

A numerical evaluation of electromagnetic methods in geothermal exploration

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ABSTRACT

The size and low resistivity of the clay cap associated with a geothermal system create a target well suited for electromagnetic (EM) methods and also make electrical detection of the underlying geothermal reservoir a challenge. Using 3-D numerical models, we evaluate four EM techniques for use in geothermal exploration: magnetotellurics (MT), controlled-source audio magnetotellurics (CSAMT), long-offset time-domain EM (LOTEM), and short-offset time-domain EM (TEM). Our results show that all of these techniques can delineate the clay cap, but none can be said to unequivocally detect the reservoir. We do find, however, that the EM anomaly from a deep, conductive reservoir overlain by a larger, more conductive clay cap is caused by the presence of the electric charge at conductivity boundaries rather

than electromagnetic induction. This means that, for detection of the reservoir, methods such as MT, which rely on electric field measurements, are superior to those where only the magnetic field is measured. The anomaly produced by boundary charges at the reservoir is subtle and will be evident only if high-quality data are collected at closely spaced measurement sites. LOTEM electric field measurements look promising and should be useful when efficient multidimensional tools are developed for LOTEM interpretation. Although CSAMT employs electric field measurements, this method is not recommended for reservoir detection because the anomaly caused by a deep reservoir is obscured by transmitter effects that cannot be isolated reliably. A combination of CSAMT and TEM measurements appears most appropriate for delineation of the clay cap.

INTRODUCTION

The target in exploration for convective hydrothermal resources is usually a region composed of faults and fractures filled with thermal fluids and hydrothermal alteration products. The low-resistivity zone produced by the brines and clays capping a geothermal system provides a feature that should be easily detectable by electromagnetic (EM) methods (Wright et al., 1985). Both inactive and active geothermal systems may be overlain by a conductive clay cap, but only an active system has an underlying hot water or steam reservoir. Such a system is described in Wright et al. (1985) and depicted in Figure 1.

The purpose of this numerical study is to examine the relative merits of several EM methods in detecting a geothermal reservoir beneath a low-resistivity clay cap under ideal circumstances. Four EM methods are considered: magnetotellu-

rics (MT), controlled-source audio-magnetotellurics (CSAMT), long-offset time-domain EM (LOTEM), and short-offset time-domain EM (TEM). Each technique is described briefly; for a more complete and detailed description the reader is referred to Nabighian (1991).

Our strategy is straightforward. For each technique, we calculate and compare the responses for two simple geothermal models; a clay cap with and without an underlying reservoir. If there is no significant difference in the response of these two idealized models, the technique is deemed inappropriate for the detection of such a geothermal reservoir. If a technique is not useful in detecting the components of our simple models, it will be of little use in a field situation. We also examine the applicability of 1-D interpretation as another means of accessing these techniques; not because 1-D interpretation is necessarily appropriate, but because it is readily

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available. Inversion of a higher dimension would have been applied if it were available currently for all these techniques.

The 3-D resistivity model, illustrated in Figure 2, was designed with the advice of Gregg Nordquist and other personnel in Unocal's Geothermal Division. It consists of a 5 ohm-m clay cap over a 25 ohm-m geothermal reservoir, embedded in a 200 ohm-m half-space. Although a reservoir with resistivity equal to or lower than the resistivity of the cap would present a better EM target, the reservoir resistivity used here reflects the higher resistivity many geothermal reservoirs exhibit and is based on measurements made by Unocal personnel in the course of their exploration and production activities.

The algorithms used in the MT study are the 3-D code of Wannamaker (1991), along with the 2-D, finite-element code described in Wannamaker et al. (1987). The program described in Newman et al. (1986) is used to compute the CSAMT, LOTEM magnetic field response, and TEM results. The LOTEM electric field results were calculated using the finite-element program in Druskin and Knizhnerman (1988). The LOTEM magnetic field and TEM responses are computed in the frequency domain and transformed to the time domain using the lagged convolution technique in Anderson (1975).

MODEL DISCRETIZATION

Discretization is a special concern in this study because of the large model size, the shallow placement of the clay cap, a need for high-frequency responses, and practical limits on computing time and machine memory. Finer model discretization increases the accuracy of a numerical simulation but

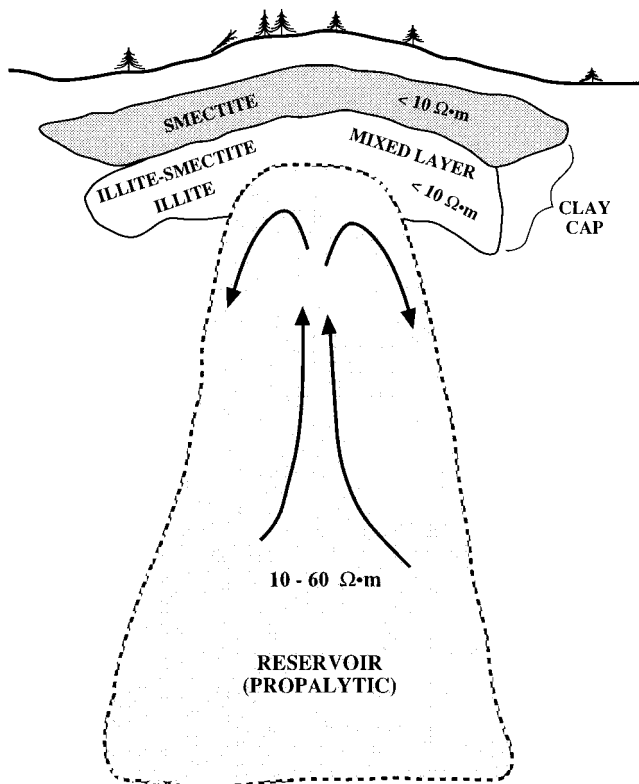


FIG. 1. Conceptual model of a geothermal system.

also increases the amount of CPU time used and memory needed. The basic model (Figure 2) incorporates twofold symmetry, thereby reducing the cell count to one quarter of the number needed to describe the complete model (Tripp and Hohmann, 1984). Accurate discretization of the reservoir is achieved with relatively few cells because of its depth extent and position beneath the conductive cap. Optimum discretization was established on the basis of convergence tests using the 2-D finite-element MT code in Wannamaker et al. (1987). This optimum discretization was used as a guide in the construction of the 3-D model. At the highest frequencies examined, the response of the 3-D model compares favorably to the 2-D response along a profile line bisecting the reservoir-cap structure and thus indicates adequate discretization for a reliable simulation. As an additional check, the LOTEM response was calculated using the finite-difference program in Druskin and Knizhnerman (1988) and showed excellent agreement with the integral equation results.

The TEM response should be more sensitive to model discretization than are the other methods owing to the close proximity of the source to the target. Therefore 3-D TEM responses were computed for three different discretizations. Based on this convergence test, a maximum of 10% error in the peak amplitude response of the clay cap is estimated for the model discretization used to obtain the TEM results. These convergence tests indicate that this error produces a reduction in the cap response and, as such, should not affect our conclusions regarding the usefulness of the TEM method in detecting the deeper reservoir.

MAGNETOTELLURICS

The MT method is based upon the measurement of natural EM field fluctuations at the earth's surface in the period range of 10^3 to 10^{-3} s. The diffusive nature of EM fields in the earth permits depth discrimination on the basis of greater penetration at longer period. MT measurements are represented as a complex impedance tensor relating the electric and magnetic field values and are usually expressed as apparent resistivity and impedance phase (Vozoff, 1991). A strength of MT lies in the use of natural sources that allow exploration of the earth to great depths. A weakness is the intermittently low signal-to-noise ratio in parts of the spectra, especially between periods of 1 to 10 s.

We calculate the MT quantities along the y -directed profile line, with a receiver every 300 m, as shown in Figure 3. The significant features of the 3-D MT response are shown in Figures 4 and 5 as pseudosections along the profile. In the pseudosection format, apparent resistivity or phase is contoured as a function of receiver location along the horizontal axis and as a function of period, in common log units, increasing downward along the vertical axis. The xy mode is shown in Figure 4 and the yx mode in Figure 5. The xy mode corresponds to the impedance calculated using the x -directed electric field and the y -directed magnetic field. Figures 4a, 4c, 5a, and 5c are pseudosections of the apparent resistivity and phase responses for the cap over reservoir model, while Figures 4b, 4d, 5b, and 5d are pseudosections for the clay cap only model.

At shorter periods, the horizontal position of the clay cap is clearly delineated by the yx apparent resistivity (Figure 5).

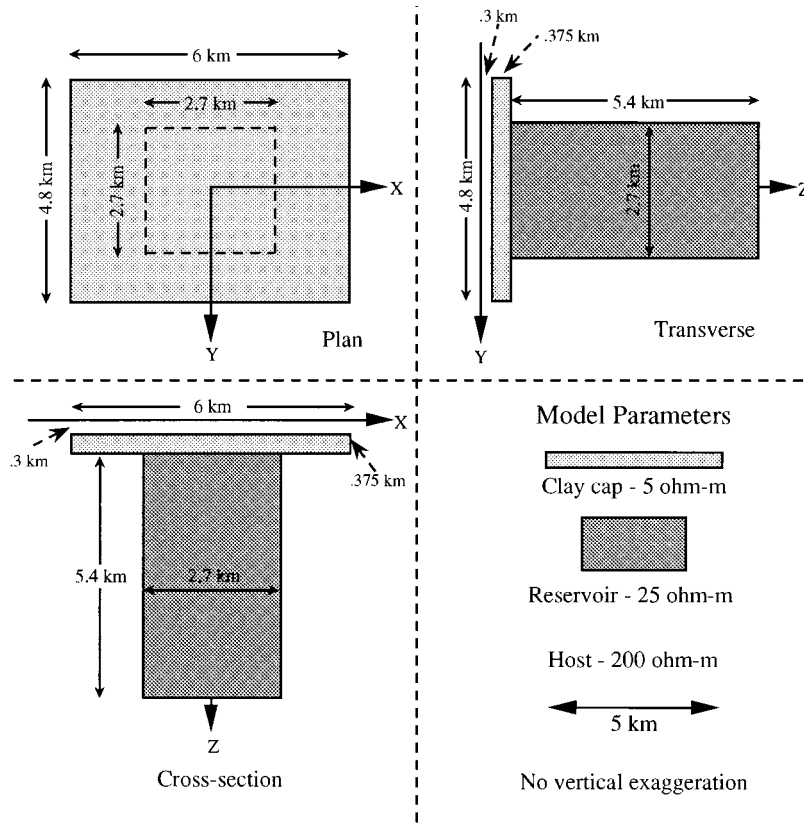


FIG. 2. Geometry of the geothermal model in plan, cross-section and transverse views. A 5 ohm-m cap overlays a 25 ohm-m reservoir in a 200 ohm-m half-space.

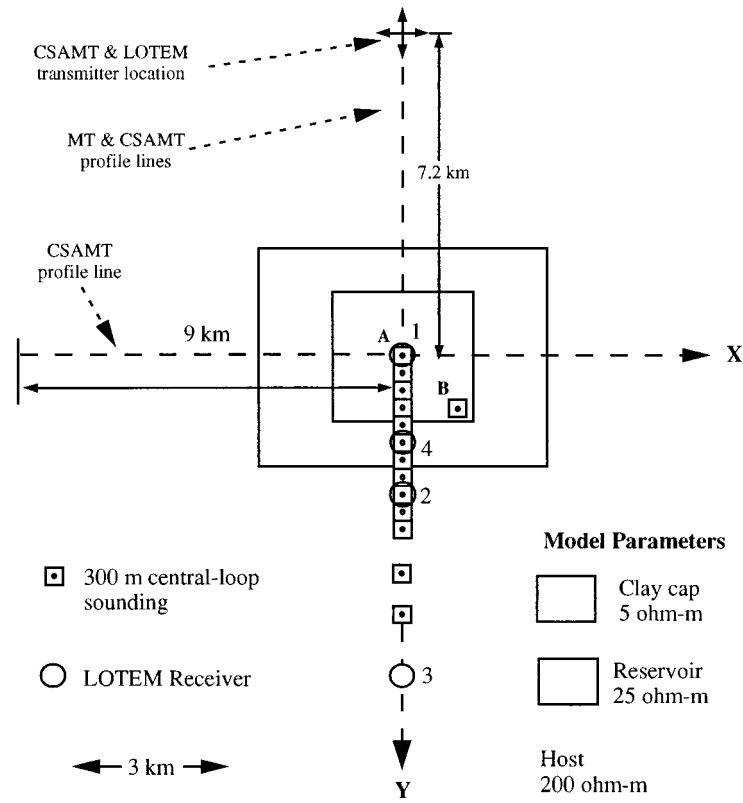


FIG. 3. Plan view of the geothermal model and survey geometry for the MT, CSAMT, TEM, LOTEM methods. The profile lines indicate the location of MT and CSAMT stations with 300 m separation. TEM and LOTEM stations are indicated by symbols.

Over the horizontal extent of the clay cap both apparent resistivity modes are depressed below the 200 ohm-m half-space to values approaching the 5 ohm-m value of the cap. The impedance phases are elevated above the half-space value of 45° over the extent of the cap, indicating its presence in both modes. Unlike apparent resistivity, the phase response is band-limited and returns to values near 45° within the calculated period range.

Differences between the response of the two models are of particular interest as they indicate the usefulness of MT measurements in detecting the reservoir. At periods greater than 0.5 s, the xy apparent resistivity over the cap remains at roughly 18 ohm-m for the model with the reservoir while the response for the model without the reservoir reaches a value of approximately 32 ohm-m. This is a subtle anomaly. A 4° anomaly is also seen in the xy phase when the reservoir is present. The reservoir anomaly for the yx apparent resistivity is limited to periods greater than 1 s. Close comparison of the xy and yx apparent resistivities reveals a slight band-limited response of the xy component when the reservoir is absent. There is also a 6 to 8° yx phase anomaly in the range of 1 to 10 s because of the presence of the reservoir. This is not a large anomaly, but it may be detectable with dense, high quality data (Gamble et al., 1979).

The favorable yx phase anomaly described above is also present for the xy mode but is less evident. This suggests that

boundary charges play an important role in the amplitude of a reservoir anomaly. Boundary charges produce the galvanic or static response that depresses the apparent resistivity response to very long periods (Pellerin and Hohmann, 1990). Apparent resistivity values are usually distorted by near-surface inhomogeneities, while impedance phase measurements are not, and unless the near-surface distortions are accounted for, it is important to examine phase measurements closely for features like the subtle anomaly produced by the reservoir (Pellerin and Hohmann, 1990). In addition to the small size of the reservoir anomaly, the peak phase response occurs primarily in the period range of 1–20 s. The reservoir response thus lies partially within the weak band of the MT signal at 1–10 s (Vozoff, 1991).

The generation of a pseudosection does not constitute an interpretation, and because 3-D interpretation algorithms for MT data are not widely used as yet, a 2-D interpretation strategy was considered. Two-dimensional algorithms are readily available (Wannamaker et al., 1987). To assess their usefulness, we used the 2-D MT model results calculated for the purpose of establishing adequate 3-D discretization. The structure of this 2-D model is identical to the section through the 3-D reservoir model along the profile line and its response is shown in pseudosection in Figure 6. For 2-D results, the impedance component calculated from the electric field parallel to structure is referred to as the transverse electric or TE mode, and the component calculated with the electric field perpendicular to structure is the transverse magnetic or TM mode. The 3-D results can be compared to the 2-D components on the basis of their orientation. With the long axis of the

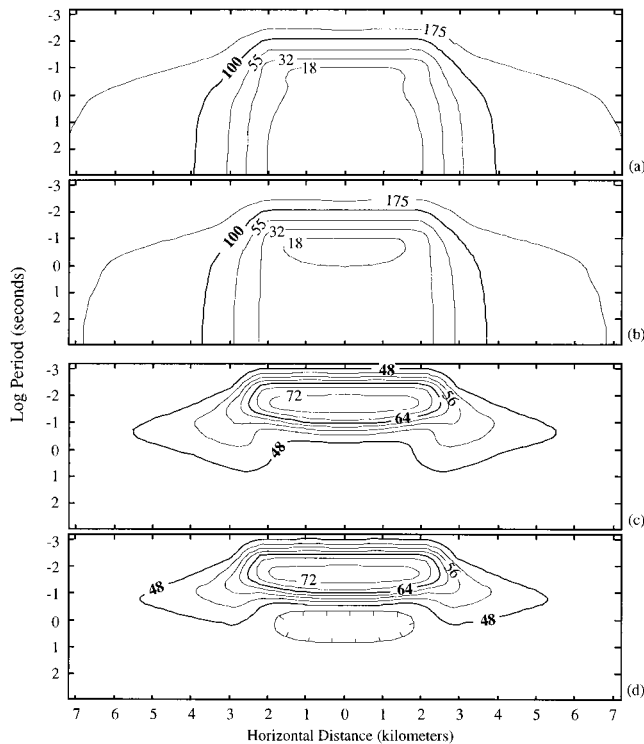


FIG. 4. Pseudosections of the 3-D xy MT impedance mode along the y -directed profile line for the models with and without the reservoir. Components are as follows: (a) apparent resistivity for the reservoir model, (b) apparent resistivity for the cap-only model, (c) impedance phase for the reservoir model, and (d) impedance phase for the cap-only model. Differences between (a) and (b), and (c) and (d) indicate the influence of the reservoir on this mode's impedance response.

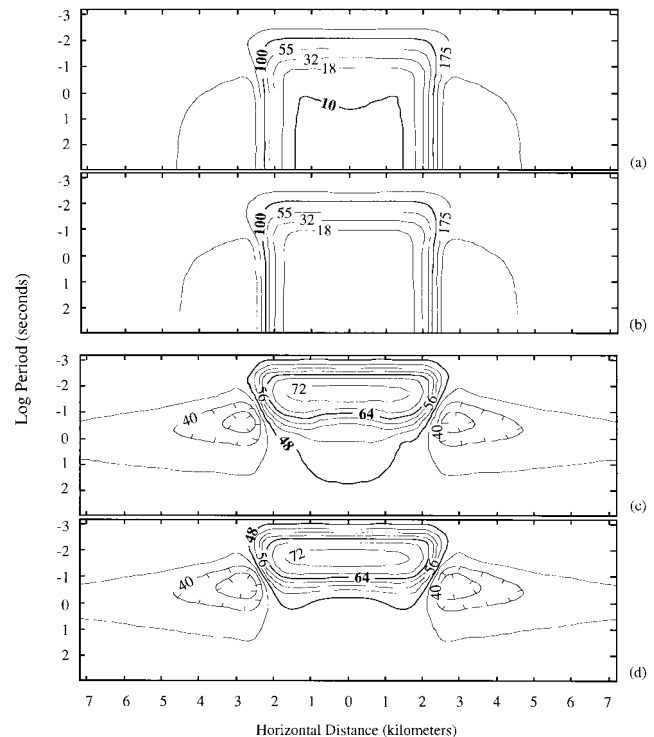


FIG. 5. Pseudosections of the 3-D yx MT impedance mode along the y -directed profile line for the models with and without the reservoir. Components appear in the same order as in Figure 4.

clay cap taken as the strike direction, we compare the xy mode to the TE mode and the yx mode to the TM mode.

Along the central profile line, the 3-D response is virtually indistinguishable from the 2-D at periods shorter than 0.1 s for both the xy (TE) and yx (TM) modes. At longer periods the TM response is slightly different than the yx , while the TE is radically different than the xy response. The TM mode apparent resistivity is depressed to lower values, and the high TM phase values persist to longer periods compared to the 3-D yx mode. We find such features as the apparent resistivity low of the TE mode band limited and a broad TE phase minimum centered on 10 s to be absent in the 3-D response (Figure 6a and 6c). Both 3-D modes resemble the TM mode and all these components are also affected by boundary charges.

The similarity of the 2-D TM response and the 3-D results imply that when measurements are made over the central portion of a structure, the 3-D responses can be interpreted in terms of the TM response of 2-D models. Conversely, 2-D TE interpretation should be used only when it can be demonstrated that, over scales ranging from receiver dipole length to the width of the survey area, the geoelectric environment is effectively two dimensional. The 2-D model results support the argument that effects caused by boundary charges are the primary source of the reservoir anomaly. Boundary charges contribute to the TM response, but not to the TE, because the TE electric field is parallel to the strike direction and is unaffected by boundary charges.

Where a strong 3-D response exists, we feel that short of 3-D inversion, an analysis based on the 2-D TM response is the safest route to an accurate MT interpretation, as advocated in Wannamaker et al. (1984). The MT interpretation strategy that equates the TE mode response and the 1-D response on the basis that they are both free of boundary charge effects is flawed because of the impossibility of separating a 3-D response into the two 2-D modes. Figure 7 shows a comparison of the 1-D response to that of the 2-D and 3-D models at their center points in terms of apparent resistivity and phase sounding curves. These 1-D curves are calculated from a layered-earth model with thickness and resistivities equivalent to the layering that exists beneath the center of the cap over reservoir model. All curves show an identical layered earth response for periods shorter than 0.1 s. At longer periods the various curves begin to diverge and form two fairly distinct sets: an $xy - yx$ TM set and a TE - 1-D set. Note that a 1-D inversion of the xy , yx mode or some average of these components will yield a distorted estimate of the resistivity beneath the cap.

CONTROLLED-SOURCE AUDIOMAGNETOTELLURICS

The CSAMT method differs from the MT method in that a grounded dipole transmitter is used to generate the source fields. At a distance greater than about 5 skin depths from the transmitter, the measured fields caused by the dipole source are plane waves like the natural generated MT signals (Zonge and Hughes, 1991). When source fields do not approximate plane waves because of the close proximity of the transmitter to the receiver, the measurement site is said to be in the near field. CSAMT measurements are usually made in a frequency range of 1 s to 0.0001 s. The controlled source is used to overcome power deficiencies in the audio-frequency portion of the natural spectrum or in areas where cultural noise levels are

high. Scalar CSAMT soundings are made by measuring only one electric field component and an orthogonal magnetic field component. Scalar soundings sites are typically positioned so that the receiving electric field dipoles are adjacent and collinear to the transmitting dipole, either directly inline with the transmitter or broadside to it.

The CSAMT source in our model consists of crossed 1-km long electric dipoles 7.2 km from the center of the model as shown in Figure 3. The modeling results are shown as scalar measurements recorded along both the y -directed profile line (inline) and x -directed line (broadside) in Figures 8 and 9. Because of our model geometry and transmitter orientation, the xy and yx modes are identical to those which would result from tensor CSAMT measurements. In a more general case or in a field study, this would not be the case. The yx impedance mode, computed for the y -directed inline transmitter along the y -directed profile line, is again presented as apparent resistivity and phase pseudosections (Figure 8). Near-field transmitter effects appear as a steady increase in apparent resistivity and a decrease in phase with increasing period. These effects commence at progressively shorter periods as the electrical transmitter-receiver separation decreases. Because of the progressive nature of the near-field effects, the inline configuration is not the preferred survey layout when the objective is to obtain a structural cross-section to the greatest practical depth. These

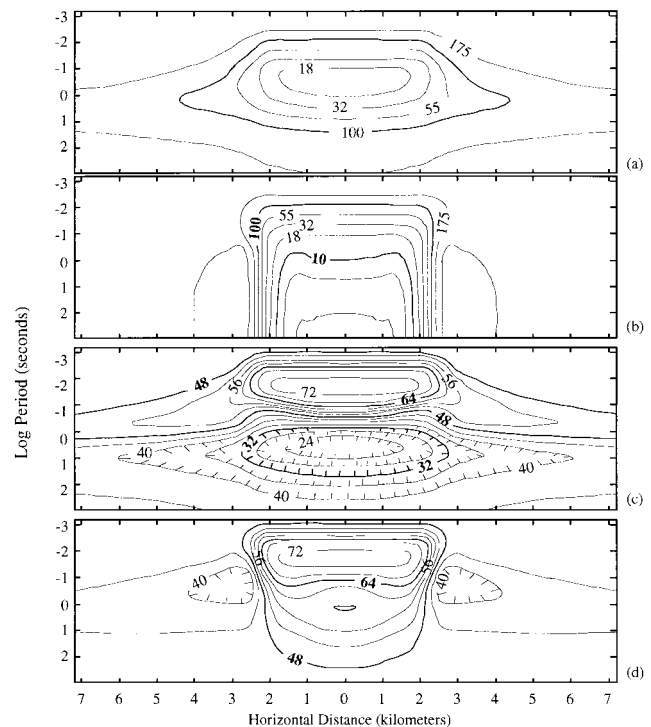


FIG. 6. Pseudosections of the 2-D MT impedance mode along the y -directed profile line for the reservoir model. Components and modes are as follows: (a) apparent resistivity for the TE mode, (b) apparent resistivity for the TM mode, (c) impedance phase for the TE model, (d) and impedance phase for the TM mode. A comparison of the 2-D results with the 3-D pseudosections in Figures 4 and 5 indicate that the 2-D TM mode mimics the 3-D response. Note the dissimilarity of Figures 4a and 6a, and Figures 4c and 6c. Note the similarity between 5a and 6b, and Figures 5c and 6d.

results do show that CSAMT can be used to effectively map a large area if the target is relatively shallow. Figure 9 shows contoured pseudosections of the xy impedance mode over the long axis of the clay cap in the more conventional broadside survey layout. Again the location of the cap is well defined in its lateral extent. The complex patterns seen in Figure 9 at approximately 7 km from the model's center are the low or null-field zones associated with a dipole transmitter (Zonge and Hughes, 1991).

Deep structures are difficult to recognize in the CSAMT model response. At the long periods needed for deep sounding, the source is too close to the target for the plane-wave assumption to be valid. We could have overcome this limitation by placing the transmitter at a greater distance from the receivers, which in turn would have produced an unrealistic simulation. Practical limits on transmitter strength and detectable signal levels guided our CSAMT model design. The MT results show that the geothermal reservoir anomaly is small but detectable at periods greater than 0.5 s and thus lies outside the frequency range of the typical CSAMT survey. Because the cap is an extensive, shallow structure whose areal extent can be accurately defined with a 1-D interpretation of either impedance mode, CSAMT could be a favorable, cost-effective reconnaissance technique for delineation of this structure.

SHORT OFFSET, TIME-DOMAIN ELECTROMAGNETICS

Conductivity anomalies exist at all scales within the earth and cause local distortions of current flow that hinder as well as help the explorationist. Current channeling caused by boundary charges distorts the electric field much more than the magnetic field. By selecting a sounding technique, such as TEM that measures only the magnetic fields, we are able to minimize the influence of boundary charges and isolate the effect of inductive currents (Pellerin and Hohmann, 1990).

Using the TEM method, measurements of the magnetic field impulse response are made within or near an ungrounded loop source. In this study, we simulate square transmitting loops, 300 m on a side, with a transmitted current of 1 A. The transmitter dimensions were chosen on the basis of common usage in industry and adequate depth of exploration. According to Spies (1989) the depth of exploration for impulse response measurements with a 300-m transmitting loop over a 5 ohm-m half-space is roughly 550 m. For a 300 m loop over a 200 ohm-m half-space, the depth of exploration increases to over 1100 m. Weighting the relative contributions of the 200 ohm-m host and 5 ohm-m clay cap by their respective thickness at the center of the system and arithmetically averaging the two values, we estimate the depth of exploration in

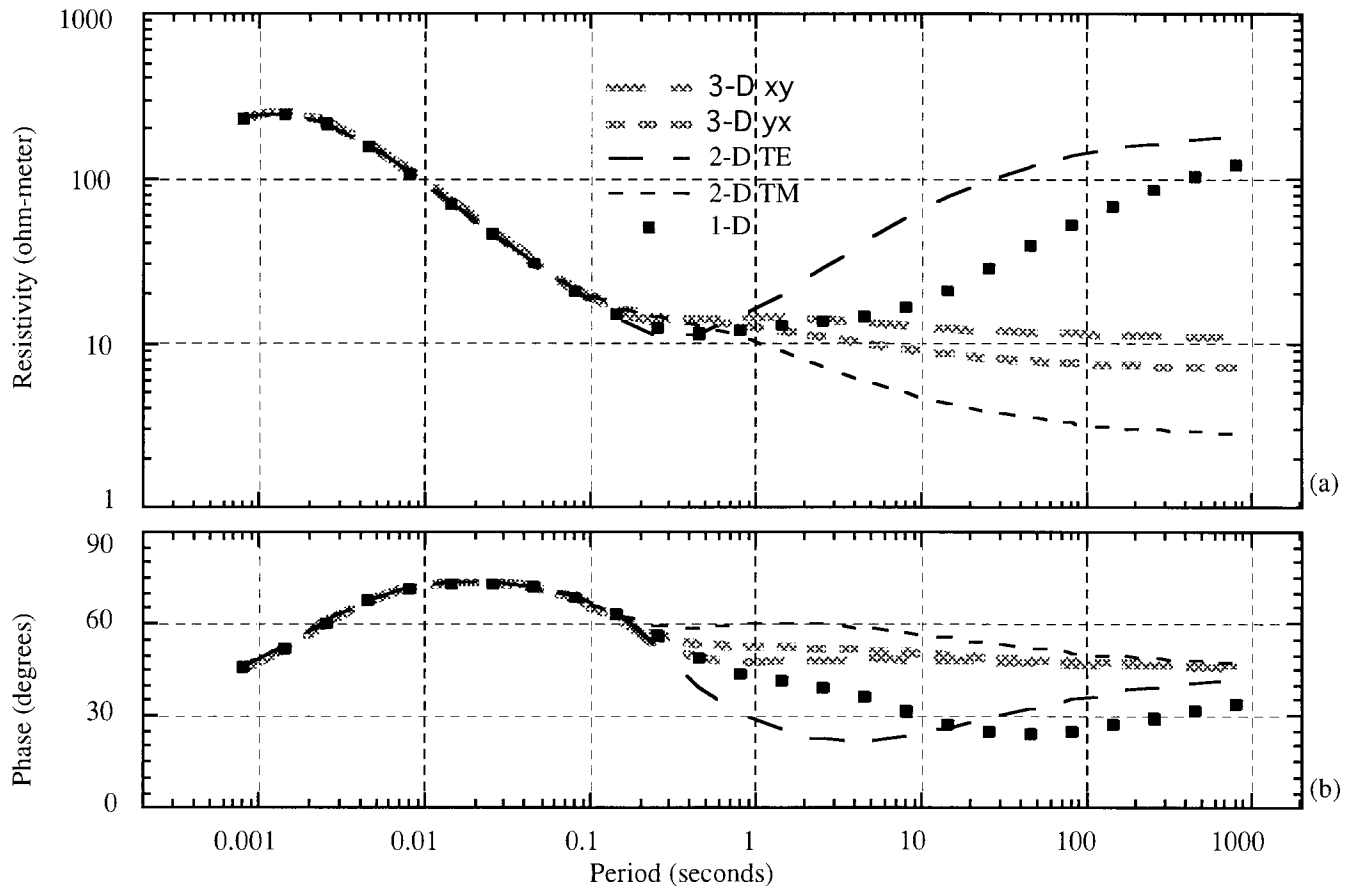


FIG. 7. Comparison of 1-D, 2-D and 3-D MT apparent resistivity and phase responses for the cap over reservoir model. The 1-D results are calculated for a layering identical to that at the center of the 3-D model. The 2- and 3-D sounding curves are from the receivers at the center of these models.

the geothermal model to be about 850 m. Hence a 300-m transmitting loop is just adequate for exploring to the cap—reservoir contact at 675 m. Figure 3 illustrates the TEM survey layout.

We find that the reservoir anomaly is not readily apparent in the sounding curves calculated from 3-D models at the edge and near the center of the geothermal system (Figure 10). For receiver A, a very slight difference between the response of both models is seen beginning at about 70 ms. The sounding near the corner of the reservoir, receiver B, shows no reservoir response. In Figure 10a we compare the 3-D response at the model center to the 1-D response of an equivalent layer structure. Differences between the 1-D and the 3-D TEM response are necessarily caused by differences in the average conductivity of the electrical basement. The relatively small size of the 3-D reservoir limits the conductive volume support-

ing late-time current compared to the larger conductance of the conductive layer in the 1-D geometry. We would therefore expect no advantage in detecting the reservoir by using a larger transmitter. While a transmitter with greater moment would allow us to record later times and increase the 1-D reservoir response, it would provide no increase of the 3-D reservoir response.

The similarity in the sounding curves shown in Figure 10 indicates that currents flowing in the 5 ohm-m cap dominate the response of the more resistive underlying structure. We examine this possibility using the contiguous line of central-loop soundings shown in Figure 3. They are inverted using the 1-D image technique developed by Eaton and Hohmann (1989). We use this technique instead of a standard layered-earth inversion because the former is more robust in the presence of 3-D structures (Eaton and Hohmann, 1989).

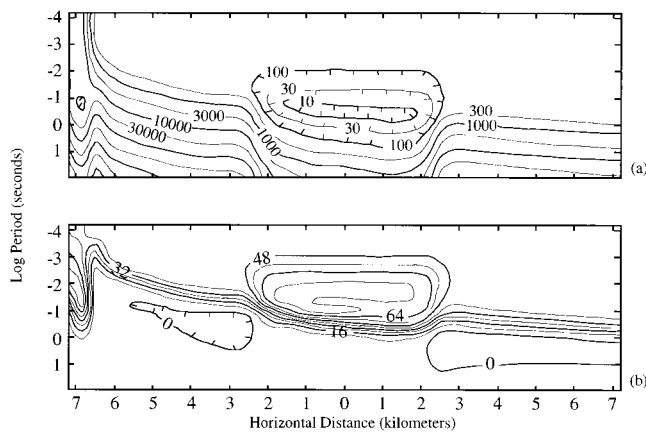


FIG. 8. Pseudosections of (a) y_x apparent resistivity (ohm-m) and (b) y_x impedance phase (degrees) for the 3-D CSAMT response of the cap over reservoir model along the y -directed profile line for the y -directed transmitter.

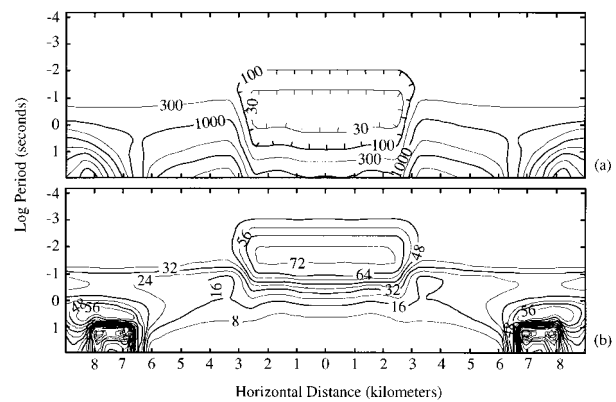


FIG. 9. Pseudosections of (a) xy apparent resistivity (ohm-m) and (b) xy impedance phase (degrees) for the 3-D CSAMT response of the cap over reservoir model along the x -directed profile line for the x -directed transmitter.

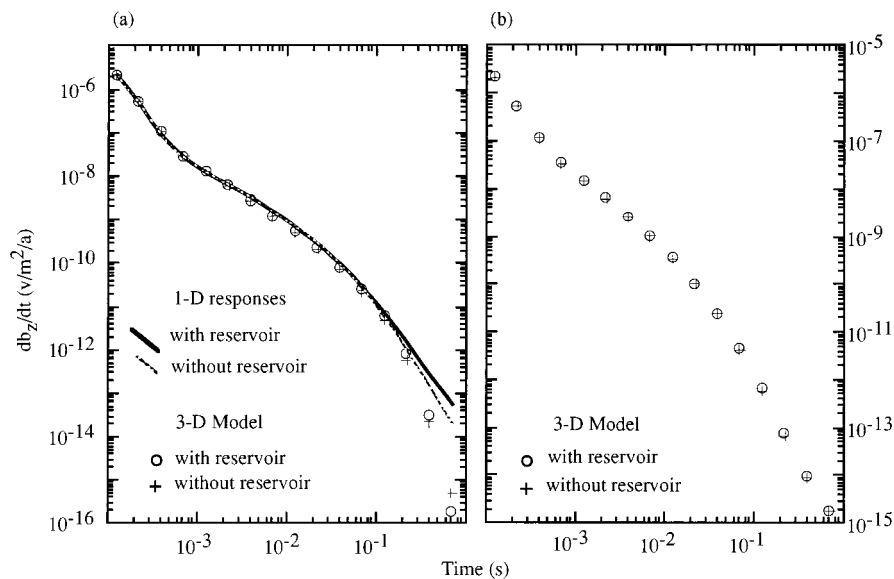


FIG. 10. TEM central-loop vertical magnetic field impulse response at receivers A (a) and B (a) in figure 3 for models with and without a reservoir and a comparison with the TEM central-loop vertical magnetic field impulse response for the 1-D equivalent models (a).

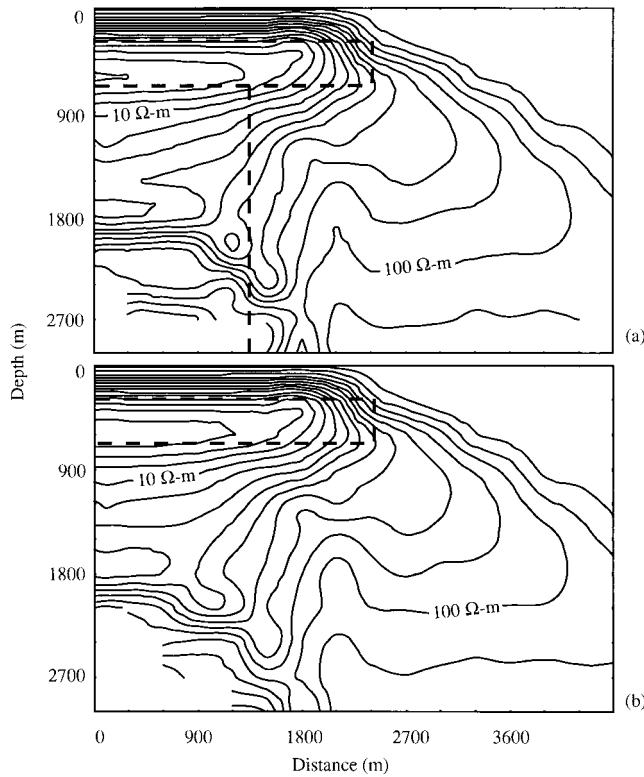


FIG. 11. Contoured resistivity section from a 1-D image interpretation of TEM central-loop soundings for the (a) cap over reservoir model and (b) the cap only model. Contours are in ohm-m. The dashed lines indicate the location of the cap and reservoir in cross-section.

Figure 11 shows the image results over half of the structure, contoured in units of ohm-m, for both models. There is little difference between the inverted response of these models but, as with the other techniques, the cap is clearly delineated.

LONG-OFFSET, TIME-DOMAIN ELECTROMAGNETICS

The LOTEM technique is a controlled source method recently described in Strack (1992). Like CSAMT, the LOTEM source is a distant grounded dipole, but unlike CSAMT, data interpretation does not include the assumption of a plane wave source. Both the magnetic and electric field transients can be measured with this technique. The geometry of the LOTEM simulation consists of an x -directed, 1-km transmitting dipole located 5 km from the edge of the clay cap and four receivers variously located above or beyond the edge of the clay cap (Figure 3).

The vertical magnetic field impulse response of the models is shown for receivers 1, 2, and 3 in Figure 12. As with the TEM method, there is little evidence of the reservoir apparent in the magnetic field response. The deep notch in the magnetic field response curve at receiver 2 is a characteristic sign reversal effect of 3-D responses. Use of 1-D algorithms is limited by such features. Kriegshauser (1991) describes this and other problems associated with 3-D interpretation of LOTEM data.

The clay cap can be located with magnetic field measurements, but the presence of 3-D effects, even at early times, makes the inversion of these results difficult. We used a singular value decomposition, layered-earth inversion program described in Strack (1992) to evaluate the usefulness of 1-D interpretation of the 3-D magnetic field response. Stations 1 and 4 are chosen for this test because they are located over the cap and do not contain sign reversals that would prohibit their use in a layered-earth inversion technique. These inversion results are shown in Figure 13 where we see that the depth to the cap is underestimated and the cap resistivity is overesti-

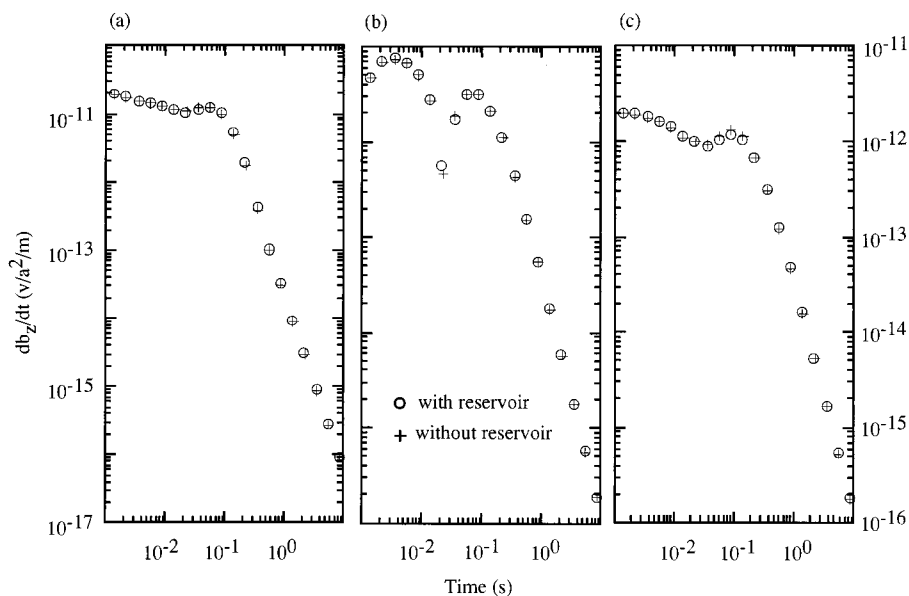


FIG. 12. LOTEM vertical magnetic field impulse response at receivers 1 (a), 2 (b), and 3 (c) of Figure 3 for models with and without a reservoir.

mated at both receivers. In addition, we do not obtain a reasonable estimate of the thickness of the cap.

We calculated the LOTEM electric field response differently than the magnetic field response. For the electric fields, we used the time-domain, finite-difference program of Druskin and Knizhnerman (1988) instead of the integral equation solution program. The Druskin-Knizhnerman code uses a true LOTEM waveform, a positive to negative step source, where the integral equation solution uses a positive to zero step

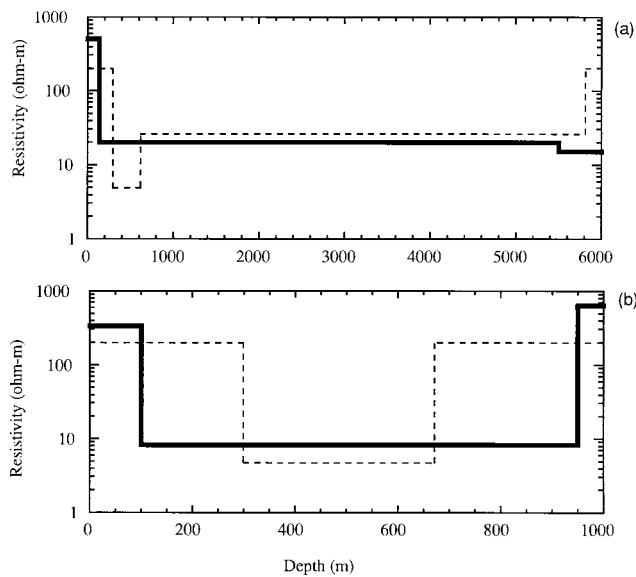


FIG. 13. Layered-earth interpretation of LOTEM magnetic field transients at receivers 1 (a) and 4 (b) in Figure 3 (solid heavy line) compared to the actual layering directly under the receivers (light, dashed line).

source. This difference in the source waveforms affects only electric field responses.

The 3-D electric field transients shown in Figure 14, correspond to LOTEM receivers 1 through 3. At receiver 1, centered over the model, a 30 nV/m anomalous response is seen in the transient for times later than 30 ms. Smaller anomalous fields are seen at receiver 2 near the edge of the clay cap and no anomalous fields are seen at receiver 3 situated well outside of both the clay cap, and reservoir. This indicates that a gradational electric field anomaly is produced by the reservoir and, with suitable interpretation, may be useful in defining such bodies. Toward this end, we examined a 1-D approach. Two distinct differences are apparent when we compare the 3-D electric field sounding for receiver 1 with its 1-D equivalent response (Figure 14a). First, the early-time 1-D response has a steeper negative slope than the 3-D model. Second, the 1-D results show a field strength increase between 10^{-2} and 10^{-1} s which is absent in the 3-D response. From these differences, we conclude that 1-D modeling is not appropriate for interpretation of the electric field response of a structure like this model geothermal reservoir. The application of LOTEM in the exploration of strongly 3-D environments awaits the development of more sophisticated tools.

DISCUSSION

Electromagnetic detection of a conductive geothermal reservoir capped by a conductive clay zone is a difficult exploration problem, and none of the techniques examined in this study are totally successful in detecting a simple reservoir. Our results do indicate, however, that the electrical anomaly arising from a deep, conductive 3-D body is caused by electric charge accumulation at resistivity boundaries, and methods measuring the electric field are superior to techniques that employ only magnetic field measurements. Among the techniques and

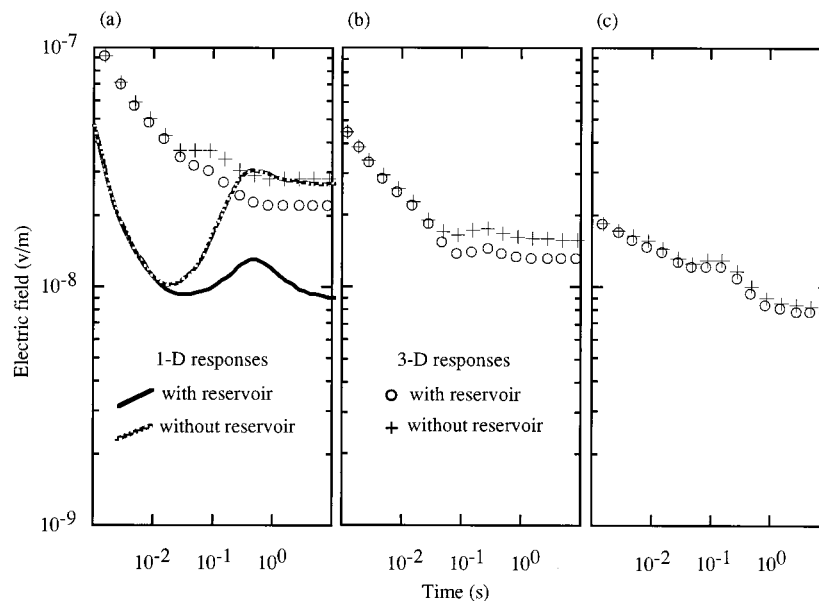


FIG. 14. LOTEM 3-D electric field response at receivers (a) 1, (b) 2, and (c) 3 in Figure 3 for models with and without a reservoir and a comparison with the LOTEM electric-field sounding for the 1-D layering found at the center of the 3-D model (a). The receiver for the 1-D model is positioned 7.2 km from an x -directed transmitting dipole.

interpretation tools analyzed in this study, we deem the 2-D interpretation of high-quality, densely spaced MT data as currently the best method of reservoir detection even though the expected anomaly is small compared to the electrical variation we would expect in a structure like the clay cap. Although CSAMT also employs electric field measurements, it is not valuable for the reservoir geometry modeled because most of the reservoir anomaly is seen at periods greater than are typically recorded, and that portion of the reservoir response lying within the recording range is likely to be contaminated by near-field effects. Interpretation tools for the LOTEM technique are still in the early stage of development, but based on the relative size of the electric field anomaly, this method looks promising. LOTEM magnetic field and TEM measurements are poor choices for delineating geothermal reservoirs because the influence of boundary charge is minimal.

All four techniques are viable methods of delineating the clay cap. Scalar CSAMT appears to be a comparatively efficient reconnaissance tool because the cap response is strong in both polarization modes. An alteration feature like the cap will probably be quite heterogeneous and its detailed mapping might require tensor CSAMT. Short-offset TEM is logistically expensive for delineation of a large target like the cap because of the need to frequently move the transmitter. The TEM method can be useful in conjunction with the MT and CSAMT methods, however, to assist in removing static shift distortions (Pellerin and Hohmann, 1990). Designed for deep exploration, LOTEM requires large current sources (up to 100 A) and large receiver loops (40 m \times 40 m) and, therefore, is not a cost-effective tool for delineation of shallow structures. Also, there are difficulties in a 1-D LOTEM interpretation near 3-D structures, even one as large as the clay cap.

We expect that detailed imaging of the clay cap would be valuable in revealing trends in zonation or indications of an outflow region and thus would be valuable when planning for exploration beneath the clay cap. Knowledge of the shallow geoelectric structural detail is also valuable for reliable interpretation of MT or LOTEM results. CSAMT or AMT, if signal and noise conditions permit, would be useful for shallow geoelectric mapping of a geothermal prospect. The use of LOTEM electric field measurements or MT for deep sounding, after mapping the extent and heterogeneity of the clay cap, should provide a complete geoelectric image of a geothermal prospect. Finally, multidimensional interpretation is strongly recommended with MT or LOTEM data.

Our appraisal of these methods has ignored practical considerations that would influence the cost and the success of a geothermal program. The relative merit of a technique given dense, noise-free data completely traversing a structure may change when one has a tight budget for exploration in a culturally noisy area.

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REFERENCES

- Anderson, W. L., 1975, Improved digital filters for evaluating Fourier and Hankel transform integrals: U. S. Geol. Survey Rep. USGS-GD-75-012, 26P.
- Druskin, V. L., and Knizhnerman, L. A., 1988, A spectral semi-discrete method for the numerical solution of 3-D nonstationary problems in electrical prospecting: *Phys. Solid Earth*, **24**, 63-74.
- Eaton, P. A., and Hohmann, G. W., 1989, A rapid inversion technique for transient electromagnetic soundings: *Phys. Earth Planet. Int.*, **53**, 384-404.
- Gamble, T. D., Goubau, W. M., and Clarke, J., 1979, Magnetotellurics with a remote reference: *Geophysics*, **44**, 53-68.
- Kriegshauser, B., 1991, Einige Aspekte der 3-D interpretation von LOTEM daten: M.Sc. thesis, Universität zu Köln.
- Nabighian, M. N., 1991, Electromagnetic methods in applied geophysics, Vol. 2, Application: Soc. Expl. Geophys.
- Newman, G. A., Hohmann, G. W., and Anderson, W. L., 1986, Transient electromagnetic response of a three-dimensional body in a layered earth: *Geophysics*, **51**, 691-706.
- Pellerin, L., and Hohmann, G. W., 1990, Transient electromagnetic inversion: A remedy for magnetotelluric static shifts: *Geophysics*, **55**, 1242-1250.
- Spies, B. R., 1989, Depth of investigation of electromagnetic sounding methods: *Geophysics*, **54**, 872-888.
- Strack, K.-M., 1992, Exploration with deep transient electromagnetics: Elsevier Science Publ.
- Tripp, A. C., and Hohmann, G. W., 1984, Block diagonalization of the electromagnetic impedance matrix of a symmetric body using group theory: *IEEE Trans. Geoscience and Remote Sensing*, **GE-22**, 62-69.
- Vozoff, K., 1991, The magnetotelluric method, in Nabighian, M. N., Ed., *Electromagnetic methods in applied geophysics*, Vol. II: Soc. Expl. Geophys., 641-771.
- Wannamaker, P. E., 1991, Advances in three-dimensional magnetotelluric modeling using integral equations: *Geophysics*, **56**, 1716-1728.
- Wannamaker, P. E., Hohmann, G. W., and Ward, S. H., 1984, Magnetotelluric responses of three-dimensional bodies in layered earths: *Geophysics*, **49**, 60-74.
- Wannamaker, P. E., Stodt, J. A., and Rijo, L., 1987, A stable finite-element solution for two-dimensional magnetotelluric modeling: *Geophys. J. Roy. Astr. Soc.*, **88**, 277-296.
- Wright, P. M., Ward, S. H., Ross, H. P., and West, R. C., 1985, State of the art geophysical exploration for geothermal resources. *Geophysics*, **50**, 2666-2696.
- Zonge, K. L., and Hughes, L. J., 1991, Controlled-source audio-frequency magnetotellurics, in Nabighian, M. N., Ed., *Electromagnetic methods in applied geophysics*, Vol. II: Soc. Expl. Geophys., 713-809.