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Borehole Effects in Triaxial Induction Logging

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ABSTRACT

The development and use of triaxial logging tools demands that the purpose of the borehole be understood and deleterious effects be removed. Recent integral equations modeling conforms the conclusion that the effect of a conductive borehole fluid and horizontal boreholes can be orders of manufactured layers that the formation forms. In a conductive borehole regime even effect of borehole surface irregularities are significant. Adaptive focusing seems to be the primary means of accounting for spurious signal due to borehole roughness.

Traditional induction tools use source arrays in which both receiving and transmitting magnetic dipoles are oriented along the borehole axis. This orientation has been preferred for traditional isotropic formation evaluation in vertical boreholes because borehole effects are minimized by the source-receiver-borehole symmetry. However, this source-receiver geometry tends to minimize the response of potentially interesting geological features, such as bed resistivity anisotropy and fracturing which parallels the borehole. Traditional uniaxial tool responses are also ambiguous in highly deviated boreholes in horizontally layered formations. Resolution of these features would be enhanced by incorporating one or more source transmitters that are perpendicular to the borehole axis. Although these transmitters can introduce borehole effects, resistive oil-based muds minimize borehole effects for horizontal source data collection and interpretation. However, the use of oil based muds is contraindicated in environmentally sensitive areas. For this reason, it is important to be able to assess the influence of conductive water based muds on the new generation of triaxial induction tools directed toward geothermal resource evaluation (e.g. Wilt, pers. comm.) and to develop means of ameliorating any deleterious effects.

The present paper investigates the effects of a borehole on triaxial measurements. The literature contains a great deal of work on analytic expressions for the EM response of a magnetic dipole contained in a borehole with possible invasion zones. Moran and Gianzero (1979) for example investigate borehole effects using such an expression. They show that for conductive borehole fluids, the borehole response can easily swamp the formation response for horizontal dipoles. This is also true when the source dipoles are enclosed in a resistive cavity, as shown by Howard (1981) using a mode match modeling technique.

The integral equations technique (IE) of Xiong (1992) is used to describe borehole effects on the formation response. It is a challenging numerical problem to compute the response of a triaxial magnetic source in a very conductive borehole, particularly when the borehole has rough and irregular walls. Approximating an elongated cylindrical object is geometrically difficult, particularly in the case of a very conductive cylinder in a resistive earth. This requires a large number of modeling cells due to ill-posedness of the computational method for media with high resistivity contrasts. In our convergence tests for a smooth borehole of 40 cm diameter, resistivity .1ohm-m, and containing a horizontal magnetic dipole transmitter in an 100 ohm-m isotropic earth, total horizontal magnetic field values calculated using 200 and 300 cells in the vertical direction and a 2x2 horizontal grid agreed to within 10%. This agreement in a difficult computational case is encouraging, but needs to be improved for acceptable modeling accuracy. One possible means of improving the accuracy is to introduce the response of the mean borehole into the integral equations formalism using an analytic expression. Such a technique, which we are presently incorporating, would also reduce the number of cells necessary for forward calculations. Elongating the borehole to 80m length by adding cells on the ends of the borehole had a vanishing influence on the horizontal components, and a recognizable but minor influence on the axial components. Also, increasing the fineness of the horizontal grid had a small effect on the fields. Such numerical modeling verifies the large effect of a conductive borehole on the response of a horizontal dipole in the borehole. The currents flowing up the borehole preferentially gather into vertical conductive features intersecting the borehole, as we have demonstrated numerically by modeling the response of a conductive borehole in an anisotropic earth. In our studies anisotropic layers or structures are used to model fracture packets.

We also use integral equations modeling to estimate the influence of borehole roughness, either by directly modeling the irregularities of the borehole walls as anomalous body cells or by exploiting a perturbation approach based on field reciprocity. The first scheme is more precise, but requires a more elaborate numeric for the estimation. The second scheme is less precise, but being semi-analytic it requires no additional cells for a forward calculation. The coupling of the horizontal source dipole to the borehole fluid is so strong that borehole irregularities can give significant responses, particularly compared to those of vertically fractures that are inline with the borehole but are electrically insulated from the borehole fluid.

IE modeling demonstrates that conductive boreholes introduce large noise bias and variance which can easily swamp or masquerade the effects of formation conductivity structures. Fortunately the conductivity of the borehole mud is known for any field situation and the geometry of a borehole can be estimated in many cases using a caliper log. The magnetic dipole array weighting scheme of Cherkaeva and Tripp (1999, 2000) and Cherkaev and Tripp (2000) can use this information to numerically focus the transmitter fields in the formation. Such a scheme uses the irregularities of the borehole to good effect. The focusing scheme facilitates a particularly rapid imaging algorithm, as discussed by Cherkaeva and Tripp (1996, 1997).

In conclusion, triaxial induction logging for formation evaluation and fracture detection in geothermal reservoirs has been identified by industry and by state and federal government as highly desirable. However, borehole effects for conductive muds will make horizontal dipole data very noisy and difficult to interpret unless compensatory schemes are identified. Source adaptive focusing is one possible scheme.

Acknowledgements

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