Project Final Report, to:
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Title: Imaging Multi-Dimensional Electrical Resistivity Structure as a Tool in Developing Enhanced Geothermal Systems (EGS)

Award No.: DE- FG36-04GO14297

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Executive Summary: The overall goal of this project has been to develop desktop capability for 3-D EM inversion as a complement or alternative to existing massively parallel platforms. We have been fortunate in having a uniquely productive cooperative relationship with Kyushu University (Y. Sasaki, P.I.) who supplied a base-level 3-D inversion source code for MT data over a half-space based on staggered grid finite differences. Storage efficiency was greatly increased in this algorithm by implementing a symmetric L-U parameter step solver, and by loading the parameter step matrix one frequency at a time. Rules were established for achieving sufficient jacobian accuracy versus mesh discretization, and regularization was much improved by scaling the damping terms according to influence of parameters upon the measured response. The modified program was applied to 101 five-channel MT stations taken over the Coso East Flank area supported by the DOE and the Navy. Inversion of these data on a 2 Gb desktop PC using a half-space starting model recovered the main features of the subsurface resistivity structure seen in a massively parallel inversion which used a series of stitched 2-D inversions as a starting model. In particular, a steeply west-dipping, N-S trending conductor was resolved under the central-west portion of the East Flank. It may correspond to a highly saline magamtic fluid component, residual fluid from boiling, or less likely cryptic acid sulphate alteration, all in a steep fracture mesh. This work gained student Virginia Maris the Best Student Presentation at the 2006 GRC annual meeting. Ongoing development is aimed at porting to multi-core processor (i.e. Xeon) workstations using OpenMP.

Objectives and Accomplishments

Under the overall goals of the DOE Enhanced (Engineered) Geothermal Systems program, we seek to create or stimulate geothermal reservoirs in regions of high heat content but lacking in existing hydrothermal resources. Defining and enhancing fluid pathways, detecting results of processes which form the subsurface heat exchange system, and ability to monitor the engineered system for changes in physical properties over time are prime topics for research in EGS which this project addressed. Broader project objectives include increasing the number of states with geothermal electric power facilities, reduced the levelized cost of generating power, and increase the power/heat energy supply for homes and businesses by improving exploration technology.

Although zeroing of the Geothermal R&D program for FY07 prevented full accomplishment of original proposal goals, outstanding progress was made in several areas. A base-level 3-D finite difference program for MT inversion supplied by colleague Y. Sasaki of Kyushu University was made a great deal more efficient in storage layout and runtime allowing inversion of realistic geothermal data sets on 2 Gb desktop PC's under Windows XP to be achieved. In particular, the 101 site data set collected by U Utah over the Coso East Flank area was inverted and all main features were recovered which were seen also in massively parallel inversion by the Lawrence Berkeley Lab group. This work gained student Virginia Maris the Best Student Presentation at the 2006 GRC annual meeting.

Project Activities and Results

Background/Approach: Despite some very solid advances, the production of reliable subsurface images of resistivity from the data has remained problematic for several reasons. These include accuracy of the basic numerical approximations to electromagnetic (EM) physics, computational resources affordable by only a very few, adequate dimensionality assumptions, and stability of the final images against starting guess or non-ideality of the data. This project aimed to overcome these difficulties by developing a fully three-dimensional (3-D) EM inversion algorithm practical on desktop PC's or workstations, and to test it against 3-D data which we have gathered in recent efforts. An EGS project which benefited from this development was that at the Coso geothermal field (P.I. Peter E. Rose, DE-PS07-00ID13913), where MT measurements in support of stimulation experiments were carried out by P.I. Wannamaker.

The 3-D inversion development herein addressed principal facets of practical subsurface imaging technology: maximal solution stability, computational accuracy, high speed, minimal storage, and hardware affordability. It has been our intention to bring meaningful 3-D inversion capability to the PC environment. Given advances in computer platforms, and the advances proposed here, the Gauss-Newton (G-N) parameter step known for its good convergence now appears practical for the largest data sets encountered so far in geothermal applications. Computational accuracy is ensured through use of a particular staggered grid finite difference (FD) implementation shown to have superior characteristics to others published so far. The chief bottleneck of the G-N approach has been laborious computation of the parameter sensitivities; a theoretical formulation to alleviate this was developed based on the integral equations (IE) method. This project also has supported Ph.D. candidate Virginia Maris thoughout her thesis program.

This project has been a cooperative effort with Professor Yutaka Sasaki of Kyushu University, Japan, and Dr. Fang Sheng of Baker-Atlas, Inc. Sasaki has written several 3-D FD forward codes and a 3-D Gauss-Newton inversion program for structure in a half-space host. Copies of 3-D forward codes were delivered to Wannamaker near the start of the project. They have been tested and modified for use at EGI, and shown to be accurate compared to our independent integral equations 3-D platform (reported in an earlier quarter). Storage capability of the program was improved by solving the parameter matrix as a vector rather than a block, which takes advantage of the symmetry of the matrix and essentially doubles the viable matrix size. A streamlined version of the program has been created for simplicity where the Gram-Schmidt solver and regularization sweep code are removed and smoothing is by slope only. Regularization was greatly improved by modifying the smoothing weights to reflect the influence of individual parameters upon the response.

The improved algorithm was applied to a suite of 101 MT soundings taken over the East Flank of the Coso geothermal system under contract to Quantec Geoscience Inc. in early 2002 under DOE and Navy support. In-field EM noise associated with production plus non plane-wave effects associated with the GW-scale Bonneville PA DC Intertie running a few miles to the west of Coso necessitated novel remote-reference MT processing techniques. In particular, the Parkfield CA MT observatory time series recorded some 260 km westward of Coso were employed to recover MT responses of the first field deployment, while the second deployment utilized a reference established by Quantec near Socorro NM 600 miles to the east with time series linked through high-speed internet ftp.

Two-dimensional inversion of an associated dense array MT profile across the East Flank revealed a steeply west-dipping conductor under the west-central portion of the survey area. Stitched 2-D inversions of mini-profiles selected from the 101 sites were interpolated to create an initial guess for 3-D finite difference inversion by the Lawrence Berkeley Lab group on a massively parallel computer. These models confirmed north-south continuity of the steep conductor under most of the East Flank, but not extending north of the main Coso Hot Springs access road. In cooperation with the modified Kyushu Univ. code, U Utah carried out 3-D finite difference inversions on a 2 Gb desktop PC and replicated main features of the steep conductor, including verifying that it extended as far north as the dense array profile, using a half-space starting model. This low resistivity zone could represent presence of high-salinity magmatic fluids, high-salinity residual fluids from boiling, or less likely cryptic acid sulphate alteration fluids, in a steep fracture network.

Details of algorithm workings, data characteristics, and final model implcations are discussed much more thoroughly in the previous GRC annual meeting paper by Maris et al, which is appended to this report. Zeroing of support to the geothermal R&D program for FY07 meant that the full development initially intended was not possible. This mainly included incorporation of layered host and finite source capability to the inversion platform. We are seeking to advance this through other sources of support. Ongoing development is aimed at porting to multi-core processor (i.e. Xeon) workstations using OpenMP.

Developed Products

Wannamaker, P. E., and Y. Sasaki, 2003, Three-dimensional electromagnetic inversion combining a finite difference forward solver with integral equations jacobians, Proc. IIIrd Quadrennial Symposium on Three-Dimensional Electromagnetics, Macnae, J., and G. Liu, eds., Australian Society of Exploration Geophysicists, Adelaide, 5 pp.

Wannamaker, P. E., P. E. Rose, W. M. Doerner, B. C. Berard, J. McCulloch, and K. Nurse, 2004, Magnetotelluric surveying and monitoring at the Coso geothermal area, California, in support of the Enhanced Geothermal Systems concept: survey parameters and initial results, Proc. 29th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, SGP-TR-175, 8 pp.

Newman, G. A., M. Hoversten, E. Gasperikova, and P. Wannamaker, 2005a, 3D magnetotelluric characterization of the Coso geothermal field, Proc. 30th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford California, January 26-28, SGP- TR-176.

Newman, G. A., M. Hoversten, P. Wannamaker, and E. Gasperikova, 2007, 3D magnetotelluric characterization of the Coso geothermal field, Geothermics, in review.

Maris, V., P. Wannamaker, and Y. Sasaki, 2007 Three-dimensional inversion of magnetotelluric data over the Coso geothermal field, using a PC, Geothermal Resources Council Transactions, 31, 187-191.

Maris, V., P. Wannamaker, and Y. Sasaki, 2007 Three-dimensional inversion of MT data over the Coso geothermal field, using a PC, Proc. IVth Quadrennial Symposium on Three-Dimensional Electromagnetics, Spitzer, K., and R. Boerner, eds., Freiberg, Germany, 4 pp.

An ascii listing of the rectilinear inversion parameter resistivity values and geometries from the Coso inversion is available from the P.I. upon request.

Three-Dimensional Inversion of Magnetotelluric Data over the Coso Geothermal Field, Using a PC

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Keywords

Magnetotellurics, inversion, Coso, electrical resistivity

ABSTRACT

Magnetotelluric (MT) data from 101 tensor stations over the East Flank of the Coso geothermal field, southeastern California, were inverted on a PC using a 3-D Gauss-Newton regularization algorithm based on a staggered-grid, finite difference forward problem and jacobians. Static shifts at each MT site can be included as additional parameters and solved for simultaneously. Recent modifications to our algorithm include the addition of an LU solver to calculate the model parameter update, to reduce storage. The inversion for the Coso data set was started from a 22 ohm-m half-space and results qualitatively resemble models from 2-D transverse magnetic (TM) inversions, and from massively parallel 3-D inversion by other workers. In particular, we resolve a steeply west-dipping conductor under the western East Flank tentatively correlated with a zone of high-temperature ionic fluids. Implementation on desktop serial PC's is an attempt to widen the potential user base. Run times for the Coso data set on a 3.4 GHz desktop are 2-3 days, with the greatest amount of run-time taken up in computing the jacobians explicitly using reciprocity. Continuing efforts are being made in storage efficiencies, in speeding the jacobian computations, and improved parameter weighting.

Introduction

The MT method has been successfully used to image subsurface electrical resistivity in complex geothermal systems, detecting variations related to fluid flow such as increased electrical resistivity contrasts due to high fluid concentrations in fractures, and to conductive alteration minerals. MT data interpretation is complicated by the commonly 3-D nature of the subsurface resistivity, including frequency-independent, apparent resistivity static shifts. Three-dimensional interpretation historically has required large computing resources and long run times (Newman et al., 2005a). The inversion algorithm of Sasaki (2004) solves simultaneously for static shift and 3-D subsurface conductivity distribution parameters on a personal computer and can handle moderate-sized data sets.

One of our goals is to apply the developed algorithm to MT data collected at the East Flank of the Coso geothermal area, a high-temperature power-producing field in southeastern

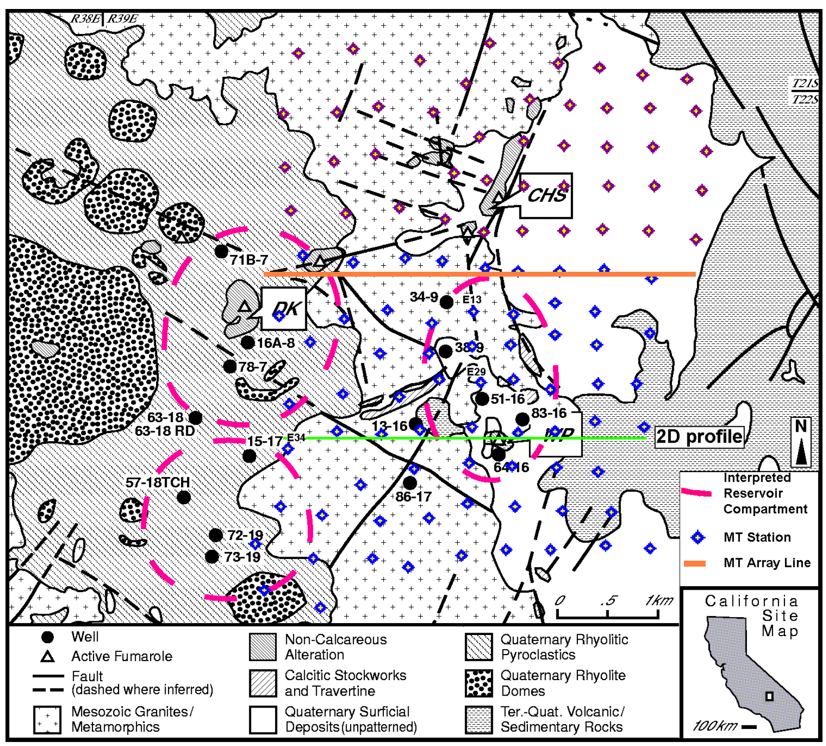

Figure 1. Map showing locations of MT soundings and dense array profile over the east flank of the Coso geothermal field by the University of Utah/EGI. The green line is the location of the 2-D profile shown in Figure 2.

California (Monastero et al., 2005). Just over 100 separated sites plus a dense array line were collected in this difficult environment by Wannamaker et al. (2004) as part of the U.S. Dept of Energy's Enhanced Geothermal Program research (Sheridan et al., 2003) (Figure 1). Interpretation of these data has included 2-D stitched vertical slices (Wannamaker, 2004; Newman et al., 2005a), and 3-D inversion using a massively parallel computer (Newman et al., 2005b, 2007).

An important structure appearing in these interpretations is a high-angle conductor most prominent in the southwest East Flank sector correlated with its producing reservoir. Previously published 3-D inversion results however do not address the removal of static shift, instead opting to reproduce them with fine discretizations, and starting guesses incorporated 2-D inversions rather than a half-space. Our longer term goal is to carry out 3-D inversion of the Coso MT data using an improved and efficient PC-based algorithm, solving for subsurface conductivity structure and static shift parameters simultaneously. In this effort, we show that most features of previous inversions can be resolved with a reduced discretization model and no static shift estimation on a desktop PC.

Inversion Scheme

The MT method consists of measuring the variations in the magnetic field surrounding the earth, originating from the magnetosphere and from thunderstorm activity, and the resulting electrical currents induced in the earth (Vozoff, 1991). The ratio of horizontal electric to magnetic fields forms the impedance, which depends on frequency, source field polarization, and subsurface geoelectric structure. The impedance magnitude (and thus apparent resistivity ρ_a), can be affected by a frequency-independent vertical shift (static shift, s) which varies with site and source polarization, and is caused by small-scale, near-surface inhomogeneities. The impedance phase (ϕ) is unaffected by the static shift.

To solve the inverse problem for both subsurface conductivity model parameters m and static shift s, and to constrain the solution, the following objective function is defined (Sasaki, 2004):

$$\psi = \left\| W\left(d_{pre} - d_{obs}\right)\right\|_2 + \lambda^2 \left(\left\| W_m C m_1 \right\|_2 + \alpha^2 \left\| W_m (m_1 - m_{apr}\right\|_2\right) + \beta^2 \left\| s \right\|_2 \qquad (1)$$

where $\| \ \|_2$ indicating the L2 norm.

The first term on the right measures the misfit between the observed data d_{obs}, and the predicted data d_{pre}, weighted by W, the reciprocal of the data standard deviation. Predicted data are calculated by applying the differential form of Maxwell's equations over a staggered finite difference (FD) grid, and solving for the secondary fields using a preconditioned bi-conjugate gradient (BCG) relaxation scheme with divergence correction. The second term imposes a smoothness constraint, with the roughness (slope) of the subsurface conductivity structure defined by a difference operator C, with damping weighted by diagonal matrix W_m. The third term imposes an adherence constraint to an a-priori model, m_{apr}. The static shifts are assumed Gaussian distributed with a mean of zero, with the size constrained by the term $\|s\|_2$,

The objective function is minimized using a direct Gauss-Newton scheme, operating on the following system of equations (Sasaki, 2004):

$$\begin{bmatrix} WF_{m_0} & WG \\ \lambda W_m C & 0 \\ \alpha W_m I & 0 \\ 0 & \beta I \end{bmatrix} \begin{bmatrix} m_1 \\ s_1 \end{bmatrix} = \begin{bmatrix} W\left(F_{m_0} m_0 + d_{pre} - d_{obs}\right) \\ 0 \\ \alpha W_m m_0 \\ 0 \end{bmatrix} \qquad (2)$$

where m_0 is the starting model, the sensitivity F_m is the matrix of derivatives with respect to the resistivity model parameters, G is a matrix of ones and zeros, used to relate corresponding predicted apparent resistivity values and static shifts, and I is the identity matrix. This system matrix depends on both the number of parameters and the number of data. We can use the LU method to solve for the parameter update by premultiplying both sides of the equation by the system matrix transpose, resulting in a symmetric square matrix of dimension equal to the number of parameters only. Using the LU method requires less computer resources than solving the original overdetermined system using the Gram-Schmidt method, allowing the solution of larger problems.

In the direct Gauss-Newton approach here, jacobians are computed through imposing fictitious reciprocal sources at all receivers (e.g., deLugao and Wannamaker, 1996; Siripunvaraporn et al., 2005). With iterative solutions, this requires the computation of many equivalent forward problems and is the limiting run-time factor for moderate data sets. Because of the current expense of the BCG sensitivity calculations, rigorous jacobians are calculated for early iterations and the sensitivity matrix on later iterations updated using Broyden's approximation.

The data normalized RMS misfit is calculated as

$$\text{nRMS} = \sqrt{\frac{\sum_{i=1}^{N/2}\left(W_i\left(\log_{10}\left(\frac{\rho_{a,i}^{obs}}{\rho_{a,i}^{pre}}\right)\right)^2 + \left(W_i\left(\phi_i^{obs} - \phi_i^{pre}\right)\right)^2\right)}{N}} \qquad (4)$$

where N is the number of data. As the predicted data approach the observed data to within the data standard deviation, the misfit should approach 1. However, a misfit of 1 is seldom achieved for real data due to non-ideality of error structure and model oversimplifications.

Inversion of Coso MT data

The Coso MT data included in the inversion consists of the apparent resistivity and phase measurements of the off-diagonal yx impedance elements, measured at 13 frequencies ranging from 0.3 Hz to 100 Hz. At present, we concentrate upon the yx data (transverse magnetic or (TM) mode in the 2-D assumption) to allow direct comparison between 3-D models and 2-D stitch models using this mode, which is more robust to 3-D effects than the xy mode (Wannamaker, 1999). Observed data were given an error floor of 0.01 $\log_{10}$ units for apparent resistivities and 0.66° deg for phases. This equals a

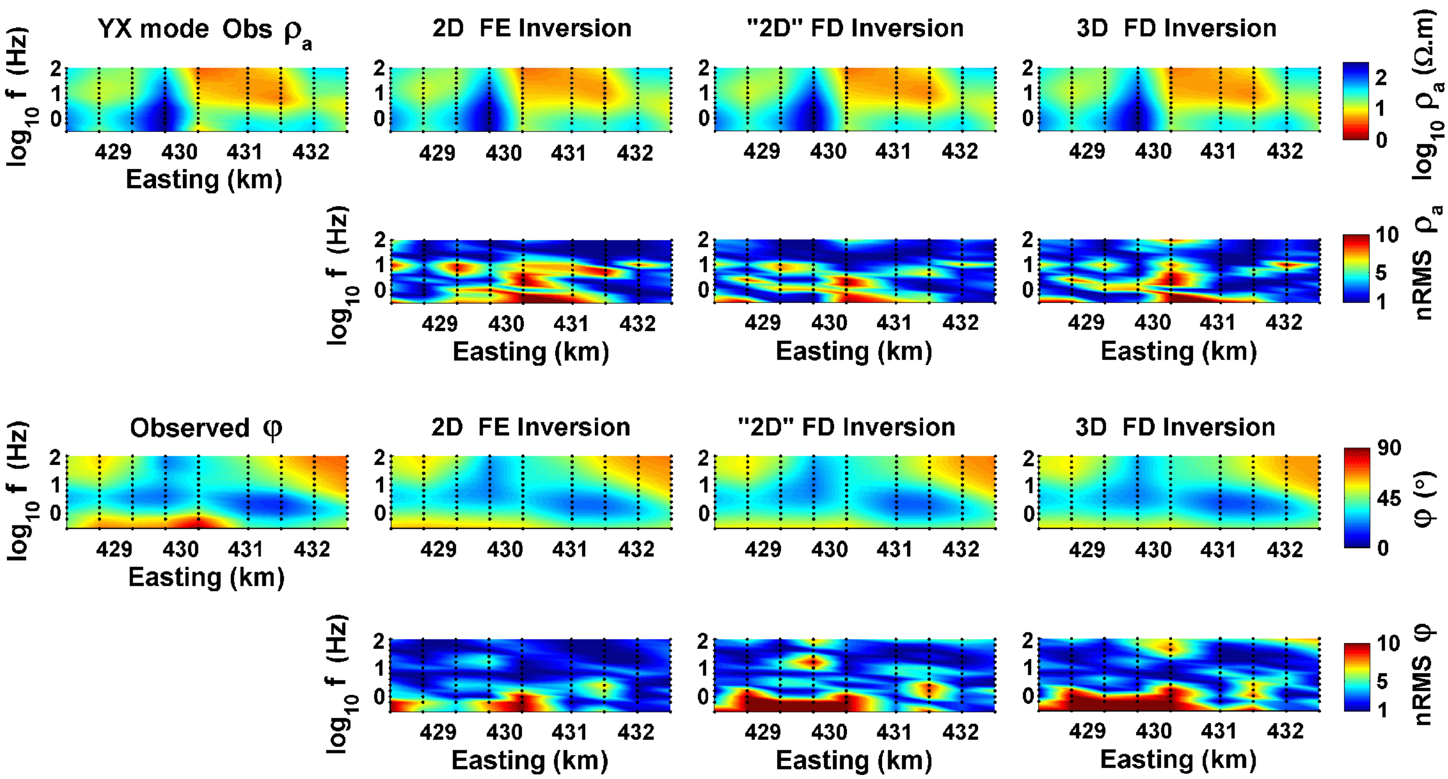

Figure 2. Observed and predicted apparent resistivity and phase pseudo-sections for the 2D profile shown in Figure 1. Observed data are shown in column (a). Column (b) consists of the predicted data calculated from the recovered model parameters obtained using the 2-D FE program. The predicted data shown in columns (c) and (d) were obtained using our 3-D program, applied solely to the profile as a 2D inversion (c) and extracted from a 3-D inversion applied to the full data set (d). The misfit between data and calculations (nRMS) were scaled by the data weights (errors). Colorbars are clipped at 1 Ω.m and 320 Ω.m for the apparent resistivity; 0° and 90° for the phase; 1 and 10 for the misfit.

1.15% impedance error floor approximately. Static shift estimation is not done for the models presented here.

We compare the inversion results obtained using the program described above to results obtained using a 2-D finite element (FE) based inversion program which also damps model slope, and utilizing the forward problem of Wannamaker et al. (1987) and jacobians of deLugao and Wannamaker (1996) and the parameter step equation in Mackie et al. (1988). The 2-D inversions were carried out on a profile of 9 stations located in the southern part of the survey area. Pseudo-sections of the observed data along this profile and the predicted data determined from the recovered models after inversion are shown in Figure 2. Additional data at 160 Hz and 230 Hz were included in the inversion done with the FE program.

The model obtained by inverting the 2-D profile with the FE program is consistent with previously published results, obtained by 2-D stitched inversion of TM mode, E-W subprofiles (Newman et al., 2005a) (Figure 3). The most prominent features in the model are a low-resistivity structure within the upper 3.5 km interpreted to correlate to the producing reservoir in the southwest East Flank sector of the Coso geothermal field, and a central large resistive horst flanked to the east by an ~1.5 km thick conductor, correlated with sediments of the Coso Wash graben. The starting model consisted of a layered background, obtained from the integrated yx mode impedance of the dense array MT measurements spanning the east-west extent of the Coso east flank (Figure 1) (Wannamaker et al., 2004; Newman et al., 2005a). The model normalized RMS misfit is 6.4.

When using our 3-D FD program to invert the 2-D profile data, we used 56 x 36 FD nodes and 27 x 21 inversion bricks in y and z directions. Each inversion block contains

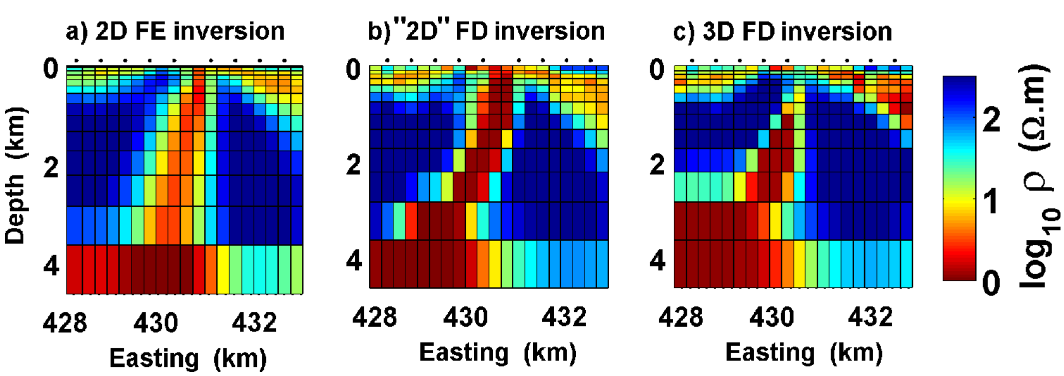

Figure 3. Vertical slice showing the recovered model parameters beneath the 2-D profile, from the inversion using the 2-D FE program (a); the 2-D inversion using our 3-D FD program (b); and extracted from the larger model obtained by 3-D inversion (c). The colorbar is clipped at 1 Ω.m and 320 Ω.m.

2 FD cells in the y-direction with at least one extra inversion block between adjacent stations. Where necessary, station positions were shifted so as to fall on the nearest node of the FD mesh at the center of each inversion block. The inversion domain is similar to that used in the FE inversion except for the top 110 m beneath the surface, where we use a coarser discretization. The starting model was a 22 Ω.m half-space, calculated by the program based on averaging the apparent resistivity data over all sites and frequencies. Rigorous derivatives were used to calculated the model update for 5 iterations; the inversion was stopped after 6 model updates, reaching a misfit of 6.6. We obtain a similar model to that obtained using the 2-D FE program (Figure 3). Differences between the models are attributed to this inversion starting from a half-space instead of a layered host, from coarser near-surface model discretization, and miscellaneous differences in accuracy between FE and FD programs.

The 3-D inversions were carried out with 101 stations. The FD mesh consists of 65 x 57 x 36 nodes in the x, y and z directions, and the inversion domain of 27 x 27 x 19 blocks. Each inversion block contains 2 FD cells in both the x and y directions, with, as much as possible, an extra inversion block between adjacent stations. The inversion domain did not extend as deeply as was used in the 2-D inversion. Rigorous derivatives were calculated and applied for the first 3 parameter updates only; remaining derivatives for three more model updates were approximated using Broyden's method. Starting from a 20 Ω.m halfspace, the misfit was 4.5 after 6 model updates.

Plan views at different depths of the resulting model are shown in Figure 4. The predicted data for the stations along the 2-D profile are shown in Figure 2; the model directly beneath the profile was extracted from the 3-D model and presented in Figure 3.

The prominent features identified in the 2-D FE inversion are visible in both the 2-D and the 3-D FD inversion results. Common features recovered by all inversions are low-resistivity zones consistent with the location of the East Flank producing reservoir and the Coso Wash sediments separated by the high-resistivity horst. Our 3-D TM model shows a weak version of the steep conductor extending north through most of the field, consistent with the 2-D TM inversion of the dense array line (Wannamaker, 2004; Newman et al., 2007). In the plan view of the 3-D model, the low-resistivity zone associated with the reservoir appears to be part of a larger south-southwest oriented feature, trending towards the main southwest producing area of the geothermal field. This differs from the model of Newman et al. (2005b) in that theirs shows more closure of the conductor to the south; this may be because we have not included the xy data, there may be edge effects from not extending the inversion domain far enough out laterally, or may be second-order differences in program regularization. However, we note that ours is the first 3-D inversion to yield the steeply dipping conductor starting from a half-space, and did not utilize an initial guess to seed the structure.

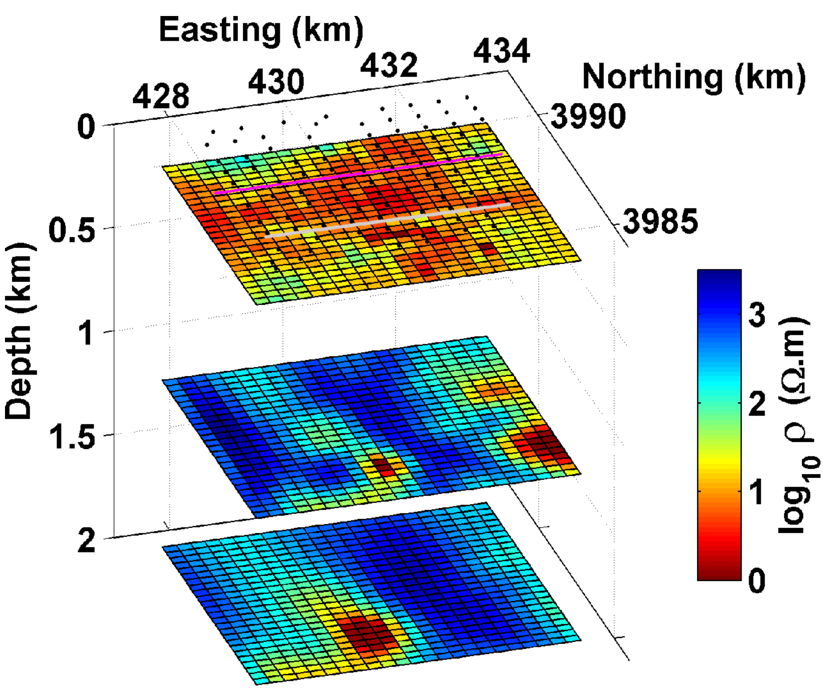

Figure 4. Plan view slices at depths of 150, 1200 and 2000 m, showing the model parameters recovered from the 3-D inversion. The MT station locations are shown without topography. The gray line indicates the approximate location of the 9-station 2-D profile shown in Figures 2 and 3. The magenta line shows approximate location of dense array MT line. The colorbar is clipped at 1Ω.m and 3200 Ω.m.

Conclusions and Plans

We have produced a 3-D resistivity inversion model of the Coso geothermal system using a PC-based algorithm whose information content is similar to that from massively parallel inversion platforms. Moreover, important features of the model were obtained starting from a half-space rather than an initial guess from stitched 2-D sections. A steeply dipping conductor under the East Flank is imaged and interpreted to be a high permeability zone containing ionic fluids. Further refinement of the model is anticipated by improving parameter regularization, by including the layered background as the a-priori model in the inversion, and by increasing the number of rigorous iterations. Additionally, we plan to increase depth extent of the inversion domain, include the xy mode data, and compare to inversions including static shift. To speed calculating the sensitivity matrix, we intend to include an integral equations based formulation as an option to replace the rigorous FD sensitivity. Storage will be saved through use of a depth-expanding parameter grid such as we have invoked in 2-D, and through allocatable arrays.

Acknowledgements

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