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Results of the Vertical Electromagnetic Profiler (VEMP) Survey at the Utah FORGE Site

David Alumbaugh, Michael Wilt, Edward Nichols, Evan Um, Keith Pickett Masami Hyodo, Kodai Arayama, and Noah Perkovich.

Lawrence Berkeley National laboratory 1 Cyclotron Rd Berkeley Ca 94720>

dlalumbaugh@lbl.gov>

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ABSTRACT

Below we discuss the recent deployment of the three-component Vertical Electromagnetic Profiling (VEMP) borehole magnetic field measurement tool at the Utah FORGE site. Our project goal was to characterize 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. Our survey configuration involved deploying VEMP within the ~3km deep 78-32B monitoring well 400m from the fracture zone while energizing the casing in injection well (16A). We used a transmitter configuration that consisted of an electrode at approximately 1.2km depth connected to the well casing and a return electrode located on the Earth's surface about 1 km to the north of the 16A well head. Low frequency (10Hz) amplitude and phase measurements of the vertical magnetic field were collected at 30m to 40m increments over a profile extending from approximately 2200 to 2600m in depth. The tool was extensively tested on the surface prior to the survey and initially performed well in the shallower sections of the well. Incoming data became noisier with greater depth and temperature, eventually requiring some 30 minutes to collect a single data point which ultimately led to only a single vertical field profile being collected. The reduced data appeared similar to model results but much noisier due to casing effects and internal noise. The cause of the poor data quality was uncovered in a post survey tool evaluation where a connector was discovered to be improperly crimped leading to intermittent noise.

1. INTRODUCTION

The Frontier Observatory for Research in Geothermal Energy or (FORGE) site is an experimental facility in southern Utah for development of tools and processes associated with Enhanced Geothermal Systems or EGS (Figure 1). The site is being used for an EGS demonstration where deviated wells are drilled into hot dry rock and hydraulically fractured to provide an underground reservoir of high temperature fluids to produce geothermal energy (Moore et al., 2020).

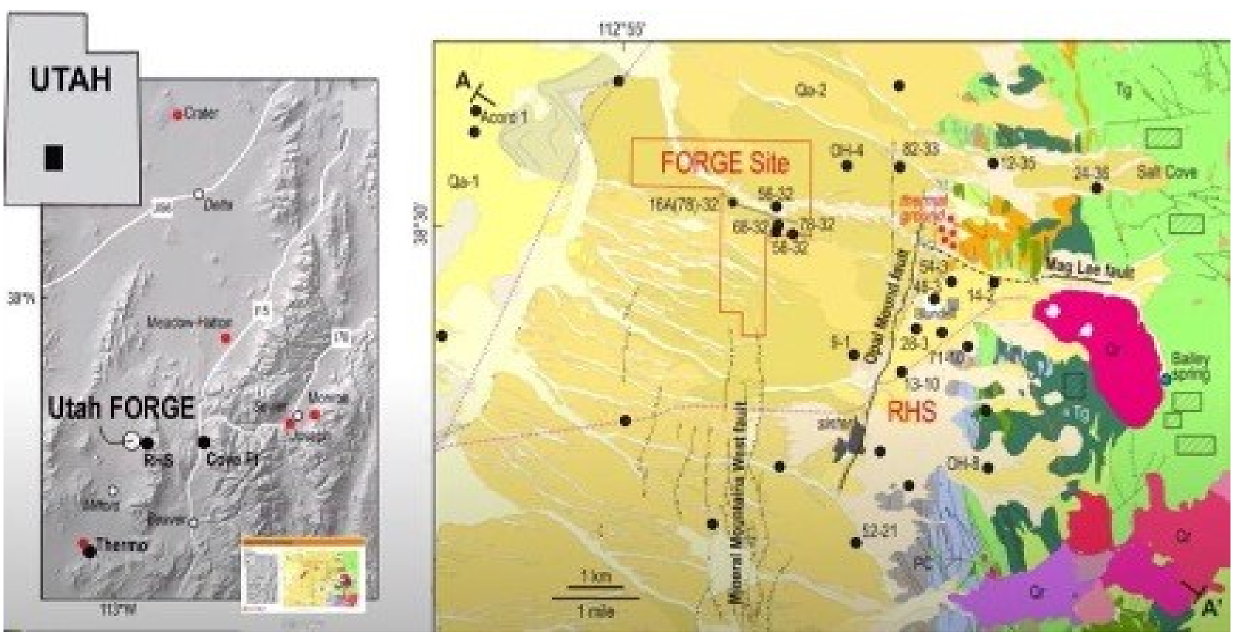

Figure 1: FORGE field site in southern Utah.

As part of the FORGE team, Lawrence Berkeley National Laboratory (LBNL) has been tasked with applying a borehole-to-borehole electromagnetic (EM) technology to image the induced fracture network from the conductivity changes associated with a change in porosity and water and steam saturation (Alumbaugh et.al., 2023).

This paper describes the results of a field survey using the Vertical Electromagnetic Profiling system (VEMP) at the FORGE site for the purpose of imaging the newly created induced fracture network. Here we provide information about the borehole transmitter and the VEMP downhole receiver tool. We also give deployment details and the results of the field survey conducted in May 2024.

2 METHODS

2.1 The Vertical Electromagnetic Profile (VEMP) System

The VEMP system was designed and built at the Berkeley company Electromagnetic Instruments Inc (EMI) for the Japanese company Geothermal Energy Research and Development (GERD) in 1995. The borehole tool was intended for subsurface electrical resistivity imaging for high temperature geothermal wells, but also for mining applications (Muira et al., 1996).

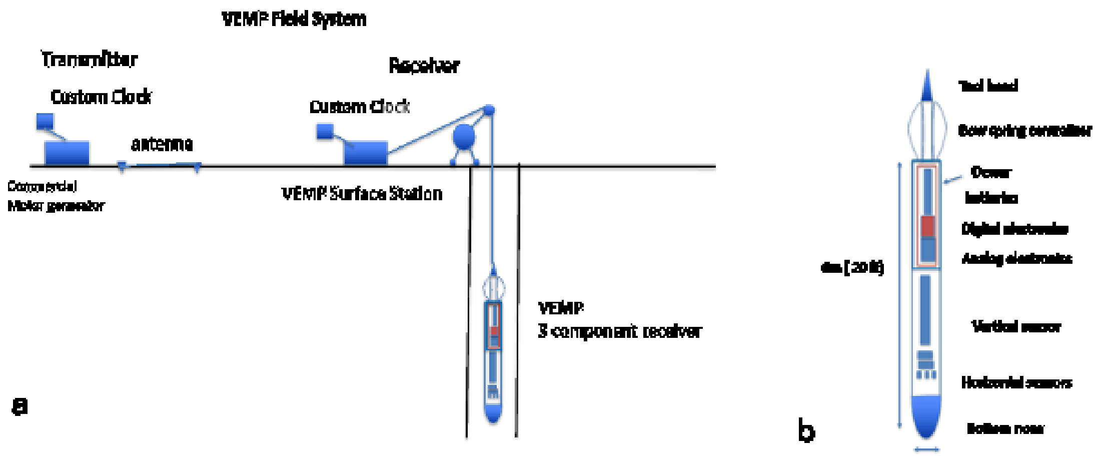

Figure 2. a) VEMP surface to borehole EM system. b) VEMP borehole receiver

The system features separate transmitter and receiver sections for surface-to-borehole logging in a high temperature environment. The system operates with the two stations logging independently but linked by a system clock (Figure 2a).

The VEMP receiver is a three-component magnetic induction sensor intended for borehole deployment at depths up to 4 km and temperatures up to 260°C. The tool was designed for imaging geothermal reservoirs and associated fracture networks from boreholes using a surface or borehole-based transmitter (Figure 2b). The three component sensors are placed within an oil compensated housing that will withstand pressures at depths up to 4 km. The axial sensor is 1.5m long with a 1 cm core of high magnetic permeability steel (mu-metal). It is wrapped with 50,000 turns or wire and connected to a down hole amplifier using a magnetic feedback configuration. The horizontal component is measured by an array of trans-axial orthogonal sensors. This consists of a series of 2.5” coils with magnetic cores connected in series/parallel. These 3-component coils provide impressive sensitivity for such a small package. All sensors have excellent sensitivity from 0.5-200 Hz. The tool also has a three-component fluxgate magnetometer, three component accelerometer and 3 component gyro which are used for tool orientation. The sonde is a 6m (20 ft) long package and 14 cm in diameter (5”) with an upper bow spring centralizer. It is deployable in boreholes of 6” or larger. The tool was ahead of its time for sensitivity and for temperature and pressure tolerance.

Below is a sample plot from a successful high temperature logging test in Dixie Valley, Nevada in 2001 (Figure 3). In that deep test the tool logged 300m of open hole and 200m of cased hole at temperatures up to 215°C using an array of transmitters from 200m to 1km from the vertical receiver well (Mallan et al., 2001). Note the observed magnetic field is very similar to simple 1-D model below the casing, however highly variable and attenuated by the metallic casing above 2180m in depth.

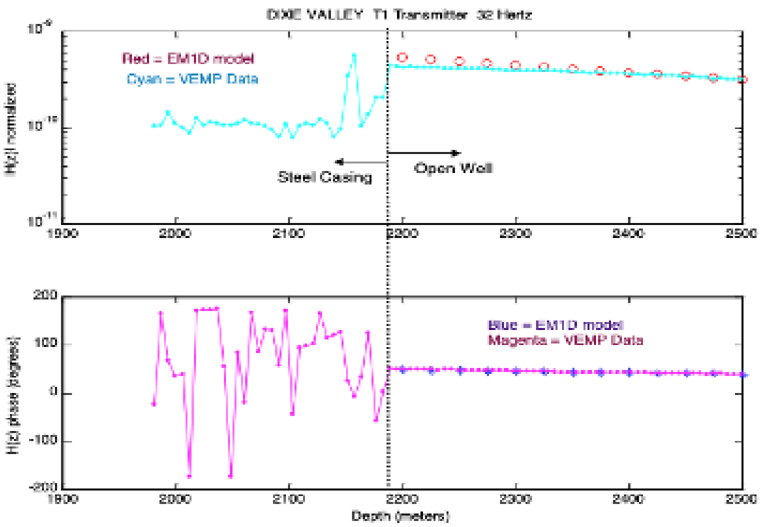

Figure 3 VEMP Vertical field profile in a Dixie Valley, Nevada from a surface bipole transmitter 200m away

The VEMP system was last deployed in 2001 and stored in Japan since then. It was sent to LBNL on loan in 2021 for the potential deployment at FORGE. As part of the testing, it was found that the mechanical parts were sound but due to its age, the downhole digital electronics were obsolete. We therefore replaced the digital electronics with a combination analog/digital system where the main sensor signals are sent up the wireline analog, and orientation temperature and power level signals are sent up the wireline on a digital circuit. The power is supplied by a small collection of lithium batteries that were rated to last 30 hours. Tool operation was validated at low temperature with laboratory and local field testing.

2.2 Transmitter Tool

A custom borehole electrode (Figure 4) was developed for deployment into the vertical section of injection well 16A-78(32). This electrode was grounded against the well casing at a depth of 1.2 km. The electrode is attached in parallel to the 7-conductors of high temperature wireline cable. This wiring is routed to the metallic lower section of the electrode and electrically connected to the well by contact with the 1.3m bronze electrode.

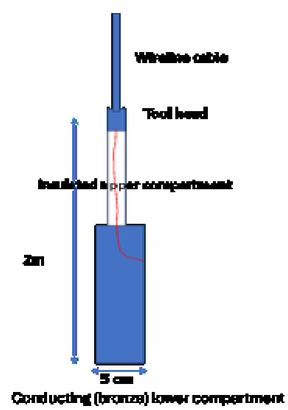

Figure 4. Schematic diagram of the downhole transmitter electrode

The transmitter was designed to impart 2-4 Amp of current at frequencies from 1-100 Hz into the casing. This produces a signal recorded by the VEMP tool that is generated from casing and surface wire current, and more importantly "leak off" currents from the electrode into the formation and induced fracture network. The signal is developed using one of a pair of GPS-synchronized clocks, which provides a square wave signal synchronous with a sister clock located at the receiver. The sister clock is used on the receiver side as a phase reference. The square wave is amplified and connected to a load consisting of the surface and downhole electrodes and accompanying wire. The system can handle up to 500 ohms of load.

3. RESULTS

VEMP was deployed at FORGE in the spring of 2024, following the stimulation operation. The receiver tool was deployed in the open in well 78B-32B using a transmitter electrode in the vertical portion of well 16A-78(32). The data collection was designed to image the induced fracture network in the reservoir (Figure 5a).

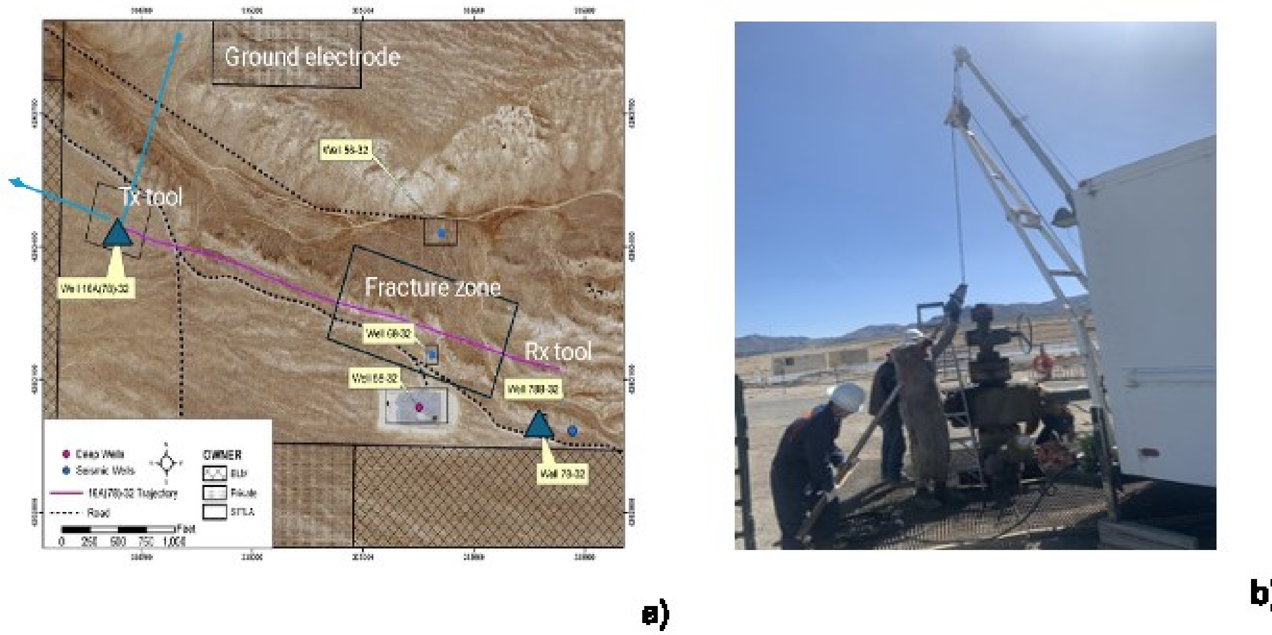

Figure 5. a) Deployment plan at FORGE. b) Deploying the transmitter tool

The survey crew consisted of two scientists from LBNL, with one student from Colorado School of Mines two logging engineers from GERD, and one contract logging engineer. Prior to logging, the survey required setting up the transmitter and receiver tools, logging vehicles as well as preparing the wells for logging.

The transmitter set-up consisted of installing a ground electrode and a pack-off on well 16A-78(32). The ground electrode consisted of 5 galvanized steel pipes connected in parallel; it was placed 1.0 km north-east of well 16A-78(32), see Figure 5a. The total resistance of the transmitter circuit, including ground wire, logging cable and the surface and casing grounding points was about 200 ohms. The transmitter well was pressurized and we needed to bleed off the pressure before a pack-off at the wellhead could be installed. This required about 3 hours and included a surface hose to divert the produced water into a nearby pond.

For the transmitter deployment we used the small wireline “Bread Truck” which has 1.4km of high temperature cable installed on the internal drum (Figure 5b). The electrode was deployed via the truck’s self-contained boom and crane. The tool was then deployed in the vertical section of the deviated well, at a depth of 1.2km without incident. We then switched on the current and were able to transmit 2 Amp of 10 Hz current reliably into the well casing.

3.1 Receiver Deployment

The VEMP system was deployed into observation well 78-32B (Figure 6b). This is a vertically oriented well of 6” diameter with a cased hole section to a depth of 2600m and 300m of open-hole section below the casing. The VEMP tool was assembled on the surface and initial testing was unsuccessful due to a number of loose connections that occurred during shipping. These were found and repaired and after several hours of troubleshooting the system was operational and we could begin logging.

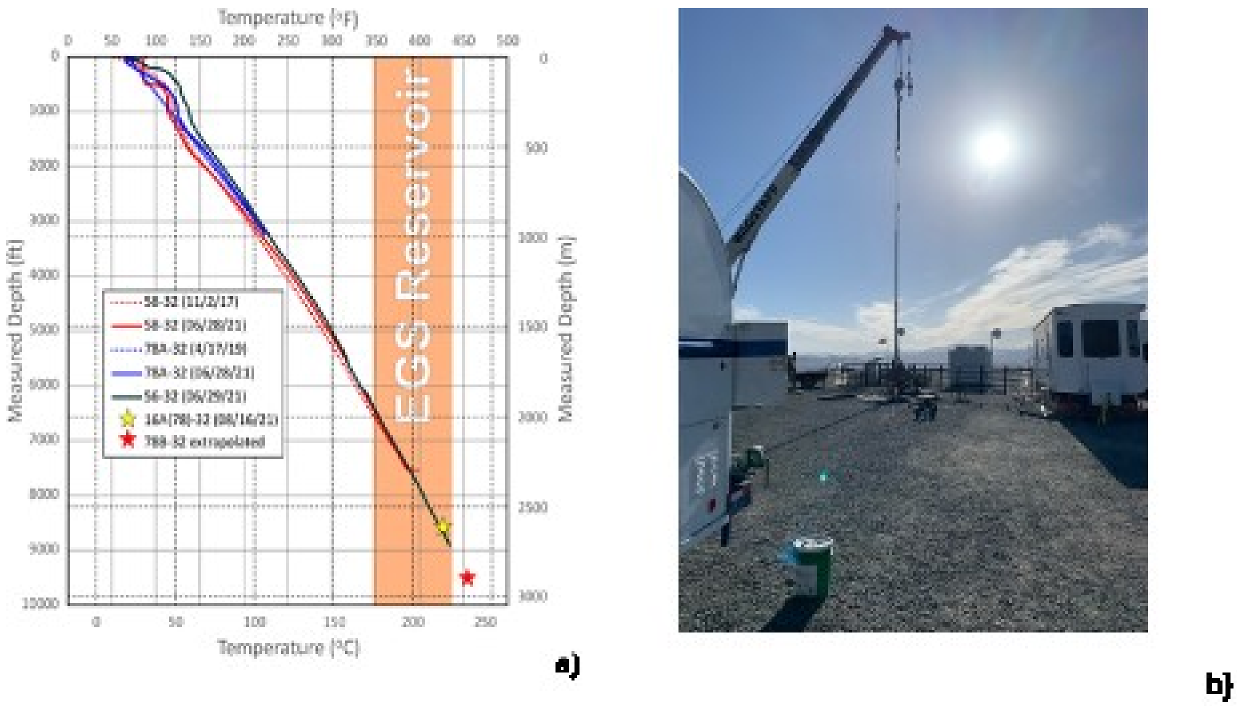

Figure 6 a) Temperature log for well 78-32B, b) Deploying the VEMP into 78-32B

3.2 Data Collection

The original plan called for logging in a vertical observation well (78-32B), located 400m southwards from the tip of the deviated well where fractures were induced. Data would be collected at depths from 1900-2600m to measure fields associated with induced currents in the fractures. We would use frequencies of 10 and 50 Hz and two surface grounding points for the transmitter.

The plan called for extensive measurements in open hole section at the base of the casing, but after repeated tries the tool was never able to successfully enter the open hole. The cause, we suspect, was the geometry of the lower part of the well. The open hole was smaller in diameter than the cased hole. Maybe the open hole was not aligned with the cased hole or perhaps ovalized. The large diameter VEMP tool seemed to repeatedly hang up on a ledge.

Due to the high temperatures in well 78-32B (see Figure 6a) the VEMP tool could only operate 8-10 hours before exceeding the 70°C temperature limit within the electronics cartridge. At these temperatures, communication with the housekeeping electronics was unreliable on the RS485 link and we could not monitor conditions. Several separate logging runs were therefore required to complete the spatial and frequency coverage. Also note that about 1.5 hours was required to lower the tool to logging depths and another 1.5 hours to bring it to surface each time.

On the second field day the VEMP receiver was tested at the surface and lowered into the well and initially positioned at 300m, well above the high temperature zone. The transmitter was switched on and the signal was easily visible at this depth thus logging was set to begin. Sample time series and spectral plots are shown in Figure 10. The left panel of the figure shows the condensed time series for the three channels, the center panel selects a short time series segment and the right panel provides the spectrum for the short segment. The time series is intermittently noisy, and this was one of the better stations recorded. We note that on the spectral plots the supplied signal, 10 Hz is evident on all three components.

The initial data points were somewhat noisy, but the signal was coming through clearly although 10-20 minutes was required for proper averaging, which is well excess of the 3 minutes planned for. In our experience data collection within steel cased wells is somewhat noisier than open holes due to the transmission of noise down the casing and the amplification of motion-induced noise by the casing. That said, the noise at this shallow depth was higher than expected. The first few data points were collected at 300m increments and data collection proceeded smoothly with each point requiring 10-15 minutes to stabilize then record data. The data stream got noisier with time and increasing temperature and was especially noisy in windy conditions. We also noticed that the tool battery voltage was falling quicker than anticipated.

After several hours we brought the tool to the surface and replaced the batteries. This process, which was repeated several times during the survey, required more than 3 hours including transit time in the well. The short battery life with three separate battery assemblages was an unexpected annoyance and finally traced to battery supplier.

Over the next several days we struggled to maintain our data collection schedule having issues with tool batteries, inconsistent communication with the downhole computer, and a steady wind which induced noise in the data via motion in the wireline cable. The data noise persistently increased throughout the operation. Data came in, but 20-30 minutes of recording was required to obtain a single measurement.

Typically, in low wind conditions, once the tool was positioned to the measurement depth, more than 5-10 minutes was required for the signals to settle down before any measurement was possible. A clamp was installed at the well head at several measurement depths to minimize the wind noise with some improvements, but even in light wind the data would still be intermittently noisy, requiring 15 minutes before a reliable estimate could be made. With a limited holding time at high temperature, this was problematic. At the surface however the tool usually reverted to normal operating conditions after cooling.

In Figure 7b we show a data set where the Y component had stopped working. The other components seemed ok so we kept recording. Later that same session the Y channel returned to “normal”. The reason is likely that the Y signal channel developed an intermittent DC offset that was over-range for the Geometrics GEODE data acquisition system, which had a limited input range. Initially, this offset was intermittent but towards the end of the survey all three components developed this condition. Note, that when the input stage saturates, the digital output is corrupted.

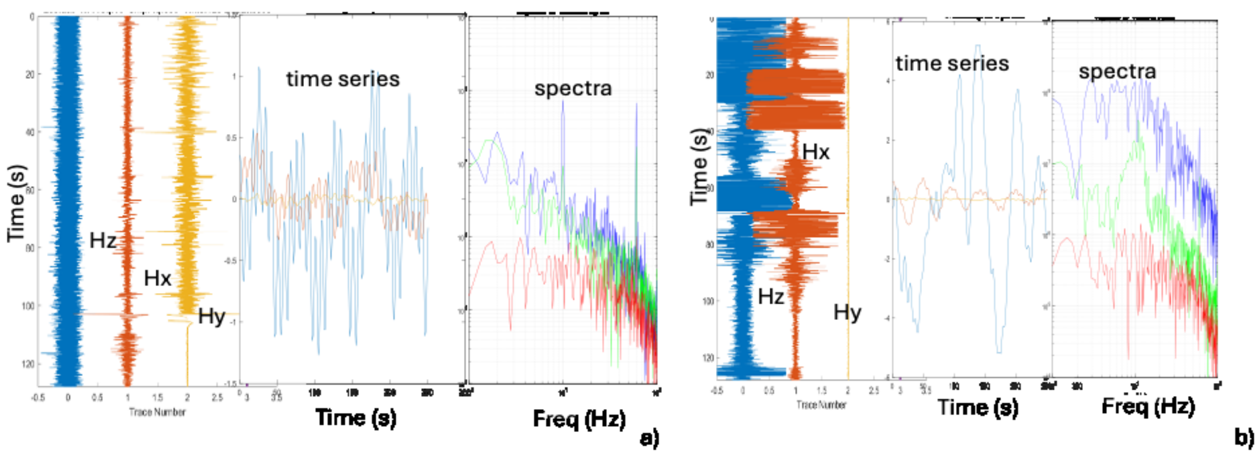

Figure 7. Full time series (left) partial time series (center) and field spectrum for the VEMP measurements at a) 2000m and b) 2100m.

Below is a summary of the most predominant sources of noise.

- Wind noise

Blustery weather conditions at the FORGE site would often shake the wireline cable held by the crane above the well head. This resulted in transmitting vibrations to the tool at depth and making downhole measurements quite noisy. We were able to apply a cable lock at the wellhead which reduced this somewhat, but in general the data quality in windy conditions was poor and it was windy perhaps 30% of the time.

- DC offset

Over time in the high temperature well the tool developed DC offsets on all three sensor channels. This condition is very problematic for the surface digital recording which had a 2 V maximum input. That is, any signal with a DC level above 2 Volt would be clipped at a static level of 2 V. At the end of the survey we used a commercial spectrum analyzer, with a +/-20 V input range, to collect data.

- Internal Oscillations

After several days logging the tool began to exhibit internal higher frequency oscillations, likely due to malfunctioning tool amplifiers.

3.3 Data Recovery and Processing

In total more than 25 hours of data were collected over 4 days on the GEODE and spectrum analyzer, although much of the data is very noisy. Due to the large volume of data collected, we are still able to process the signals and at a number of stations we obtained a stable estimate of the vertical field component. The horizontal field components are noisier and are only useful at a few stations.

The data processing was often a laborious process undertaken by dividing the time series into 50% overlapping 2000-point sections, then using the median of the set of transfer function estimates to identify a “robust” estimate. We then sorted them according to coherence with the source waveform and plotted the results. In Figure 8a we show the results from a good station. Here we see a good coherence and stable amplitude and phase estimates for all three field components. The vertical field is the set of upper plots the X and Y components are plotted below. The left column shows the coherency of the data relative to the system clock, the center column plots the amplitude and the rightmost plots the phase.

We note that when the coherence exceeds 0.95 the data scatter is typically quite low. Each Geode run typically consisted of 16000-64000 pts, with 3-8 runs being taken at each depth for a total acquisition time of ~15 min per depth. Some depths were repeated on different runs and in general were found to match within 10%.

In Figure 8b we show results from a more typical station. Here the vertical field seems good but the horizontal components are quite noisy and unstable. We struggled in these situations to get a good estimate of the horizontal magnetic fields.

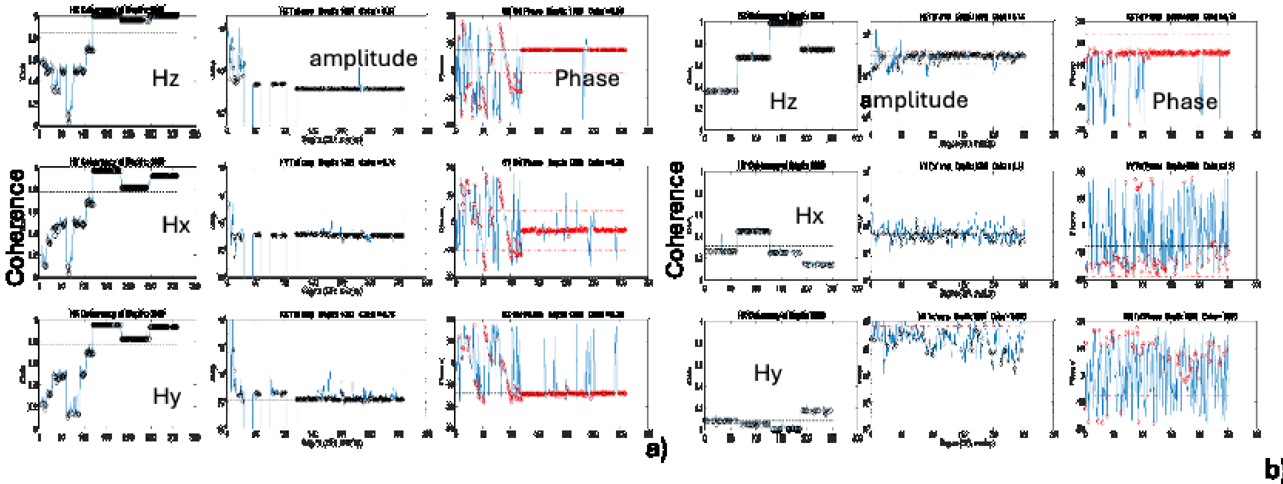

Figure 8 a) VEMP data reduction for a "good" station b) VEMP data reduction for an "average" station

We note that the vertical component was usually better in quality than the horizontal components. This is because the vertical compoenent has more sensitivity due to its axial orientation and is less susceptible to motion induced noise (tool rotation).

We averaged together the best estimates of the vertical field for all profile stations and compiled them into Table 1 and Figure 10 as shown below. This is our estimate of a vertical field amplitude and phase profile; the horizontal component measurements did not yield a useful profile. The data are plotted as relative amplitude where the data are normalized by a single point at the beginning of the profile. This presentation is typical for data collected within a steel cased well, because the casing attenuation constants are not known. The phase data are collected with respect to the system clock

Table 1. VEMP. Vertical Field Profile

Depth (m)	Normalized Amplitude	Phase (deg)
1890	1.0	
1945	0.6	
2073.1	1.39	
2164	1.33	
2225.2	.93	-33.6
2256.1	.944	-38.8
2286.6	1.27	-47.1
2317.1	1.17	-49.1
2347	1.32	-56.6
2378	1.03	-52.8
2408.5	1.56	-64.6
2439	1.39	.68.6

2469.5	1.03	-68.6
2500	.923	-81
2530.5	.978	-72.6
2561	.912	-68.9
2573	.56	-70.6

4.0 Interpretation

A 3D EM model was prepared for the FORGE experiment that included the effects of the induced fracture zone and also accounted for the steel-casing current source (Figure 9). The fracture zone shown in Figures 6 and 9 constitutes a conductive prism with the equivalent resistivity (~100 ohm-m) to a set of parallel fractures in a non-conductive background. To generate the model response our initial step involves computing current densities along a vertical steel-cased well using a 3D cylindrical EM modeling code (Heagy and Oldenburg, 2022). Subsequently, we distribute a series of equivalent current sources along the well's trajectory within a complex 3D resistivity model. We then discretize this model using a tetrahedral mesh and simulate the borehole EM responses excited by the casing source using a 3D finite-element EM code (Um et al., 2024). This multi-step process enables us to simulate 3D casing source EM responses within a complex 3D model.

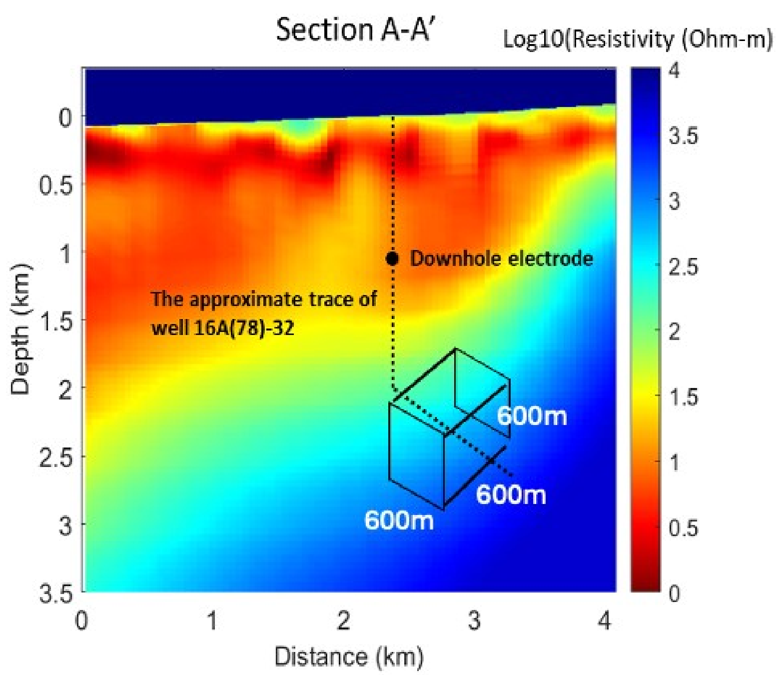

Figure 9. 3D resistivity model from FORGE. The fracture zone outlined

In Figure 10 we plot the normalized amplitude and phase data along with model data from the calculation described above. Here the base model (without the fractures) is given by the black curves and the fracture model is shown in the green curve; the collected data are the plotted points. We observe that the shape of the collected data roughly matches the model data but the scatter is far outside of the difference between the curves indicating that we cannot differentiate between the cases with our collected data.

The scatter in our collected data is a combination of the casing affect and the noisy data collection. Earlier in the paper (Figure 4) we showed a 32 Hz data from the earlier Dixie Valley survey plotted at a similar scale. These data clearly show a similarly noisy vertical field in the steel-cased section of the well and much quieter data in the open hole. Note that these data were of very good quality so the scatter this plot suggests that much of the scatter in the FORGE data is also due to casing effect.

We note that we could have somewhat negated the casing effect by taking the ratio of the horizontal to vertical fields, as they were each affected by the casing in similar fashion. This however was not possible due to the poor quality of the horizontal field data.

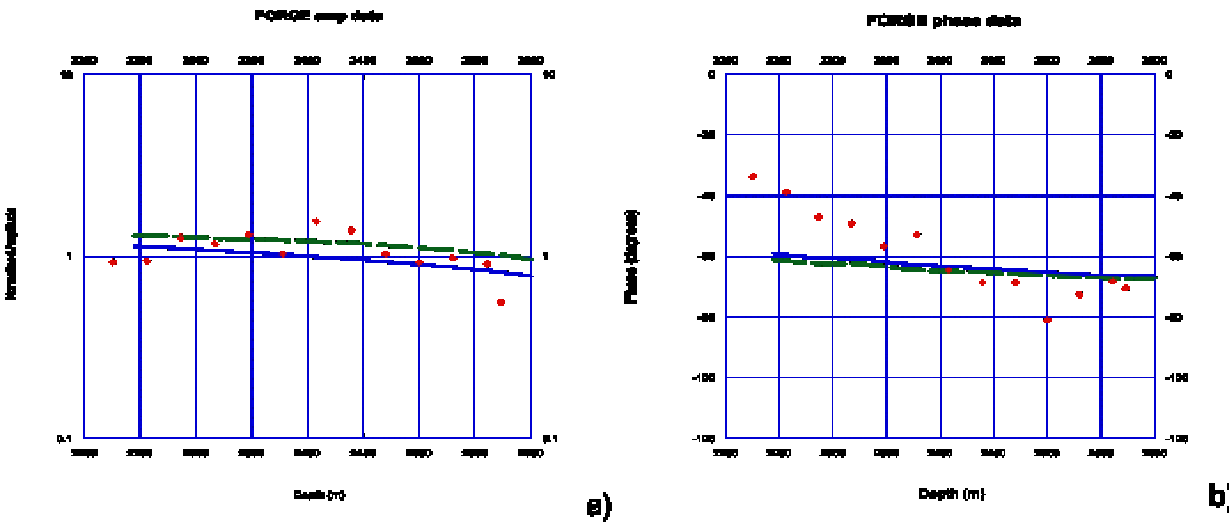

Figure 10. Field and model data from the VEMP profile at Forge. The plotted points are the observed data. The blue curve is the background model response and the green curve is the model response including the fractures.

After returning to the lab we opened the tool again and began an investigation of the noise. After a short time we discovered an intermittent connection at the base of the amplifier section, as it connects to the sonde. It seemed that the basal connector was never properly crimped and several of the wires, when under tension, seemed to easily detach when heated. This suggests that high temperature solder was not used on this connector. We fixed these issues and the tool is now functioning properly. We note that the tool worked well in Dixie Valley 20 years earlier in high but somewhat lower temperatures. Perhaps the lag time and long exposure to the higher temperatures at FORGE weakened the electrical connections.

5.0 CONCLUSIONS

Although the VEMP tool is now mechanically repaired there remain issues with the downhole computer and modem which did not work properly at high temperature causing us to lose orientation data and our ability to monitor downhole conditions within the dewar. This will need to be upgraded prior to the next deployment.

On the positive side the tool worked and we collected data at depth in high temperatures. In addition, the tool survived; it endured through many hours at depths exceeding 2600m and temperatures exceeding 220^0C and returned still functional. However, the data collection was unworkably slow due to a lot of internally generated noise as discussed above. The VEMP remains a one-of-its-kind tool, and the sensors and housing seem intact after the field experiment at FORGE.

Acknowledgements

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