Geothermal Resources Council TRANSACTIONS, Vol. 16, October 1992

EVALUATION OF ELECTROMAGNETIC METHODS FOR GEOTHERMAL RESERVOIR DETECTION

Jeffery M. Johnston[1] Louise Pellerin[2] Gerald W. Hohmann[3]

(1) University of Utah Research Institute, Earth Science Lab, Salt Lake City, UT
(2) U.S. Geological Survey, Denver, CO
(3) University of Utah, Salt Lake City, UT

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 difficult exploration problem. Using three-dimensional (3-D) numerical models we evaluate four 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. All 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 the presence of the free electric charge at conductivity boundaries rather than EM induction; hence methods which rely on electric field measurements are superior to those where only the magnetic field is measured. Among the techniques and interpretation tools analyzed, we deem 2-D interpretation of MTdata 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 will be evident only if high-quality data are collected at closely spaced measurement sites. 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 transmitter 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 best suited to locate an alteration zone (clay cap) and the presence of an underlying geothermal reservoir as described by Simmons and Browne (1990) (Figure 1). 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.

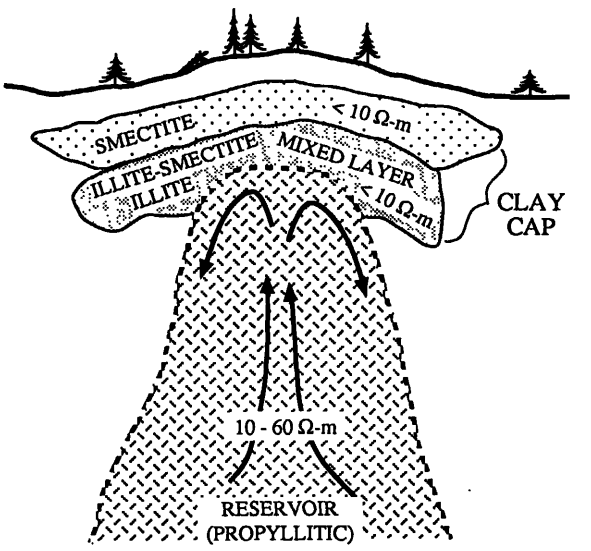

Figure 1. Schematic of a generalized geothermal system.

Methods that do discriminate between the two models will ultimately be tested on more complicated models incorporating reservoir outflow and zoning within the clay cap.

The 3-D resistivity model simulating the generalized system is shown in Figure 2 and was designed with advice from Gregg Nordquist and his colleagues at 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 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 and found to be in excellent agreement.

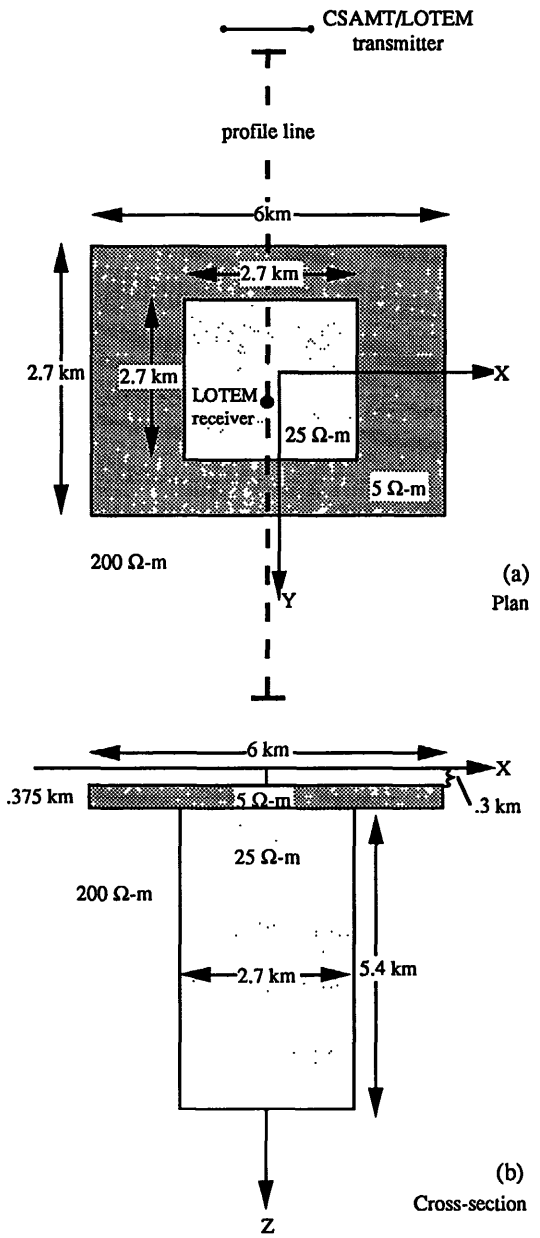

Figure 2. Resistivity model of a geothermal system in (a) plan and (b) cross-section.

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 noted. The similarity in the response of the two models at periods lower than 0.3 seconds indicates

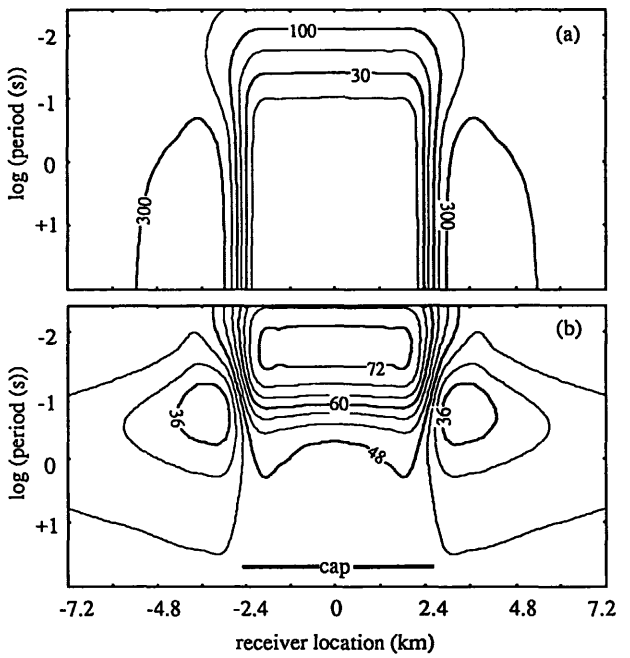

Figure 3. MT (a) Apparent resistivity and (b) phase pseudosection for 3-D model without the reservoir. Contours are in (a) ohm-m and (b) degrees.

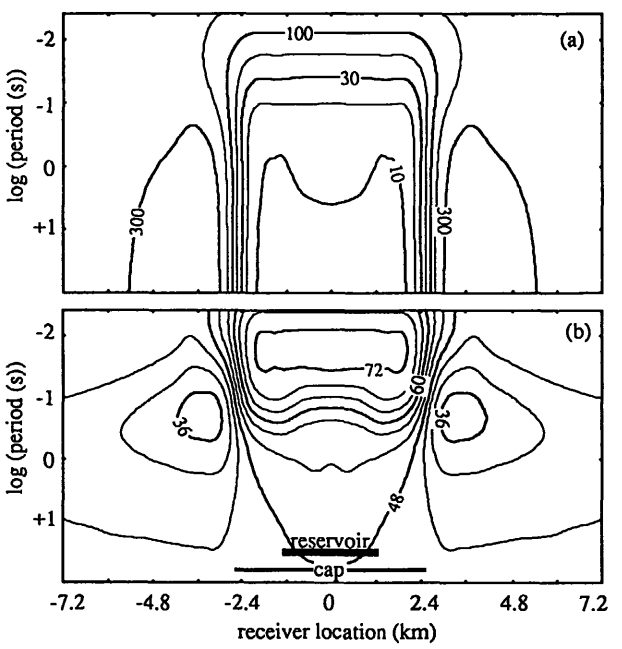

Figure 4. MT (a) Apparent resistivity and (b) phase pseudosection for 3-D model with reservoir. Contours are in (a) ohm-m and (b) degrees.

that the response at these periods is due almost entirely to the cap.

The strongest reservoir anomaly is seen in the MT quantities whose electric field components are perpendicular to the elongation direction (strike) of the cap; the transverse magnetic (TM) mode relative to cap's strike direction. This indicates that much of the reservoir anomaly arises from the effects of boundary charges (Wannamaker et al., 1984). The anomaly is seen at periods greater than 0.3 seconds as differences between the two model's response: approximately 0.25 of a decade of log apparent resistivity and 7° phase with maximum values at 1 second. While the anomaly is small, it is detectable and seen in both the apparent resistivity and phase. The other polarization mode (TE), 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 thus apparent in both modes.

Comparisons of the 3-D, 2-D, and 1-D response for an MT site at the model's center suggests that, sufficiently far from its edges, a 1-D interpretation of the clay cap may be adequate provided the cap has large lateral extent and shallow placement. Location of the reservoir, however, requires at least 2-D interpretation. The similarity of the 2-D, TM mode (not shown) with its 3-D counterpart implies that a 2-D interpretation based on this component should adequately locate the reservoir.

CONTROLLED SOURCE AUDIOMAGNETOTELLURICS

The MT reservoir anomaly has its strongest expression at those frequencies where the natural MT signals have the least power. On prospects where strong cultural noise sources exist, controlled source EM techniques may be considered and, based on our MT results, the CSAMT method may have particularly merit. Apparent resistivity and phase pseudosections along the profile line for the reservoir model are shown for a 1 km bipole transmitter, carrying 1 ampere of current, 5 km from the edge of the cap (Figure 5). The electric field component used to calculate these values 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). Unfortunately, the longer period reservoir response is masked by the transmitter's near-field effect and no significant difference is seen between the two model's response.

Near-field transmitter effects are indicated by the steady increase of apparent resistivity and the constant decrease of phase values. While moving the transmitter a greater distance from the target will restrict the near-field effects to longer periods, this action also reduces signal strength and may take it below detectable limits before a reservoir anomaly is seen. Moreover, correction techniques for near field effects have only been developed for apparent resistivity (Bartel and Jacobson, 1987) and not phase. Additional difficulties in applying 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). Nevertheless, CSAMT can be an effective tool for delineation of the clay cap if used properly (Sandberg and Hohmann, 1982) and tensor CSAMT should permit the estimation of the cap's depth and conductivity contrast.

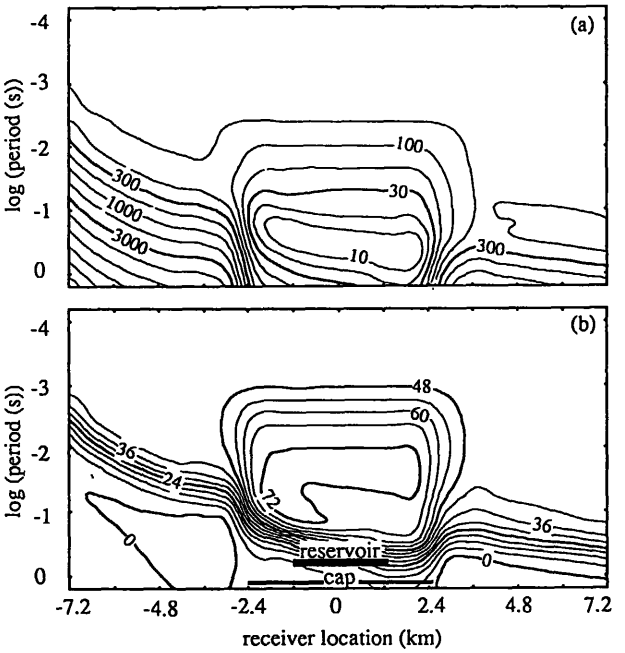

Figure 5. CSAMT (a) apparent resistivity and (b) phase pseudosection for 3-D model with the reservoir. Contours are in (a) ohm-m and (b) degrees.

LONG-OFFSET TIME-DOMAIN ELECTROMAGNETICS

The LOTEM technique is relatively new (Strack, 1991) and, while LOTEM data interpretation methods are still in the initial stages of development, the technique appears promising. Using the same grounded bipole source as the CSAMT technique, either the magnetic field impulse or electrical field transients are measured at distant sites, and processed without relying on the plane wave assumption. Figure 6 shows electric field transients and Figure 7 shows magnetic field impulse transients for models with and without the reservoir. The receiver location is noted on Figure 2. A 0.1 decade electric field anomaly is seen at about .3 s, while no anomaly is apparent in the magnetic field data. Ultimately, an interpretation strategy using the response for both fields may better accentuate the response to the reservoir. Examination of the model results at various receivers indicates that both the electric and magnetic LOTEM responses can be used to map the clay cap. However, 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.

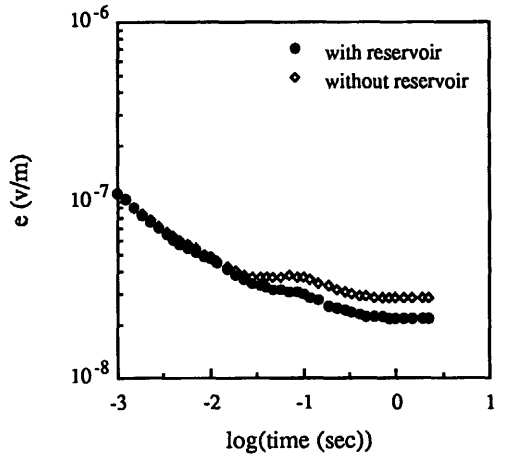

Figure 6. LOTEM electric field transients for models with and without a reservoir. Receiver location is noted on Figure 2.

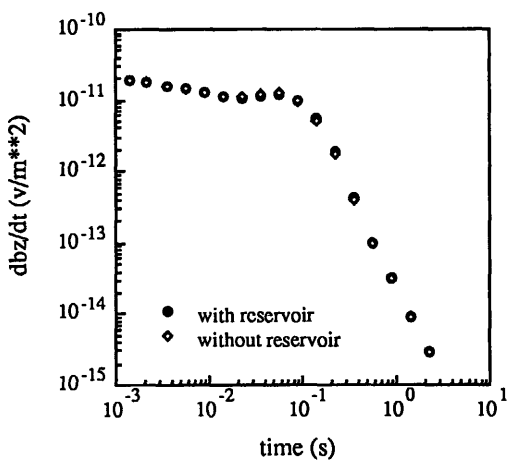

Figure 7. LOTEM magnetic field transients for models with and without a reservoir. Receiver location is noted on Figure 2.

SHORT-OFFSET TIME-DOMAIN ELECTROMAGNETIC

To illustrate the performance of the TEM technique we consider 300m by 300m loop transmitters with point receivers at both the center of the loop and offset from its center by a few loop radii These data are inverted as central-loop soundings 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, its resistivity, and produce a reasonable estimate of its depth, yet they lack any reservoir anomaly. TEM measurements are less sensitive to boundary charges than the other techniques evaluated in this study and therefore should be the least effective in detecting the reservoir. For the sake of economy,

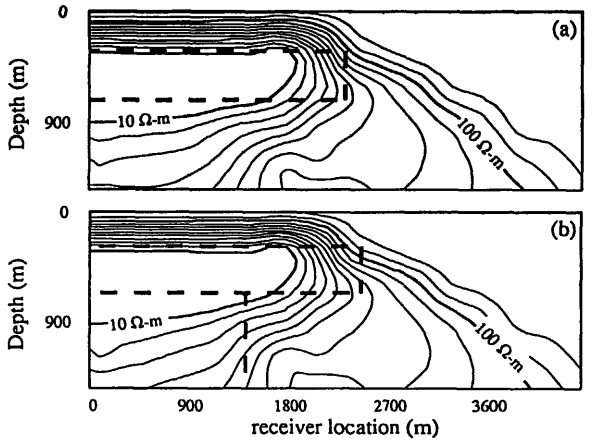

Figure 8. Image interpretation of TEM central-loop soundings for 3-D model of (a) the cap only and (b) the cap and the reservoir. Dashed line depicts true model. Contour interval: 10 ohm-m.

only the response on a portion of the profile line was computed. In either a numerical model or a field experiment, the TEM transmitter/receiver ratio is high, and therefore relatively expensive. This will be a major survey design factor when using TEM in mapping a feature as extensive as the clay cap.

CONCLUSIONS

All four techniques are viable for delineating the clay cap. The MT results predict a modest reservoir anomaly that should be apparent in a high quality, high density data set and its interpretation would require use of multi-dimensional algorithms. The MT method is probably not optimum for mapping the extent of the clay cap because its shallow placement requires measurements in the audio range where natural MT signal strength is low. CSAMT is a comparatively rapid and cost-effective mapping technique; the cap's CSAMT 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 considered 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 also not a cost-effective tool for delineating shallow structures. Also, 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. Regardless of the technique(s) used, detailed imaging of the cap to assess homogeneity, trends in zonation, or indications of an outflow region will be valuable for planning exploration beneath the clay cap and, if available, for better understanding MT or LOTEM measurements.

ACKNOWLEDGEMENTS

We would like to thank Gregg Nordquist, Berthold Kriegshauser, Phil Wannamaker and Alan Tripp for many enlightening discussions. The Consortium of Electromagnetic Modeling and Inversion at the University of Utah funded the study and the San Diego Supercomputing Center's Cray YM-P was used to satisfy the large computing requirements.

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., and Knizhnerman, L.A. 1988, A spectral 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, Hohmann, G.W., and Ward, S. H., Magnetotelluric responses of three-dimensional bodies in layered earths: Geophysics, **49**, 1517-1533.

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.