

SUBSURFACE ELECTRICAL MEASUREMENTS AT DIXIE VALLEY, NEVADA, USING SINGLE-WELL AND SURFACE-TO-WELL INDUCTION LOGGING

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ABSTRACT

Extended logging and surface-to-borehole electromagnetic induction measurements were performed at the Dixie Valley Geothermal Field as part of an ongoing effort to employ electromagnetic induction logging to geothermal reservoir characterization. The principal goal of this effort is to discern subsurface features useful in geothermal production, such as larger scale mapping of geothermal reservoirs and smaller scale mapping of producing fractures in and around geothermal wells. The foremost goal of these measurements is to provide experience and insight that will be used toward the future development of geothermal, geophysical borehole technologies. Extended induction logging was performed during October 1998, using the MAIL (Multi Array Induction Logging) system. This system provides near well resistivity structure useful in explicating near well features. Surface-to-borehole induction logging was performed during December 1999, using the VEMP (Vertical Electro Magnetic Profiling) system. This system provides regional resistivity structure around the well useful in describing features distant from the well. Combined, these systems provide a comprehensive image of the resistivity structure surrounding the borehole.

INTRODUCTION

The objective of geothermal reservoir mapping, by whatever method, is to guide drilling programs in the placement of production and injection wells; thereby, reducing costs and maximizing exploits. A cooperative effort by Lawrence Berkeley National Lab (LBNL), Lawrence Livermore National Lab (LLNL), ElectroMagnetic Instruments, Inc. (EMI) and Geothermal Energy Research and Development Co., Ltd. (GERD), set forth to study the employment of electromagnetic (EM) induction logging as a means of mapping geothermal reservoirs. As part of this effort, the application of recently (over the past decade) developed technology, for geothermal reservoir mapping, was conducted at the Dixie Valley Geothermal Field (Figure 1) in west central Nevada. The intent was to gain insight that would be used in the development of the next generation, geothermal, EM induction logging tool.

Dixie Valley, located in west central Nevada, is a northeast trending basin, bound by the Stillwater Range to the west and the Clan Alpine Mountains to the east. It is home to the Oxbow Geothermal, Inc. power plant, which produces 65 Megawatts of electricity from the geothermal reservoir.

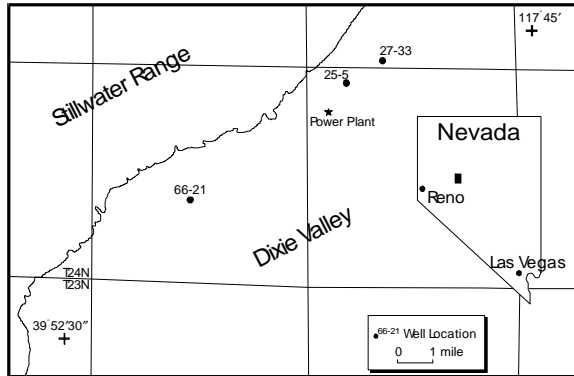


Figure 1. Map showing investigated wells in Dixie Valley.

MAIL TOOL

The MAIL (Multi Array Induction Logging) is a long offset, single borehole, electromagnetic induction logging tool designed to withstand high temperatures and high pressures. It was developed by NEDO (New Energy and Industrial Technology Development Organization), GERD and EMI to map the three-dimensional conductivity structure surrounding geothermal wells. The primary target for the MAIL was producing fractures. The tool's initial geothermal test was conducted in Kakkonda geothermal field in northern Honshu, Japan (Sato et al., 1996), where it was deployed into temperatures exceeding 190°C and to depths below 2.5 km.

More recently, the tool was tested in the Lost Hills oil field, located in southern California (Wilt et al., 1997). This test was designed to map for low resistivity zones associated with high temperatures produced by a steam flood. The results of this test showed a low resistive zone, compared to an induction log collected immediately following drilling, at the area of a nearby steam injection. In addition, the data from the horizontal sensors showed significant perturbation, indicating a heterogeneous nature about the steam flood.

The primary characteristics of the MAIL tool, which allow for three-dimensional mapping, are the multiple, long source-receiver separations and the three-component receivers. The long source-receiver separations allow for sensitivity to structure at a distance away from the borehole. The three-component receivers provide additional sensitivity to 2D and 3D features, necessary for modeling 2D and 3D structures.

Description

Figure 2 shows a schematic drawing of the MAIL tool, as deployed at Dixie Valley. The transmitter and receiver components are housed in a temperature

resistant, glass epoxy composite body, able to withstand temperatures up to 260°C, and utilize an oil compensation system to accommodate pressures to depths of 4 km. The electronics are housed in a stainless steel dewar, allowing the tool to operate in extreme temperatures.

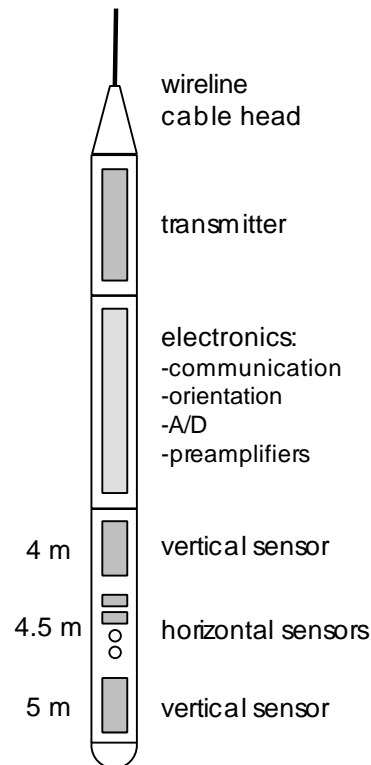


Figure 2. Schematic drawing of MAIL tool.

The transmitter broadcasts at 3, 12, 24 and 42 kHz. Signal measured at the receivers is amplified, digitized and stacked prior to transmission to the surface. The tool is connected to a surface station, which provides tool power and communication. Tool operation and data display and storage are controlled by a laptop PC computer, which is linked to the surface station. A three-component magnetometer and accelerometer, within the electronics package, provides tool orientation data, necessary for rotating the horizontal receiver data to common coordinates.

Deployment

During October 1998, the Oxbow power plant was shut down for periodic maintenance. This provided an opportunity to deploy the MAIL into an active injection well, 25-5, and production well, 27-33.

Well 25-5 was logged in the depth interval of 1370 m to 1860 m, which is the bottom, uncased section of the well. A well completion diagram indicated a maximum depth of 1900 m, but the MAIL tool encountered obstruction at 1860 m, possibly due to

sediment fill. The injection zones were indicated to be at 1820 m, 1850 m and 1870 m.

Well 27-33 was only partially logged, due to break down in the logging cable head.

Results

Figure 3 shows results obtained from well 25-5. The left graph shows the conductivity profile obtained from the vertical receivers, Z1 (upper) and Z2 (lower). Note the significant conductivity variation at 1580 m. This is attributed to the formation transition from the sedimentary to basalt region. The right graph shows the total horizontal field amplitude, measured from horizontal receivers, as a fraction of the field amplitude measured by Z2. This is done to show the fields produced by the formation relative to the primary field produced by the transmitter. The results show the horizontal field is roughly 1% to 2%, relative to the field produced by the transmitter, and with no substantial perturbations. Perturbations in the horizontal fields would indicate near-well, non-homogeneous features.

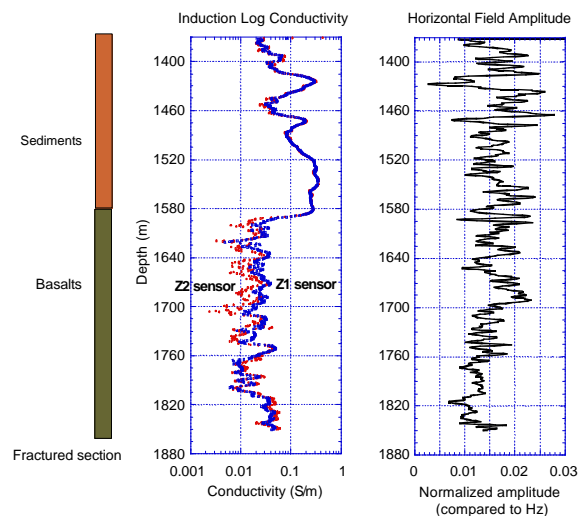


Figure 3. MAIL results for well 25-5 showing a conductivity profile obtained from the vertical receivers and the horizontal field amplitude normalized by the vertical field.

VEMP TOOL

The VEMP (Vertical Electro Magnetic Profiling) is a surface-to-borehole, electromagnetic induction logging tool designed to withstand high temperatures and high pressures. It was developed by NEDO (New Energy and Industrial Technology Development Organization), GERD and EMI to map the large scale, three-dimensional conductivity structure surrounding geothermal wells. Particularly sought after was increased resolution than produced

by surface EM methods. Initial geothermal tests were conducted in Kakkonda geothermal field in northern Honshu, Japan in 1994 (Miura et. al., 1996) and 1996. The tool was deployed into temperatures exceeding 190°C and to depths below 2.5 km. The purpose of these tests was to map the general conductivity structure surrounding the well.

The three-component receivers provide additional sensitivity to 2D and 3D features, necessary for modeling 2D and 3D structures. This is important, since the geology associated with active geothermal areas is usually complex.

Description

Figure 4 shows a schematic drawing of the VEMP tool. The receiver components are housed in a temperature resistant, glass epoxy composite body, able to withstand temperatures of up to 260°C, and utilize an oil compensation system to accommodate pressures to a depth of 4 km. The electronics are housed in a stainless steel dewar, allowing the tool to operate in extreme temperatures.

Signal measured at the receivers is amplified, digitized and stacked prior to transmission to the surface. The tool is connected to a surface station, which provides tool power and communication. Tool operation and data collection are controlled by a laptop PC computer, which is linked to the surface station. A three-component magnetometer and accelerometer, within the electronics package, provides tool orientation data, necessary for rotating the horizontal receiver data to common coordinates.

The surface transmitter was an electric bipole, operated using the Zonge GGT-25. The VEMP tool and surface transmitter were synchronized with high precision quartz clocks. This allows synchronous stacking of the data. The transmitter frequencies were 4 Hz and 32 Hz.

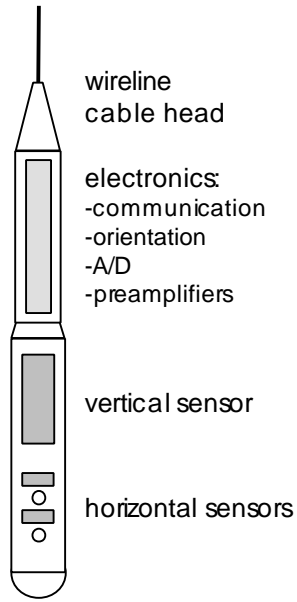


Figure 4. Schematic drawing of VEMP tool.

Deployment

The VEMP tool was deployed in well 66-21, over the depth interval of 1980 m to 2500 m. The tool was unable to be deployed below 2500 m, due to obstruction in the well. Measurements were collected with the VEMP at fixed depths of 7.6 m (25 ft) intervals.

Figure 5 shows the transmitter stations layout used in the VEMP survey. Station 5 was only partially logged, due to break down in the logging cable head. The transmitter sites were positioned such that the bipole was perpendicular to the station profile line that traversed the top of the well and extended up to the foot of the Stillwater Range. Each electric bipole was 600 m in length, with the electrodes consisting of metal plates buried beneath the surface. A maximum of 12 to 15 Amps was driven through the bipoles; electrode contact resistance prevented the supply of more current through the electrodes.

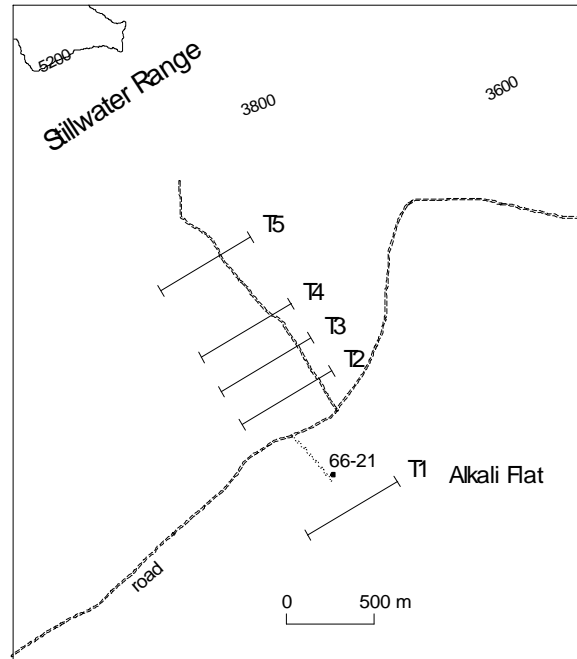


Figure 5. Transmitter layout for VEMP survey.

Results

Initial interpretation of the VEMP data consisted of 1D forward model analysis using EM1D (Lee, 1988). Respective 1D models were constructed to fit the data for each transmitter station. This is only a first order approximation; though, it does provide initial insight as to the nature of the 2D model. The interpretation was carried further with 2D forward model comparisons using a 3D forward model, QL3DEM (Zhdanov and Fang, 1997). After several manual iterations, based on the EM1D results and a priori logging data (Wilt and Goldstein, 1985), the model in Figure 6 was obtained. This model's layering is consistent with previous logging data, and the 2D structure at the surface is representative of the Alkali Flat, at the center of Dixie Valley. Model results and the field data are shown in Figures 7 & 8, respectively. Though there are discrepancies in the 32 Hz amplitude and the 4 Hz phase, it is generally a good comparison, and is considered a good starting model for inverse analysis. It is likely that the inversion process would require model constraints, due to the lack of receiver data along the entire borehole's depth, and possibly additional transmitter locations would be beneficial.

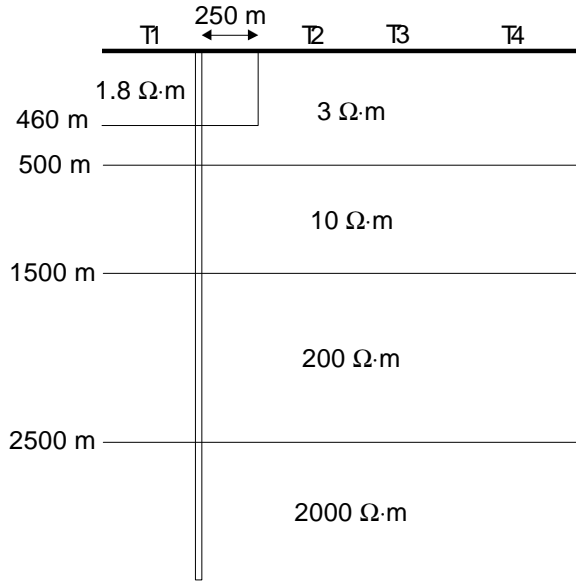


Figure 6. VEMP 2D model.

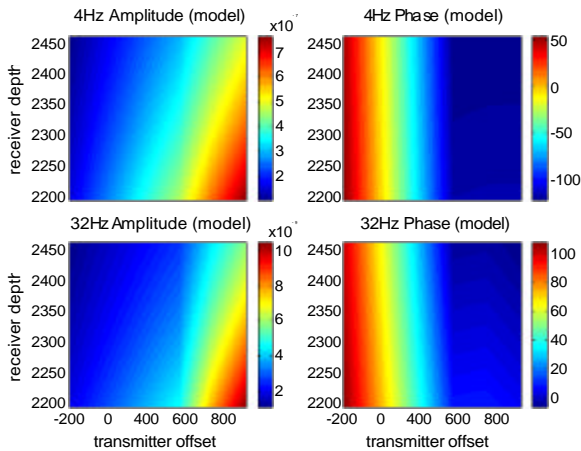


Figure 7. Model VEMP data produced from the model in Figure 6.

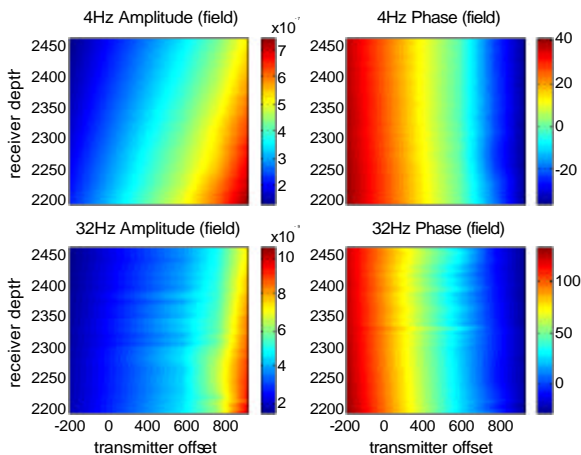


Figure 8. Measured VEMP data.

CONCLUSIONS

The MAIL performed well, providing vertical field data showing many conductive varying features, most predominantly the boundary at a possible sediment-basalt boundary. The lack of significant response from the horizontal field data may be due to the fact that the tool did not fully penetrate the fracture zones. Unfortunately, circumstances prevented data collection in the production well, therefore, inhibiting efforts to model a fracture zone.

The VEMP data were modeled somewhat successfully using forward modeling. The resultant model is consistent with previous logging data and the known geology, and is considered a good starting model for inverse analysis. Though the presence of the range front bounding fault was not considered in the forward model analysis, this should be considered in the inverse analysis.

Although the deployment of both the MAIL and VEMP tools was not carried out in the same well, the two data sets do show agreement at the layer boundary indicated by the MAIL conductivity profile and the VEMP forward model analysis. In addition, although data collection did not meet expectations due to equipment problems and borehole obstructions, the data collected at this test, and previous tests, show this technology to be a viable technique for mapping geological and hydrological features associated with geothermal activity.

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REFERENCES

- Lee, K., 1988, Computer code EM1D
- Miura, Y., Osato, K., Takasugi, S., Muraoka, H., and Yasukawa, K., (1996), "Development of the Vertical Electro Magnetic Profiling (VEMP) Method," *Journal of Applied Geophysics*, **35**, 191-197.

Wilt, M., Takasugi, S., Uchida, T., Kasameyer, P., Lee, K., and Lippmann, M., "Fracture Mapping in Geothermal Fields with Long-Offset Induction Logging," Proceedings: Twenty-Second Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 27-29, 1997.

Wilt, M. and Goldstein, N., (1985), "Electromagnetic Soundings for Geothermal Resources in Dixie Valley, Nevada," Lawrence Berkeley Laboratory DOE report (LBL-19321).

Sato, T., Osato, K., Takasugi, S., and Uchida, T. (1996), "Development of the Multi-Frequency Array Induction Logging (MAIL) Tool," Geothermal Resources Council Transactions, **20**(9), 637-642.

Zhdanov, M. and Fang, S., 1997, computer code QL3DEM.