3D EXTENDED LOGGING FOR GEOTHERMAL RESOURCES: FIELD TRIALS WITH THE GEO-BILT SYSTEM

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ABSTRACT

Geo-BILT (Geothermal Borehole Induction Logging Tool) is an extended induction logging tool designed for 3D resistivity imaging around a single borehole. The tool was developed for deployment in high temperature geothermal wells under a joint program funded by the California Energy Commission, Electromagnetic Instruments (EMI) and the U.S. Department of Energy. EMI was responsible for tool design and manufacture, and numerical modeling efforts were being addressed at Lawrence Livermore Laboratory (LLNL) and other contractors. The field deployment was done by EMI and LLNL.

The tool operates at frequencies from 2 to 42 kHz and, its design features a series of three-component magnetic sensors offset at 2, 5 and more than 10 meters from a three-component magnetic source. The combined package makes it possible to do 3D resistivity imaging, deep into the formation, from a single well. The manufacture and testing of the tool was completed in spring of 2001, and the initial deployment of Geo-BILT occurred in May 2001 at the Lost Hills oil field in southern California at leases operated by Chevron USA. This site was chosen for the initial field test because of the favorable geological conditions and the availability of a number of wells suitable for tool deployment.

The Chevron site features a fiberglass-cased observation well in the vicinity of a water injector. The injected water, which is used for pressure maintenance and for secondary sweep of the heavy oil formation, has a much lower resistivity than the oil bearing formation. This, in addition to the non-uniform flow of this water, creates a 3D resistivity structure, which is analogous to conditions produced from flowing fractures adjacent to geothermal boreholes. Therefore, it is an excellent site for testing the 3D capability of the tool in a low risk environment.

Field measurements yielded a data set suitable for 3D imaging. The Geo-BILT data corresponds to existing conventional logging data and shows clear indications, in several depth intervals, of near-well 3D structure. 3D inversion of these data produced a model consistent with non-planar water flow in specific layers.

The next deployment, scheduled in the Dixie Valley Geothermal field in March 2002, will constitute the first test in a high temperature environment. Initial modeling shows that the system should be able to detect producing fractures within 50 ft of the well.

INTRODUCTION

Geothermal resource evaluation in boreholes has always been difficult due to the complex geology and hostile, downhole conditions. Using standard oil field logging devices has proven unsatisfying, as these are ineffective in non-layered geology and high temperature boreholes. In the past several years, a series of experimental induction resistivity tools were developed by EMI, in cooperation with researchers in Japan, for fracture detection and formation evaluation in geothermal wells (Sato et. al., 1996; Miura et. al., 1996). In this paper we describe the latest in this series of tools, the Geo-BILT.

The Geo-BILT (Geothermal Borehole Induction Logging Tool) project entails the development of a
full tensor, extended induction logging device capable of operating in high temperature boreholes. The project was begun in 1999 with the tool design and numerical modeling. Tool manufacture proceeded in 2000 and was completed in February 2001.

In this paper, we describe the tool design and operation and give results from a field test. We also give a geological interpretation of the results and discuss future deployments in geothermal fields.

TOOL CHARACTERISTICS

Figure 1 is a schematic drawing of the Geo-BILT device. The tool design features a series of three-component sensors offset at 2, 5 and more than 10 meters from a three-component source. At present, only the first two sensors have been manufactured; the third is planned for the fall of 2002. Geo-BILT operates at 4 frequencies: 2, 6, 17 and 42 kHz. The source, driven by a square wave, is capacitively tuned to near resonance for each frequency, resulting in a quasi-sinusoidal signal that is transmitted by the X, Y and Z source antennas.

Geo-BILT

3-C Transmitter
3-C Receiver (2m)
3-C Receiver (5m)
3-C Receiver (10m)

Figure 1. Schematic drawing of Geo-BILT tool.

The source antennas are coincident, multiturn coils wound around a common center with matched inductances, allowing them to be tuned with a single set of capacitors. The antennas are air-core coils wound around a machined frame made of high temperature fiberglass. They are roughly 1m long and the magnetic moment of all of the sources is approximately 10 A-m². This is sufficient strength for operation at source-receiver offsets of up to 50m.

The transmitter signal is generated downhole using a driver circuit controlled by the clock. The driver is basically a very efficient power supply switch that generates a square wave signal with a minimum of heat dissipation. Capacitive tuning of the square wave signal results in the sinusoidal transmitter waveform.

Geo-BILT has three-component magnetic induction sensors offset at 2 and 5 m from the source. These sensors are multiturn coils each wound around a common center. The axial receivers are simple multiturn coils wound around the casing; the transaxial receivers are made of small coils 3 inches by 1.5 inches with a mu-metal core. The sensors and attached amplifiers are designed for optimum sensitivity in the frequency range 2-50 kHz.

The tool features a three-component magnetometer and accelerometer package for tool orientation. Three separate toroidal sensors are used for transmitter current monitors, and a series of temperature and voltage sensors are used for assessing the operating conditions.

The signals are channeled from all receivers and sensors into a downhole A/D and computer module. Data are first digitized by a 16-bit, 4-channel A/D and averaged on the downhole computer. The Fourier coefficients are then transmitted to the surface along with a selected stacked digital time series and the tool status data. These data are collected on a laptop computer connected to the surface station.

The surface station supplies power to the transmitter as well as receiving digital signals from the downhole computer. Power for the receiver section is supplied by a downhole battery pack. The battery pack was added after the initial testing phase of the system demonstrated that we needed higher isolation between the source and receiver sections to eliminate stray coupling. This isolation was accomplished by eliminating as many wire connections as possible between the source and receiver sections. The only remaining connection between the source and receiver sections is a transformer isolated clock line and one shielded twisted pair for communication.

TOOL OPERATION AND DEPLOYMENT

The Geo-BILT borehole tool consists of three major sections that range from 12 to more than 23 feet long (Figure 1). Tool assembly is accomplished by laying the pieces horizontally on tool stands and fitting together the joints using hand tools; the process takes about an hour on site. When fully assembled the tool is more than 45 ft long and must be hoisted as one piece. We have devised a special rolling sling for accomplishing this (Figure 2).
The tool is deployed using standard 7 conductor wireline cable and an encoder/counter for depth control. Due to its length, a 60 ft crane is required to deploy the tool. After assembly and initial testing, the tool is typically hoisted and positioned over the well. We then collect “free space” data at the frequencies selected for logging, and these data are used as part of the calibration corrections.

Two main logging modes are available for data collection. In the fast mode, only the vertical (axial) transmitter is activated, and data are collected on all sensors. For the complete mode, all three transmitters are activated, and data are collected on all sensors. The fast mode allows a quick survey of the well; the complete mode is for collection of detailed data to be used in 3D inversions.

The borehole is logged while the tool is moving. The logging speed ranges from 10 to 20 ft per minute depending on the frequency and the selection of fast or complete logging modes. At a rate of 10 ft/minute, we can obtain a full tensor measurement about every foot.

GEO-BILT FIELD TRIAL AT LOST HILLS, CALIFORNIA

The initial deployment of Geo-BILT occurred from May 8-11, 2001 at the Lost Hills oil field in southern California at leases operated by Chevron USA (Figure 3). The Lost Hills oil field is located at the western margin of the San Joaquin basin in Kern County, California (Stosur and David, 1976). Production is mainly from an upper member of the Miocene Monterey Formation known as the Belridge Diatomite. This reservoir is comprised of diatomaceous mudstone (diatomite) that averages 800 ft in thickness and is characterized by very low matrix permeability, high porosity (35-65%) and good oil saturation (50%).

Data were collected in a fiberglass cased observation well adjacent to an active water injector. The flood alters the formation resistivity, due to the lower resistivity of the injectate, thereby creating a 2D and 3D resistivity structure that may be imaged from the observation well. We note that the injection well (11-8w) is hydraulically fractured resulting in a vertical fracture trending roughly North 60 E (Figure 3).

The injected water is a combination of produced water and make-up water from a shallower and less saline source. The overall fluid is 30 percent more resistive than the formation water, but the injected fluid will still dramatically reduce the formation resistivity as it fills up void space or mobilizes oil or gas. In Figure 4 we show deep induction logs from wells 11-8wr and 11-8w, measured before and after the start of the water injection, respectively. The difference between these two logs is due to the effect of the water injection on the near well formation. The logs indicate resistivity decreases of up to 50 percent in several layers where the water injection is significant. In particular, the F, H and K intervals show the greatest change due to the flooding.

This site and these wells were also used for crosswell EM and seismic experiments. The crosswell EM data were collected between wells OBC1 and OBC2 in October 2000. These data were used to provide an interwell resistivity section in the north-south direction that can be used to compare to the Geo-BILT interpretation.
Field experiment

The Geo-BILT system was used to log two intervals, the complete reservoir (1200-2100 ft) and the main water flooded interval (1400-1800 ft). Data were collected at all four frequencies using the complete (slow) mode, and all logs were measured at least twice. These repeated logs help to establish repeatability and to identify conditions such as thermal drift and capacitive coupling. The complete set of logs required about 16 hours over two days. The tool worked reliably for the entire survey.

Data processing was completed in two stages: 1) calibration adjustment and 2) tool rotation. In the calibration adjustment, we adjust the data with respect to measurements made in free space. The final processing consists of tool rotation, using the three-component magnetometer data to orient the tool axes to geographic north (X coordinate).

Results

Figure 5 shows apparent resistivity logs, with repeats, from the vertical source and the 2m and 5m offset vertical sensors. We also show the logs from the commercial (Halliburton) deep induction resistivity log, measured several months prior in the same well. The plots show a good correlation with the commercial log, although both Geo-BILT logs are somewhat smoother due to the longer receiver offsets. The slight variation between the repeated logs is most likely due to thermal drift. We have not completed a full system calibration so the thermal constants are as yet unknown. Figure 6 shows the apparent resistivity logs for the horizontal component, maximum coupled sources and receivers (Hxx and Hyy) in the same well, with repeats.

These Hxx and Hyy logs are quite different in appearance to the vertical logs in Figure 5 and somewhat different from each other. The horizontal logs appear sharper and choppier than the vertical logs, and although many layers correlate, others do not. Note that the 2m and 5m offset logs appear quite different from each other. The 2m plots are sharper and show smaller swings at layer boundaries. We suspect that these logs are responding to the thinner layers.

Notice that the variance of the repeated horizontal logs is considerably higher than the vertical logs. This is probably due to the fact that each log is in fact the rotated resultant of two individual logs. We therefore see the combined effect of the drift on both logs as well as the result of the propagation of any calibration differences between the sensors and sources.

The logs Hxx and Hyy are similar to each other in overall appearance over much of the section but quite different in several specific zones. For example, at depths between 1600 and 1750 ft, the logs are quite different in appearance. We note that these depths
correspond to the largest water influx from the adjacent water injector, and the differences between the logs might correspond to an injection induced anisotropy (i.e. 3D structure due to water flooding).

Samples of the null coupled logs (Hxz and Hzy) are provided in Figure 7. Here we show the amplitude of the horizontal fields from the vertical source for the entire reservoir depth (1200-2100 ft). Note that these fields are theoretically zero for a homogeneous or horizontally layered structure in a vertical well, but they are clearly not zero here. In particular, there are significant anomalies centered at depths 1350, 1450, 1700 and 1925 ft. We note that these depths correspond to layers most affected by water flooding from the adjacent injector (Figure 4).

![Figure 7. Geo-BILT logs of Tx-Rx and Tz-Ry for 2 m and 5 m separations.](image)

We note that the characteristics of the null fields are different in each of these anomalous zones as evidenced by the variation of the X and Y component logs. This suggests that the flow direction and characteristics are different in each interval.

Although the magnitude of these null coupled fields is quite small, between 0.1 and 2 percent of the direct coupled field, the repeated logs show that these data are very reproducible. In fact, from these data we estimate that the reproducibility is roughly 100 parts per million.

**DATA INTERPRETATION**

Collected crosswell and Geo-BILT data were both interpreted utilizing automatic inverse computer codes. For both cases we assume a starting model based on the induction resistivity logs. In the crosswell case we interpolate the logs between the wells for a 2D starting model; for the Geo-BILT data we use the logs to construct a 1D layered section.

Crosswell data were fit with the 2D inversion code (SINV2D) developed by Sandia lab (Alumbaugh and Newmann, 1996). This code has been used for more than 3 years in crosswell data interpretation (Wilt at al, 2000).

Geo-BILT data were fit with a 3D inverse code, INV3D, also developed by Sandia Laboratories (Alumbaugh and Newmann, 1996). Although this code has been used in crosshole and surface data, these are the first single well data used for 3D inversion. 3D inversion is very computationally intensive, and for that reason it is impractical to use this tool on the entire data set. For these data, we focused attention on the depth interval from 1400-1800 ft, where the largest 3D effects were observed in the data and where there is strong evidence of water flooding at the injection well (Figure 4).

**Crosswell EM Results**

In Figure 8 we show the resistivity cross-section derived from the crosswell EM data between wells OB-C1 and OB-C2. Included at the sides of the section are color coded induction logs, for OB-C1 and OB-C2, for reference. The figure shows a roughly flat lying multilayered section throughout much of the image, although there is a clear lateral boundary near well OB-C1 in the deeper parts of the section.

![Figure 8. Resistivity section from crosswell EM data.](image)
The induction logs from well 11-8w and 11-8wr are color coded and superimposed on the section. It is encouraging to note that the cross-section closely matches the resistivity from well 11-8wr, although this information was not used to constrain the inversion. Note the difference in resistivity between the borehole induction logs on either side of the image. Well OB-C1 is considerably higher in resistivity than OB-C2, especially at the basal section below 1650 ft.

Focusing on the section near OB-C1, we can see a clear lateral boundary at a depth of 1900 ft, about 15 ft south of well OBC1 and a much more diffuse boundary at a depth of 1700 ft.

The implication from this image is that the existing water flood has mainly penetrated into the deeper, diatomite rich layers in the section. In these layers, it has reduced the resistivity by up to 50 percent. It also suggests that the edge of the water flood in some of these layers has reached well OBC1, but in other layers it is still short of the well.

**Geo-BILT Interpretation**

Geo-BILT results are interpreted in two ways. First, the apparent resistivity logs are examined qualitatively by matching them to the geologic sections. This allows for some average determination of saturations. The cross-coupled logs are then examined for near well anomalous zones that may be related to fractures or in this case water flooded horizons. A more rigorous interpretation is the application of these data in a 3D inversion. Here we wish to reconstruct a 3D resistivity distribution around the borehole that honors both the data as well as being consistent with the known geology.

We applied the 3D inversion to the 6 kHz Geo-BILT data in the depth interval from 1400-1800 ft as a test. For simplicity we used only the vertical component transmitter and all three orthogonal receivers at the 5 m offset. These data were fit in stages. We first applied a layered inverse code to fit the vertical component data (ZZ). Using this as a starting model we fit the null component data to a 3D resistivity distribution. The final solution was then checked against all data. This procedure, although somewhat laborious, was found to be more effective in the long run. Our attempts to fit all data simultaneously produced poor data fits or unreasonable models.

Even for this limited depth interval the 3D inversion was a lengthy process. Each inverse model required 2-5 days for convergence. In addition the results were dependent on the weighting of data, the starting model and the noise level and calibration correction of collected data. The results were that numerous runs were made over a two month period to produce the model shown below.

In Figure 9a-c we show two cross-sectional views and one planar view of the 3D resistivity distribution near well OBC1 between 1400 and 1800 ft in depth. The final 3D model is consistent with the logs and the geology, and the data fit is adequate (within 10 percent).

The main feature of the model is low resistivity zone that extends southwards and eastward from the well from the well towards the injection fracture. The model also shows a higher resistivity body encircling the observation well and centered just north and west of it.
We note that the logs in Figure 4 shows that the undisturbed formation is roughly 4-4.5 ohm-m and the fully swept formation is approximately 1.8 ohm-m. The 3D model shows that well OBC1 is located in a transitional zone between these two extremes. The injected water is probably not moving as a coherent front; some of it has injected saltwater has moved past OBC1 and some has not reached the well.

We expect that the placement of an ellipsoidal high resistivity body near the well is at least partially a result of the use of only 3 field components and one source-receiver separation (5m) in the inversion. We don’t expect that the true resistivity adjacent to well OBC1 is 6-9 ohm-m but we suspect the inversion was unable to accurately resolve the true resistivity distribution adjacent to the well because of the limited data set and the use of only a single aperture (5m) in the data set.

The final model is a fairly rough portrayal of the resistivity structure near well OBC1 but we can learn at least two things from it. The first is that the inversion defined an anomalous zone confined to depth range from 1660 to 1740 ft within 25 ft of the wellbore. The second is that the resistivity of this zone is greater north and east of the well.

With experience we expect that the 3D single well inversion results will become more “geological” and free from data or model imprinting. We expect this will coming as more data is incorporated into the inversion and more constraints are added; this of course also relies on better computational resources in the future.

**DIXIE VALLEY GEOBILT SIMULATION**

The previous field study was especially useful as it places sensitivity and error level limits of the tool in a geothermal environment. We can use this information as to assemble some models for geothermal application to determine the limits on target detections. The simulation shown below was intended for use in an experimental design for a field experiment planned at the Dixie Valley geothermal field in early March 2002. The structure and background resistivity of the model was selected to match the field conditions at the Dixie Valley geothermal field in central Nevada.

We show forward calculations, using QL3DEM (Zhdanov and Fang, 1997), for two, 3D models of a 5 ohm-m fracture zones crossing (model A; Figure 10)
or passing near the well (model B; Figure 11) in a 500 ohm-m background. In the models, the 5 ohm-m target extends ±100 m (≈330 ft) in the Y direction and dips roughly 60 degrees. We calculate the response for the 5 m offset sensor and for a 20 m offset sensor.

In Figures 12 and 13, we plot the expected field response of a crossing and missed conductive fracture together with the noise level as measured in the Lost Hills field experiment. The figures show the field levels for 5 m and 20 m offsets using the direct coupled (ZZ) and null coupled (ZX) transmitter-receiver configurations.

As expected, the long offset sensor seems to be critical in resolving structure for a missed fracture zone, but the 5 m sensor seems to be able to detect, if not resolve, a fracture 25 ft from the borehole.
CONCLUSIONS

3D resistivity imaging from a single well has long been a goal of the geothermal exploration community. This is finally possible with the GeoBILT tool. The remaining obstacles will be identified in upcoming geothermal tests. These include tool deployment issues in irregular and deviated wells and tool stability in a hostile environment.

ACKNOWLEDGEMENTS

We acknowledge assistance from geologist Mike Morea and reservoir engineer Dale Julander in geologic interpretation of the Lost Hills data. We also thank LLNL field engineers Pat Lewis and Duane Smith for aiding in tool deployment at Lost Hills.

REFERENCES


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