of Education and Training, a world class facility. Many data processing and modelling codes used in this project have been kindly provided through the academic community. The University of Adelaide are thanked for supporting many students and staff on this project both financially and logistically.

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