Monitoring of unconventional resources using magnetotellurics

Nigel Rees *
The University of Adelaide
Adelaide SA 5005
nigel.rees@adelaide.edu.au

Graham Heinson
The University of Adelaide
Adelaide SA 5005
graham.heinson@adelaide.edu.au

Simon Carter
Wuhan University
Wuchang, Wuhan, Hubei, China, 430072
simon.carter@adelaide.edu.au

Lars Krieger
Institute for Geothermal Resource Management, Bingen.
lars.krieger@adelaide.edu.au

SUMMARY

The success of unconventional gas extraction is dependent on establishing sufficient permeability in otherwise low-porosity and low-permeability formations. In the case of shale gas, permeability can be established through hydraulic stimulation of deep formations, either through existing fracture networks or by creating new pathways for fluids to flow. Coal seam gas (CSG) permeability can be established through de-pressurisation of coal beds by extracting existing sub-surface fluids.

The primary geophysical technique for the monitoring of hydraulic stimulation and de-pressurisation has been microseismic, which measures small seismic events associated with rock fractures. The magnetotelluric method (MT) presents itself as an alternative geophysical approach for monitoring unconventional resource development. MT is directly sensitive to electrical resistivity with depth and orientation and could be used to infer fracture orientation, fluid migration and hydraulic conductivity.

We report on the first industrial MT field surveys for the spatial and temporal monitoring of fluid movement resulting from both hydraulic fracturing of a shale gas reservoir and de- pressurisation of a CSG formation. We show that increasing permeability enables conductive fluids to connect resulting in small drops in bulk resistivity. Such changes in resistivity can be mapped through modelling and inversion allowing a determination of areas with greater permeability and hence production capacity.

Key words: magnetotellurics, coal seam gas, shale gas, monitoring, permeability.

INTRODUCTION

Extraction of unconventional energy such as shale gas and coal seam gas (CSG) has become a major global industry over the last decade, with success driven by establishing sufficient permeability in otherwise low-permeability formations. Economic production of shale gas involves enhancing the permeability of the shale matrix by injecting fluids at high pressure to create permeable pathways for the trapped gas to escape (Curtis, 2002; Donaldson et al., 2014). Extraction of CSG involves depressurisation, a process whereby large volumes of groundwater are extracted from coal measures to reduce formation pressure allowing the trapped gas to desorb from the coal (Aminian and Rodvelt, 2014; Seidle, 2011). Both of these extraction techniques involve connection of fluids travelling through porous media, which may result in bulk electrical resistivity variations.

We propose the application of the passive magnetotelluric method (MT) as a novel approach to monitoring variations in electrical resistivity resulting from extraction of unconventional resources. MT is directly sensitive to electrical resistivity with depth and orientation and could be used to infer fracture orientation, fluid migration and hydraulic conductivity. Two industrial field surveys were undertaken to test MT as a monitoring technique. The first survey involved monitoring a CSG depressurisation in Queensland, Australia, over a period of four months. The second survey was conducted in Moomba, South Australia and involved monitoring hydraulic fracturing of a shale gas formation.

METHOD AND RESULTS

The MT method measures variations of Earth's electric field, **E**, and magnetic induction, **B**, at the surface over time to determine conductive structure at depth. Magnetotelluric signals are generated from the interaction of solar winds with the Earth's magnetic field (frequencies < 1 Hz) and equatorial thunderstorm activity (frequencies > 1 Hz) (Garcia and Jones, 2002; Chave and Jones, 2012). In the bandwidth of 0.5 to 5 Hz and 800 to 2000 Hz, there exists what is commonly referred to as the dead band at which there exists a minimum in the power spectrum. MT measurements recorded in this frequency range usually suffer from reduced quality of magnetotelluric transfer functions (Simpson and Bahr, 2005; Chave and Jones, 2012).

MT data acquisition involves measuring orthogonal components of **E** and **B** fields at Earth's surface. The relationship between orthogonal components of **E** and **B** is defined by the complex-valued, frequency dependent impedance tensor **Z**

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \end{pmatrix}. \quad (1)$$

The components of **Z** are characterised by a scaled amplitude termed apparent resistivity (ρ_a)

$$\rho_{a,\mathrm{ij}}(\omega) = \frac{1}{\mu_0 \omega} \left| Z_{\mathrm{ij}}(\omega) \right|^2 \quad (2)$$

and a signal phase angle ϕ

$$\phi_{\mathrm{ij}}(\omega) = \tan^{-1}\left(\frac{\Im(Z_{\mathrm{ij}})}{\Re(Z_{\mathrm{ij}})}\right) \quad (3)$$

where ω is the angular frequency and μ_0 represents the magnetic permeability. A measure of the depth of investigation, an electromagnetic skin-depth δ can be defined as:

$$\delta(\omega) = \sqrt{\frac{2}{\omega\mu\sigma}} \approx 500\sqrt{\rho T} \quad (4)$$

where ρ represents the mediums resistivity (σ is the conductivity) and T is the signal period.

Our monitoring instrumentation records continuous time-series at 651 Hz (sampling interval of 1536 µs) over the entire length of the experiments. MT response functions were generated from the time series data as a function of both time during the survey and location in the array. For each site, windows of 72 hours (for CSG monitoring) and 96 hours (for shale gas monitoring) of down-sampled 100 Hz data were extracted (Krieger and Peacock, 2014). MT transfer functions (impedance tensors) and error estimates in the bandwidth of 10 to 0.01 Hz were estimated from each individual section of the time-series data (Chave and Thomson, 2004).

CSG monitoring:

An MT survey of a CSG production test site in the Surat Basin, Queensland, Australia, was conducted from December 2013 until April 2014. The target lithologies were the Walloon Coal Measures in the depth range of 300 – 700 m below the surface. We deployed 52 electric field data loggers (**E**-loggers) and 3 sets of magnetic induction sensors (**B**-loggers) to produce MT response functions along two orthogonal lines, each 2.5 km in extent and crossing various production wells (Figure 1).

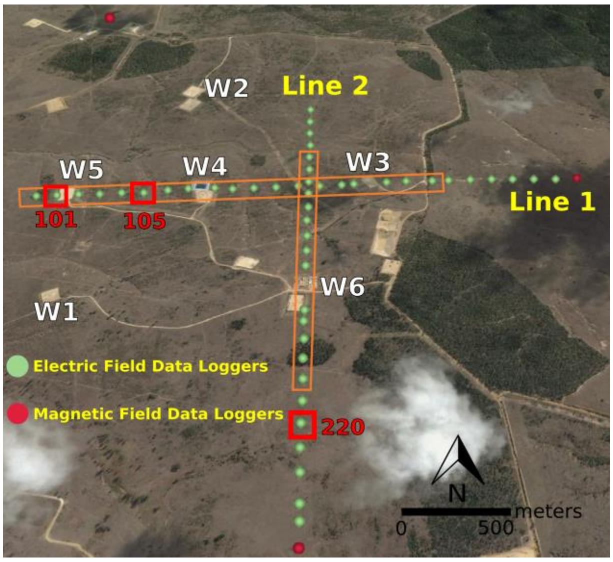

Figure 1: Location of 52 MT electric field loggers along two lines, each approximately 2.5 km long, and a reference station in the north-west of the figure. Magnetometers were deployed at the eastern end of Line 1 and the southern end of Line 2, and at the reference site. The location of nearby operational wells (W1 – W6) are shown. The orange boxes represent the sites used for the 2D modeling studies and the red boxes represent the sites used for the 1D time-lapse inversions. Site spacing was 100 m and the instruments were recording continuously for four months.

Two-dimensional (2D) inversions (Rodi and Mackie, 2001) of responses along the recorded profiles pre- and post- depressurisation were conducted using the MT modelling software Winglink. Figure 2 shows the percentage decrease in resistivity between the pre- and post- inversions along Line 1. Significant decreases in resistivity in the order of 10 – 15% occur, confined to an area between the mainly active production location Well 4 and the recently activated Well 5. Despite the inherently limited depth resolution of MT, the inversions indicate a depth range of change that coincides with the targeted Upper and Lower Juandah Coal Measures. In contrast, no significant change is observed in the overlying Springbox Sandstone, which contains major regional aquifers (Hamilton et al., 2014).

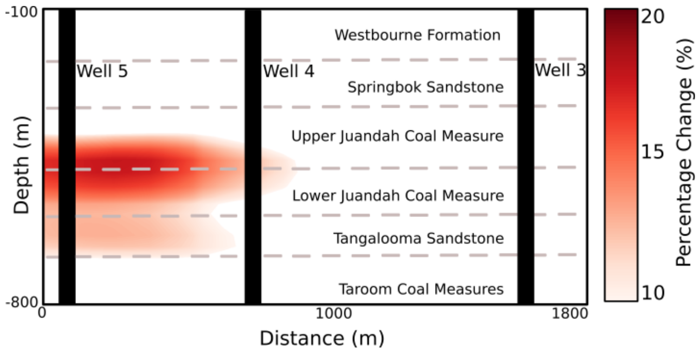

Figure 2: The percentage decrease in resistivity structure between days before and after depressurisation.

The temporal evolution of resistivity change for three sites (red boxes in Figure 1) in our study area is highlighted in Figure 3, where 1D inversions show changes in the subsurface resistivity as a function of time. For all stations, MT responses were generated for each 72 hour block of the survey from the 24th February to the 3rd March. The immediate effects of the detailed pumping and production schedule can be observed, with Site 105 showing the largest decrease in resistivity in the Juandah Coal Measures. Much weaker effects can be observed at station 101 although the time line of the water production rate is still clearly reflected in the temporal resistivity profile. The resistivity structure of the most distant station (220) is far less affected by production when compared with closer stations.

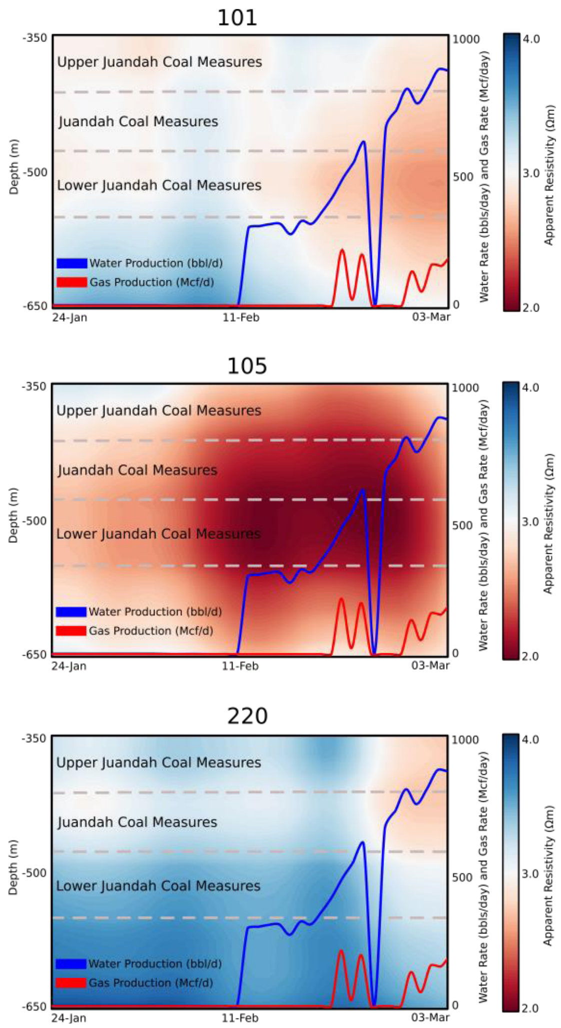

Figure 3: Time-lapse inversion showing the temporal variation in the target coal seam resistivity beneath sites 101, 105 and 220 (see red boxes in Figure 3) from 24-Jan-2014 until 03-Mar-2014. The blue line represents the water production rate (bbl/d) and the red line represents the gas production rate (Mcf/d) from Well 4. The color bar represents resistivity from 2 to 4 Ω m.

Shale gas monitoring:

Hydraulic fracturing of a shale gas reservoir was conducted in the Cooper Basin, with the Permian Murteree Shale targeted by a 915 m lateral horizontal well (Moomba 193) at 2700 m depth. A ten-stage hydraulic fracture program commenced from 29 May to 10 June, followed by a drawback phase from 15 June to 13 July 2014. The total fluid volume injected was 19 ML, with 2.8 ML recovered at the surface. The untreated injection fluid had an electrical resistivity of 1.33 Ω m.

We deployed an MT array from mid-May to mid-June 2014 surrounding the Moomba 193 well in order to monitor the hydraulic fracturing (Figure 4). The instrument layout consisted of electric field loggers placed in a cross-pattern approximately 200 m apart. Two magnetic field loggers were deployed at the ends of Lines 1 and 3, with a third logger deployed 15 km away from Moomba 193 to act as a remote reference.

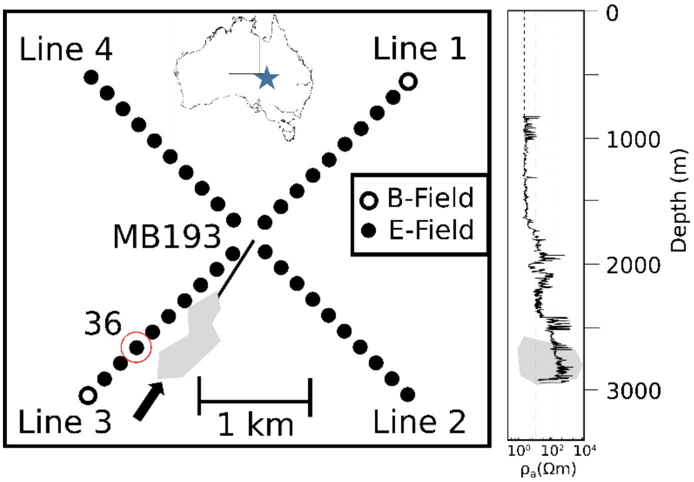

Figure 4: Schematic of the survey area showing the set-up of the electric and magnetic field data loggers. The approximate orientation of Moomba 193 is shown with the associated wireline log to the right of the figure.

In order to determine the spatial change in resistivity, the response functions from each line in our survey area before (20 May to 24 May) and during (05 June to 08 June) pumping were inverted using a two-dimensional scheme (Rodi and Mackie, 2001). Figure 5 shows the percentage reduction in resistivity between inversions before and during pumping for the four lines in our study area. Significant change in the resistivity structure of between 20 - 40 % below Line 3 is observed at a depth interval coinciding with the Moomba 193 well (~ 2700 m). All other lines show no change in the interval of interest.

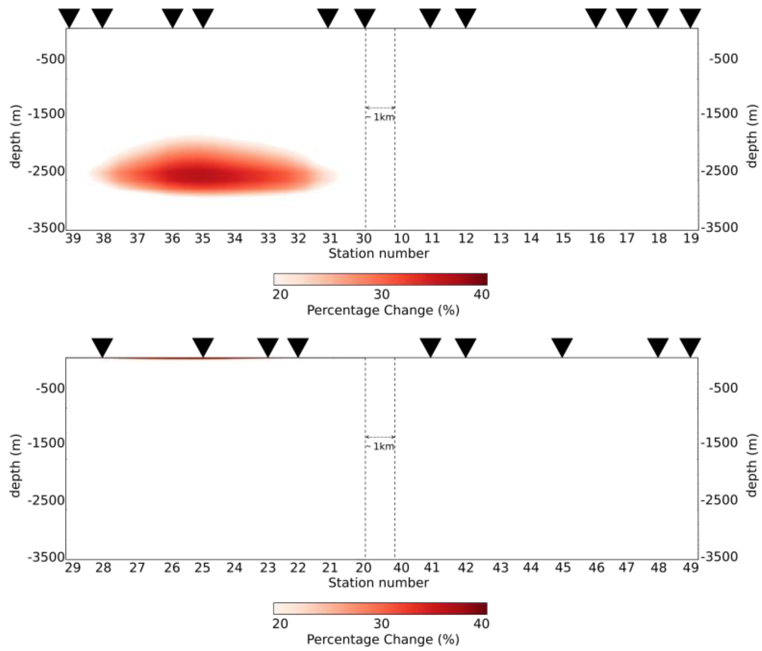

Figure 5: The percentage decrease in resistivity structure between days before and during hydraulic fracturing. Percentages above 20 % were considered significant and smaller changes were omitted. Here we can see the major change occurring along Line 3 at a depth of approximately 2700 m.

The temporal evolution of subsurface resistivity for two sites (one near hydraulic fracturing and one far away) are shown in Figure 6. Here, the apparent resistivities for four different periods are plotted against time. Site 36 shows relatively uniform resistivities for periods below the dead-band over the 1-month interval. Periods greater than the dead band show a clear drop in resistivity coinciding with the start of pumping.

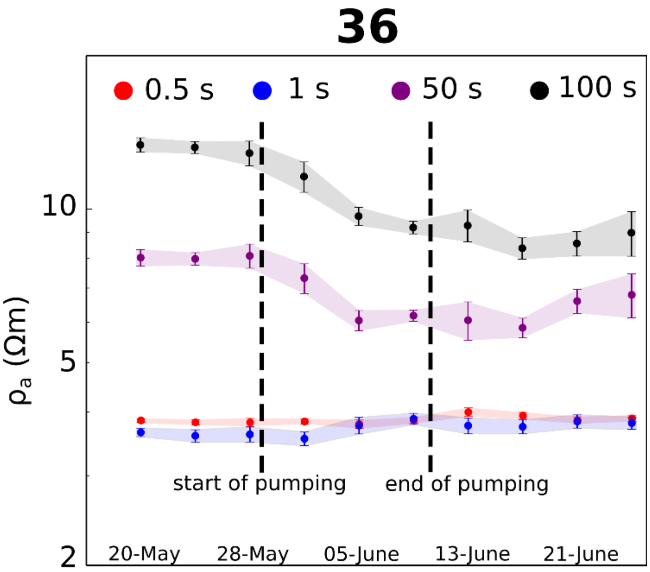

Figure 6: Time-lapse change in apparent resistivity for various periods for station 36 (red circle in Figure 4). A significant drop in resistivity at periods above 20 seconds is observed coinciding with the start of hydraulic fracturing.

CONCLUSIONS

Subsurface resistivity changes within the depth ranges of realistic CSG depressurisation and shale gas hydraulic fracturing intervals have been monitored with MT arrays. These response changes are above measurement error, consistent across the survey profile and comparable with production schedules. Spatial and temporal changes in response can be mapped through modelling and inversion to image resistivity changes with depth and distance.

Results from these first time surveys are promising and demonstrate that MT has great promise for monitoring both de-pressurisation and hydraulic fracturing. Nevertheless, more definitive case studies are required in order for this technology to become more commonplace. MT is an advantageous technology in that it is low-cost, leaves little environmental impact and can be deployed for continuous long-term monitoring. There exist great opportunities for innovation in survey design, potentially integrating both the MT and microseismic methods. Incorporating all known constraints in space, time and fluid characteristics can further constrain and improve interpretations and conclusions.

ACKNOWLEDGMENTS

We thank many people at QGC and Santos for making these projects possible and for their enthusiasm to try out a new approach. Santos and QGC staff facilitated all aspects of access, logistics and background data, without which the project would not have occurred. Magnetotelluric equipment was made available through AuScope and the Australian Geophysical Observing System (AGOS) through the Australian Department of Education and Training, and we are grateful for access to a world-class facility. AGOS are thanked for funding the shale gas MT monitoring project, as part of the sub-surface observatory program. Many data processing and modelling codes used in this project have been kindly provided through the academic community and are referenced within. The University of Adelaide are thanked for supporting many students and staff on these projects both financially and logistically.

REFERENCES

Aminian, K., and Rodvelt, G., 2014, Evaluation of coalbed methane reservoirs, in Coal Bed Methane: From Prospect to Pipeline: Esevier, **1**, 4, 63–91.

Chave, A.D., and Jones, A.G., 2012, The magnetotelluric method: Theory and practice: Cambridge University Press.

Chave, A.D., and Thomson, D.J., 2004, Bounded influence magnetotelluric response function estimation: Geophysical Journal International, 157, 988–1006.

Curtis, J.B., 2002, Fractured shale-gas systems: AAPG bulletin, 86, 1921–1938.

Donaldson, E.C., Alam, W., and Begum, N., 2014, Hydraulic fracturing explained: Evaluation, implementation, and challenges: Elsevier.

Garcia, X. and Jones, A.G., 2002. Atmospheric sources for audiomagnetotellurics (amt) sounding. Geophysics, 67(2): 448 - 458.

Hamilton, S., Golding, S., Baublys, K., and Esterle, J., 2014, Stable isotopic and molecular composition of desorbed coal seam gases from the Walloon Subgroup, eastern Surat Basin, Australia: International Journal of Coal Geology, 122, 21–36.

Krieger, L., and Peacock, J.R., 2014, MTpy: A Python toolbox for magnetotellurics: Computers & Geosciences, 72, 167–175.

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

Seidle, J., 2011, Fundamentals of coalbed methane reservoir engineering: PennWell Books.

Simpson, F., and Bahr, K., 2005, Practical magnetotellurics: Cambridge University Press.