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FRACTURE MAPPING IN GEOTHERMAL FIELDS WITH LONG-OFFSET INDUCTION LOGGING

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ABSTRACT

The mapping of producing fractures in a geothermal field is an important technical objective in field development. Locating, orienting, and assessing producing fractures can guide drilling programs and optimize the placement of production and injection wells. A long-offset multicomponent borehole induction resistivity tool capable of surviving the high temperatures encountered in geothermal wells has recently been developed and tested in a high temperature environment. Several characteristics of this device make it ideal for detecting producing fractures. Whereas commercial induction logging devices have source–receiver separations of 1 m, this device has multiple sensors with separations up to 8 m, allowing for deeper penetration and the ability to straddle fracture-induced washout zones in boreholes. The three-component measurements also make it possible to map the strike and inclination of nearby fractures and other three-dimensional structures. This, in turn, allows for accurate projection of these structures into the space between wells.

In this paper, we describe the design of the tool and show results of a performance test carried out in an oil-field steam flood. Data from vertical sensors are compared to conventional logging results and indicate the recent formation of a low-resistivity zone associated with high temperatures due to steam flood breakthrough. Horizontal field data indicate that the high-temperature zone is irregular in the vicinity of the borehole and more pronounced closest to the steam injector.

INTRODUCTION

The mapping of producing fractures in a geothermal field is an extremely important technical objective in field development. Locating, orienting, and assessing producing fractures can guide drilling programs and optimize the placement of production and injection wells. This results in fewer dry holes and substantial cost savings in field development.

Recently, NEDO and GERD developed a long-offset borehole induction resistivity tool capable of surviving high temperatures (Sato et. al., 1996). This Multi-Frequency Array Induction Logging (MAIL) tool features an array of multicomponent sensors offset 4 to 8 m from the transmitter. This array and the multifrequency operation make it possible to resolve fracture zones within geothermal wells.

In this paper, we briefly describe the design and operation of the tool and compare it with more conventional induction logging tools. We then show field results from an observation borehole near an oil-field steam flood. In our field example, the well encounters a nonuniform high-conductivity zone associated with subsurface steam.

DESCRIPTION OF THE MAIL TOOL

The MAIL tool was designed by NEDO and GERD engineers in 1994 and was built by an American contractor, Electromagnetic Instruments. It was designed for high resolution mapping of the conductivity structure in geothermal wells. A schematic drawing of the tool (Figure 1) indicates that it has a multifrequency transmitter section in one end and an array of induction coil and fluxgate sensors distributed throughout the rest of the tool. Five vertically oriented induction coil sensors are spaced 4, 5, 6, 7, and 8 m from the transmitter; two horizontal field sensors are situated at 7.5 m; and a three-component fluxgate magnetometer lies 3 m from the source. The fluxgate magnetometers are used for tool orientation. The transmitter may operate at 3, 12, 24, and 42 kHz, but it is more powerful at the lower frequencies.

Signal detection, synchronous stacking, and analog to digital (A/D) conversion are accomplished within the tool before transmission to a personal computer (PC)-controlled surface station. Software on the PC is used to control the data collection sequence, apply calibration corrections, and display and store results.

The tool has also been hardened for a high-temperature, high-pressure environment. Special temperature-resistant polycarbonate materials house the sensors, and a high-vacuum stainless-steel dewar protects electronic components so that the tool can withstand downhole temperatures of 260°C for up to 12 hours. This configuration makes the tool suitable for use in many geothermal wells. An oil compensation system is used for pressure maintenance to depths of up to 4 km.

Several characteristics of this device make it ideal for detecting producing fractures. The long source–receiver offsets of the induction coil sensors make it useful for detecting structure well away from the borehole. Typical induction logging devices have source–receiver separations of 1 m, whereas this device has separation up to 8 m allowing up to 10-m penetration into the formation. In addition, many producing fractures in geothermal wells are associated with washout and lost-circulation zones, thereby making conventional (short-offset) logging ineffective. Long-offset sensors, which easily straddle such zones, are affected less by nearby well structure. In addition, the multiple sensors and frequencies allow for building radially and azimuthally varying images of the resistivity with depth. Finally, the three-component measurements also make it possible to map the strike and inclination of fractures or other heterogeneities. This, in turn allows for the accurate projection of these structures into the space between wells.

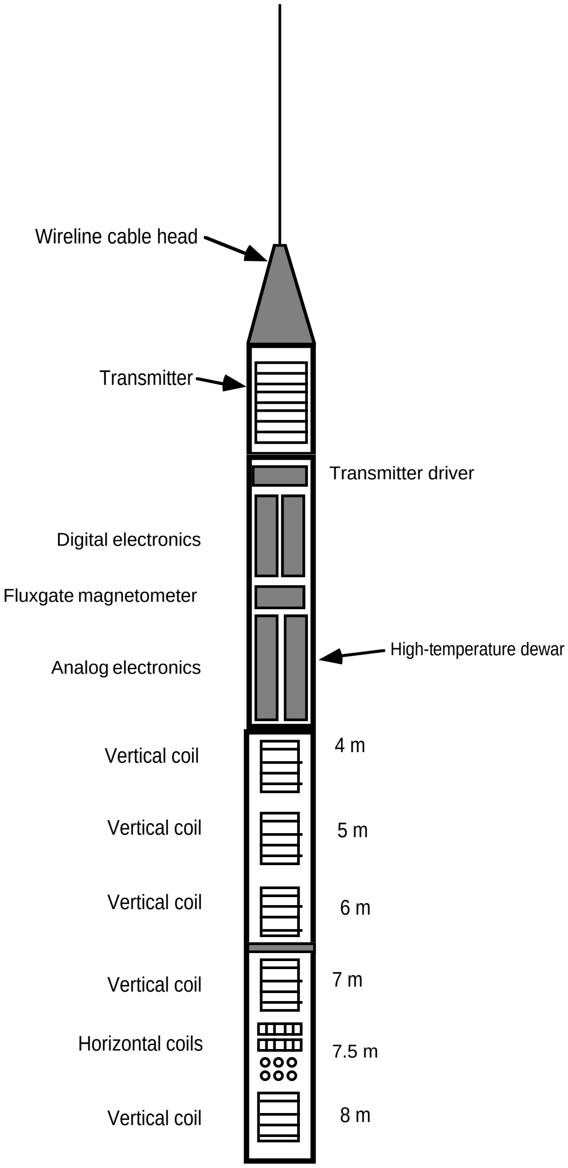

Fig. 1. Schematic diagram of the MAIL long-offset induction logging device.

FIELD APPLICATION

The MAIL tool was initially tested in the WD-1 well at the Kokkanda geothermal field in central Japan in 1995. The tool was operated at temperatures in excess of 190°C at depths exceeding 2.6 km (Sato et al., 1996; Uchida et al., 1996). Results from this test were designed to identify low-resistivity zones associated with through-going fractures.

Recently, a performance test of the tool was made at the Lost Hills oil field in central California, where Mobil Exploration and Production U.S. operates a shallow steam flood for enhanced oil recovery.

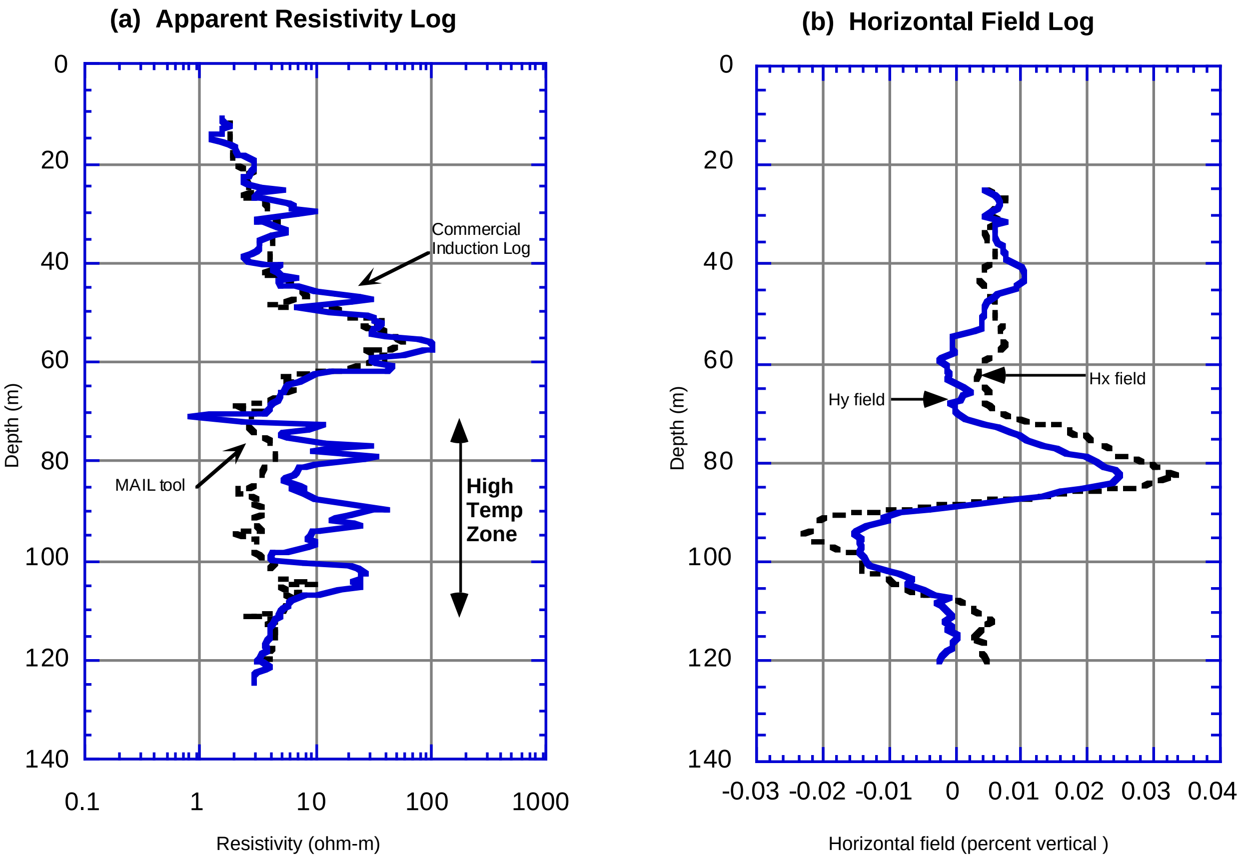

Fig. 2. (a) Comparison of apparent resistivity logs measured with the MAIL tool and conventional induction logging data in the same borehole. Note: the MAIL data was collected after steam injection. (b) Horizontal magnetic fields from the MAIL in the same borehole.

Several steam injectors and fiberglass-cased observation wells are available at this site for making measurements. This site was chosen for its well-characterized structure and the presence of a high-temperature zone near the observation well.

We deployed the tool in a fiberglass-cased observation well located 30 m from a steam injector. The observation well has several nonuniform, high-temperature zones due to the recent steam flood in addition to evidence of a high-conductivity zone adjacent to the well (probably pyrite from gas evolution). In the past, we used this and a companion observation well for crosshole electromagnetic studies that tracked the injected steam plume for several years (Wilt et al., 1995). We therefore have a good idea of the electrical resistivity structure in the region between the boreholes.

In Figure 2a, we show the commercial induction resistivity log from the borehole collected immediately after drilling in 1992 and the MAIL 5-m offset log from December 1996. The two responses are similar in the upper reaches of the well but differ below 60 m, where the resistivity measured with the MAIL tool is significantly less than the commercial log. This difference is primarily due to the high-temperature zone in the borehole (in excess of 130°C) caused by the nearby steam injector. The replacement of insulating oil with hot water and steam is consistent with the more than 50% reduction in resistivity observed with the logs. The MAIL log is smoother than the older induction log because of the longer source–receiver offsets.

In Figure 2b, we plot the horizontal field responses from the MAIL log in the same borehole. Note that for a homogeneous or horizontally layered medium, the horizontal fields from a single borehole logging device are zero. These fields are nonzero only where the formation adjacent to the borehole is heterogeneous. They may therefore indicate a fracture zone or a nonsymmetrical structure, such as a steam zone. In this case, the horizontal fields display a crossover anomaly with peaks corresponding to the boundaries of the high-temperature zone. This structure is consistent with a low-resistivity zone (steam plume) that is more pronounced east of the well, or toward the steam injector. Note that these data have not been corrected for tool rotation, which is necessary before the data can be interpreted.

We are presently fitting the field data with three-dimensional electrical resistivity models to determine the geometry of the low-resistivity zones adjacent with the wellbore. We will use two-dimensional data resistivity models obtained from crosshole electromagnetic studies for the initial guess models.

CONCLUSION

The advent of long-offset induction logging could potentially have significant consequences for geothermal field development. The orientation of producing fracture zones could potentially be determined from these measurements; it may also be possible to locate nearby producing zones from "near miss" exploration boreholes.

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