Final Report

Imaging Tools for Electrical Resistivity in Geothermal Exploration and Reservoir Assessment

Task 3; DE-FG07-99ID13853

A.C. Tripp
University of Utah
1476 Federal Way, Salt Lake City, Utah 84103
actripp@mines.utah.edu

Introduction

Because reservoir production is primarily in fractured rock, a great deal of effort has been spent devising means of remotely sensing fractures and fracture zones using geophysics. Since increased fluid content or alteration of fractures can give rise to an electrical conductivity contrast, electromagnetic (EM) means of probing have been investigated extensively over the years. Although direct and indirect fracture responses have been noted in many field situations, a fracture response can be subtle and progress has been sporadic. The purpose of this project was to facilitate inductive fracture detection by providing the interpretation tools and knowledge-theoretic framework for innovative high resolution fracture detection and delineation.

We have sought to facilitate increased resolution of fractures by:

1) Identifying more realistic electrical models for fractures, further defining the geophysical target for cooperative interpretation in fracture environments;

2) Investigating suitable software for calculating the EM response of realistic electrical fracture models including anisotropy, borehole metallic casing, and innovative basis functions;

3) Investigating cooperative knowledge adaptive EM experiment design and interpretation for fracture detection and delineation;

4) Providing modeling support for triaxial induction tool development by EMI, Inc.

Triaxial Device Modeling Support

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 does not necessarily hold 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 will have a time window over which the borehole response is minimized. Time domain devices with coincident sources and receivers, 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.

We have calculated borehole responses for the triaxial geometry in support of the EMI, Inc. development of a frequency domain triaxial induction tool. Resolution analyses for a conductive fracture and conductive boreholes using uniaxial and triaxial inductive logging are discussed in Bertete-Aguirre et al. (2000). These analyses, which use analytic sensitivity formulae, demonstrate that for magnetic dipole sources perpendicular to the borehole axis, conductive boreholes and their irregularities do mask the effects of conductive features at depth. Eccentering is also troublesome in this environment. Adaptively focusing an inductive source array to utilize the irregularities as elements of the source array optimizes the resolution of conductivity features away from the borehole (Cherkaev and Tripp, 2000; Bertete-Aguirre et al., 2001a)

Although a triaxial tool is extremely useful it is not a panacea. Cherkaev et al. (2000) and Bertete-Aguirre et al (2001b) demonstrate that full utilization of a triaxial tool in investigating the petrophysics of anisotropic material requires complementary sources of information. In the absence of this information, an interpretation of triaxial tool data often does not have a distinct advantage over an interpretation of traditional induction tool data.

EM Response of Fractal Conductivity Distributions

A long standing approximation in EM logging for fractures has been to assume that a fracture is an extended thin sheet, perhaps a half-plane. This approximation can be useful and is theoretically and numerically convenient. Convenience notwithstanding, examination of core, FMS logs, and outcrop reveals that fracture zones can be geometrically self-similar over dimensional scales of less than millimeters to kilometers. In such a case, a strict geophysical model would have to account for such a fractal structure to truly represent the resistivity structure of the earth.

One method espoused in the electrical engineering literature models fractal structures with almost-periodic functions, such as band-limited Weierstrass functions. This representation gives a facile means of scaling small alternating sequences of open fracture and matrix rock, as observed in a borehole, to uniaxial anisotropic fracture packets . Parallel and transverse resistivities as functions of averaging window are easily calculated from such a distribution assuming that dip of the bedding with respect to the borehole is known - as would be the case with the auxiliary use of a FMS log, for example. The averaging windows are adjusted to the resolving length of the EM logging device under consideration and the EM frequency or time domain response of the subsequent averaged anisotropic layers or units are calculated using codes incorporating anisotropic conductivities. The EM response of fractal conductivity variations, such as might be measured in a fracture envelope, have been presented in Tripp et al.(2001).

The time domain method of electromagnetic exploration has several distinct advantages over the frequency domain method, although instrumentation difficulties have apparently limited its use in inductive logging. One of its advantages is that the nature of the response is nicely visualized as a temporally diffusing field. For this reason, and to provide support for possible future work in a time-domain instrument for geothermal investigations, we have inverse Laplace transformed Moran and Gianzero's frequency domain expression for the response of an anisotropic earth. The expressions for the temporal vector and scalar potentials of an anisotropic earth are contained in Tripp et al. (2001).

Mapping Fluid Flow with Electromagnetics

The development of a triaxial induction tool facilitates new approaches to EM reservoir examination. Fracture detection as usually envisaged uses EM fields to detect conductivity contrasts originally present in the rock. This approach can be fine, but suffers from the fact that the detectable parameter is a secondary characteristic of the reservoir properties of interest. However, if the fracture system is accessible, a fluid of enhanced electrical conductivity or magnetic susceptibility can be introduced which is traceable through its inductive signature on a triaxial induction tool. In this case fluid movement is being monitored, which is of direct interest in reservoir studies. The following idea has been discussed by Tripp and Cherkaev (2001).

Since high resolution of fluid movement is essential, all EM monitoring of the injected fluid will use adaptive array theory (Cherkaev and Tripp, 2000), which optimizes the resolution of a conductivity or magnetic susceptibility perturbation on an a-priori parameter distribution. Approximate real time inversion permit a source array which is adaptive during the course of the fluid injection.

The design of the chemical and physical properties of the injection fluid is a matter of some moment. The conductivity can be controlled by the ionic content, but the ionic content must not have deleterious effects on the physico-chemical properties of the formation. The EM response is also enhanced by the addition of fine ferromagnetic particles. These might be useful as a proppant in hydrofrac experiments.

The EM response can be interpreted in two ways. First it can be inverted to electric currents, which will approximate the hydrologic fluid flow lines. This is a linear inversion problem. The second method is to invert the EM data to anomalous electrical conductivity and magnetic susceptibility distributions and then use a mixing law to estimate the volume fraction of introduced fluid in the formation. In either case, we develop a dynamic estimate of fluid flow in the formation.

The EM measurements give an estimate of the transient saturated flow in the isolated zone, which may be put to use by the reservoir engineer as appropriate. We can demonstrate one approach which is intriguing. Assuming a diagonal hydraulic conductivity tensor, the Darcy equations become

$$v_x = - K_x (?h/?x),$$

$$v_y = - K_y (?h/?x),$$

and

$$v_z = - K_z (?h/?x).$$

Augmenting these equations with the equation of continuity gives the equation of flow through a saturated anisotropic porous medium

$$(?/?x) (K_x (?h/?x)) + (?/?y) (K_y (?h/?y)) +(?/?z) (K_z (?h/?z)) = S_s (?h/?t),$$

where S_S = ?g (?+n??, ? is the aquifer compressibility, n is the porosity, and ? is the fluid compressibility.

Assuming that estimates of porosity n^{est} and fluid flow (v_x^{meas} (**x**, t), v_y^{meas} (**x**, t), v_y^{meas} (**x**, t)) are made using electromagnetic means, the flow equation becomes

$$(?/?x) (v_x^{meas}) + (?/?y) (v_x^{meas}) +(?/?z) (v_x^{meas}) = S_S (?h/?t).$$

Since we know S_S and assuming an initial formation head, we can write

$$h = (1/ S_S) ?\{ (?/?x) (v_x^{meas}) + (?/?y) (v_x^{meas}) +(?/?z) (v_x^{meas}) \} dt .$$

Then by Darcy's equations, $K_i = -v_i / (?h/?i)$.

This gives a 3D hydraulic conductivity distribution. Since the solution involves a temporal and a spatial differentiation, data conditioning will be an issue in the application of the mathematical solution.

Inversion to Scattering Current Densities

Much has been made of inversion of EM data to electrical conductivity distributions. Another approach to using EM data to delineate fluid flow paths is to invert the data to the scattering current. We believe that this approach offers some advantages in speed and applicability, particularly when implemented using Sinc function techniques. Our research on this topic will be reported in Tripp et al. (2002).

Propagation through Metallic Casing

A major problem in applying EM logging in a geothermal reservoir is the presence of steel casing in many wells. Luckily, EM signal can be measured through casing, although the effect of the casing must be considered. Our preference is to discover means of correcting data from standard tools for the casing effect rather than depend on special use tools for probing through casing.

Simple analytic models demonstrate that certain components of low frequency EM fields are measurable through casing. For example, the parallel component of the magnetic field is not greatly affected by the casing parameters if the frequency of the field is sufficiently low. However the magnetic permeability of casing biases the perpendicular component of the magnetic field at all frequencies.

These considerations leave a few options. First, we can use the frequencies and the components that are not affected by the casing. This is a simple option that might be adequate for applications. However it means that some sacrifice in resolution will be made.

The second option is to introduce ports into the casing. These ports could be sections of non-conducting tube or could be slots in the casing. The effects of the slots or ports would then be estimated and removed from the data.

The third option, which is most technically challenging but has the most potential use is to characterize the physical properties of the casing and then use the properties together with mathematical modeling to include the effect of the casing in the modelling.

Research on estimating and ameliorating the effects of casing on EM measurements is contained in Tripp (2002).

Technology Transfer/Collaborations

Technology transfer

Our research has been presented in the professional papers referenced below. Our calculations of the triaxial borehole response and focusing has been done in technical support of the EMI, Inc. triaxial tool development.

Collaborations

EMI, Inc. has offered insight into the use and development of triaxial devices. Dr. H. Bertete-Aguirre of Lawrence Livermore Laboratories has collaborated on triaxial modeling under separate DOE funding. Dr. E. Cherkaev, of the University of Utah Department of Mathematics, has collaborated on aspects of mathematical modeling under complementary DOE funding. Prof. Dali Zhang, Visiting Scholar at the University of Utah Dept of Mathematics assisted on aspects of the mathematical analysis at no cost to the project. Finally Prof. F. Stenger has provided insight into numerical analysis at no cost to the project.

Project Publications to Date

Bertete- Aguirre, H., Cherkaev, E., and Tripp, A.C., 2000 , Borehole effects in triaxial induction logging: Proceedings of the Geothermal Resources Council 2000 Meeting.

Bertete- Aguirre, H., Tripp, A.C., and Cherkaev, E., 2001, The borehole environment in triaxial induction logging: Proceedings of the 2001 Stanford Workshop on Geothermal Reservoir Engineering.

Bertete- Aguirre, H., Tripp, A.C., Cherkaev, E., and Jarrard, R.D., 2001, Triaxial induction logging for everyone - credos and caveats: Presented at SAGEEP.

Bertete- Aguirre, H. and Tripp, A.C., 2002 , Imaging triaxial induction logging data: 2002 Stanford Workshop on Geothermal Reservoir Engineering.

Cherkaev, E. and Tripp, A. C., 2000, Optimal design of focusing inductive arrays for inhomogeneous medium: Proceedings of the 2000 IEEE International Conference on Phased Array Systems and Technology, p. 485-488.

Cherkaev, E., Tripp, A.C., and Jarrard, R.D., 2000, High resolution adaptive induction logging - Petrophysical and electromagnetic considerations: Proceedings of the SPIE 2000, v. 4129.

Tripp, A.C., Moore, J., and Cherkaev, E., 2001, Representation and inductive response of fractal resistivity distributions: Proceedings of the 2001 Stanford Workshop on Geothermal Reservoir Engineering.

Tripp, A.C.and Cherkaev, E., 2001, High resolution EM for petrophysical characterization: Presented at the 2001 AAPG Annual Convention.

Tripp, A.C., 2002 , Borehole casing characterization and calibration: In Preparation.

Tripp, A.C., Stenger, F., Jarrard, R., and McNearny, R., 2002 , Geotechnical flow tracking with electromagnetics: In Preparation.