CONF-920378--8

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JUN 3 0 1992

GEOTHERMAL PROGRAM REVIEW X

PROCEEDINGS

"Geothermal Energy and the Utility Market - The Opportunities and Challenges for Expanding Geothermal Energy in a Competitive Supply Market"

March 24 - 26, 1992
San Francisco, CA

Sponsored by:

U.S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
Geothermal Division
Washington, DC 20585

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GEOTHERMAL GEOPHYSICAL RESEARCH IN ELECTRICAL METHODS AT UURI

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ABSTRACT

The principal objective of electrical geophysical research at UURI has been to provide reliable exploration and reservoir assessment tools for the shallowest to the deepest levels of interest in geothermal fields. Three diverse methods are being considered currently: magnetotellurics (MT, and CSAMT), self-potential, and borehole resistivity. Primary shortcomings in the methods addressed have included a lack of proper interpretation tools to treat the effects of the inhomogeneous structures often encountered in geothermal systems, a lack of field data of sufficient accuracy and quantity to provide well-focused models of subsurface resistivity structure, and a poor understanding of the relation of resistivity to geothermal systems and physico-chemical conditions in the earth generally. In MT, for example, interpretation research has focused successfully on the applicability of 2-D models in 3-D areas which show a preferred structural grain. Leading computer algorithms for 2-D and 3-D simulation have resulted and are combined with modern methods of regularized inversion. However, 3-D data coverage and interpretation is seen as a high priority. High data quality in our own research surveys has been assured by implementing a fully remote reference with digital FM telemetry and real-time processing with data coherence sorting. A detailed MT profile across Long Valley has mapped a caldera-wide altered tuff unit serving as the primary hydrothermal aquifer, and identified a low-resistivity body in the middle crust under the west moat which corresponds closely with teleseismic delay and low density models. In the CSAMT method, our extensive tensor survey over the Sulphur Springs geothermal system provides valuable structural information on this important thermal regime and allows a fundamental analysis of the CSAMT method in heterogeneous areas. The self-potential (SP) method is promoted as an early-stage, cost-effective, exploration technique for covered hydrothermal resources, of low to high temperature, which has little or no adverse environmental impact and yields specific targets for temperature gradient and fluid chemistry testing. Substantial progress has been made in characterizing SP responses for several known, covered geothermal systems in the Basin and Range and southern Rio Grande Rift, and at identifying likely, causative source areas of thermal fluids. Quantifying buried SP sources requires detailed knowledge of the resistivity structure, obtainable through DC or CSAMT surveys with 2-D or 3-D modeling. Borehole resistivity (BHR) methods may help define hot and permeable zones in geothermal systems, trace the flow of cooler injected fluids and determine the degree of water saturation in vapor-dominated systems. At UURI, we develop methods to perform field surveys and to model and interpret various borehole-to-borehole, borehole-to-surface and surface-to-borehole arrays. The status of our BHR research may be summarized as follows: (1) forward modeling algorithms have been developed and published to evaluate numerous resistivity methods and to examine the effects of well-casing and noise; (2) two inverse two-dimensional algorithms have been devised and successfully applied to simulated field data; (3) a patented, multi-array resistivity system has been designed and is under construction; and (4) we are seeking appropriate wells in geothermal and other areas in which to test the methods.

INTRODUCTION

Hydrothermal fluids and steam have large resistivity contrasts with their host rocks. The ability to discern these quantities, and to map basic structural controls based on their resistivity expression, are of high importance in establishing geothermal resources. At the University of Utah Research Institute (UURI), we have been advancing several methods of electrical and electromagnetic (EM) geophysics to address these goals. Magnetotellurics (MT), and its controlled-source, high-frequency complement CSAMT, can be important resistivity exploration tools for the shallowest to the deepest levels of interest in geothermal systems. While demanding careful and sophisticated instrumentation and processing techniques, the multidimensional interpretation capabilities of the MT method are developed more fully than for other EM methods. Detection of thermal fluid flow and high permeability which are concealed from the surface is a primary need in exploration both for low- and high-temperature systems. This need can be met in a cost-effective manner by the self-potential (SP) technique. Within established resource areas, a more precise understanding of reservoir bounds, re-injectate flow paths, and vapor regimes is desireable relative to exploration environments. The resolving power of surface surveys may be inadequate to meet this, however, and has motivated research into borehole resistivity methods (BHR). Our electrical geophysical program covers field application, numerical simulation, data processing and instrumentation components. Advances in these components for any one of the three principal sub-fields introduced above is seen to have important implications for the other two.

MAGNETOTELLURICS AND CONTROLLED-SOURCE AUDIOMAGNETOTELLURICS

Starting with our first research efforts in MT in the late 1970's, three principal shortcomings in the plane-wave technique have been addressed. These were a lack of interpretation tools to treat the effects on plane-wave responses of the very inhomogeneous structures encountered in geothermal systems, a lack of field MT data of sufficient accuracy and quantity to provide well-focused models of subsurface resistivity structure, and a poor understanding of the relation of resistivity to geothermal systems and physico-chemical conditions in the earth generally. The advances discussed here reflect primarily those funded by the DOE; equally substantial developments have resulted from NSF support (Wannamaker and Hohmann, 1991).

Numerical Simulation and Inversion. - Investigation of high-temperature resources in the structurally complex Basin and Range province beginning over a decade ago made obvious the fundamental effects which high-contrast resistivity inhomogeneity could impose upon MT responses. This observation has only been reinforced by our work in other environments. Two-dimensional models are usually a minimum requirement, and much valuable information in past MT data could not be extracted because reliable and practical 3-D approaches were lacking. Multidimensional interpretation codes have always required a larger computer than was available to most users. Gains in computer technology have been rapid but run-times are still very long and algorithm efficiency remains an important research goal. Moreover, the required accuracy in such programs is only a very recent achievement.

Our 2-D finite element algorithm, initially developed with NSF support but greatly augmented under DOE funding, is now the leading algorithm for MT simulation of complex resistivity cross-sections. Accurate and stable solutions were accomplished using a direct secondary field formulation for the finite elements (Wannamaker et al., 1987). Triangular elements have allowed precise simulation of topographic and bathymetric responses (Wannamaker et al., 1986; Figure 1). This program, together with its response-parameter Jacobians, has been combined with the regularized inversion concept to create the first minimum structure code for 2-D MT inversion (deGroot-Hedlin and Constable, 1990). The regularization damps the slope or curvature of a smooth resistivity solution while simultaneously minimizing data-model error until estimated chi-squared error is achieved, and so curtails spurious model artifacts not demanded by the data. However, the resultant resistivity models can be sharpened substantially through incorporation of external structural constraints, which accomodate topography and sloping subsurface boundaries. Efficiency also can be greatly improved by implementing iterative matrix solutions, e.g., conjugate gradients, for solving the large, damped step matrix, as well as the adjoint or reciprocal method of Jacobian derivation.

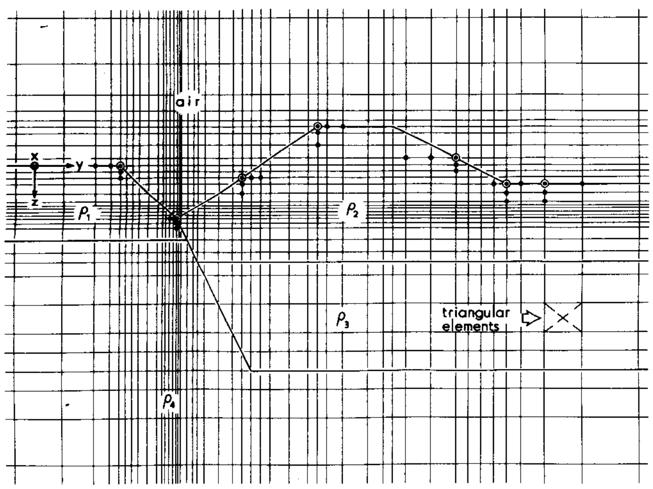

Figure 1. Central portion of example earth model as it would be simulated by our finite element algorithm. Example nodal locations used in computing auxiliary fields are shown with dots and are selected according to the character of the topography. Example field points are circled.

For three-dimensional numerical modeling and inversion, we have emphasized the integral equations technique. Early versions of the algorithm provided much insight into the applicability of 1-D and 2-D interpretation schemes in complicated environments (Wannamaker et al., 1984). Current advancements in this 3-D code include the ability to handle structures which outcrop, which transect layer interfaces of the 1-D host, and which extend indefinitely in one or more dimensions (Wannamaker, 1991a; Figure 2). While differential equations techniques have traditionally been viewed as more economical for arbitrarily complicated structures, enormous gains in efficiency for integral equations are possible. Development of the specific modeling technique we use is important also to serve as checks on accuracy of independent approaches of other authors. Augmentation of our 3-D code to accommodate finite EM sources is now receiving attention. This work is important in simulating finite source effects in CSAMT surveys and the code will also serve for modeling finite source EM data generally, including borehole EM applications. The 3-D modeling efforts are in close cooperation with those lead by Gerald Hohmann at the Department of Geology and Geophysics, who is supported by the DOE/OBES program and a consortium of industry users.

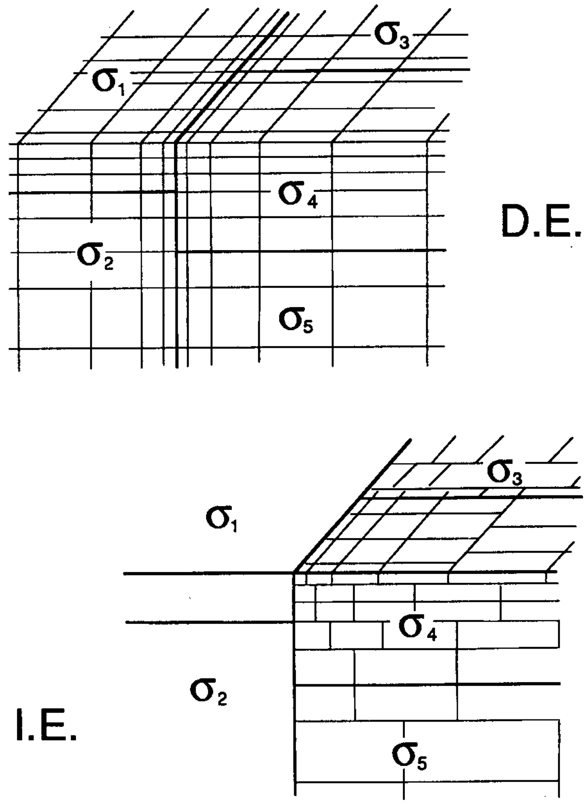

Figure 2. Schematic 3-D structure as is would be represented in both differential equation (D.E.) and integral equation (I.E.) modeling. For details of integral equations theory and test computations, see Wannamaker (1991a).

Field MT and CSAMT Surveys. - Our perception of the rigorous needs of modeling and instrumentation research have in large part been defined by our experience with field data. This started with study of an extensive MT data set over the Roosevelt Hot Springs thermal area in S. W. Utah about ten years ago (Wannamaker, 1983; Ross et al., 1982). The viability and limitations of CSAMT for delineation of shallow resistivity structure in geothermal systems was demonstrated about the same time (Sandberg and Hohmann, 1982).

A major geothermal field prospect, the Long Valley magmatic system, was addressable with the development of appropriate modeling techniques and in-house instrumentation at UURI (Wannamaker et al., 1991). A detailed profile of 24, high-quality MT soundings was deployed across the center of the caldera to exploit the NNW-trending preferred orientation of structure and facilitate selective 2-D modeling. Based on 3-D computer simulations using integral equations (Wannamaker et al., 1984), an accurate model resistivity cross section could be obtained by emphasizing the data subset corresponding to current flow across strike (the so-called TM mode), which is relatively immune to structural variations along strike (Figure 3). Confirmation of adequate sampling of the MT response over young volcanic rocks of the west moat was obtained with a contiguous profile of time-domain EM soundings donated by Unocal. A caldera-wide conductive layer containing the Early Rhyolite tuff and uppermost unwelded Bishop Tuff was mapped as well as substantial axial graben alteration related to Moat Rhyolite events. Low resistivity below 5 km depth under the west moat and axial graben may represent deep hydrothermal fluids with potential magmatic contributions, and shows very good correspondence with teleseismic delay and low density zones inferred independently. The data subsets representing current flow along strike (the TE mode impedance and vertical magnetic field), together with generic 3-D model simulations, demonstrated the finite strike extent of the mid-crustal, west moat conductor, also confirmed teleseismically.

deserves finite EM source simulation of at least a simplified 3-D model of the area. Such modeling would also address 'textbook' versus observed field patterns over the survey area,

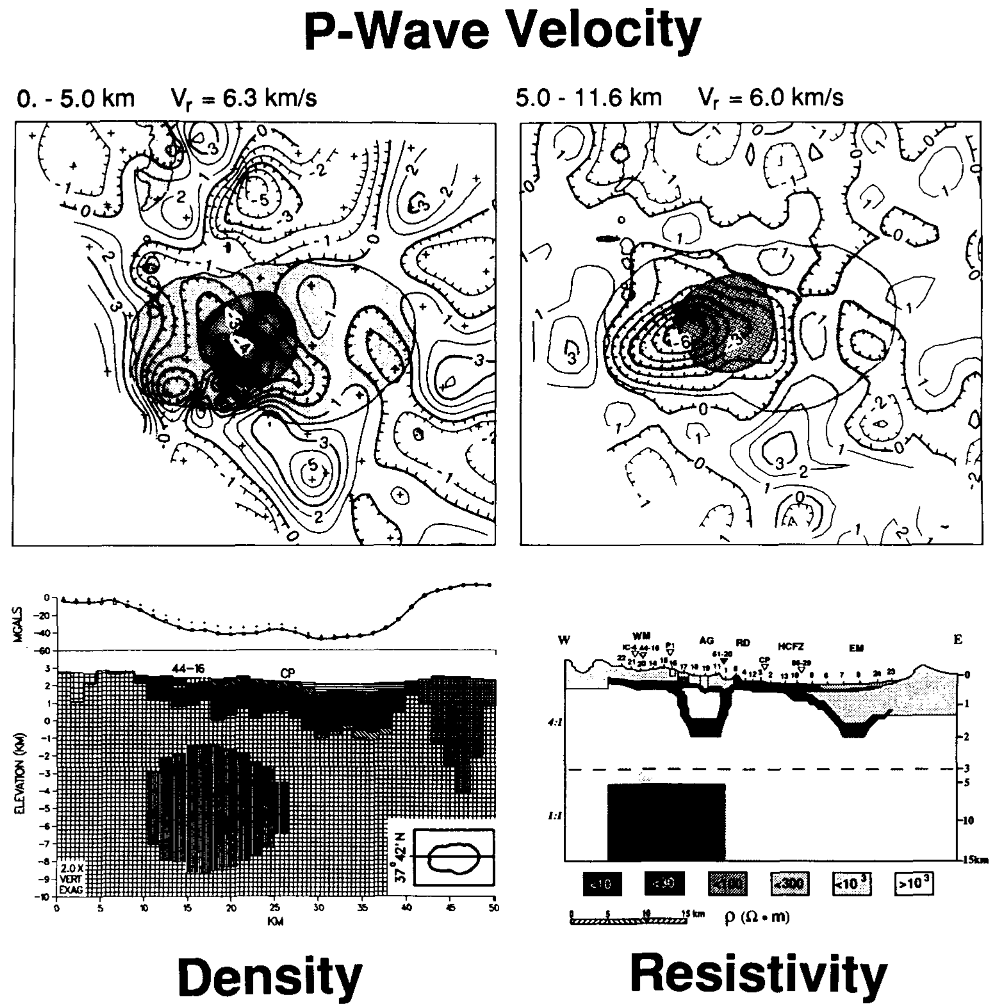

Figure 3. Resistivity model of Wannamaker et al., (1991) from MT compares closely with teleseismic delay (top left and right) and low density (bottom left) models derived by others (Wright et al., 1991). Low-resistivity alteration along bounding faults of axial graben is also implied. A conductive layer near the top of the Bishop Tuff, coincident with an important hydrothermal acquifer, is traced across the entire caldera. Note change in vert. exag. from 4:1 to 1:1 at 3 km depth in our model.

We have recently completed an extensive tensor CSAMT survey of the Sulphur Springs geothermal area, Valles Caldera, New Mexico, funded by DOE/OBES (Wannamaker, 1991b). The survey consisted of 45 high-quality soundings acquired in continuous profiling mode using two independent transmitter bipoles energized some 13 km south of the VC-2B wellhead (Figure 4). Agreement between the CSAMT and available MT data is very good over almost all the period range of overlap indicating that we are free of calibration problems and that far-field results are generally being obtained. Although the bulk of the resistivity model construction is still ahead, Sulphur Springs may serve as a natural testbed of traditional assumptions and methods of CSAMT. For example, unexpected near-field effects in the CSAMT data are apparent at 1 to 2 Hz; how near-field effects are determined by the host rocks to the survey area, by the local survey structure, or by the ensemble of resistivity structures from the transmitter to the survey area an important issue in viability of scalar or vector data compared to a full tensor collection. We have observed examples where source field orientation combined with minor heterogeneity causes substantial scalar-tensor disagreement, but not necessarily a vector-tensor one.

Instrumentation and Data Processing. - Superior instrumentation and data processing are vital to obtain accurate estimates of the MT responses, particularly at times of low natural field strength. Our experience in a variety of field experiments, both DOE and NSF sponsored, has made clear the necessary or highly desireable features of a wideband MT system. First, widespread and increasing cultural EM interference calls for fully remote reference measurements (10 km or more base-reference separations), although substantial gains have been made with even a local reference. Second, rapid and flexible deployment of the E-field apparatus independent of the magnetic setup, including capability for continuous E-profiling, is needed for efficient and adequate response sampling. Productivity here may be much enhanced by obtaining most of these data only at relatively short periods. Back-pack portability of the E-field apparatus is important and feasible although suitable lightweight induction coils also are being manufactured. Furthermore, because productivity and dynamic range in wideband data are so important, digital telemetry to carry base and reference signals to the central control computer are highly desireable to allow complete MT soundings on site and to greatly reduce setup time. A schematic showing our current design of deployment modes, much of which is implemented and functioning, is given in Figure 5.

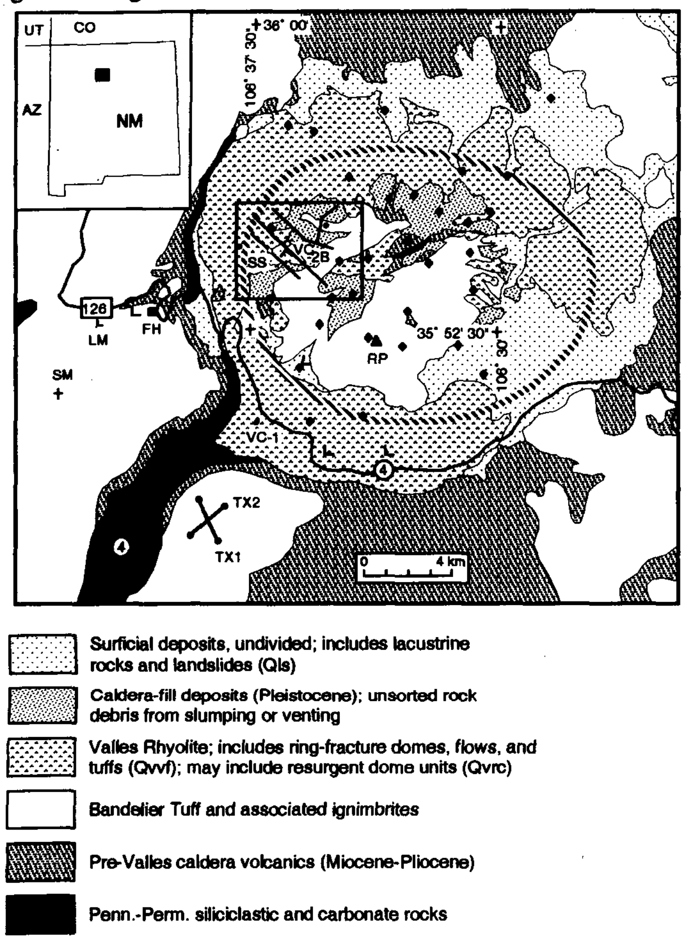

Figure 4. Map of Valles caldera showing principal geologic features and survey layout. Crossed bipole antennae are about 13 km SSW of CSDP corehole VC-2B and Sulphur Springs (SS). CSAMT data were taken outside the caldera at SM and natural field MT data at LM. Other MT sites include SAGE program (L symbols) and 31 soundings donated by recently by Unocal Co. (diamonds).

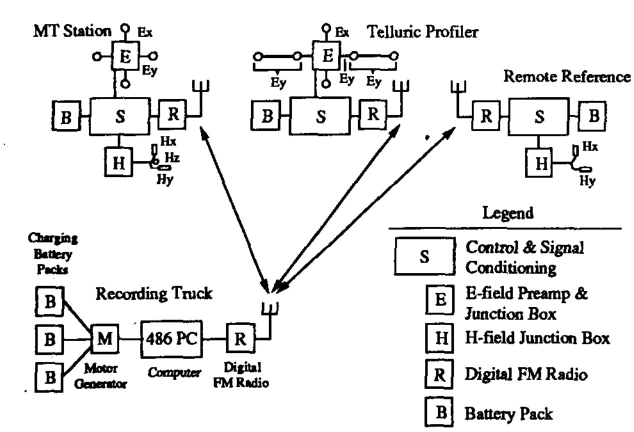

Figure 5. Schematic diagram portraying operational modes of UURI field MT instrument. Modes include 7-channel standard base-remote setup, 10-channel dual site collection, and 4-channel E-field profiling with 3-channel base H-field unit and remote reference.

Our original seven-channel MT system incorporating a local reference has been thoroughly rebuilt over the last four years, under a combination of DOE, NSF, and cost-shared funding from both the University of Utah and UURI, to exploit modern advances in computer equipment and analog hardware. Our system now consists of portable, battery-powered, CMOS computer-controlled signal conditioning units deployed at MT station and reference sites. The measurement sites are controlled by, and time-series data is sent by digital FM radio to, a separate control location comprised of an IBM compatible 486 PC and digital radio modem. Digital communications with A/D conversions at the sites preserves data dynamic range, provides a very low-noise environment, and allows closed-loop communications with automatic retry upon loss to ensure a continuous data stream from each unit. At the control truck, a multitasking system allows data processing concurrent with acquisition. Time series are processed using cascade decimation; spectra may be sorted on the basis of various multiple coherences to allow virtually complete definition of a tensor sounding on-site (Stodt, 1983). The time series are archived, however, for possible robust processing later. The standard 7-channel mode with a magnetic remote reference is operational now and several new soundings have been acquired (Johnston, 1992). The system is now being expanded to a third remote unit of 5-channels to provide E-field profiling and simultaneous dual MT site capacity.

SELF-POTENTIAL SURVEYING FOR COVERED GEOTHERMAL RESOURCES

Self-potential (SP) surveys have been used often in mapping anomalies related to thermal fluid flow in geothermal systems and is attractive due to its low expense and simplicity of application. Major developments by R. Corwin, D. Fitterman, D. Hoover, and W. Sill in the 1970's and 1980's examined the general nature of SP anomalies in geothermal systems, established the probable physical phenomena taking place, and developed new approaches for numerical modeling of the data. Although many surveys were conducted by the geothermal industry, the wide variety of anomalies, effects of topography or near-surface hydrology, and some poor or ambiguous survey results prevented the method from gaining the acceptance we believe it deserves. Testimony from industry at a recent DOE Exploration Technology Workshop at Lawrence Berkeley Laboratories (September, 1991) included these telling comments: "SP anomalies have the highest correlation with heat flow or temperature gradient results of all the geophysical methods"; and "What we need are more examples of good SP data related to other data bases from known geothermal systems". The UURI SP effort addresses these issues, and focuses on the use of SP as a reconnaissance technique, using geologic target selection criteria, for covered geothermal resources. Our experience with SP in the Sevier Thermal Area of the eastern Great Basin (Figure 6) exemplifies the issues and potential of the method.

Concealed Resources in the Escalante Desert. - A conceptual model for geothermal occurences suggests that hidden resources are present beneath alluvial cover in the Basin and Range province. This model draws on experience at the Newcastle (Utah) system where a hot water (108°C maximum) acquifer between 70 and 110 m depth was discovered accidently upon drilling of a new farm irrigation well (Blackett et al., 1990). A thermal reservoir temperature of about 130°C was inferred geochemically. With the exception of surface expression, geologic conditions at Newcastle are similar to many other known geothermal areas in the Basin and Range. Such convection systems typically include recharge in higher elevations and deep circulation of meteoric water along fracture zones in regions of elevated heat-flow. Fluids then discharge to the surface along or near the intersection of these zones with NNE-trending range-front faults (Figure 7).

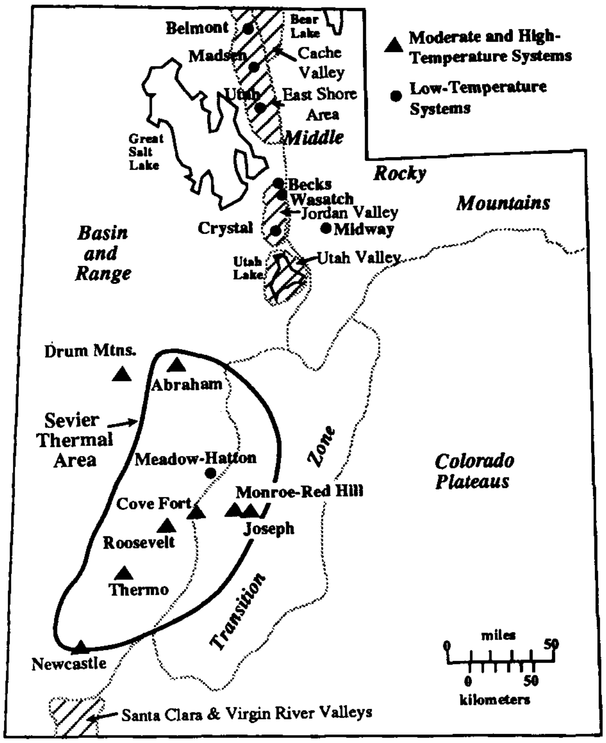

Figure 6. Geothermal systems of the Sevier Thermal Area, Utah, showing the location of study areas. Cross-hatch pattern denotes other low-temperature geothermal basins.

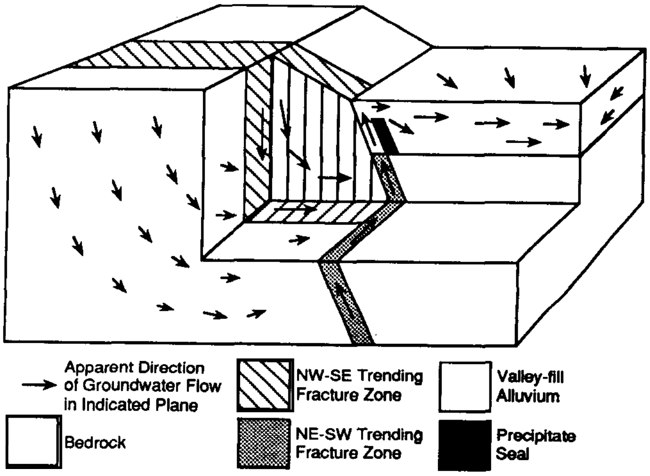

Figure 7. Conceptual model indicating possible patterns of groundwater flow in the Newcastle hydrothermal system (modified from Blackett et al., 1990). NE-SW trending fault zone corresponds to Basin and Range normal faulting.

Following the unexpected discovery of thermal waters at Newcastle, extensive dipole-dipole resistivity and SP surveys were carried out (Ross et al., 1990). The resistivity data imply a thermal outflow plume and, with numerical modeling, indicate a probable upflow zone adjacent to the trace of the major range-front fault (Antelope Range fault) and including the area of highest heat flow (Figure 8). The SP data quality was enhanced by preparing and watering potholes hours prior to measurement; noise levels within 1 mV were thereby achieved. The survey mapped a well-defined 108 mV minimum, with a 2:1 elongation along strike of the Antelope Range fault, near the two highest temperature gradient holes. Several other SP anomalies of a few tens of mV were also delineated. The principal anomaly is consistent with a point or small 3-D source at depths of the order of 20 to 60 m. The correspondence with high near-surface temperatures, and a probable fluid conduit indicated by resistivity data and geologic mapping, leave little doubt that the SP source nicely defines the main thermal upwelling zone; the throat of this geothermal system. We note that the dipole-dipole and the SP surveys each were conducted within one week, including mobilization from 280 miles away. This argues for their cost-effectiveness especially for moderate-temperature systems where electric power production is not the intended goal.

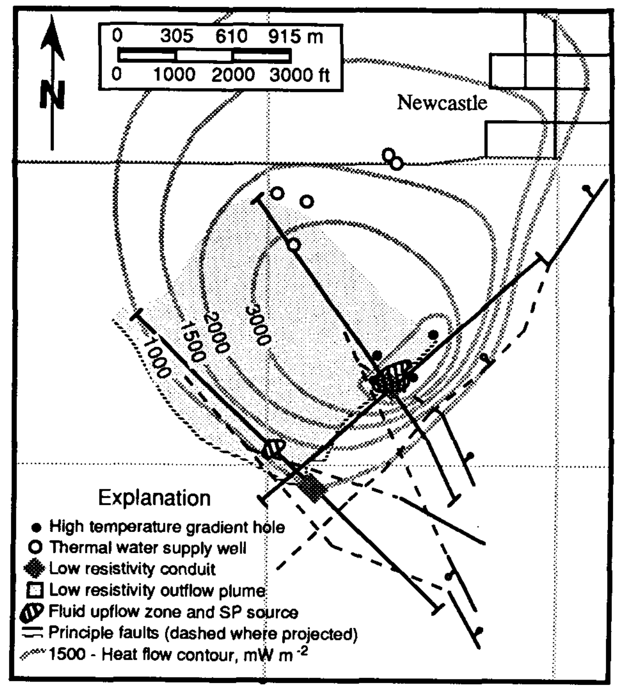

Figure 8. Interpretation summary showing probable fluid conduits indicated by resistivity and SP data, the outflow plume, and faults projected beneath alluvium (Ross et al., 1990).

Given the promising experience at Newcastle, SP surveying was carried out at two other prospects in the Sevier Thermal Area; Wood's Ranch and Thermo (Ross et al., 1991). Survey procedures were modified to improve accuracy and efficiency by using a radial or 'spoke' technique to minimize cumulative errors. Perpendicular and parallel profiles could also be taken using the same central reference electrode when more detail was needed. Wetting electrode holes to improve contact is feasible, if done with care, but choosing survey periods to utilize recent rainfalls and moist near-surface conditions is perhaps more desireable. Data repeatability of a few to several mV typically was achievable with these procedures.

At Wood's Ranch study area, two wells drilled for irrigation showed a flowing temperature of 36.5°C at the surface and chemical geothermometry suggests a likely reservoir temperature maximum of 110 - 120°C (Ross et al., 1991). Surface thermal manifestations are otherwise absent. About 25 line-km of SP data was obtained at an average station spacing of 61 m and covered an area of about 8 km^2. The survey defined a broad, elliptically-shaped negative anomaly oriented northeast and lying between the two thermal wells. This anomaly is interpreted to reflect upward movement of thermal fluids along a relatively narrow, NE-oriented fracture zone, which subsequently become diluted and cooled while mixing with other ground waters. At Thermo Hot Springs, thermal water discharges weakly from two spring mounds located along NE-oriented normal faults near the center of the Escalante Valley and imply reservoir temperatures of about 130°C from chemical geothermometry (Ross et al., 1991). The SP survey covers 10.4 km^2 and includes 45 line-km of data at station spacings of 30 and 60 m. Modest anomalies either positive or negative are associated with the thermal mounds. However, a broad, complex minimum with values locally under 100 mV occurs about 1.6 km S. E. of the southern mound and suggests a source depth of less than 100 m. This is considered a prime site for thermal gradient drilling. Drillhole information is lacking in this specific area, but thermal gradient data nearer the mounds suggest that the system may extend eastward from them. Compared to Newcastle, the tie between geothermal sources and SP anomalies at both Wood's Ranch and Thermo is weak and additional data collection at these sites is highly desireable.

SP Studies in the Southern Rio Grande Rift. - Three detailed SP surveys have been completed in southern New Mexico as well in close cooperation with Mr. J. Witcher of New Mexico State University. At Rincon, discovery of which was announced just in 1991 by Witcher, the SP survey showed more detail and tracked the thermal anomaly more closely than radon soil-gas surveys. A NNW extension of the thermal zone was implied and also a possibly substantial, deeper source to the NE corresponding to one anomalous radon soil-gas station. At Radium Springs, where recent greenhouse expansion is taxing the known near-surface reservoir, SP and radon surveys have identified other possible fluid upflow zones. Well-defined SP minima exceeding -100 mV were observed at both the Rincon and Radium Springs areas. Initial results at the better-known Tortugas Mountain geothermal area, which provides space heating for New Mexico State University buildings, indicate a SP minimum corresponding to the known production area. This last covered resource area deserves fuller characterization.

Numerical Simulation Considerations. - Quantitative evaluation of SP anomalies for causative sources requires knowledge of the earth resistivity structure, because it controls current flow patterns due to the thermoelectric (TE) or the electrokinetic (EK) cross-coupling sources. Modeling the SP data within a constrained resistivity structure to obtain strength and distribution of cross-coupling sources requires specification of the primary flow pattern, where the primary flow is temperature for the TE effect or hydraulic pressure for the EK effect (Sill, 1983). TE sources were preferred by Sill (1983) at the Monroe-Red Hill system due to the fundamental appearance of the SP anomalies, but the resultant model cross-coupling properties were larger than typically measured in the laboratory perhaps reflecting some EK component. Distributed anomalies such as that at Wood's Ranch may deserve more quantitative modeling for source distributions. Improved modeling and data acquisition approaches for CSAMT described earlier or for DC resistivity discussed in the next section should allow better-focused estimates of thermal fluid flow locations. Our substantially augmented DC algorithm itself could be modified straightforwardly for more accurate SP modeling including finite source strike extent within an otherwise 2-D resistivity model. This is considered a realistic approximation for many situations in the Basin and Range and Rio Grande Rift.

BOREHOLE ELECTRICAL GEOPHYSICS

There are several potential applications for borehole electrical surveys in geothermal energy development. First, the exploration problem usually involves finding hot (>150°C) subsurface regions of high enough permeability to produce economic quantities of fluids from depths ranging from 300 m to over 3000 m. Zones of higher permeability filled with hot waters are normally expected to be conductive relative to the wall rock of the reservoir, but may not be appropriate targets for surface methods because of depth and resolution considerations. Second, injection of spent geothermal fluids is an important part of the exploitation scheme because it avoids environmental problems with surface disposal and can provide reservoir recharge. The injectate flow path must be neither too direct, causing short circuit between injection and production wells, nor must it be too long, giving no effective recharge. It is thus important to know the fate of cooler injected fluids, which are normally expected to have a higher resistivity than reservoir fluids at normal temperature. Third, rapid development of vapor-dominated hydrothermal systems can result in sharp pressure declines and production of hydrochloric acid from wells, such as evident in The Geysers field and at Lardarello. Testing the theory that both pressure decline and HCl result from drying of the residual liquid water seems a suitable task for borehole electric geophysics. However, rather little is known about the electrical properties of steam-filled rocks.

There are, on the other hand, significant problems for borehole electrical surveys in geothermal exploration and production. Developing modeling and interpretation methods is perhaps the easy and less expensive part of the task. The problem of operating in geothermal wells is not trivial. Production wells are typically at temperatures of 150°C to 350°C. In liquid-dominated systems, the water may contain 2,000 to 350,000 mg/l of dissolved salts as well as dissolved gases and may be very highly corrosive. In vapor-dominated systems, the steam is highly invasive, penetrating the seals in tools even though their temperature limit has not been exceeded. Making electrical contact with wallrock in open holes under production may be difficult. Perhaps half of geothermal production wells have a slotted steel production liner hung from the bottom of the cemented casing. EM methods may be preferrable for cased holes and for highly resistive wall rock, but have additional problems in application.

Most of our work to date has been in development of the galvanic resistivity method. This preference reflects the relatively simple down-hole equipment, consisting only of electrodes. There is no need to place electronics in the hot, corrosive geothermal environment. Because the down-hole equipment is simple, adaptation of conventional logging equipment has been relatively straightforward. Nevertheless, development of borehole electrical techniques for geothermal application is truly in a research stage, and many important problems remain. Although logging companies offer standard logs for many geothermal applications, none offer the type of borehole surveys we are discussing here. While much progress toward field survey capability for deep, hot holes has been made, evaluation of the techniques in the field still remains.

Numerical Simulation and Inversion. - Since the early 1980's, numerical studies of borehole electrical responses have been undertaken at UURI. Most were reviewed of late by Wright (1990). They have included techniques of cross-borehole and surface-to-borehole, mise-a-la-masse, TDEM, VLF, CSAMT, and magnetometric resistivity (MMR) surveying, and conductive well casing effects. Their purpose generally was to illuminate fundamental anomaly characteristics as a function of electrode array, resistivity contrast, structural attitude, and in the presence of geological noise and topography. The MMR method is interesting in that the layered host creates no response leaving only anomalous structure to affect the readings (LaBrecque and Ward, 1987). Pellerin et al., (1992), with support to G. Hohmann's group by DOE/OBES, point out that interpretation for the purely direct-current MMR technique is much easier than for similar time or frequency domain EM data with a vertical electric source, and only MMR is easily correctable when the borehole deviates from the vertical.

One recent achievement of note has been the study of conductive well casing effects by LaBrecque (1989). Many wells are only partially cased, and this study showed that the uncased portion can be surveyed with accuracy. For the borehole-to-surface method, casing effects are small once the transmitter pole is completely below the casing and the receiving dipole is one casing length away from the wellhead. Figure 9 illustrates resistivity profiles for a surface receiver dipole and a current pole moving down the borehole. The effect of the casing does not extend far beyond its lower extremity and the anomaly due to the body is clearly seen. For the cross-borehole method (not shown), effects of casing at the top of the receiving hole can be ignored when the dipole receiver is completely below the bottom of the casing regardless of the transmitter depth. Casing in the transmitter hole produces somewhat more of a problem, but acceptable results can be obtained when the transmitter electrode is completely below the casing and the receiving dipole is 0.5 casing lengths below the casing bottom.

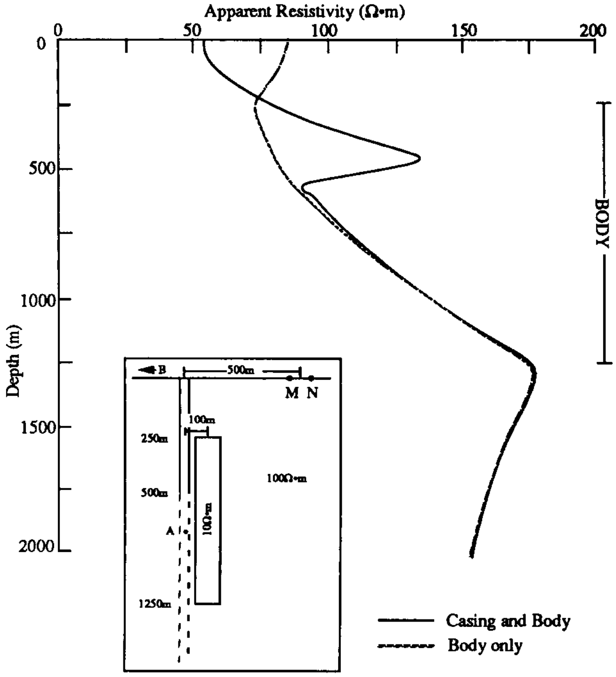

Figure 9. Borehole apparent resistivity profile for a downhole pole source, a 100 m long surface receiving dipole, and a conductive vertical prism nearby the hole. The borehole is cased to 500 m and the receiver is situated laterally 500 m from the borehole (after LaBrecque, 1989).

LaBrecque (1989) went on to demonstrate a line-integral method to compute forward and inverse models. This algorithm directly determines locations of boundaries of arbitrarily polygonal-shaped regions as well as the conductivities within them. The approach allows introduction of as much ancillary information as possible and can reduce inherent non-uniqueness in the method. Considered also was the very important question of what happens when some of the assumed constraints are incorrect and the inversion is forced to consider an inappropriate class of solutions. Erroneous constraints were shown to be disastrous often, making obvious our need to be certain of these in modeling field prospects.

Beasley (1989) produced a forward and inverse program for 2-D, cross-borehole DC resistivity responses using a secondary potential formulation of the finite element method. A first-order roughness matrix was used to smooth the solution although maximal smoothness was not explicitly sought. Inversion studies with the code emphasized enhanced oil recovery process monitoring (Beasley and Tripp, 1991), but some of the results are applicable to geothermal field evaluation especially in prospects with extensive sedimentary rocks. In Figure 10, a basic model with a horizontal, 20 m thick stratum is buried 500m in a half-space host of 10 ohm-m. It is immediately overlain by a 2 m thin shale layer initially of 10 ohm-m. Before steam-flooding, the stratum has a resistivity of 50 ohm-m. The intruded steam zone itself increases formation resistivity to 500 ohm-m and a hot water-oil bank zone of 10 ohm-m bounds the steam and unprocessed pay zone. The overlying thin shale decreases in resistivity, on the other hand. The domain and properties of each of these zones in the flood model is shown at the top of the figure. The 2-D forward response of this scenario forms the synthetic data set which is inverted after the addition of 5% Gaussian noise to each reading.

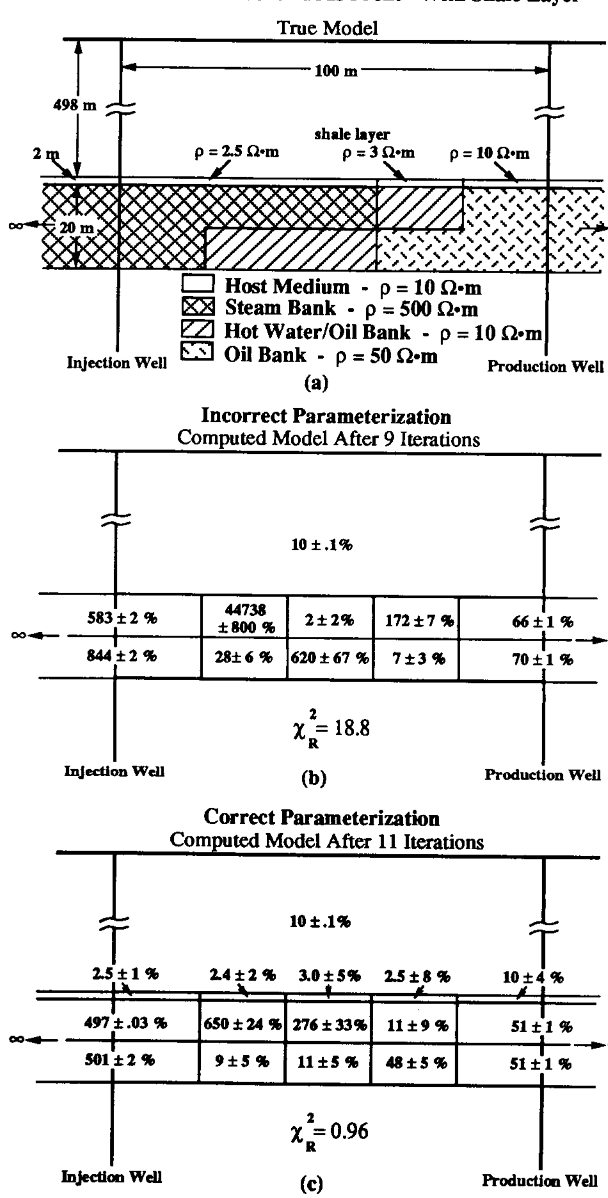

Figure 10. (a) The true model of the oil reservoir capped with a variable resistivity shale layer after the nonvertical steam flood has migrated toward the production well. The steam flood is lead by a hot water/oil bank. (b) The computed model

after 9 iterations with insufficient model parameterization. The resistivities of the starting model are 10 ohm-m for the host medium and shale and 500 ohm-m for all parameters contained in the reservoir zone. The computed resistivity and percent standard deviation of each parameter are given. (c) The computed model after 11 iterations with a sufficient model parameterization. The starting resistivities and parameter statistics are as above.

Since at pre-injection temperatures, the shale layer is not distinct from the host, it might be overlooked initially in an inversion. Results with an inversion parameterization not accounting for the shale appear in the middle of Figure 10 and are quite erroneous. Fortunately, the extremely large reduced chi-squared is incompatible with an acceptable solution and calls for a reparameterization. With the shale accounted for, the inversion can recover each of the different zones with reasonable accuracy. In short, if geometric or other external constraints are to be used, we must be certain of them; otherwise, the inverse model must be allowed a more arbitrary but damped variation.

Present-day research has focused on computational accuracy and generalization and efficiency of inversion capability. For the 2-D problem, accuracy of the spatial inverse Fourier transform to achieve the electric potential in Cartesian space from a series of wavenumber (k_x) potentials has been greatly increased by a combination of Gaussian quadrature techniques exploiting the known logarithmic singularity at small k_x, and the exponential decay at large k_x. Accuracy around 2 ppk now appears possible, and further gains should come by emphasizing bipolar sources even when the return current pole may be quite distant. Response-parameter Jacobians are evaluated using electrical reciprocity, which provides the sensitivities for arbitrary numbers of parameters as is needed in modern minimum structure inversion. An accurate linear relation between the Jacobians and percent frequency effect is exploited for modeling and inversion of IP responses. The next major step is implementation of a regularization matrix for smooth inversion capability, and eventually the flexibility to incorporate independent geometric contraints to sharpen resistivity estimates.

Field Data Acquisition. - We are currently renewing work on this aspect of the project after a major slow-down due to budget restrictions. Our principal effort during the coming year will be to complete our field system and obtain a set of data from one or more areas. We believe that a field data set is of high priority at this time in order to determine the effectiveness of present interpretation approaches and to plan further work on interpretation algorithms. Second in priority will be to continue development of interpretation methods for borehole electrical methods. For completion of the field equipment, we have only to interface transmitting and receiving equipment (Zonge Engineering Research Organization) with the two winches and cables we have purchased and refurbished during the last year. We have purchased a used logging vehicle with the two winches and have had it reconditioned. We have acquired 5,000 feet of high-temperature logging cable that will be used for the receiver array and 3,000 feet of high-temperature cable for the downhole transmitter. These are mounted on the winches. Our next step is to determine downhole electrodes and install them. Probably our first test survey will be surface-to-borehole measurements in two uncased, 500 ft. deep holes recently drilled in the Ferron sandstone of central Utah for petroleum reservoir studies carried out also at UURI. Use of these holes is desireable due to logistics, lack of hostile conditions, and detailed characterization of the lithologies from the reservoir studies.

Borehole resistivity field data sets are difficult to come by and we will exercise our interpretation algorithms on data of opportunity not directly related to geothermal prospecting. Wang et al., (1991) have inverted mise-a-la-masse borehole-to-surface data from a series of shallow-depth hydraulic fracturing experiments in a landfill site using the DC alpha-center method. The well-casing of an injection borehole was electrically energized to constitute a vertical line source of current and potentials were measured at various points on the surface near the borehole both before and after hydraulic fracturing was performed using a conductive fluid (Figure 11). The advantages of the alpha-center technique are its speed and simplicity, and its ability to handle 3-D geometry and indicate positions of conductive inhomogeneities. The forward solution was incorporated into an iterative least-squares inversion algorithm, with constraints applied to the alpha-center parameterization to facilitate modeling of fractures. Inversion for position and orientation of fracturing was relatively satisfactory though less so for fracture length.

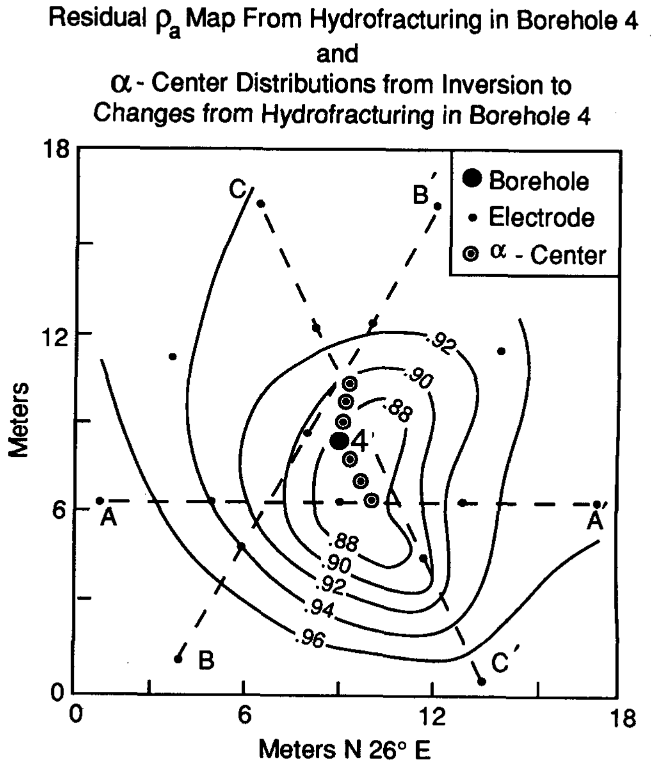

Figure 11. Residuals obtained by dividing post-fracture apparent resistivities by the pre-fracture apparent resistivities, and best-fitting alpha-center inversion of the fracturing induced around the borehole, in the presence of a fixed background distribution of alpha-centers as discussed in Wang et al., (1991). Borehole location denoted by numeral 4. Offset of model structure from anomaly may be due to coarse data sampling.

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