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Magnetotelluric monitoring of permeability enhancement at enhanced geothermal system project

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ABSTRACT

Magnetotelluric (MT) data were collected across the Habanero Enhanced Geothermal System (EGS) project in the Cooper Basin, South Australia. A baseline regional MT survey consisting of two profiles were collected to delineate subsurface resistivity structure. An MT monitoring survey was conducted during stimulation of the Habanero-4 well. Inversions of the MT data in 2-D reveal three main resistivity layers to a depth of 5 km. The surface layer is ≤6 Ωm, 1.5 km thick, and composed of poorly consolidated sediments of Lake Eyre and Eromanga Basins. The second layer is ≤25 Ωm, 2 km thick, and correlated to consolidated Cooper Basin sediments. A high resistivity zone below depths of 3.5 km is interpreted as the hot intrusive granodiorite of the Big Lake Suite related to the Habanero EGS reservoir. The second MT survey was conducted during stimulation of Habanero-4, where 36.5 million liters (ML) of water with a resistivity of 13 Ωm was injected over 14 days. Analysis of pre- and post-injection residual phase tensors show possible conductive fractures oriented in a N-S direction for periods greater than 10 s. Apparent resistivity maps also revealed that injected fluids possibly propagated towards N-S direction. This result is in agreement with micro-seismic events observed at the Habanero EGS during fluid injection. The MT responses close to injection show on average 5% decrease in apparent resistivity for periods greater than 10 s. The main reasons for observing subtle changes in resistivity at Habanero EGS is the screening effect of the conductive thick sedimentary cover. Analysis of time-lapse models indicate an increase in total conductance of about 25 S in the N-S direction, which likely indicate anisotropic permeability generated by hydraulic stimulation. Overall, the MT monitoring at Habanero EGS highlights the need for favorable geological settings and/or controlled source and downhole EM methods to measure significant changes in resistivity in EGS reservoirs.

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1. Introduction

Enhanced geothermal systems (EGS) are unconventional geothermal resources with low permeability and relatively high temperature (typically >200 °C), which require fluid stimulation to enhance hydraulic connectivity in existing fracture system (Audigane et al., 2002; Evans et al., 2005; Muñoz, 2014). A significant number of EGS potential resources occur around the world in varying geological settings (DiPippo, 2012; Ziagos et al., 2013; Bendall et al., 2014; Chamorro et al., 2014). The productivity of EGS reservoirs critically depends on the permeability of the fractures in the host rock.

Micro-seismics is the main geophysical method used to investigate fractures opened during hydraulic stimulation (Wohlenberg and Keppler, 1987; Baria et al., 2004; Cuenot et al., 2008; Cladouhos et al., 2013; Baisch et al., 2015). It gives information about opening of fractures; however, it does not provide information about fluid movement or fracture inter-connectivity (Cladouhos et al., 2013). Magnetotellurics (MT) has been used to image electrically conductive fluid-filled fractures in EGS reservoirs to a depth of 4–5 km (Geiermann and Schill, 2010; Peacock et al., 2013; Didana et al., 2014, 2015; MacFarlane et al., 2014).

Bedrosian et al. (2004) conducted the first MT monitoring study around a natural gas exploration well in the North German Basin during hydraulic stimulation at a depth of 4 km. The 2D MT models did not recover changes in subsurface resistivity following the fluid injection because of low data quality (low signal-to-noise ratio) (Bedrosian et al., 2004). Peacock et al. (2012) and Peacock

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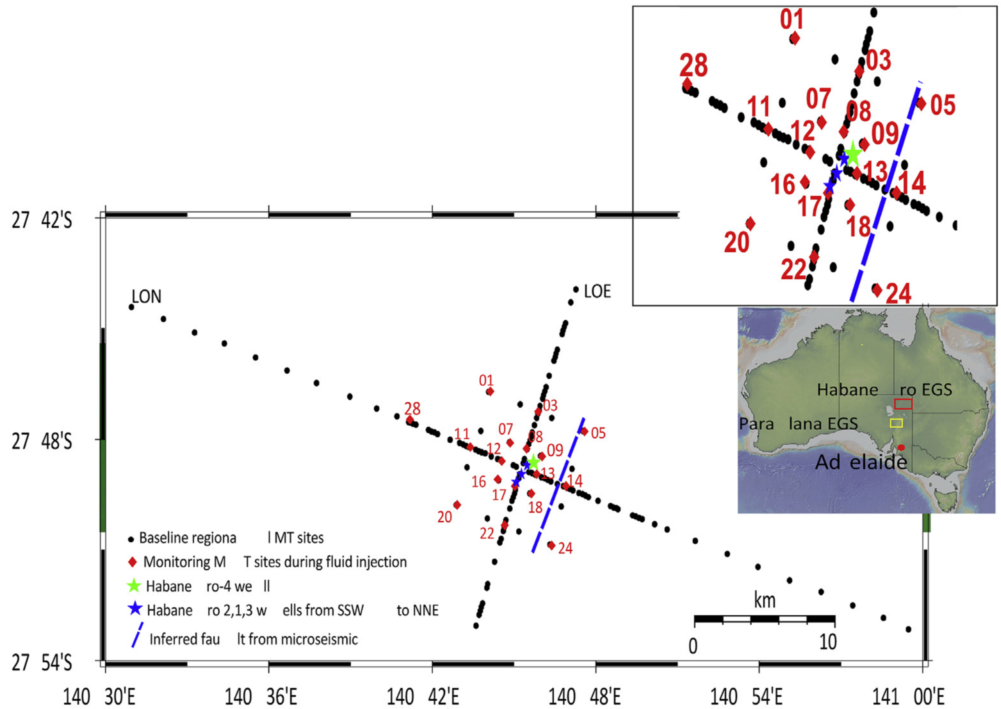

Fig. 1. Location map of MT sites at the Habanero EGS located in South Australia. Black dots denote MT stations from Quantec Geoscience Ltd recorded before stimulation (baseline survey) in August, 2012. The red diamonds denote broadband MT stations acquired by University of Adelaide during fluid injection of the Habanero-4 well, which lasted for 19 days (November 15–December 3, 2012). Green star Habanero-4 well and blue stars are Habanero-2, 1, 3 wells from SSW to NNE, respectively. The red square on the inset map of Australia is the Habanero EGS project area. The yellow square on the inset map of Australia is the Paralana EGS project area. The central part of the location map is enlarged in size on the inset for visualization. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al. (2013) also used MT for monitoring the injection of 3.1 ML of saline fluids into an EGS reservoir at a depth of 3.6 km at Paralana, South Australia, over a period of 4 days. The MT responses from the pre- and post-injection data showed an average decrease of 10% and 5% in the xy and yx components of apparent resistivity, respectively (Peacock et al., 2012, 2013). Furthermore, using residual phase tensor analysis, Peacock et al. (2013) demonstrated that the injected fluids propagated along pre-existing fault system oriented in a NNE direction. The micro-seismic survey conducted at Paralana EGS showed fractures opened in a NNE, NE, and ENE direction along pre-existing fault systems (Hasting et al., 2011; Albaric et al., 2014). These studies showed MT and micro-seismics are complementary methods in characterizing fluid injection into EGS reservoirs. In addition, time-lapse changes in the MT response can be modeled to image the reservoir as demonstrated by Rosas-Carbajal et al. (2015) using 3D probabilistic inversions. The current study is building on previous studies at Paralana, to show that the MT technique can work in different geologic settings.

The Habanero EGS project is Australia's most advanced deep geothermal project and is located in South Australia about 800 km NE of Adelaide (Fig. 1). The area is characterized by relatively high surface heat flow, with an average heat flow of 100 mW/m^2 ascribed to high heat producing granites (Beardsmore, 2004; Meixner et al., 2012). Four EGS wells have been drilled into the hot granitic basement to a maximum depth of 4.3 km with a maximum downhole temperature of 244 °C (Hogarth et al., 2013). The Cooper and Eromanga sedimentary basins (~3.6 km thick) act as an insulating cap over the granitic EGS reservoir (Holl and Barton, 2015). The project area is characterized by a compressive stress field oriented approximately in E-W direction (Reynolds et al., 2005, 2006).

In November 2012, the Habanero-4 well was stimulated by injecting 36.5 ML of near-surface aquifer-sourced water (13 Ωm at 25 °C) over 14 days (Hogarth et al., 2013; McMahon and Baisch, 2013; Holl and Barton, 2015). During the extended stimulation, 20200 micro-seismic events were located (McMahon and Baisch, 2013). The main target of the stimulation was a sub-horizontal fracture zone (~5 to 10 m thick and dipping 10° to the west south west) at a depth of 4077 m in the hot granitic reservoir (Bendall et al., 2014; Baisch et al., 2015; Holl and Barton, 2015; McMahon and Baisch, 2015). This sub-horizontal fracture zone (Habanero fault) is crossed by all Habanero EGS wells (McMahon and Baisch, 2013; Bendall et al., 2014) and is the permeable reservoir of the Habanero EGS system.

The goal of this project is to use MT to monitor temporal and spatial changes in subsurface bulk resistivity structure caused by enhanced permeability due to injected fluids. We first collected a baseline survey along two profile lines before the fluid injection and created 2D resistivity models. Then we set out stations just before the injection and continuously collected data till 3 days after the hydraulic stimulation for a total of 19 days. We analyzed the monitoring data using resistivity maps, residual phase tensor and time-lapse inversion.

2. Geological and geophysical setting

The Cooper Basin is an intracratonic basin containing late Carboniferous to middle Triassic fluvial and shallow marine sedimentary rocks (Hill and Gravestock, 1995; Meixner et al., 2014). The Cooper Basin sediments overlay the Warburton basin and are overlain by the Eromanga Basin and Lake Eyre Basin (Gatehouse et al., 1995) (Fig. 2). Together, the Lake Eyre-Eromanga and Cooper Basins are about 3.6 km thick and act as a regional top seal (insulating cap rock) for the Habanero EGS, as confirmed by geothermal and petroleum drilling (Petroleum, 1984; Geodynamics, 2004). The Toolachee and Patchawarra units in the Cooper Basin, which have low mean thermal conductivities of 1.63 and 2.10 W/mK, respectively, act as the main insulating units (Meixner et al., 2012) (Fig. 2). The heat source for the Habanero EGS reservoir is the high-

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