PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 6-8, 2023
SGP-TR-224

Deep Borehole EM Deployment for Fracture Mapping at the FORGE Geothermal Site

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Keywords: VEMP, electromagnetic, casing source, geothermal, and Utah FORGE

ABSTRACT

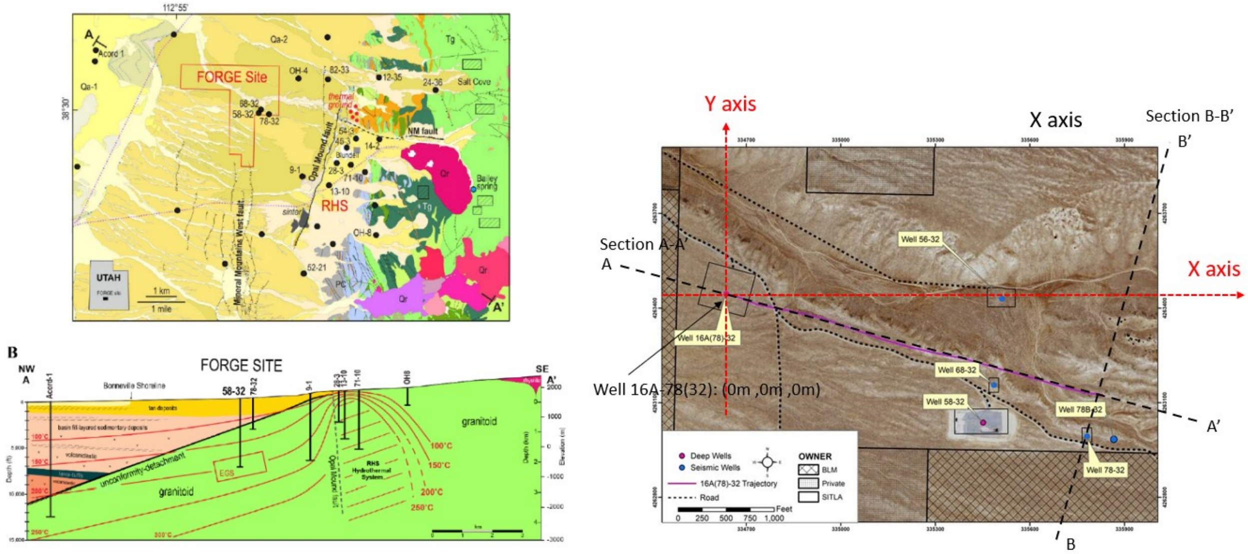
This paper presents and discusses the simulation and possible deployment of the three-component Vertical ElectroMagnetic Profiling (VEMP) borehole magnetic field measurement tool at the Utah FORGE site with the goal of characterizing the size and porosity of the stimulated geothermal reservoir. The VEMP tool contains a three-component magnetic field sensor with primary sensitivity between 1 and 128 Hz, and was specifically designed for high temperature borehole deployment and subsurface imaging in geothermal wells. The first US-based high temperature test involved a successful deployment in a geothermal well at Dixie Valley [1] before being deployed in Japan. Lawrence Berkeley National Laboratory (LBNL) recently received funding as part of the Utah FORGE project to refurbish the 25 year-old tool and if modeling proves sensitivity to the stimulated volume is sufficient, deploy it at the FORGE site just prior to and after the main stimulation/flow test in late 2023. The VEMP tool was shipped from a Geothermal Energy Research and Development (GERD) storage facility to LBNL in early 2022 where the sensors and high temperature vacuum dewar that protects the tool electronics were determined to be working, and an interim analogue acquisition system was designed and implemented. In parallel to this tool refurbishment, an 3D electromagnetic numerical modeling study was initiated to determine if there is enough sensitivity to the stimulated zone to warrant deployment at the FORGE site. The resistivity model uses a 3D MT inversion result [2] as the base model, and an estimated 1% porosity increase within a 400m wide by 500m high stimulated reservoir zone as determined from discreet fracture network modeling by [3] as well as from microearthquake (MEQ) data collected during a preliminary stimulation. A number of different source-receiver configurations were examined in the modeling study, and the most promising configuration involves electrically energizing the steel well casing of the deviated injection/production well, and deploying the VEMP tool towards the bottom of two nearby monitoring wells. This paper will provide a synopsis of the original VEMP construction and testing, recent modifications to and testing of the tool, and an overview of the numerical EM acquisition design study.

1. INTRODUCTION

The U.S. Department of Energy's (DOE) Frontier Observatory for Research in Geothermal Energy (FORGE) is a field laboratory that provides a range of opportunities to develop and test new technologies for characterizing, creating and sustaining enhanced geothermal systems (EGS) in a controlled environment [4][5]. In 2018, the U.S. DOE selected a site in south-central Utah for the FORGE laboratory. The site is located 350 km south of Salt Lake City, Utah (Figure 1). This region has been the site of numerous geoscientific studies since the 1970s for geothermal development, at the nearby at Roosevelt Hot Springs. In 2017, a vertical scientific well, (58-32), was drilled and tested to a depth of 2290 meters at the FORGE site to provide additional characterization of the reservoir rocks. Conventional diagnostic evaluations of the logging data suggest that natural fracturing and shearing has occurred. These observations support the conclusion that the Mineral Mountains granitoid is an appropriate host for EGS development.

Geophysical activities at the Utah FORGE site include interpreting previous data from geothermal exploration activities in the region and the set of new data collected at the site. Evaluated data sets include reflection seismics, gravity and magnetotellurics (MT), and images/interpretations of these data were used as part of the site characterization work [2]. The new gravity, leveling and electrical surveys were collected as baseline data prior to the fracturing and reservoir development at FORGE [2]. As a partner in the FORGE development, Lawrence Berkeley National Laboratory (LBNL) is tasked with collecting novel borehole controlled-source electromagnetic (EM) measurements with the goal of using the data to define various parameters of the EGS reservoir and stimulated fractures.

In this paper, we describe the EM tool to be used for imaging the EGS at the Utah FORGE site, show data collected with this tool in an earlier field study, and provide 3D numerical EM modeling results that demonstrate its potential sensitivity in terms of characterizing the stimulated reservoir. The target zone for simulation is electrically resistive granitoid bedrock between 1525 and 2896 m in depth. The bedrock is in turn covered with a 1400m to 1500m thick cover of electrically-conductive basin sediments. Notice that the basement-sediment interface dips from east-to-west, and thus the sediment thickness increases across the site as one moves westward. Based on analysis of MEQ data collected during a preliminary stimulation event in April of 2022 as well as discrete fracture network (DFN) modeling studies [6][7], the size of the EGS is expected to be several hundred meters in width and height. Given the depth to the reservoir coupled with the limited size of the simulated zone and moderate expected increase in fracture porosity of 1%, surface-based EM methods will not provide sufficient sensitivity to detect changes caused by the stimulation. Accordingly, in this study, we focus on deploying novel borehole methods for characterizing the stimulated reservoir. Specifically we have recently obtained access to the vertical electromagnetic profiler system (VEMP) [8], a three-component magnetic field borehole sensor designed for subsurface imaging in high-temperature geothermal environments [1]. In this paper, we describe this unique downhole EM tool, provide data collected with this tool in an earlier field study, and provide some numerical simulation results to show its potential sensitivity for use in the FORGE project.



(a) (b)

Figure 1: (a) Location map of the FORGE site in central Utah. RHS denotes the Roosevelt Hot Springs geothermal field (after Wannamaker et al., 2020). (b) Location of injection (16A-32) and monitoring wells at the FORGE site (FORGE website).

2. THE VERTICAL ELECTROMAGNETIC PROFILER (VEMP) SYSTEM

The VEMP system was designed and built at Electromagnetic Instruments Incorporated (EMI) with funding provided by the Geothermal Energy Research and Development (GERD) in 1995. The tool was intended for high temperature borehole deployment and subsurface imaging especially in geothermal wells, but also for mineral exploration applications [8]. Originally the VEMP system required separate surface transmitter and downhole receiver sections for surface-to-borehole logging (Figure 2). The system operates with separate stations logging independently but linked by high accuracy clocks. In the previous use of the VEMP system, the transmitter consisted of a 1 to 30 Ampere current injected into either a surface electric (bipole) or loop antenna using frequencies from 1 Hz to 128 Hz. The current is logged with an inductive current monitor synchronously with the borehole receiver signals.

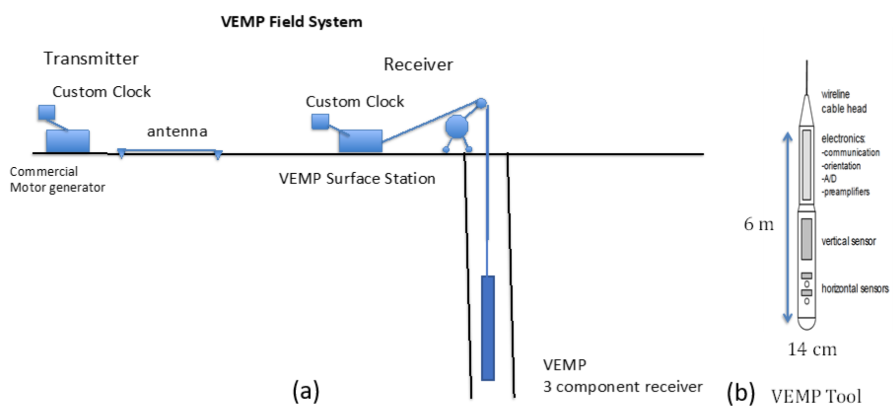


Figure 2. (a) The VEMP surface to borehole field system and (b) the schematic of the VEMP borehole receiver.

The VEMP receiver consist of a borehole 3-component inductive sensor, and a fluxgate magnetic orientation sensor (Figure 2b). The tool sensors were quite advanced for their time and are likely still state of the art. The axial sensor is 1.5m long with a 1 cm core of mu metal. It is wrapped with tens of thousands of turns of wire and connected to a down hole amplifier in a magnetic feedback configuration. It has excellent sensitivity from 1-128 Hz. The horizontal components are measured by a patented array of transverse orthogonal sensor coils connected in series with parallel feedback windings. These coils provide a temperature stable and high sensitivity measurement in a small package.

The original version of the system operated by synchronizing separated transmitter and receiver site clocks and then deploying the source and receiver acquisition units separately. The file and logging characteristics are all recorded manually and data is collected at the receiver end using a depth encoder and moving the tool between adjacent stations. Figure 3 shows a sample plot from a successful high temperature logging test in Dixie Valley Nevada [1]. In that test the tool logged 300m of open hole and 200m of cased hole at temperatures up to 250 C at depths to 2500m at a frequency of 32 Hz. The figure shows a good correspondence of the open hole data to a 1D model consistent with the borehole logs. The EM data in the cased hole section is smaller in amplitude and noisier due the heterogenous nature of the steel casing, but the basic signal is still present and above background noise levels [1].

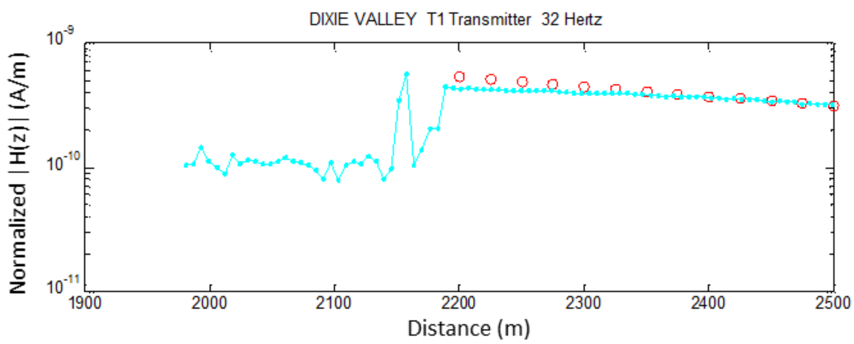


Figure 3. VEMP vertical sensor tool response from a 200m long surface dipole transmitter that was 800m long 1.5 km away.

The tool was last used in 1999 and has been in storage since then. Under a recent agreement with GERD, LBNL has obtained the tool on loan for the FORGE project and has completed a preliminary evaluation. We have found that all analog systems and the thermal components are fully functional but the digital acquisition system is quite dated, and at present not functional. We have therefore replaced the digital acquisition system with an analog pre-amplifier and have wired the sensors to differentially drive up the cable analog so the analog magnetic field signals are collected by a surface 24-bit acquisition system via a standard 7-conductor logging cable. Note that we chose to implement this analogue version of the data acquisition system rather than a downhole digital acquisition system due to unknown costs and delivery times associated with Covid-19 related supply chain issues. Orientation data are collected using an on-board fluxgate magnetometer which is logged in an internal memory card. This analog version of the system was tested at our local field facility in Richmond, California and found to be working according to original specifications.

3. DEPLOYMENT OF VEMP AT FORGE

For the FORGE project, we will take advantage of the unique capabilities and high temperature tolerance of the VEMP system to measure downhole magnetic fields associated with formation resistivity changes caused by stimulation activities at the site. In fact, this tool was designed for such fracture imaging and thus it is ideal for collecting EM data at FORGE. The tool is tolerant at temperatures up to 260 Cº. The internal preamplifiers, power supply and digital electronics are inside a custom vacuum dewar which was designed to give the tool 18 hours of operation in the hot borehole. It has a high-sensitivity three-component magnetic sensor ideal for detecting fractures and/or dipping structures. As mentioned above, VEMP is designed to have maximum sensitivity at low frequencies (1-128 Hz) allowing for large source receiver separations, and can operate in open hole or within steel well casing.

The VEMP system was originally intended to use a surface loop or dipole transmitter in combination with the borehole receiver to image the subsurface. However, at the FORGE site, the depth to the stimulation zone coupled with the 1400m to 1500m of conductive overburden significantly limit the frequency range and the amplitude of electric current that can penetrate down to the reservoir. For the FORGE project, it is necessary to provide alternative source field that are of a high enough frequency to provide resolution of the target zone while at the same time provide strong enough electric currents within the reservoir to provide adequate signal-to-noise ratios within the measured data. In order to provide for this, we propose to electrically energize the steel casings of the injection and production wells downhole [9], which provides for much larger currents and signals in the basement complex than can be provided by a surface source. Previous numerical modeling studies (eg. [10],[11],[12], and [14]) have demonstrated that the applied electric current injected into the steel casing will slowly leak off with distance away from the injection point, and that the nature of current leakage is dependent on the resistivity contrast between the casing and the formation. Thus, as part of a survey design modeling study there exists an optimization study to determine the best depth within the vertical section of the wells to inject the current. In addition, because the stimulated EGS is higher in porosity and is assumed to be fully hot-water saturated, the electrical resistivity will be considerably lower than that of the unfractured granitic host. In the next sections, we will describe several different casing source configurations and simulate and analyze their sensitivity to the stimulated zone.

4. BULDING 3D FORGE RESISTIVITY MODEL AND MODELING CASING SOURCE

In order to evaluate the sensitivity of the VEMP system to monitoring a stimulated zone at the FORGE site, we first build a 3D electrical resistivity model. Figure 4 shows a 3D view of the model which is based on 3D MT inversion performed in [2]. Because the EM source electrodes and VEMP tool are placed inside or close to a steel-cased well, the casing effects must be modeled for reliable survey design as well as eventual data interpretation. In general, it is numerically challenging and impractical to directly discretize an arbitrarily-oriented steel-cased well in a 3D reservoir-scale or regional-scale EM earth model. The 3D discretization requires using a number of very small elements/cells because a typical steel well casing is only millimeters thick, while at the same time it is a million times more conductive than surrounding geology. The number of elements required for discretizing such a well casing exponentially increases as the well length increases, making 3D EM modeling in non-trivial models using the true casing dimensions intractable even on a large-scale parallel computer [10][11].

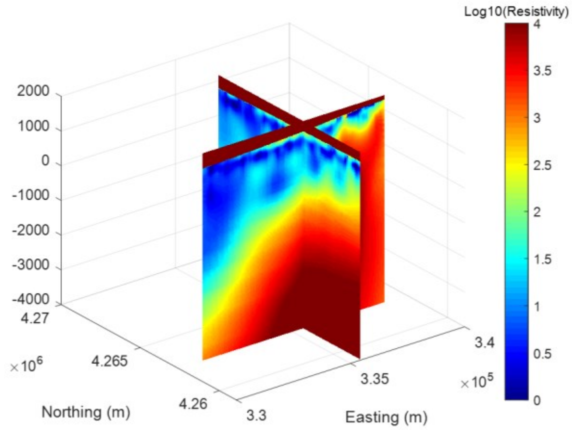


Figure 4. The 3D electrical resistivity model derived from the 3D MT inversion at the FORGE site.

As mentioned above, we plan to electromagnetically energize the existing 16A(78)-32 and/or the planned 16B (78)-32 wells as our source. The measured length of these wells is about 3.35km, and they deviate at about 65 degrees from its vertical surface trajectory after reaching 1828 meters in depth. Due to the aforementioned problem of accurately discretizing and modeling a deviated steel casing, we do not attempt to directly simulate the completed well but rather will approximate the effects of the energized steel-cased well by replacing the energized casing with a series of equivalent electric dipole sources [12][13]. This approximation enables us to simulate the casing-source EM responses of the 3D FORGE EM model without critically increasing computational costs and complexity.

In order to implement the casing source within the 3D FORGE resistivity models where the lower part of the injection/production wells are deviated, we propose the following steps. First, we construct a layered Earth model whose resistivity structure is consistent with resistivity that exists along the trajectory of well 16A in the 3D FORGE MT inversion result. Next, a vertical steel-cased well whose true depth is the same as the measured length of the deviated well is inserted into the layered model. Third, we simulate the EM casing-source using 3D SimPEG [14]. SimPEG is an open-source Python package for simulation and gradient-based parameter estimation in geophysical applications. While the great majority of 3D EM geophysical modeling algorithms use a 3D Cartesian coordinate system, SimPEG supports a cylindrical coordinate system and enables us to simulate the vertical casing source responses at relatively low computational costs (e.g., several hours on a high-end workstation computer) because a vertical well naturally fits within the cylindrical coordinate system without excessive mesh refinement. To verify the accuracy of the casing currents that are extracted from the SimPEG model, we compare the SimPEG results against those produced using a method of moments (MoM) solution [12]. Figure 5 compares the casing current density vectors calculated between MoM and SimPEG which shows good agreement with each other, indicating that the current density vectors extracted from SimPEG are accurate.

To use the SimPEG derived current densities in our 3D EM survey design study, we next extract complex-valued current densities in the vertical direction as a function of depth along the outer surface of the steel cased well. This set of the current densities are then mapped to a series of electric dipoles along the well trajectory, where the magnitude and phase of each dipole is adjusted appropriately approximating the effects of an energized steel-cased well [12][13]. Using this technique allows to approximate the current density vectors along the trajectory of well 16A and/or 16B within the 3D earth model, and thus we can simulate the casing-source EM responses to the FORGE resistivity model using a general-purpose 3D EM modeling code [12].

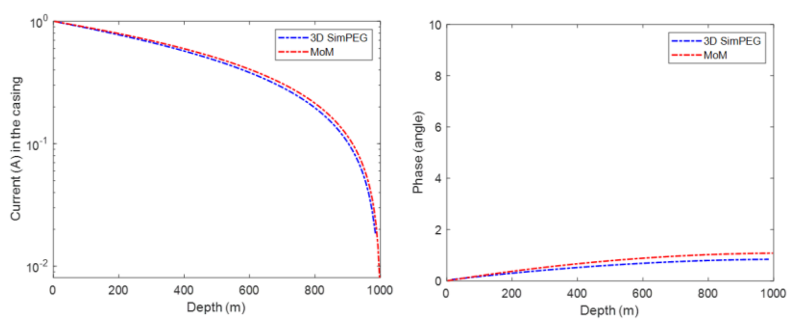


Figure 5. Comparisons between the current density vectors calculated using the 3D SimPEG and MoM method. The steel-cased well is 1km deep. The source electrode is connected to the top of the well casing (electrical resistivity: 10^{-6} Ω-m; outer radius: 0.1m, thickness: 0.02m) and the return electrode is located 2km away from the well head. The source is operating at 1 Hz. A 100 Ω-m half-space model is used.

5. SENSITIVITY OF VEMP AND ELECTRIC FIELD MEASUREMENTS TO 3D SIMULTATED ZONE

In order to calculate the resistivity of a hypothetical stimulated zone generated by fracturing the granite basement rock, we used the effective medium theory algorithm [15] that assumes a series of penny shaped cracks filled with electrically conductive fluid relative to the host medium are embedded in on otherwise homogenous medium with resistivity of 3000 Ω-m. The radius of the cracks was assumed to be 10 m which falls with the distribution assumed for the DFN modeling [6][7] and the width was assumed to be 2 mm. The water filling the pore space was assumed to have a salinity of 400ppm which is consistent with the culinary water in the area that will be used during the stimulation, and a temperature of 425 F° which is a measured temperature at that depth was used to determine the resistivity of the fracture-filling fluid. Combining these parameters yields a water resistivity of 2 Ω-m.

Table 1. Statistics for four-sets of fractures used for the DFN modeling

	Orientation		Intensity	
Set Description	Mean Trend/Plunge [deg]	Mean Strike/Dip [deg]	P_{32} [1/m]	[%]
South striking moderately dipping west	88.5/46	178.5/44	0.42	36.1%
East striking steeply dipping south	1.5/13.5	91.5/76.5	0.35	30.1%
North striking steeply dipping east	260/17	350/73	0.20	17.2%
SSW striking vertical	131/5	221/85	0.19	16.6%
			1.15	**100.0%**

The effective medium formulation allows the user to orient cracks in the *X* (i.e., the well axis), *Y*, and /or *Z* direction. In the first case (fracture model 1), we assumed all fractures that were filled with the electrically conductive fluid were oriented only perpendicular to the well bore (i.e., the *YZ* plane). This yields an electrically anisotropic reservoir with a resistivity in the X direction of 2970 Ω-m, and in the *Y* and *Z* directions the computed resistivity is 190 Ω-m. In the second case (fracture model 2) we used the statistics shown in Table 1 for four different sets of fractures as employed in the DFN modeling to determine that 28% of the fracture have a component with a *XY* orientation, 32% an orientation with an *X-Z* alignment, and 40% with a *YZ* orientation. Using these statistics yielded a more isotropic resistivity with values of 302 Ω-m in the *X* direction, 270 Ω-m in the *Y* direction, and 256 Ω-m in the *Z* direction. We created two different reservoir models using these two sets of anisotropic resistivities in order to determine if there will be sensitivity within the EM measurements to whether the stimulated reservoir is isotropic or anisotropic. The resulting resistivities were then used to fill a zone with reservoir dimensions determined by a combination of the previously mentioned MEQ data analysis and the 3D DFN modeling results provided in [6]and [7] to produce the post-stimulation model shown in Figure 6.

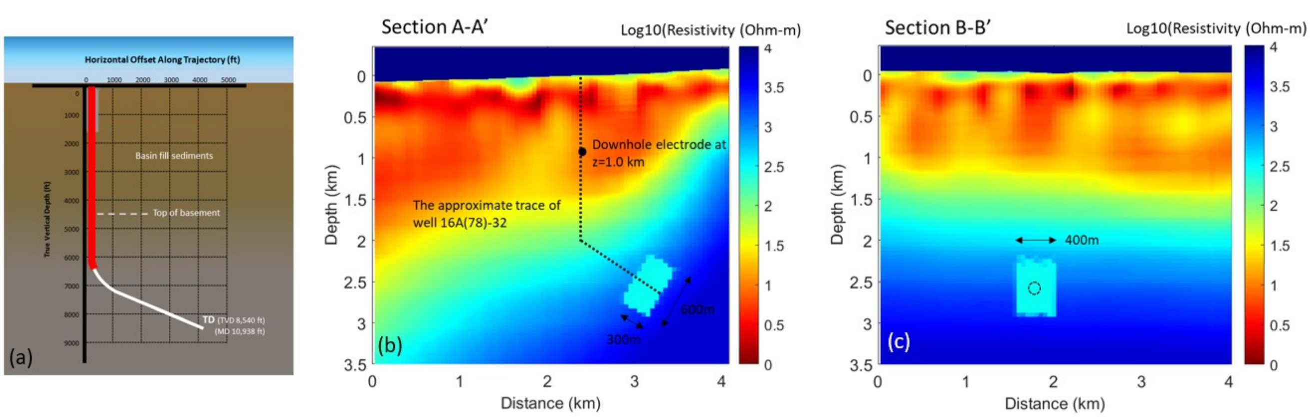


Figure 6. (a) The trajectory of the injection well (16A(78)-32). Cross-sectional views of the 3D electrical resistivity after stimulation along (b) section A-A' (Figure 1B) and (c) section B-B' (Figure 1B).

To provide for a sufficient amount of electric current within and around the stimulated zone, the source electrode is connected to the casing of the injection well at 1.0 km in depth and the return electrode is grounded 2km away from the wellhead. The injected current preferentially flows along the cased well and interact with the stimulated zone while some of the current leaks off from the well. The VEMP tool is placed in two nearby observation wells (wells 58-32 and 78B-32) shown in Figure 1b and measures three-component magnetic fields. Note that we have also simulated measurements made with a vertically oriented electric dipole receiver to measure the vertical component of electric field in the open hole sections of the two observation wells. Because electric fields can only be measured in the open well sections of the observation wells, the electric fields were computed at two depths below the casing shoe of well 58-32 which has 100 feet of open hole at the bottom of the well, and a range of positions over 300m at the bottom of well 78B-32. The VEMP tool can measure magnetic fields in either open or steel-cased well section, but we do not think that the tool can be placed below z=2600 m (~8500 feet) in well 78B-32 because the tool diameter may be too large to get into the open hole section.

Figure 7 shows the resulting three-component magnetic field and vertical electric field measurements with and without the stimulated reservoir, as well as the percent-differences between the two fracture models and the background model. To ensure realistic EM measurement scenarios, we assume that 1) the proposed EM acquisition configuration should provide at least a 10% amplitude anomaly between modeling data calculated with and without the stimulated zone and 2) the field amplitudes are sufficiently larger than known sensor noise levels. In this study, noise levels are set to 10^{-8} V/m for electric fields, 10^{-14} T for vertical magnetic fields, and 10^{-13} T for the horizontal magnetic fields. As shown in Figure 7, the magnetic field measurements provide up to 80% amplitude anomaly between the background and fracture models, sufficiently exceeding the sensitivity required for borehole EM imaging, while the vertical electric fields are highly sensitive to the stimulated zone.

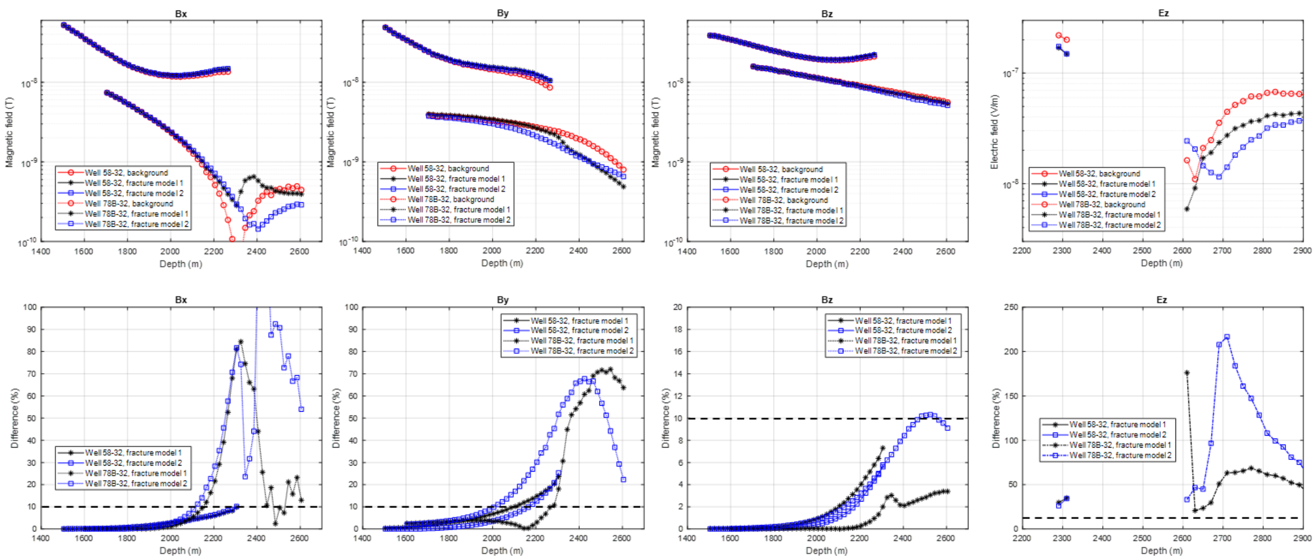


Figure 7. Comparison in simulated EM measurements (the 1st row) at 50 Hz before and after stimulation and their relative differences (the 2nd row). Three components of the magnetic fields (the first to third column) and the vertical electric fields (the fourth column) are plotted. The source current is set to 1 Ampere.

7. SUMMARY

In this paper, we described the recent refurbishment and modifications of the original VEMP system for deep borehole deployment at the Utah FORGE site. Through testing the modified VEMP system at our local field test facility, we have confirmed that it can be deployed in a high-temperature borehole environment. Though the VEMP system was originally intended to use a surface-based EM source, at the Utah FORGE site we are proposing to use electrically energized steel-casing sources in order to provide sufficient electric currents into and around stimulated reservoir which lies well below a 1400m to 1500m thick section of conductive overburden. We have described a 3D modeling workflow through which a steel-cased well is replaced with an equivalent set of electric dipole sources along the trajectory of the deviated well. This approximation significantly reduces the computational costs and complexity associated with modeling a steel-cased well. Our 3D numerical modeling results indicate that the magnetic fields that the proposed EM measurements are sufficiently sensitive to the stimulated zone when the deviated injection well is energized with an electrical current and the VEMP measurement system is placed in nearby monitoring wells. The 3D modeling also suggests that the vertical electric field measurements are highly sensitive to the stimulated zone and thus can be used as additional constraints for detecting and imaging the target. Our current plans are to deploy the system and make a suite of measurements at the FORGE site in the Fall of 2023 just prior to the planned simulation, and then just after the stimulation has been completed.

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