ENHANCED DATA ACQUISITION AND INVERSION FOR ELECTRICAL RESISTIVITY STRUCTURE IN GEOTHERMAL EXPLORATION AND RESERVOIR ASSESSMENT

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Project Background

Predictive capability for subsurface resource location is one of the most desireable aspects of a geothermal exploration tool. Electrical resistivity is a primary physical property of the Earth which can be strongly affected by geothermal processes. Since an increased fluid content due to fracturing, and the development of more conductive alteration minerals (clays, etc.), can give rise to an electrical resistivity contrast, electromagnetic (EM) methods of probing have been investigated and applied for many years. The reliable mapping of electrical resistivity should increase chances of discovering blind geothermal resources, in defining the extent of geothermal reservoirs, in imaging controlling structures for geothermal systems, and in resolving permeable fracture zones (DOE/OGT Strategic Plan, 1998). Our research group at the University of Utah has provided solutions of global import in this field with respect to numerical simulation capability, interpretation philosophy, instrumentation, and field studies as detailed below.

Project Objectives

Our efforts are aimed at reduced drilling costs and increased reservoir base through more reliable technology for exploration and enhanced geothermal systems. Progress requires improvements in density and quality of field EM data, developing refined electrical models and EM modeling algorithms for the geothermal environment, and incorporating independent geological data in cooperative interpretations for EM data. For imaging subsurface resistivity structure, several modes of EM propagation have been used ranging from man-made sources in the time-domain to natural and artificial sources in the frequency domain. Due to the depth of exploration potential and the likelihood of substantial advances in data quality and imaging capability as proposed herein, we are emphasizing the magnetotelluric (MT), CSAMT, and galvanic (DC) resistivity/IP methods. This approach also exploits emergence of new-generation array collection instrumentation for simultaneous MT-DC surveying.

Plans and Approach

One way to improve resistivity structural resolution is by developments in non-linear 2-D inversion of magnetotelluric (MT/CSAMT) and DC resistivity/IP responses. The standard approach is to minimize an objective function $W_\lambda(m)$ which is a weighted sum of data misfit and departure from *a priori* information:

$$W_\lambda(m) = \{(d-F[m])^T C_d^{-1}(d-F[m])\} + \lambda\{(m-m_o)^T C_m^{-1} (m-m_o)\}$$

The inversion of diffusive EM data must be stabilized, and the particular approach is embodied in the choice of the form of C_m. Our novel method is model-adaptive and exploits basic resolution principles of electrical methods such as similitude and fundamental correlations (e.g., conductivity-dimension) to avoid model artifacts, instead of using brute-force smoothing by damping slope or curvature.

Geothermal systems and other earth structure of course can be 3-D so we pursue this modeling capability as well. For adapting our own techniques and allowing efficient technology transfer, we require a straightforward, freely available source code. We have been cooperating with Y. Sasaki of Kyushu University who has provided such a program, implementing the 2^{nd}-order, E-field staggered grid formulation (Smith, 1996; Alumbaugh et al., 1996; Sasaki, 1999, 2001). Accuracy, versatility and run time tests were done against the integral equations platform of Wannamaker (1997), and the finite difference H-field code of Mackie et al. (1994). Currently, we are modifying and applying this algorithm to temporal changes in resistivity structure of geothermal fields with production over time, as described below. Prototype finite EM source and inversion capability have been tested also, and we will be improving upon those.

As a complement to commercial surveying capability, we are completing a multi-station field MT system with unique modes of acquisition and processing which is aimed particularly at eliminating man-made EM interference in already-producing geothermal systems. Increases in productivity and data accuracy are sought through simultaneous band acquisition with multi-site control via digital radio telemetry. The principal difficulty with the standard MT response model is the assumption that all noise on the system output (electric field) is uncorrelated with noises on the system inputs (magnetic field), whereas in the case of cultural interference the noises on the inputs and output are correlated. This is not met by the standard remote-reference method and we have been formulating a more complete MT noise model for this problem.

Research Results

Inversion tests for the 2-D MT case have been run on several sample data sets from Nevada, Utah and New Zealand. An example appears in Figure 1 for contracted data taken by Quantech Geoscience over the Carlin gold trend of north-central Nevada in a contiguous profiling array. There are 57 100-m bipoles oriented in cross-strike orientation (TM mode) which is the more robust mode for 2-D interpretation (Wannamaker, 1999). Electrical structures have been confirmed by excavation or drilling. A prototype 2-D inversion program for the pole-dipole resistivity/IP problem utilizing analogous regularization principles has recently been completed and tested using synthetic data. Program structuring is underway for joint MT/DC inversion, desireable since the two methods have differing resolving capability when it comes to conductive versus resistive structures. Quantech has recently fielded a system acquiring array MT and DC measurements simultaneously, and we are proposing to apply this new-generation system and our inversion capability to basic structural and resource problems at the Dixie Valley thermal area.

An example calculation using our 3-D modeling algorithm is given for the Oguni system, in cooperation with John Pritchett of SAIC using the STAR P-T-X reservoir simulator (Figure 2). Input to the simulator includes ambient (t = 0) P-T-fluid composition-permeability conditions from available drilling and sampling, together with laboratory data on electrical properties of fluids and bulk mixtures versus P-T-X. After 50 years of production, dry steam zones are predicted to form near-surface close to and east of Hagenoyu-Matsuya hot springs (Figure 2a). The primary steam (higher resistivity) zone is predicted at a depth ~500 m also under the main southern production area, especially under well GH-19. Higher resistivities at ~750 m depth under the

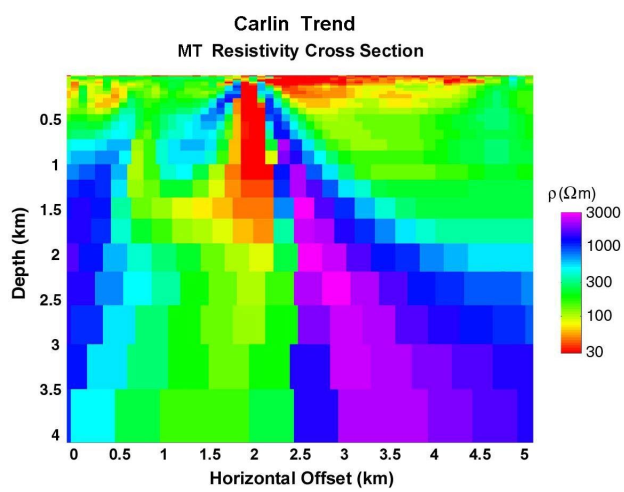

Figure 1. Electrical resistivity model cross-section derived from inversion of 57 MT sites taken as contiguous, 100 m bipoles across major gold prospect of the Carlin trend or north-central Nevada. Data courtesy of Quantech Geoscience Ltd.

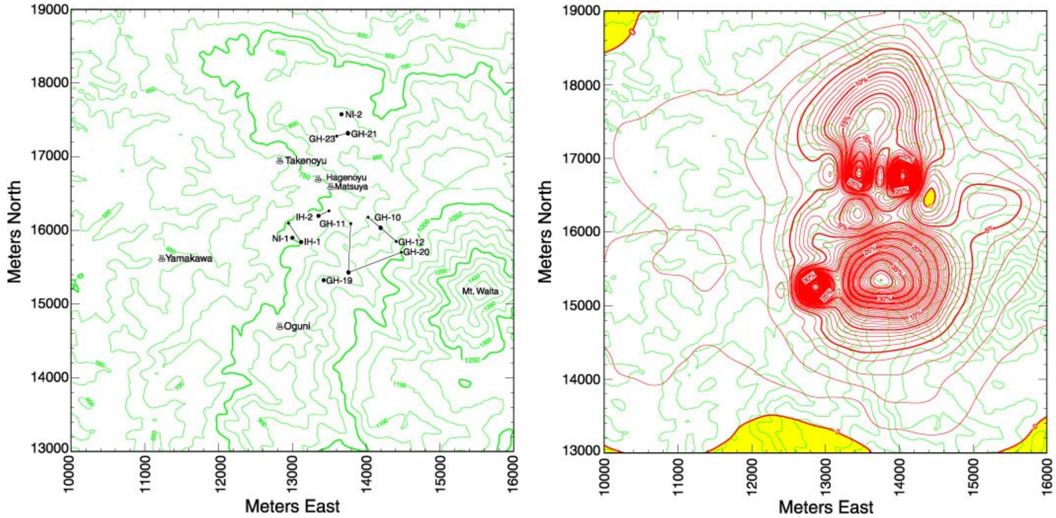

Figure 2a (left). Topography and locations of wells used for electrical power production in 50-year performance forecast for model Oguni geothermal field. Figure 2b (right). Relative 1 Hz apparent resistivity increase (in %) after 50 years of production/injection at Oguni.

NI-2 and GH-21 injection well areas occur due to injection of cooler fluids. Simulated increases in apparent resistivity due to steam formation and cooler water reinjection reach 40% beyond the initial (t = 0) response, and should be readily detectable in careful repeat MT surveys.

The overall design of the U. Utah/EGI MT system is essentially finished and we are dealing currently with the engineering details to implement the system (Figure 3a). The power supply units, interface boards to integrate E-field pre-amplifiers, channel cards, and E-field junction cases for low-impedance measurements are built. Firmware development is advanced in the areas of A/D control, timing control, custom high-speed synchronous serial data links, and paged memory communications protocols. A set of 900 MHz low-power digital spread-spectrum radios was acquired and tested to provide a low-power data telemetry option for system operations. Capability has been developed to measure accurately in ultra-high impedance environments (e.g., recent volcanics). We have developed a complete noise model for such systems which allows separation of non-plane wave noise transfer functions from the MT plane-wave function of primary interest (Figure 3b). As part of our improved robust processing developments to apply this model, we have implemented three-stage, combined coherence-sorting/jackknife outlier removal.

Technology Transfer/Collaborations/Education and Outreach

Quantech Geoscience Inc., which is emerging as the leading private contractor for array MT/resistivity data acquisition at prospect scales, has been using our prototype MT inversion code on newly acquired data sets in Nevada and report that it is the preferred imaging algorithm of all available. It has been incorporated into the industry-standard Geotools® and developed models are being linked to the GOCAD® geological object interpretation package. Quantec has contracted privately to modify the matrix solvers for use on new-generation, Intel-based computer clusters for parallel processing (Hargrove et al., 2001). The Utah 2-D finite element forward problem and derivatives is a founding component of the popular Occam-II inverse code used in many applications including new marine MT surveying for oil prospecting (Key et al., 2001). The generalized Green's functions relating EM fields of diverse sources and receivers derived by Wannamaker are at the heart of the 3-D finite difference algorithm of Alumbaugh et al (1996). A modified version of our 3-D MT modeling code is implemented by SAIC Corp. (J. Pritchett, project leader) for geothermal field production monitoring. This builds upon their previous reservoir simulations using DC resistivity and anticipates the need for CSAMT source modeling in real-world applications to noisy fields.

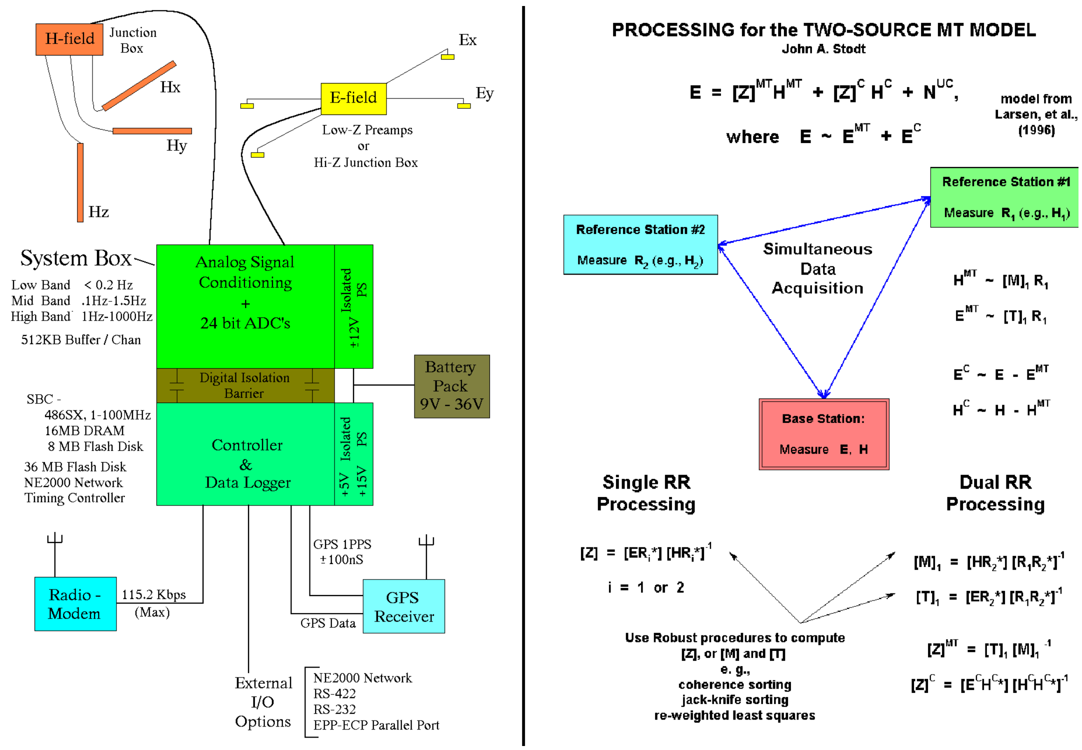

Figure 3a (left). Schematic of Utah MT system currently being completed under DOE support. Design combines simultaneous multi-band collection with high-speed, longer distance telemetry for effective productivity and noise suppression. Novel processing approaches (3b, right) consider two-source transfer functions (plane-wave plus cultural), to be applied at the Dixie Valley system.

The University of Utah MT system is a principal component of the EMSOC MT instrument facility, with companion support by the U.S. National Science Foundation. Complementary NSF support has clarified physical conditions of fluid existence in the deep crust and contrasted modes of occurrence of non-fluid conductivity causes (Wannamaker, 2000; Wannamaker et al., 2000). Convincing ties between fluid generation/movement, deformational regime and resistivity structure are demonstrated for the active New Zealand South Island, and for the U.S. Great Basin, using MT data from the Utah system (Wannamaker et al., 2001, 2002a; Wannamaker and Doerner, 2002). A full draft manuscript on our unique regularized inversion has been constructed for journal submission (Wannamaker et al., 2002b). Wannamaker was general co-chair of the 2nd G. W. Hohmann 3DEM symposium yielding 80 short papers (Wannamaker and Zhdanov, 1999) and over 20 full reviewed papers in a special Elsevier volume (Zhdanov and Wannamaker, 2002).

Our group has advanced EM methods for geothermal and other purposes with support from the DOE, NSF, USGS and private sources. The University environment is optimal for recognizing and combining technologies developed in diverse fields for application in geothermal exploration needs, and for educating our future personnel in problem-solving methods. Wannamaker has been a graduate advisor to numerous students at the University of Utah and elsewhere. These include Kim Kariya, Jeff Johnston, Louise Pellerin, Randall Mackie, Patricia Lugao, William Doerner, Fang Sheng, Carl Nettleton, Darrell Hall, Todd Ehlers, Efthemios Tartaras, Gabor Hursan, Victor Gonzalez, Weidong Li, Tim Sodergren, Derrick Hasterok, and Imam Raharjo. He has served as associate editor in electromagnetics for the journals Geophysics, Pure and Applied Geophysics, and Journal of Geophysical Research, and has been a reviewer of several books. He is Trustee and Treasurer of the Gerald W. Hohmann Memorial Trust for Teaching and Research in EM geophysics, which has created two student scholarships and a career achievement award from the SEG (see article in Leading Edge, Oct. 1998, pg. 1368).

Future Plans

Current two-dimensional inversion technology will be generalized to joint MT/DC applications. These represent the two dominant techniques in electrical methods of geothermal exploration and they are complementary in their resolution of subsurface structures. Application of the algorithms is to be for arbitrary data distributions, but will also be tailored to include the contiguous bipole array setups common to the contracting industry. We will be modifying the prototype finite source 3-D code by incorporating the accurate and versatile Green's functions from our long-standing integral equations algorithm. The first modules to be implemented will be for CSAMT and for the DC/IP method. Initial tests with topographic models show that reasonably accurate results are possible with this code. Our inversion approach will be able to accommodate the results of focused electrical array research by A. Tripp, also supported by DOE/OWGT, such that optimal data acquisition will be combined with appropriate inverse model construction for both surface and downhole EM arrays. It is our intention to provide a compact, easy-to-use 3-D platform which is completely in the public domain for both private and academic use.

We are proposing to address important structural and resource problems in a classic Basin and Range geothermal system by application of dense array EM measurements and improved inversion and instrumentation technology. The system selected is Dixie Valley, Nevada, the hottest extensional system in the province (Benoit, 1999; Blackwell et al., 2000). Basic goals of such a survey are 1), resolve a fundamental structural ambiguity at the Dixie Valley thermal area (single rangefront fault versus shallower, stepped pediment; 2), delineate fault zones which have experienced fluid flux as indicated by low resistivity (thereby contrasting permeable and impermeable areas); 3), image the disposition of the igneous (resistive) formations in the subsurface, which are interpreted to comprise good reservoir rock due to brittle rheology; and 4), from a generic standpoint, demonstrate the maximal resolving capability of complementary, fully sampled electrical data for subsurface structure. This is a large MT data set to manipulate so there is a substantial processing effort in the two-source method here. University of Utah instrumentation will be applied in acquiring data components not covered by the array, to define the resulting compromise in information content.

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