

THE BOREHOLE ENVIRONMENT IN TRIAXIAL INDUCTION LOGGING

H. Bertete-Aguirre¹, Alan C. Tripp², and E. Cherkaev³

¹ Lawrence-Livermore National Laboratory,
Livermore, California, hba@llb.gov

² Department of Geology and Geophysics, University of Utah,
Salt Lake City, Utah 84112, actripp@mines.utah.edu

³ Department of Mathematics, University of Utah,
Salt Lake City, Utah 84112, elena@math.utah.edu

ABSTRACT

The transmitter-receiver geometry used in traditional uniaxial induction logging was not accidental - a conductive smooth borehole gives a null response for axial magnetic field sources and sensors. However this nulling is not necessarily true for triaxial devices, which are designed to resolve features such as formation anisotropy or vertical fractures which are invisible to traditional tools.

Triaxial devices may be fabricated in the time or frequency domain. In the frequency domain, where the transmitter and receiver are separated, as in the EMI, Inc. device, borehole effects for conductive bore-fluids will be present and can overwhelm the response of formation features unless corrective means are taken, such as a focusing of the source fields. Borehole irregularities, such as breakouts, washouts, and key seats will also give responses which might mask formation properties. Time domain devices with separated transmitters and receivers, as discussed by Gianzero and Su, will have a time window over which the borehole response is minimized. Time domain devices with coincident sources and receivers, such as that discussed by Nekut, will have an appreciable borehole response. In the case of both frequency and time domain methods, numerical modeling of the borehole response is essential for full understanding and remediation of deleterious borehole effects.

Modeling borehole responses can be done using analytic modal responses, integral equations methods, or difference methods. Estimates of differential measurement sensitivities to borehole irregularities are approximated by a simple perturbation formula. Numerical modeling using integral equations for separated source-receiver geometries establishes bounds on the resolution of formation features in the presence of borehole fluid and borehole irregularities.

INTRODUCTION

Traditional induction logging tools, developed for use in the oil and gas industry, have provided some success in detecting fracture zones and in delineating lithologic units intersected by exploration boreholes (Tripp and Ross, 1999). Recently, various authors have discussed the development of induction logging tools specifically designed for exploring and exploiting geothermal fields (Wilt et al., 1997; Sato et al., 1996). Among the tools under development is a device with triaxial magnetic dipole sources and receivers (Wilt, pers. comm.), which has the potential of increasing the resolution of conductive fracture zones paralleling the borehole. A plethora of interpretation issues is raised by the design and deployment of such a device - which we view as representative of a new generation of high resolution induction devices. In particular, a magnetic dipole source perpendicular to the borehole axis will induce significant axial electric currents in a conductive bore fluid which may overprint a response from interesting formation structures. The present article reviews the state of knowledge concerning this borehole response. We also estimate the magnitude of the response for several models of the borehole and offer means of remediating the measurement to emphasize the response of geophysically interesting targets in the formation.

Since fractures and fracture zones in geothermal areas tend to be vertical, the triaxial device would be most useful in near vertical drill-holes. In highly deviated boreholes, traditional induction sources oriented along the borehole axis would have a much greater response to vertical conductive fracture zones than tools using a source dipole perpendicular to the borehole axis.

PHYSICAL AND ELECTRICAL STRUCTURE OF THE BOREHOLE ENVIRONMENT

Boreholes are seldom uniformly cylindrical and their drilling requires lubrication. These two factors mean that the electrical structure immediately surrounding the borehole is inhomogeneous and may affect electromagnetic measurements in the borehole. The important factors to consider in developing an electrical model of the borehole is the mechanical competence and the permeability of the formation and the electrical conductivity of the drilling mud.

In the best of all possible worlds, drilling mud would have no electrical conductivity contrast with the formation. Intuitively, an oil-based mud which is more resistive than the formation would affect the measurement less than a water-based mud. However, oil based mud is often proscribed because of environmental concerns (J. Baumgartner, Socomine, pers. comm.) and the presence of a water-based mud is unavoidable.

There is a variety of systematic irregularities which are encountered in boreholes. Breakouts occur as axisymmetric stress release features along the minimum horizontal stress S_h (Hickman et al., 1985; Plumb and Hickman, 1985; and Zoback et al., 1985). Zoback et al. (1985), among others, have investigated the relationship between breakout dimensions and the ambient stress regime.

The formations encountered in drilling are sometimes poorly consolidated. In such cases, washouts of the formation into the drilling mud can occur, leaving irregular pocks in the borehole wall.

The mechanical action of the drill stem also can lead to irregularities. For example, drill stem corkscrewing can cause significant borehole cavities (J. Baumgartner, Socomine, pers. comm.; Baumgartner et al., 2000). In highly deviated wells, the drill string can settle, resulting in an asymmetric key seat. Any of these features can obscure the response of an interesting formation structure, such as a fault zone.

EM BOREHOLE RESPONSE

a) Uniform Borehole

A seminal work on triaxial logging was provided by Moran and Gianzero (1979). Using an analytic approach, they investigated the effect of borehole fluid - formation contrast on resolution on formation conductivity using horizontal source and receiver dipoles. They found that indeed a high borehole - formation resistivity contrast can lead to very large

borehole masking of the formation response for conductive borehole fluids. Resistive fluids had a lesser, although still noticeable influence.

Another work examining the effect of the borehole on horizontal dipole fields is that of Howard (1981), who examined the response, calculated with a modal match method, of a horizontal dipole in a resistive cavity, simulating a tool, to a borehole containing perfectly conducting fluid. The response was designed to give an upper limit to the effect of borehole fluid on horizontal dipole measurements. These calculations support the notion that the borehole effect can be significant. Landt (1978) has also discussed the influence of a tool cavity on triaxial measurements.

b) Irregular Borehole

As the studies of Moran and Gianzero have shown, a conductive borehole response can overwhelm the formation response for separated sources and receivers in the frequency domain. If the mud conductivity and the borehole diameter is known, then the magnitude of this response can at least be calculated, and subsequent measurements be viewed as perturbations of the borehole response. However, it may be that borehole irregularities such as breakouts, filled with conductive mud, will themselves be a significant source of noise. The response of such irregularities needs to be calculated with integral equations or finite difference techniques.

The integral equations code of Xiong (1992) was used to calculate the borehole effects on the formation response. Since the code uses the method of collocation, approximating the borehole with cubic cells is a challenging geometric problem, particularly for a very conductive borehole in a resistive earth, where fields vary rapidly and the integral equation becomes increasingly ill-posed as the resistivity contrast increases.

As a test of convergence, a smooth 40 cm diameter cylinder of length 40m and resistivity .1 ohm-m, situated in a 100 ohm-m isotropic earth, was discretized using 200 and 300 cells along the long axis. The lateral extent of the cylinder was discretized in a 2x2 grid, and group symmetry of the cylinder was used to reduce the extent of the calculation (Tripp and Hohmann, 1984). The agreement in the total horizontal magnetic fields at a number of receivers and horizontal magnetic dipole sources for the two vertical discretizations agreed to within 10%. Elongating the borehole to 80m did not have an appreciable effect on the fields. Similarly, increasing the fineness of the cross-sectional discretization did not change the calculated fields significantly.

Adding irregularities as individual cells is possible,

but in practice is awkward and computationally expensive. A better approach for developing a rapid appraisal of the influence of borehole features is to calculate sensitivity coefficients in the vicinity of the borehole.

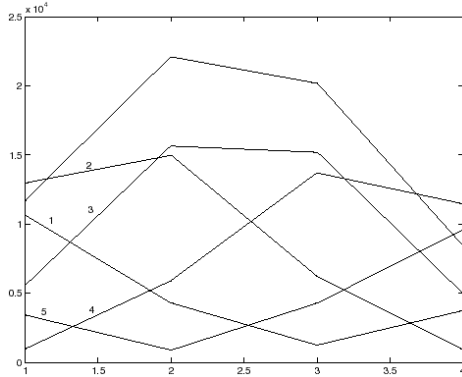


Figure 1. The anomalous voltage response of a conductive fault measured at the receivers due to the transmitter dipoles (curves numbered by 1 through 5) and the superior response due to the optimized focused array current (the top curve).

Differentiating the EM fields with respect to the electrical conductivity of a point in the earth introduces an electric source at the point. EM reciprocity can then be used to interchange the function of the receiver and this source. Hence, the final expansion of the sensitivity coefficients, given in Appendix 1, is a weighted dot product, at the position of the perturbed electrical conductivity, of the electric field due to the original transmitter and the electric field due to the receiver acting as a transmitter. Since the electric fields can be calculated at many points in a formation rapidly and inexpensively, sensitivity coefficient contours can be developed quite conveniently.

This sensitivity analysis demonstrates that indeed conductive boreholes emphasize the effect of borehole irregularities on the horizontal components of horizontal dipoles. Tool eccentricity introduces asymmetry into the sensitivity profiles.

The borehole environment is quantifiable by measuring or calculating the conductivity of the mud and imaging the surface of the borehole by some technique, such as a caliper or televiwer log. With this information, the theory of adaptive focusing (Cherkaev and Tripp, 1998, 1999, 2000) is applicable. Figures 1 through 3 demonstrate the effect of focusing on an array of 5 transmitters and 4 receivers. The transmitters are located every 1 meter from 2028m to 2024m, with the receivers located every meter from 2027.5m to 2024.5m. The

geometry and the conductivity of the borehole is the assumed information. The transmitter dipoles are transverse to the borehole axis and the transverse field is the received field.

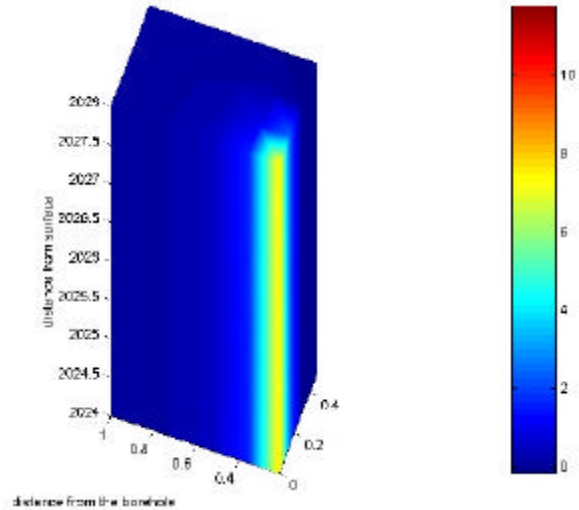


Figure 2. Hx field without focusing.

Figure 1 shows the response of a conductive fault measured at the receivers due to the transmitter dipoles (curves numbered by 1 through 5) and the superior response due to the optimized focused array current. As shown in Figures 2 and 3, the focusing localizes the field in the vicinity of a conductive fault, whose response was included in the forward response but which was not assumed in the focusing calculation.

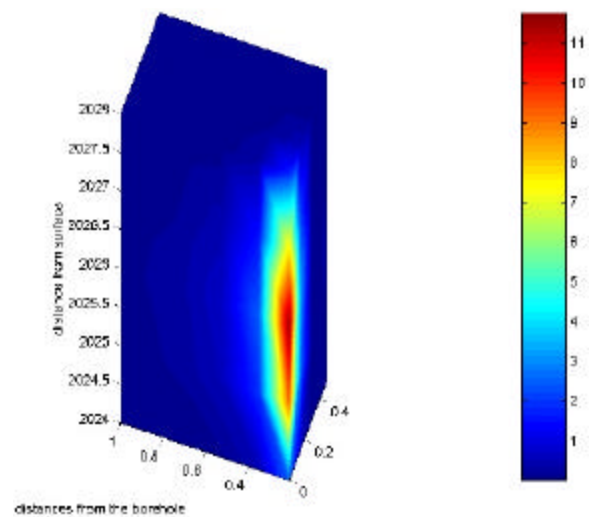


Figure 3. Hx field due to the optimally focused array.

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APPENDIX 1:

BOREHOLE IRREGULARITY MODELING

Assume a magnetic dipole transmitter of moment $I dS=1$ at \mathbf{p}_t oriented in the i direction and a magnetic field receiver at \mathbf{p}_r oriented in the j direction. Here i and j can assume the values $x, y,$ or z . Assume a possibly three-dimensional conductivity distribution σ^* .

We wish to determine the change in the measured magnetic field $H_{ij}(\mathbf{p}_r)$ due to a conductivity perturbation $\delta\sigma_k$ in a cell k of incremental volume δv_k . Then following Tripp and Hohmann (1993),

$$\delta H_{ij}(\mathbf{p}_r) = (-1 / j\omega\mu) \cdot [E_x^j(\sigma^*, \mathbf{p}_k, \mathbf{p}_r) E_y^j(\sigma^*, \mathbf{p}_k, \mathbf{p}_r) E_z^j(\sigma^*, \mathbf{p}_k, \mathbf{p}_r)] \cdot [E_x^i(\sigma^*, \mathbf{p}_k, \mathbf{p}_t) E_y^i(\sigma^*, \mathbf{p}_k, \mathbf{p}_t) E_z^i(\sigma^*, \mathbf{p}_k, \mathbf{p}_t)]^T \delta\sigma_k \delta v_k,$$

where $E_x^j(\sigma^*, \mathbf{p}_k, \mathbf{p}_r)$ is the x component of the E field measured at \mathbf{p}_k due to an j directed unit magnetic dipole at \mathbf{p}_r and other field values are defined similarly.