Evaluation of Electromagnetic Methods in Geothermal Exploration

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SUMMARY

Using three-dimensional (3-D) numerical models we evaluate four electromagnetic (EM) techniques - magnetotellurics (MT), controlled-source audio magnetotellurics (CSAMT), long-offset time-domain EM (LOTEM) and short-offset time-domain EM (TEM) - for use in geothermal exploration. The size and low resistivity of a clay cap in a geothermal system make it an easy target for EM methods, whereas electrical detection of a deeper geothermal reservoir under the cap is a difficult exploration problem. Any of these techniques can delineate the clay cap, but none can be said to unequivocally detect the reservoir. Our results, however, do indicate that an anomaly from a deep, conductive reservoir overlain by a larger, more conductive cap is due to electric boundary charges; hence electric field measurements are superior to those that employ only the magnetic field. Among the techniques and interpretation tools analyzed, we deem 2-D interpretation of MT data the best means of reservoir detection. However, the maximum expected anomaly of 0.25 log units in apparent resistivity and roughly 7° in phase from the reservoir is compromised if an outflow region is present. LOTEM electric field measurements look promising, especially since multi-dimensional tools are being developed for LOTEM interpretation. Although CSAMT employs electric field measurements, it is not recommended for reservoir detection because the reservoir anomaly can be obscured by near-field effects that cannot be reliably isolated. A combination of CSAMT and TEM measurements appears most appropriate for delineation of the clay cap.

INTRODUCTION

The purpose of this investigation is to identify which EM technique - MT, CSAMT, TEM, or LOTEM - is suited best to locate a clay cap and the presence of an underlying reservoir as depicted in the generalized geothermal system in Figure 1 (Simmons and Browne, 1990). The strategy is straightforward. Two simple numerical models are constructed; one with a reservoir and clay cap and one with only a clay cap. If an EM method cannot discriminate between these two simple, idealized models, it probably will fail in a field test. Methods that do discriminate between the two models are tested on more complicated models incorporating reservoir outflow and zoning within the clay cap.

The resistivity model, shown in Figure 2 is designed with advice from Gregg Nordquist and colleagues of the Geothermal Division of Unocal. The programs used in simulating the EM responses are described by: Wannamaker et al. (1987) and Wannamaker (1991) for MT; and Newman et al. (1986) for CSAMT, TEM and LOTEM magnetic field calculations. Berthold Kriegshauser at the University of Utah computed LOTEM electric field responses using the finite element program of Druskin and Knizhnerman (1988).

The 3-D model approximating a simple geothermal system incorporates two-fold symmetry to conserve computational time while permitting discretization adequate to insure accurate simulation. All methods were evaluated using the same model discretization. An optimum discretization was selected on the basis of convergence tests using the 2-D finite-element MT code of Wannamaker et al. (1987). The response of the optimum 2-D MT model was compared to the 3-D response along the profile line bisecting the elongated 3-D reservoir model with the identical cross-section as the 2-D model, and found to be in excellent agreement.

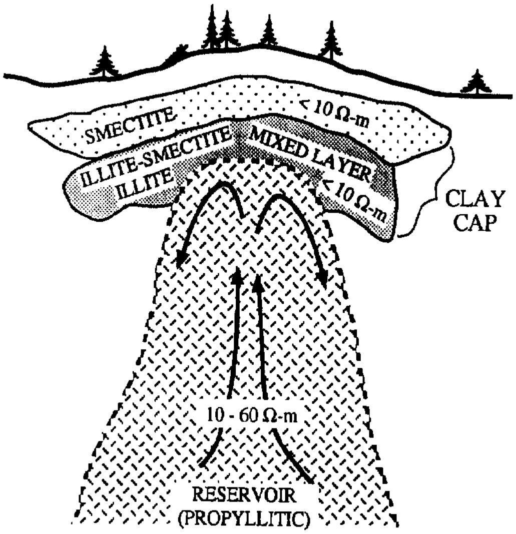

Figure 1. Schematic of a generalized geothermal system.

MAGNETOTELLURICS

Figures 3 and 4 show MT pseudosection plots of the apparent resistivity and impedance phase for the yx polarization along the NS profile line of the 3-D models without and with the reservoir. The edges of the cap are clearly visible and coincide with the steep gradients of both apparent resistivity and impedance phase, as is noted. The similarity in the response of the two models at periods lower than 0.3 seconds indicates that the response at these periods is due almost entirely to the cap.

At periods greater than 0.3 seconds noticeable differences appear between the two model responses that indicate a reservoir anomaly of approximately 0.25 of a decade of log apparent resistivity and 7° of phase with maximum values at 1 second. While this anomaly is small, it is detectable in both the apparent resistivity and phase. The other polarization mode, in which the electric field is parallel to regional strike, shows a much less obvious anomaly. The effect of boundary charges, depressing values of the apparent resistivity to long periods, is apparent in both modes.

Comparisons of the 3-D responses with 2-D and 1-D responses show that 1-D interpretation of the clay cap can be adequate, due to its large lateral extent and shallow placement, provided that only data sufficiently far from the edges are interpreted. Interpretation of the reservoir, however, requires a 2-D interpretation. Two-dimensional, transverse magnetic (TM) interpretation of the mode containing the electric field component perpendicular to regional strike can recover the 3-D reservoir anomaly, because the strongest response of the reservoir anomaly is due to boundary charges.

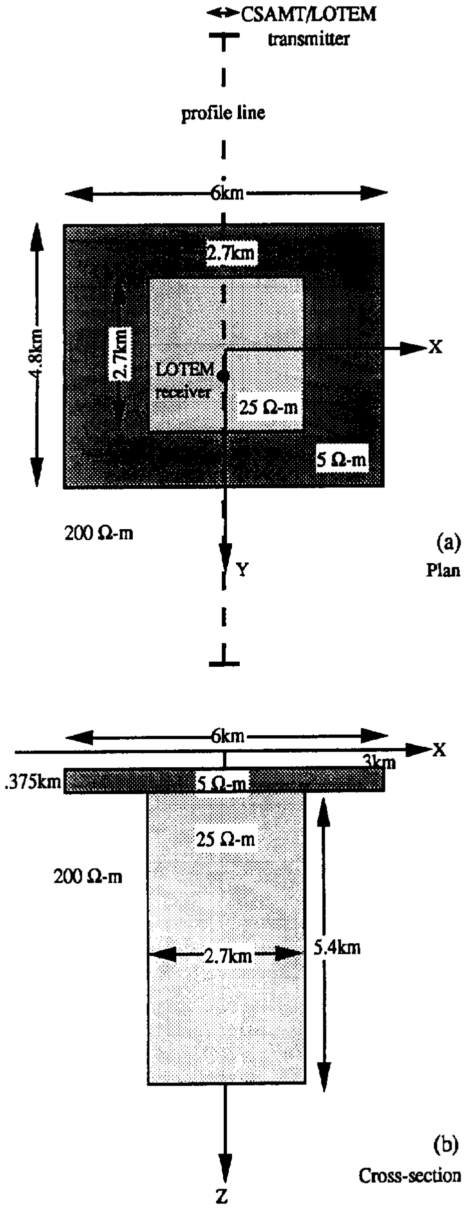

Figure 2. Resistivity model of a geothermal system in (a) plan and (b) cross-section.

CONTROLLED SOURCE AUDIOMAGNETOTELLURICS

The clay cap is defined in the high frequency range of a MT sounding and the reservoir anomaly is in the low power trough of the MT spectrum, so the CSAMT method naturally comes to mind. Apparent resistivity and phase pseudosections along the profile line for the model with the reservoir are presented in Figure 5. The transmitter, a 1 km bipole carrying 1 ampere of current, is 5 km from the edge of the cap. The electric field is parallel to the transmitter. As with MT, the cap is clearly defined for short periods, where the plane-wave assumption is valid (Zonge and Hughes,1991). However, the reservoir is

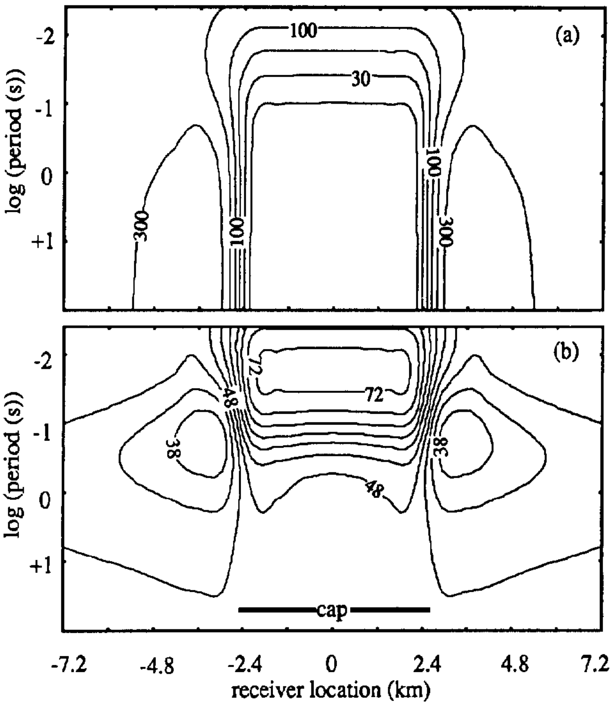

Figure 3. MT (a) Apparent resistivity and (b) phase psuedosection for 3-D model without the reservoir. Contours are in (a) ohm-m and (b) degrees.

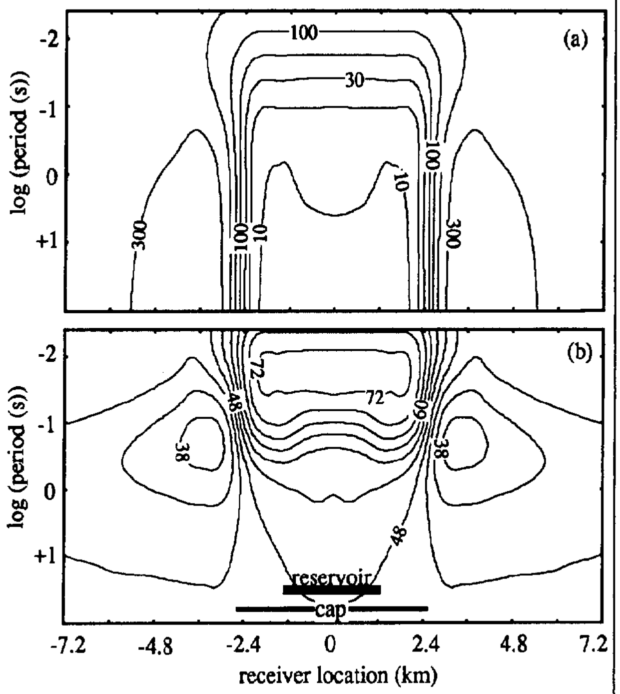

Figure 4. MT (a) Apparent resistivity and (b) phase pseudosection for 3-D model with reservoir. Contours are in (a) ohm-m and (b) degrees.

mainly in the near-field, as determined by the steady increase of apparent resistivity and the constant decrease of phase values. Moving the transmitter to detect a deep body in the far-field often results in the signal strength dropping below detectable limits. Moreover, correction techniques have only been developed for the apparent resistivity parameter (Bartel and Jacobson, 1987) and not the phase. Additional problems plaguing the CSAMT method include null and highly oblique field zones (Zonge and Hughes, 1991), transmitter overprint (Boschetto and Hohmann, 1991) and static shifts (Pellerin and Hohmann, 1991). Even so, CSAMT can be an effective tool for delineation of the clay cap (Sandberg and Hohmann, 1982) if properly used.

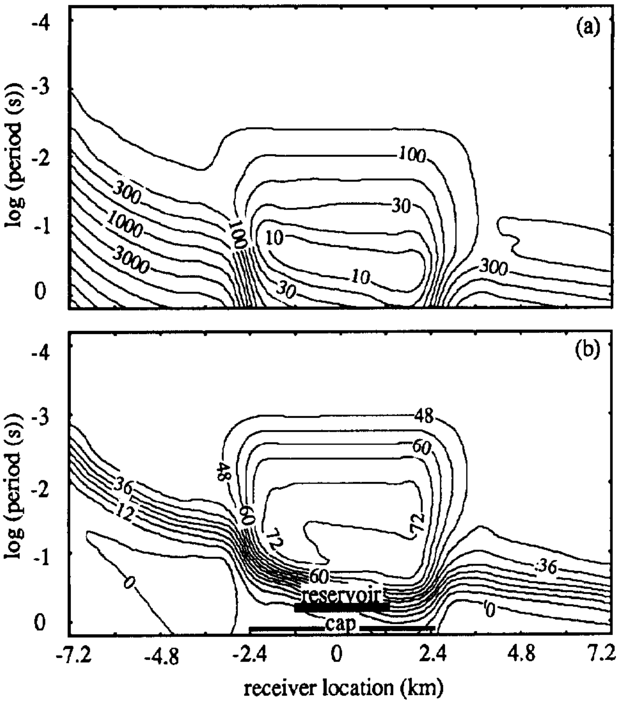

Figure 5. CSAMT (a) apparent resistivity and (b) phase psuedosection for 3-D model with the reservoir. Contours are in (a) ohm-m and (b) degrees.

LONG-OFFSET TIME-DOMAIN ELECTROMAGNETICS

The LOTEM technique is relatively new (Strack, 1991), but appears promising. Using the same grounded bipole source as the CSAMT technique the magnetic field impulse or electrical field transients are measured at distant sites, but processing does not involve a plane wave assumption. Examination of transients for both fields accentuate the difference between the magnetic and electric field response to the reservoir. Figure 6 shows electric field transients and Figure 7 shows magnetic field impulse transients for models with and without the reservoir at the receiver noted on Figure 2. A small, electric field anomaly, which requires multi-dimensional interpretation, is present, while none is present for the magnetic field. Both electric and magnetic LOTEM responses can be used to map the cap, but LOTEM measurements are strongly affected by 3-D structures (Kriegshauser, 1991) and the 1-D interpretation techniques available for delineation of the cap with the other EM methods may not be as successful with the LOTEM technique.

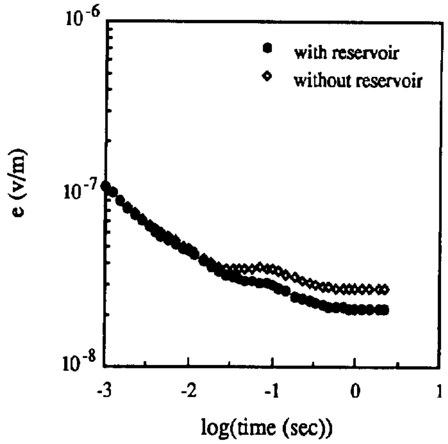

Figure 6. LOTEM electric field transients for models with and without a reservoir. Receiver location is noted on Figure 2.

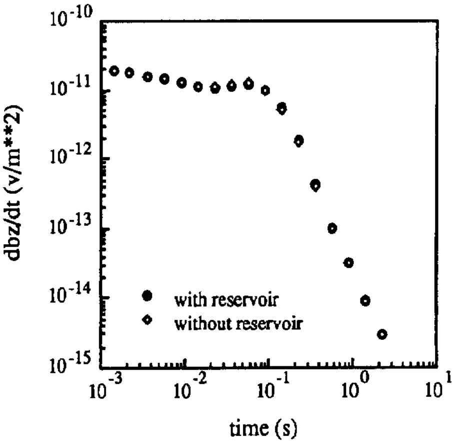

Figure 7. LOTEM magnetic field transients for models with and without a reservoir. Receiver location is noted on Figure 2.

SHORT-OFFSET TIME-DOMAIN ELECTROMAGNETIC

To illustrate the performance of the TEM technique we consider 300m by 300m transmitters with point receivers at the center of the loop and with a few radius offset, and invert central-loop soundings responses along the profile line using the 1-D image inversion technique of Eaton and Hohmann (1989). Figure 8a is an estimated resistivity cross-section for the model with the cap alone and Figure 8b for the cap and the reservoir. These results clearly show the location of the clay cap but the lack of a reservoir response, as was apparent in the sounding curves also. TEM measurements are less sensitive to boundary charges than the other techniques evaluated here and therefore are least effective in detecting the reservoir. Only the response on a portion of the profile line is computed for computation efficiency. Both numerically and in the field, the use of many transmitters, as is necessary in the TEM method, is expensive and needs to be kept in mind when designing a survey.

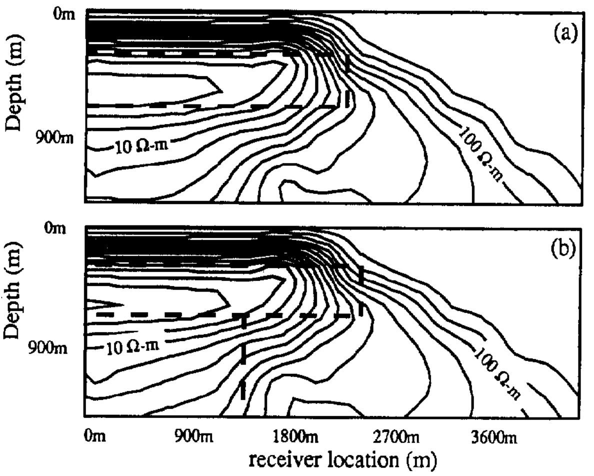

Figure 8. Image interpretation of TEM central-loop soundings for 3-D model of (a) the cap only and (b) the cap and the reservoir. Dashed line depicts true model. Contours are in ohm-m.

CONCLUSIONS

All four techniques are viable for delineating the clay cap. The MT method is not optimum for this task, however, because the shallow placement of the cap requires the use of measurements in the audio range where natural signal strength is low. MT shows a modest reservoir anomaly that may be measurable, but requires multi-dimensional interpretation. CSAMT is comparatively rapid and cost-effective; the cap response is clear in both polarization modes, and is in fact 1-D for much of the area within the cap. Continuous electric field profiling may be feasible to ensure adequate sampling of the cap (Torres-Verdin and Bostick, 1992). Because of the need to frequently move the transmitter, short-offset TEM is logistically expensive for delineation of a large target like the cap. The TEM method can be useful in conjunction with the MT and CSAMT methods, however, to remove static shift distortions (Pellerin and Hohmann, 1990). LOTEM, designed for deep exploration, requires large current sources (up to 100 amps) and large receiver loops (40 m by 40 m) and, therefore, is not a cost-effective tool for delineating shallow structures, and there are difficulties in 1-D LOTEM interpretation near 3-D structures, even one as large as the clay cap. However, a LOTEM electric field anomaly due to the reservoir is comparable in amplitude to the MT anomaly. Detailed imaging of the cap to assess homogeneity, trends in zonation, or indications of an outflow region will be valuable when planning for exploration beneath the clay cap and for better understanding the MT and LOTEM results.

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REFERENCES

Bartel, L.C., and Jacobson, R.D., 1987, Results of a controlled-source audiofrequency magnetotelluric survey at the Puhimau thermal area, Kilauea Volcano, Hawaii: Geophysics, **52**, 665-677.

Boschetto, N.B., Hohmann, G.W., 1991, Controlled-source audiofrequency magnetotelluric responses of three-dimensional bodies: Geophysics, **56**, 255-264.

Druskin, V.L., und Knizhnerman, L.A. 1988, A spectal semi-discrete method for the numerical solution of 3-D nonstationary problems in electrical prospecting: Physics of the 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.

Kriegshauser, Berthold, 1991, Einige Aspekte der 3-D interpretation von LOTEM daten: M.Sc. thesis, Institut fur Geophysik und Meteorologie der Universitat zu Koeln.

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.

Sandberg, S.K., and Hohmann, G.W., 1982, Controlled-source audiomagnetotellurics in geothermal exploration: Geophysics, **47**, 100-116.

Simmons, S.F., and Browne, P.R.L., 1990, A three-dimensional model of the distribution of hydrothermal alteration mineral within the Broadlands-Ohaaki geothermal field: Proc.12th New Zealand Geothermal Workshop.

Strack, K.-M., 1992, A practical review of deep transient electromagnetic exploration: Elsevier, Amsterdam.

Torres-Verdin, C., and Bostick, F.X., Jr., 1992, Principles of spatial surface electric field filtering in magnetotellurics: Electromagnetic Array Profiling (EMAP): Geophysics, **57**.

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.

Wannamaker, P.E., 1991, Advances in three-dimensional magnetotelluric modeling using integral equations: Geophysics, **56**, 1716-1728.

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, 713-809.