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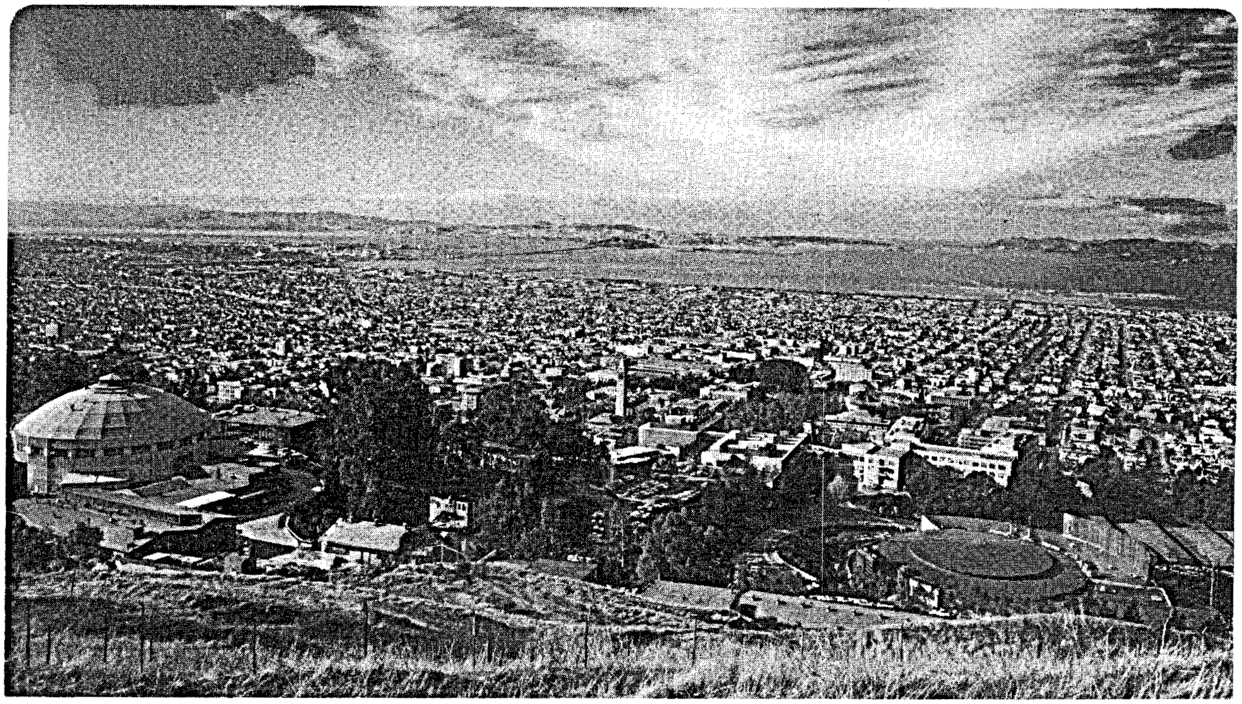

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DISCLAIMER

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EXPERIENCE WITH THE EM-60 ELECTROMAGNETIC SYSTEM FOR GEOTHERMAL EXPLORATION IN NEVADA

M. Wilt, N.E. Goldstein, M. Stark,*
J.R. Haught,† and H.F. Morrison†

ABSTRACT

As part of a joint program between the Department of Energy/Division of Geothermal Energy and private geothermal developers, Lawrence Berkeley Laboratory (LBL) conducted controlled-source electromagnetic (EM) surveys at three geothermal prospects in northern Nevada. Over 40 soundings were made in Panther Canyon (Grass Valley), near Winnemucca; Soda Lakes, near Fallon; and McCoy, west of Austin, to test and demonstrate the applicability of LBL's EM-60 system to geothermal exploration.

The EM-60 is a frequency-domain system using three-component magnetic detection. Typically, we apply ±65 A to a 100-m-diameter four-turn horizontal loop, generating a dipole moment $>10^6$ MKS over the frequency range 10^{-3} to 10^3 Hz. With such a source loop, we have made soundings at transmitter-receiver separations of up to 4 km, providing a maximum depth of penetration of 4 km. Recorded spectra are interpreted by means of simple apparent-resistivity calculations made in the field and by layered-model

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inversions computed in the laboratory. The EM interpretations are then compared with other available geological/geophysical data sets for the purpose of combined interpretation and method evaluation. Experience with the EM-60 system in Nevada has shown it to be an efficient and possibly more cost-effective alternative to dc resistivity and magnetotellurics for geothermal exploration. An average of two soundings per field day for depths of exploration up to 2 km was obtained routinely.

Results from EM-60 work at Panther Canyon compare very favorably with earlier dipole-dipole resistivity surveys. Both methods adequately outlined an irregularly shaped, buried conductive body associated with a region of high heat flow, but the same area was covered with the EM-60 in just over half the field time required for the dipole-dipole resistivity survey. At Soda Lakes, 13 high-quality EM soundings were obtained from two transmitters in six field days under ideal field conditions. With the EM-60 data, we were able to map the depth to and inclination of a buried conductive body associated with an area of high subsurface temperatures. In this case, the EM results confirmed an earlier MT survey interpretation and gave additional detailed near-surface information. At the remote and mountainous McCoy site, data interpretation was complicated because of the rugged terrain. By modifying existing interpretative software, we were able to calculate the effects of tilted-source dipoles and elevation differences on soundings and thus interpret data. The EM soundings detected a conductive zone at a depth of 200 m at the south end of the prospect, where a nearby drillhole had encountered water at 100°C at the same depth. In addition, EM soundings at McCoy provided information on a deep conductor below 2 km which has yet to be drilled.

INTRODUCTION

In 1976, Lawrence Berkeley Laboratory, in conjunction with the University of California at Berkeley, made preliminary measurements with a prototype horizontal-loop EM prospecting system near Leach Hot Springs in Grass Valley, Nevada (Jain, 1978). Encouraging results from this work led to the development of the frequency-domain EM-60 horizontal-loop system, which has now been operated for over 500 hours at several geothermal sites in Nevada and Oregon (Morrison et al., 1978). The objectives of LBL's controlled-source EM program are to develop new hardware and software tools for geothermal exploration and to demonstrate the technical feasibility and cost-effectiveness of the technique.

The EM method may be a significant improvement in geothermal exploration over dc resistivity and magnetotellurics (MT) for three reasons: (1) the maximum depth of exploration with EM is approximately equal to the distance between the transmitter and receiver (for dc resistivity, almost five times the source-receiver separation is required for the same depth of exploration); (2) the EM method can provide comparable field data in less time and at less expense than dc resistivity or MT; and (3) distant lateral inhomogeneities, which often affect MT data, have relatively minor effects on EM data because the strength of the fields decreases sharply with increasing distance from the transmitter.

As part of the DOE-Industry Coupled Case Studies Program for the northern Basin and Range Province, LBL conducted EM-60 surveys at three geothermal target areas in northern Nevada: Panther Canyon in Grass Valley; Soda Lakes, near Fallon; and McCoy, west of Austin (Figure 1). These areas were chosen on the basis of industry interest, access to land, and, to some extent, availability

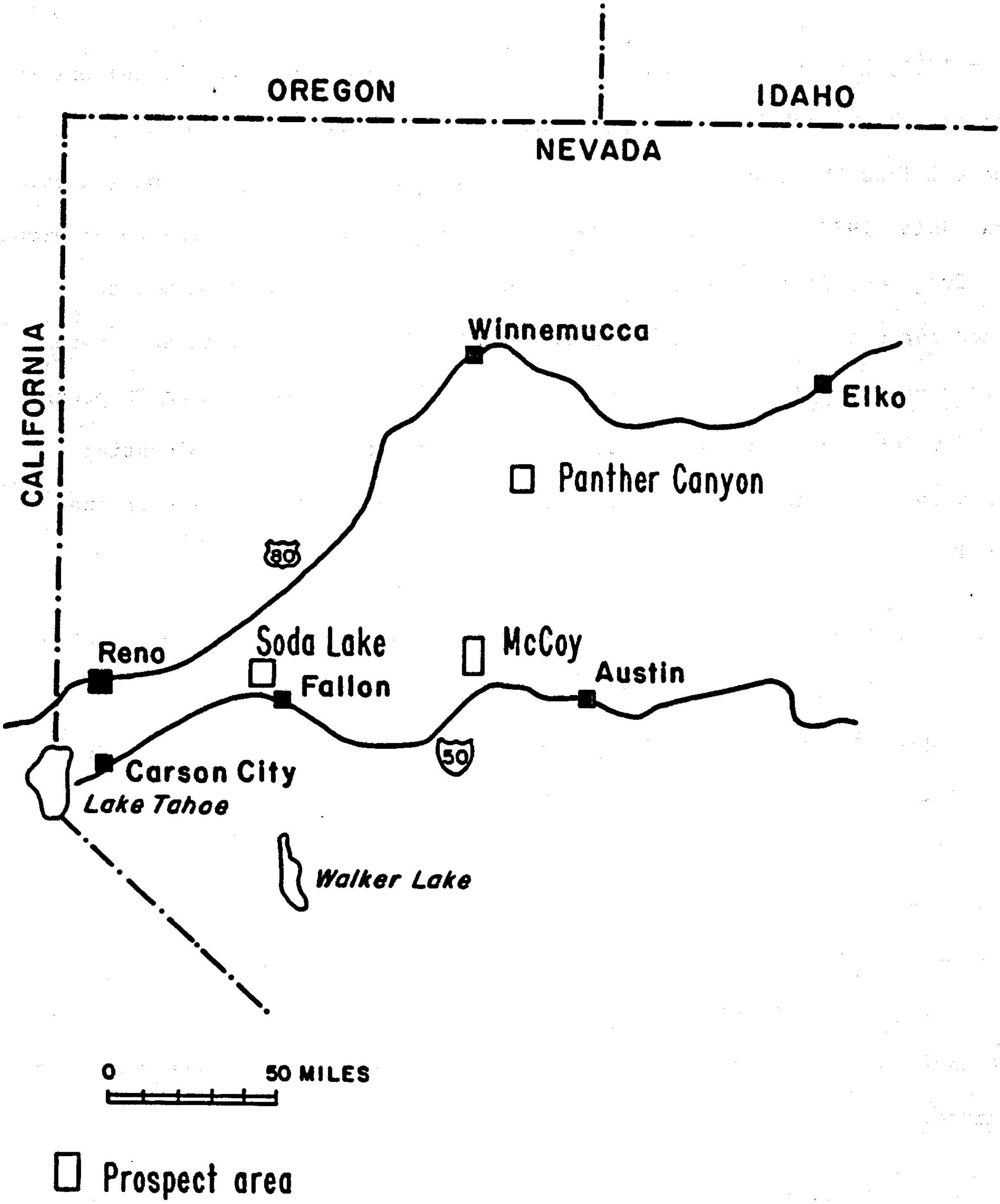

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Figure 1. Location map for the three EM-60 surveys conducted in 1979 by LBL.

of other geological and geophysical data. This paper summarizes the significant findings in each area; more complete descriptions, including field data and layered-model inversions, are given in Stark et al. (1980) and Wilt et al. (1980a,b).

EM-60 SYSTEM DESCRIPTION

With the EM-60 system, the earth is energized by means of an alternating magnetic field created by a square-wave current applied to a horizontal loop (Figure 2). Power is provided by a Hercules gasoline engine linked to a 60-kW aircraft alternator; the two components are mounted on the bed of a 1-ton four-wheel-drive truck (Figure 3). The alternator output is full-wave rectified and capable of providing ±150 V at up to 400 A to the loop. The current waveform is created with a transistorized switch, which consists of two parallel arrays of 6 to 60 transistors mounted in sets of 3 in interchangable modules (Morrison et al., 1978). The operator remotely sets the fundamental frequency of the current waveform from 10^{-3} to 10^{3} Hz. Frequency settings are controlled by a quartz clock; four frequencies per decade are available.

The dipole moment, which is a measure of the source strength, is determined by the resistance and inductance of the loop. At frequencies below about 50 Hz a four-turn, 50-m radius loop of 6-gauge wire will yield a dipole moment of 3×10^{6} MKS. This provides adequate signal for transmitter-receiver separations less than about 4 km. Above 50 Hz the loop inductance causes the moment to decrease and the current waveform to become quasi-sinusoidal. Because of the reduced moment, high frequency information becomes more difficult to obtain at larger transmitter-receiver separations. The 50-m loop has proven satisfactory for most geothermal operations: it can be laid out

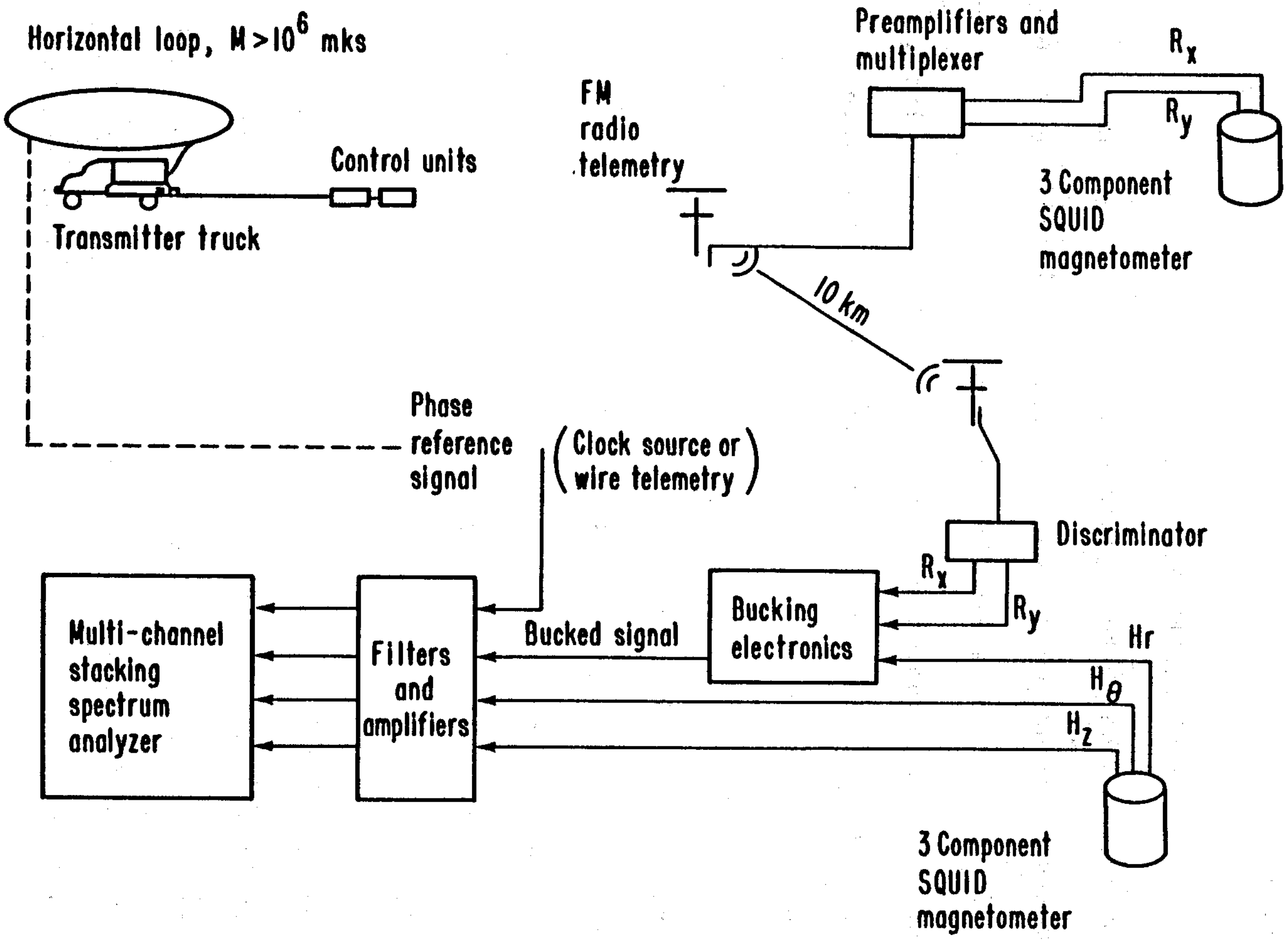

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Figure 2. Schematic diagram of the EM-60 horizontal-loop prospecting system as used in Nevada in 1979.

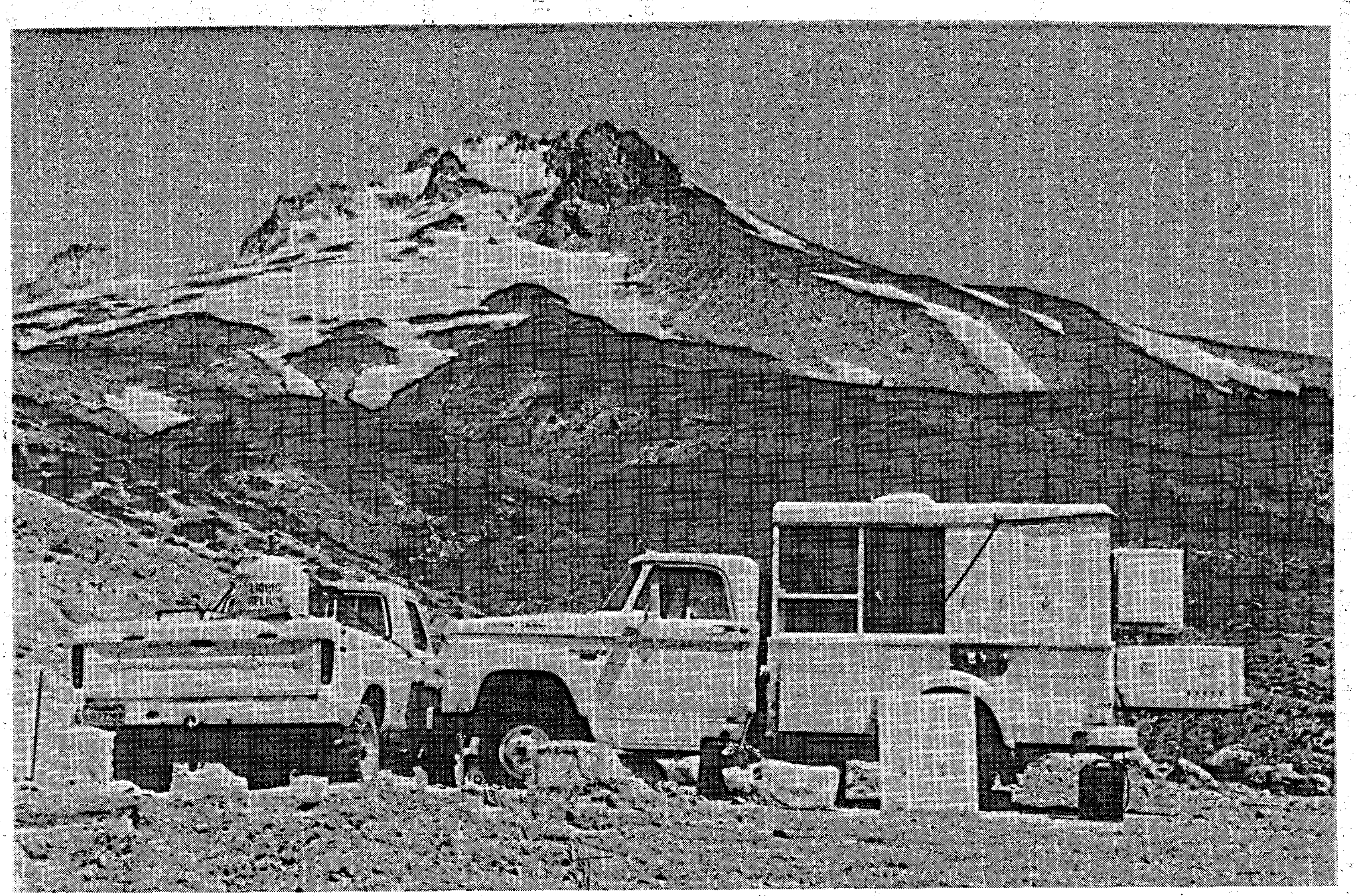

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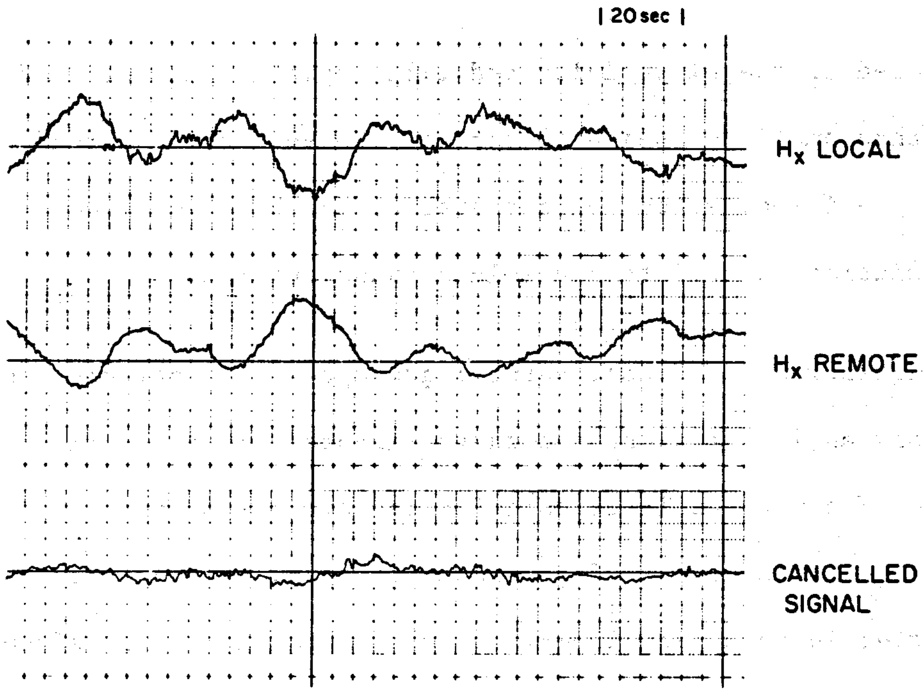
Figure 3. The EM-60 transmitter.

from a truck in about 30 minutes, and it provides sufficient power for exploration depths of up to 4 km. If greater depth of penetration is required, larger loops and/or heavier gauge wire can be used. However, to achieve a two-fold increase of exploration depth, more than a four-fold increase in source strength is required and logistical problems associated with the greater weight and length of wire must be considered.

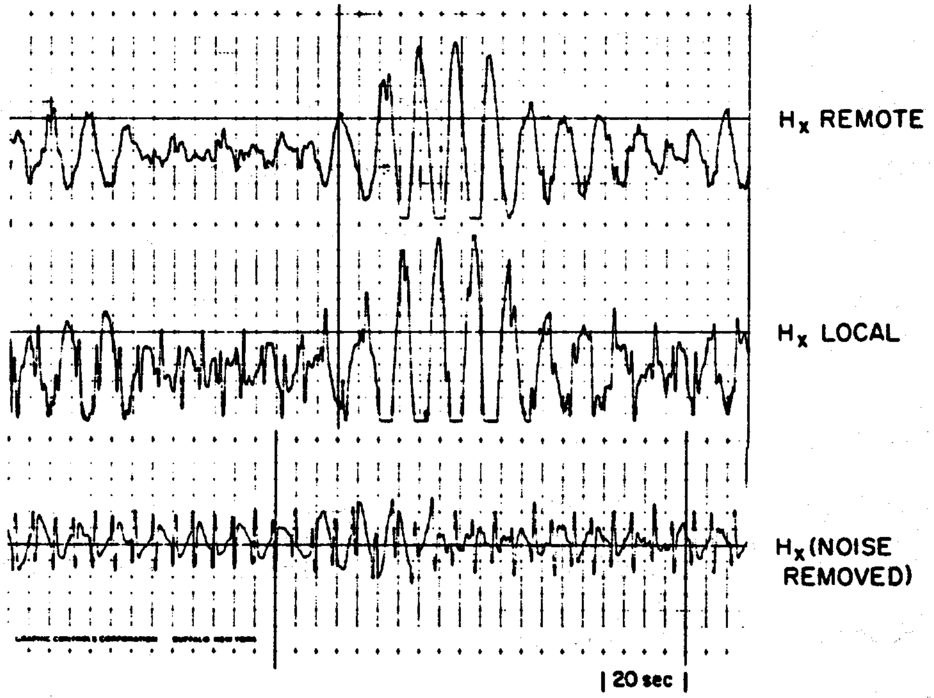
Magnetic fields are detected at receiver stations with a three-component SQUID magnetometer oriented to measure the vertical, radial, and tangential components with respect to the loop. Electric dipoles may also be used in combination with or instead of magnetic sensors. Signals are amplified and anti-alias filtered before input to a six-channel, programmable, phase-sensitive receiver. Through the receiver key-pad, the operator sets the parameters that control signal processing: (a) fundamental period of the waveform to be processed; (b) maximum number of harmonics to be analyzed, up to 15; (c) number of cycles to be stacked prior to Fourier decomposition; and (d) number of input channels of data to be processed. Processing results in a raw amplitude estimate for each component and a phase estimate relative to the phase of the current in the source loop. Raw amplitude estimates must later be adjusted for dipole moment and distance between loop and magnetometer.
In the original system, phase referencing was maintained by using a hard-wire link between a resistor shunt on the loop and the receiver. This reference voltage was applied directly to channel 1 of the receiver for phase comparison.

In practice, the hard-wire link was found to be a source of noise, particularly above 50 Hz. We consequently eliminated the absolute phase reference at high frequencies in favor of relative phase measurements between vertical and radial components. With relative phase measurements, interpretation is based on the ellipticity and tilt angle of the combined magnetic fields rather than amplitude-phase spectra of the vertical and radial fields. Recently, high-precision, synchronous quartz clocks have been added for phase reference, permitting us to obtain absolute phase information up to 1 kHz.

At low frequencies (<1.0 Hz), natural geomagnetic signal amplitude increases roughly as 1/f, and the secondary (induced) magnetic field decreases as 1/f. The net result is an effective signal-to-noise ratio that decreases as $1/f^2$. High levels of geomagnetic noise can therefore be a formidable barrier in obtaining low-frequency information. To reduce the effect of geomagnetic noise, a second (reference) magnetometer is placed far enough from the transmitter loop (usually about 10 km) so that the observed remote fields will consist only of the geomagnetic fluctuations (Figure 2). Once installed, the reference magnetometer can often remain fixed over the course of a survey. The remote signals are transmitted to the mobile receiver station from the reference station via FM radio telemetry. Before the loop is energized, the remote signals are inverted, adjusted in amplitude, and then added to the receiver station geomagnetic signal to produce essentially a null signal. Once the loop is energized, the resulting receiver magnetic signal is essentially free of geomagnetic noise. A good example of this simple noise-cancellation scheme is shown in Figure 4. The resulting signal-to-noise improvement of roughly 20 dB has allowed us to obtain reliable data to 0.05 Hz, an addition of three or four important data points on the sounding curve. These points are of great value for resolving deeper horizons. This noise cancellation scheme has reduced low-frequency averaging times by a factor of four and has allowed us to obtain low-frequency information even at high geomagnetic noise levels.



A. NATURAL MAGNETIC FIELD CANCELLATION



B. SAMPLE FIELD RECORD TRANSMITTER FREQUENCY = 0.1 Hz

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Figure 4. Example of data improvement using the telluric noise cancellation scheme. (A) Natural geomagnetic signal and initial cancelling at the receiver site with transmitter off. (B) Same system with transmitter on.

DATA INTERPRETATION

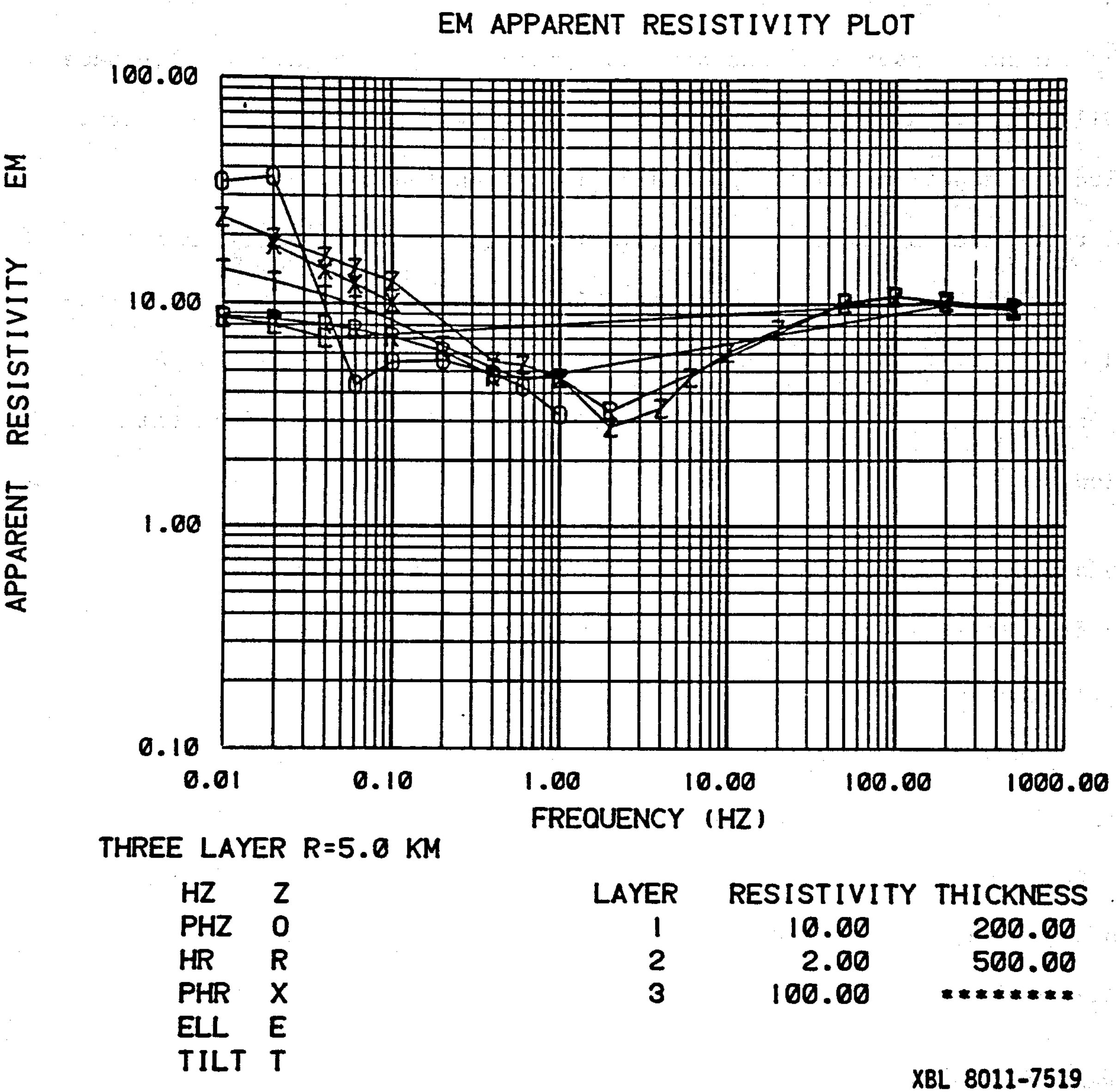
Apparent Resistivity Function

Apparent resistivity vs frequency curves can be calculated from EM spectra by matching observed field data to generalized, homogeneous half-space curves (Wilt and Stark, 1981). The generalized curves are a plot of spectral field value vs induction number (B), which is a function of the frequency, transmitter-receiver separation, and resistivity of the half-space. A resistivity spectrum can therefore be obtained by matching observed data to the generalized curve and calculating the conductivity from the induction number. For a multi-layered section, an apparent resistivity curve is obtained from this calculation.

An example of such a curve calculated from a three-layer model is given in Figure 5; calculations for each type of measured data reflect the layered-model section shown at the bottom, although there is scatter between the curves. The curves are generally used for qualitative interpretation. They give asymptotic values for earth resistivities and indicate the resistivity type section, thus allowing more accurate "first guesses" for the layered-model inversion algorithm. The curves are also useful for evaluating data quality in the field and for isolating noisy data for deletion prior to inversion.

Layered-Model Inversion

Quantitative interpretation is accomplished by least-squares inversion of observed data to fit one-dimensional models. Layered-model forward solutions may be calculated for a finite-loop source or for a point dipole source (Ryu et al., 1970; Anderson, 1979). The loop-source solution is perfectly general and is more accurate when soundings are made close to the source. The point-dipole solution is calculated using digital filters and is identical to the



LAYER	RESISTIVITY	THICKNESS
1	10.00	200.00
2	2.00	500.00
3	100.00	********

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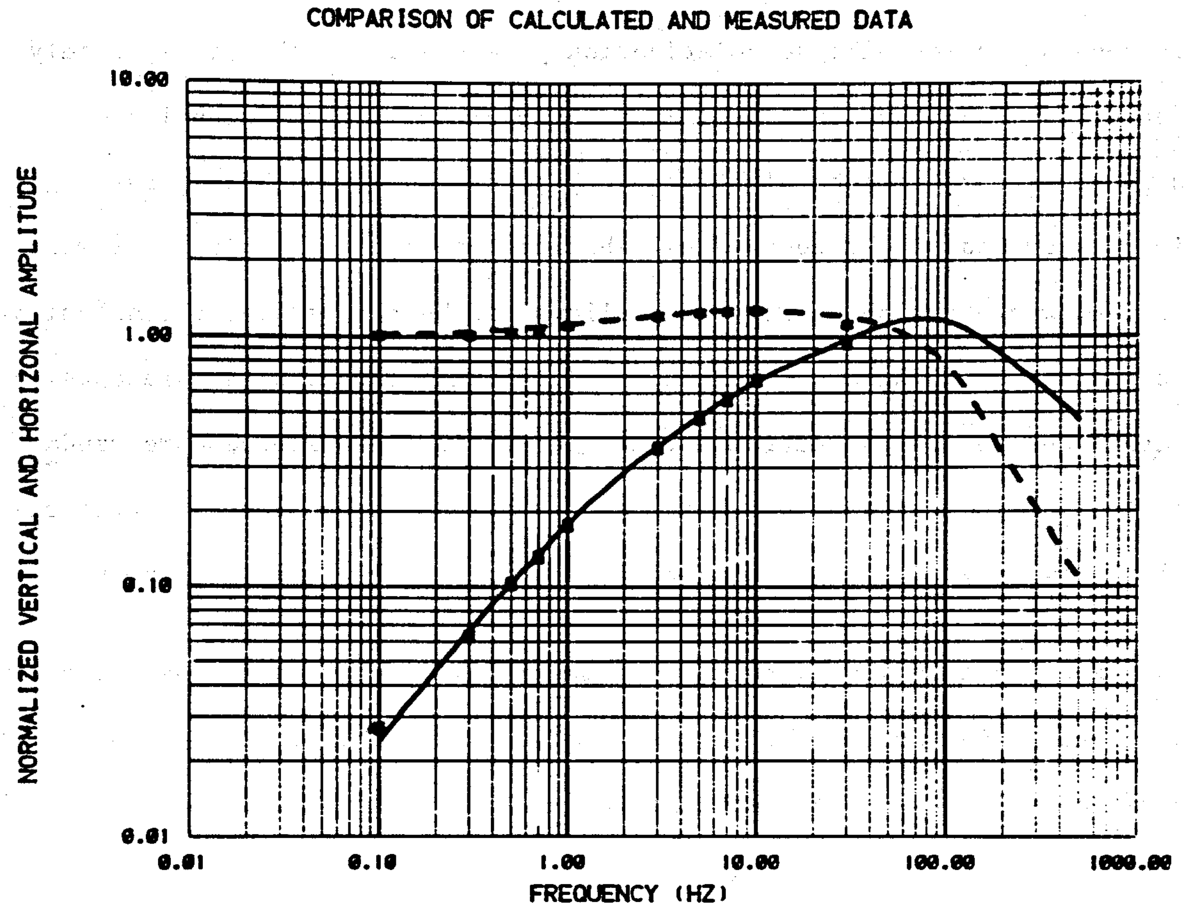
Figure 5. EM apparent resistivity spectra calculated from layered-model theoretical data.

loop solution for transmitter-receiver separations greater than ten loop radii. Since the digital filter calculation is much less expensive, the point dipole source is normally used in the layered-model inversion program. The inversion program uses the Marquardt least-squares algorithm to fit amplitude-phase and/or ellipse polarization parameters jointly or separately to layered models (Inman, 1975). This program allows the use of polarization parameters to fit the high-frequency points where absolute phase data is noisier and simultaneously use absolute phase data to fit the lower frequencies, where the phase reference allows for better parameter resolution. Observed data are weighted by the standard deviation of field measurements. These are accurate representations of true error if noise sources are random. When sources are non-random, which is the usual case, the error estimates are probably somewhat low, thus leading to low estimates of parameter errors.

Our experience indicates that one-dimensional interpretation seems to give adequate results because of the fast spatial decay of the dipole fields. Because of the rapid fall off in field strength with distance, dipole fields seem to be much less affected by nearby lateral discontinuties and current channeling, which, for example, impair one-dimensional MT interpretations. Although we rely mainly on one-dimensional interpretations, two-dimensional forward modeling of dipole EM data may be done for special cases (Lee, 1978). The finite element program used is very expensive and cumbersome, however, and the model considered must be fairly simple to yield an accurate solution. The program is used chiefly for theoretical studies, although it has been used occasionally to help interpret field data affected by severe two- or three-dimensional geology.

An example of a layered-model inversion for an EM-60 sounding is given in Figures 6 and 7. The vertical and radial amplitude and ellipticity



SODA LAKE .72 KM NW T1

CALCULATED DATA		MEASURED DATA		LAYER	RESISTIVITY(OHM-M)		THICKNESS(M)	
HR	———————	HR	X	1	12.11±	.00	305.4 ±	2.
HZ	— — —	HZ	*	2	1.77±	.02	.1000E+11±	0.

DATA VARIENCE ESTIMATE 15.23

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Figure 6. Examples of the EM-60 vertical and horizontal amplitude spectra and their fit to a two-layer model.

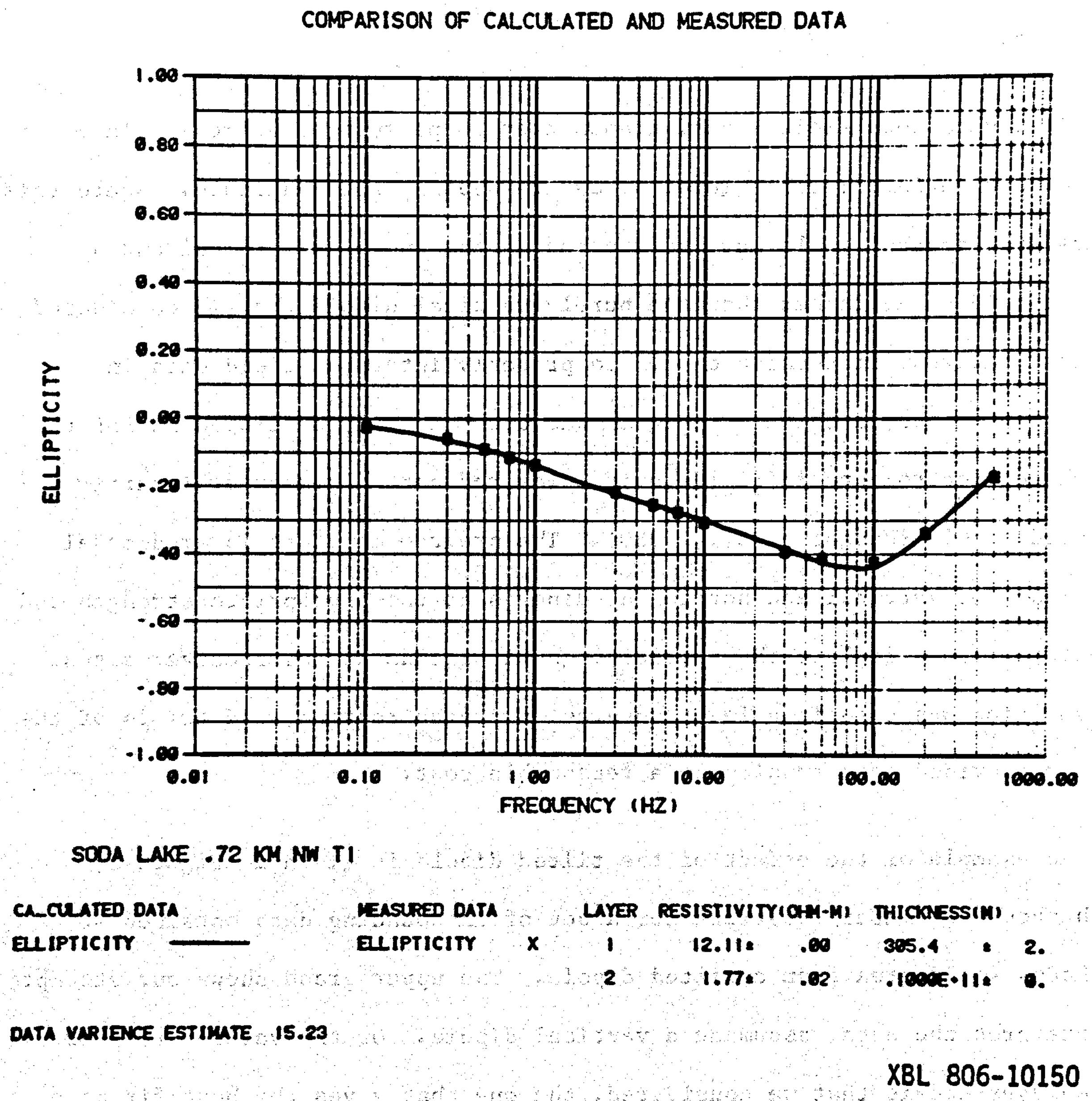

Figure 7. Example of an EM-60 ellipticity spectrum and its fit to a two-layer model.

spectra shown are three of the six spectra normally calculated for a field sounding, the other being vertical and radial phase and tilt angle. The data were fitted jointly to the two-layer model shown at the bottom of each figure. Note that because of noise associated with the hardwire link, good amplitude data were obtained only up to 30 Hz, but good ellipticity data were obtained to 500 Hz.

In mountainous field areas, transmitter loops must sometimes be laid out on inclined surfaces, since level areas are usually not available. Where this occurs, the source dipole must be treated as the sum of a vertical and a horizontal dipole, rather than the purely vertical dipole that is considered in the idealized, flat-earth case. To properly interpret field data in mountainous areas, a computer program has been recently developed at LBL to calculate electromagnetic fields over a layered earth from an arbitrarily oriented dipole (Haught et al., 1980). The program combines layered-model solutions for vertical and horizontal dipoles at the appropriate strength and orientation to calculate the correct magnetic fields at the receiver sites. The solution was used in a least-squares inversion routine, and trials of the program provided good results at a reasonable cost.

An example of the effect of the tilted dipole is given in Figure 8, which shows two interpretations for a set of EM sounding data obtained at the McCoy field area from a tilted dipole. The upper graph shows our attempt to interpret the data, assuming a vertical dipole. Of the various two- or three-layer models that we considered, the one that gives the best fit is a three-layer section that indicates the presence of a conductor at about 1.3 km in depth. The bottom of Figure 8 shows a layered-model fit for a two-layer section with a tilted dipole source. Here the fit is superior, and with no

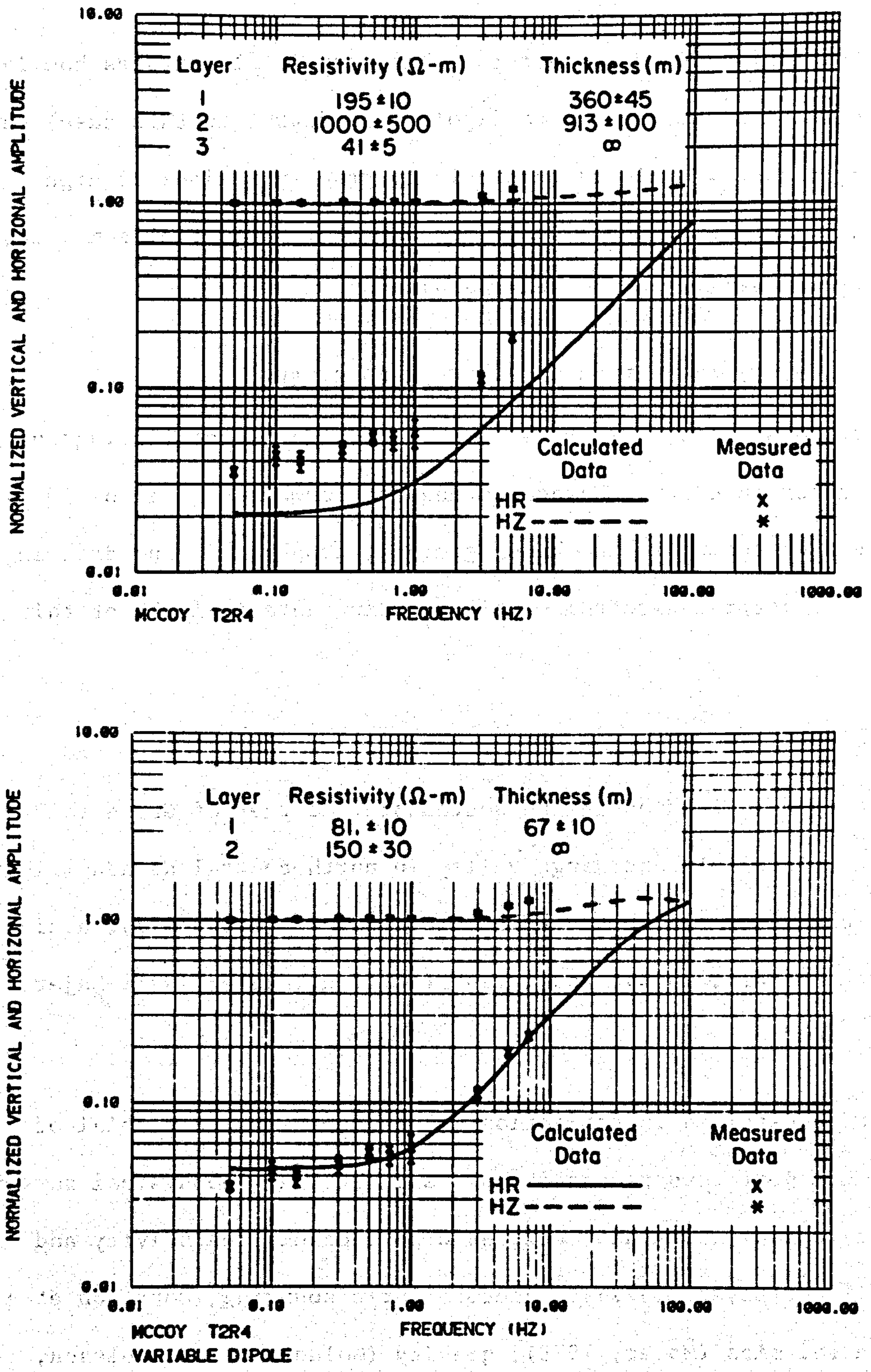

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Figure 8. Comparison of inversions from a vertical dipole source (top) and a tilted dipole source (bottom).

indication of a deeply buried conductor. This example illustrates how ignoring even small inclinations at the source dipole (one degree in this case) can give misleading results. This is particularly true in regions of high resistivity, such as McCoy, where small secondary magnetic fields may easily become distorted by tilting of the source dipole.

FIELD SURVEYS WITH THE EM-60 SYSTEM

In the sections below, we give a summary of significant findings of field surveys taken in central Nevada during the summer and fall of 1979. For each project we summarize the known geology, geophysics, and drilling history, and we interpret electromagnetic sounding data in light of this information.

Panther Canyon

Panther Canyon is located in the southeastern corner of Grass Valley, a northerly trending Basin and Range valley in north-central Nevada (Figure 9). The region is characterized by high heat flow (Sass et al., 1977), active hot springs (Olmsted et al., 1975), and recent faulting (Noble, 1975; Majer, 1978).

As part of a detailed investigation of the geothermal potential of Grass Valley, LBL performed reconnaissance and detailed geophysical surveys throughout the region. Work has included dipole-dipole resistivity and telluric profiling (Beyer, 1977), magnetotelluric sounding (Morrison et al., 1979), passive seismics (Majer, 1978), gravity (Goldstein and Paulsson, 1978), and heat flow (Sass et al., 1977). Composite profiles and synthesis of these and other data are given in Beyer et al. (1976).

Geothermal interest in Panther Canyon was heightened after several shallow boreholes indicated anomalously high heat flow values (7 HFU, or about three times the regional average). Subsequent telluric profile and dipole-dipole resistivity studies revealed a low-resistivity zone at depth beneath the heat flow high, thus suggesting the presence of geothermal waters at depth. The region was also found to be seismically active (Majer, 1978), with swarm-type activity along a NE-SW fault aligned with Panther Canyon. Electromagnetic soundings were made over the heat flow anomaly near the Panther Canyon area for the purpose of providing further information about the cause of that anomaly and for comparison to existing dipole-dipole and telluric data. The EM-60 field survey consisted of eight soundings arranged along two orthogonal lines crossing at the transmitter loop; transmitter-receiver separations ranged from 400 to 1600 m. The EM stations are located along survey lines used previously for the dipole-dipole survey (Figure 9).

Electromagnetic sounding data from Panther Canyon were interpreted by individual layered-model inversions of spectra; best-fit models were then pieced together along the profile, and sections were plotted at a distance halfway from the source to the receiver. Good data were collected at all sites, and reasonable models were obtained from inversions.

Figure 10 is a north-south resistivity cross section over the Panther Canyon thermal anomaly. The figure gives a comparison of a two-dimensional model made from dipole-dipole resistivity data and the composite resistivity section made from EM-sounding results. At first glance, the interpretations are remarkably similar. Both cross sections indicate resistive surface material overlying an irregular southward-dipping conductive body. Depth to resistive basement is shown to vary between 250 and 800 m below the surface.

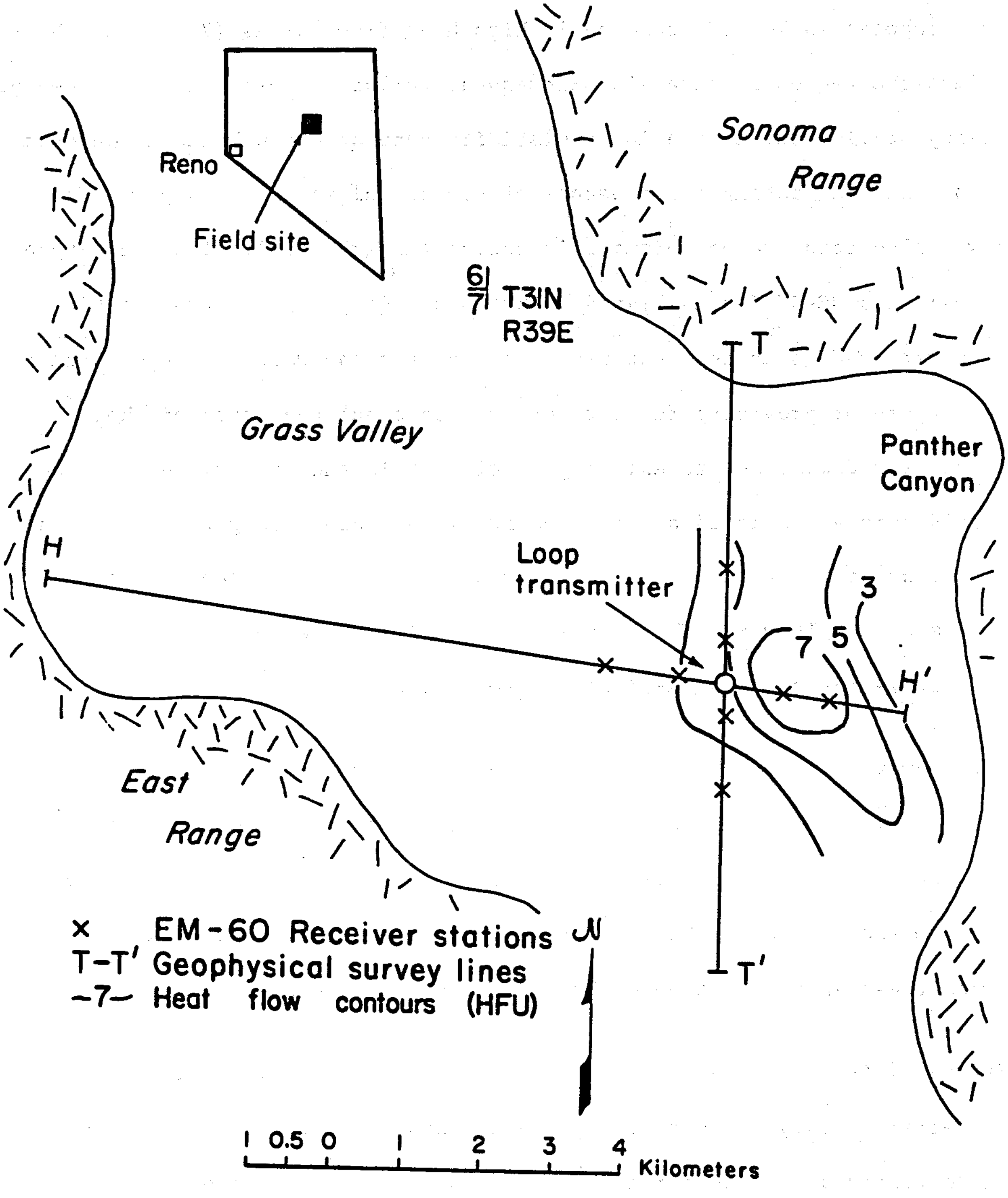

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Figure 9. Location of the EM stations in the Panther Canyon area, Grass Valley, Nevada with respect to the heat flow anomaly.

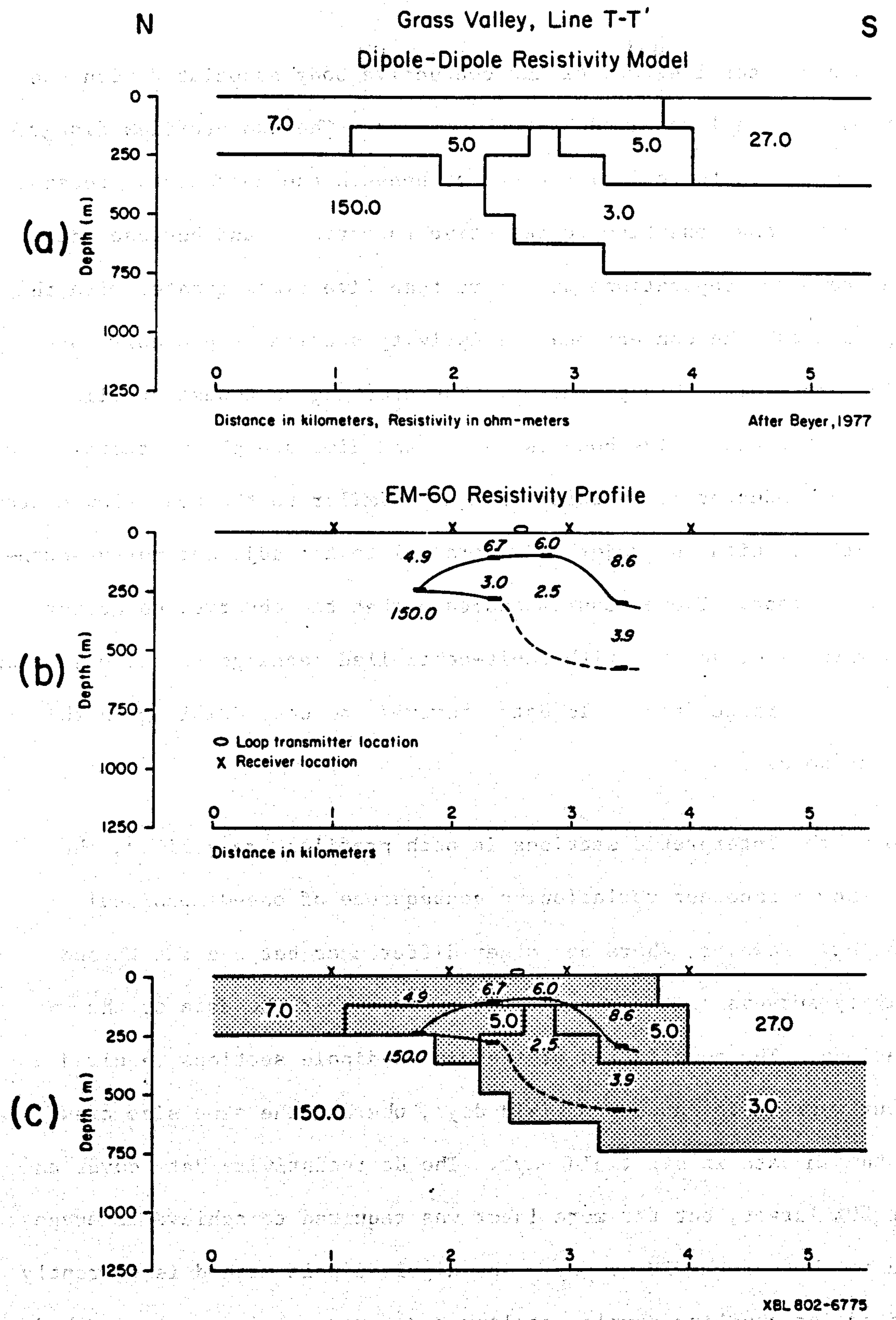

Figure 10. Resistivity cross section over line in Panther Canyon: (a) two-dimensional dipole-dipole resistivity model; (b) profile of one-dimensional EM-60 electromagnetic soundings; (c) comparison of parts (a) and (b).

The depth to and lateral extent of the conductive body associated with the thermal anomaly is well resolved by both methods. The two profiles disagree somewhat on the depth to resistive basement beneath the conductor. Because the EM method is less sensitive to resistive formations, and because the transmitter-receiver separations were more than five times greater with the dipole-dipole data, the conventional resistivity section is probably more accurate in determining this parameter. The crossing east-west profile indicates that the conductive body is narrow and dips steeply westward. The outline of the conductor is therefore roughly similar to the heat flow contours, forming an ellipse with the major axis parallel to the adjacent north-south-trending range front. These results indicate that the observed conductor could be a warm-water aquifer with fault-controlled recharge to the east along the border of the range front. To date, however, no deep drilling in this area has been done.

Although the interpreted sections in both profiles are similar, the EM results show a smoother variation, a consequence of one-dimensional interpretation. However, there are other differences between the EM and dc resistivity surveys that are not apparent in either the data or the interpretations. The compilation of the dipole-dipole sections required a crew of four working for about 20 field days, whereas the same size crew collected the EM data in six field days. The dc resistivity data cover an area about 50% larger, but far more labor was required to achieve coverage comparable to that of the EM survey. The dipole-dipole method is currently better suited for handling complex geology and for resolving resistive bedrock, but deep EM interpretations require much shorter transmitter-receiver separations, thus reducing the effects of lateral inhomogeneities on interpretation. The two cross sections suggest that, even in regions of two- and three-dimensional geologic structure, EM data will adequately resolve major features without severe distortion.

Soda Lakes

Soda Lakes geothermal anomaly is located about 8 miles northwest of Fallon at the western boundary of the Carson Sink of west central Nevada (Figure 11). The Carson sink is a large depression filled with unconsolidated sediments to a depth of at least 6000 ft (Garside and Schilling, 1979). The Soda Lakes area is characterized by flat to hummocky topography, numerous small lake beds, and several small basaltic volcanic manifestations of Quaternary age. Soda Lake and Little Soda Lake fill explosion craters, probably formed within the past 10,000 years (Garside and Schilling, 1979). The geothermal anomaly, located 5 km north of Soda Lake, was discovered accidentally in 1903 when drillers found boiling water at a depth of 60 feet in a water well. A recent shallow temperature survey of the region by the U.S. Geological Survey has revealed high temperatures over a 5 km^2 area (Figure 11). Temperature contours are elongated to the northeast, which is the direction of regional groundwater flow (Olmsted et al., 1975).

Magnetotelluric soundings, dipole-dipole resistivity and reflection seismic surveys have all been conducted in the Soda Lakes region; in addition, three deep exploratory wells have been drilled. Data obtained during these surveys were made available to LBL by Chevron Resources, Inc. as part of the DOE-Industry Coupled Program.

Dipole-dipole resistivity data and MT soundings indicate that the subsurface may be approximated by a three- or four-layer section. The top

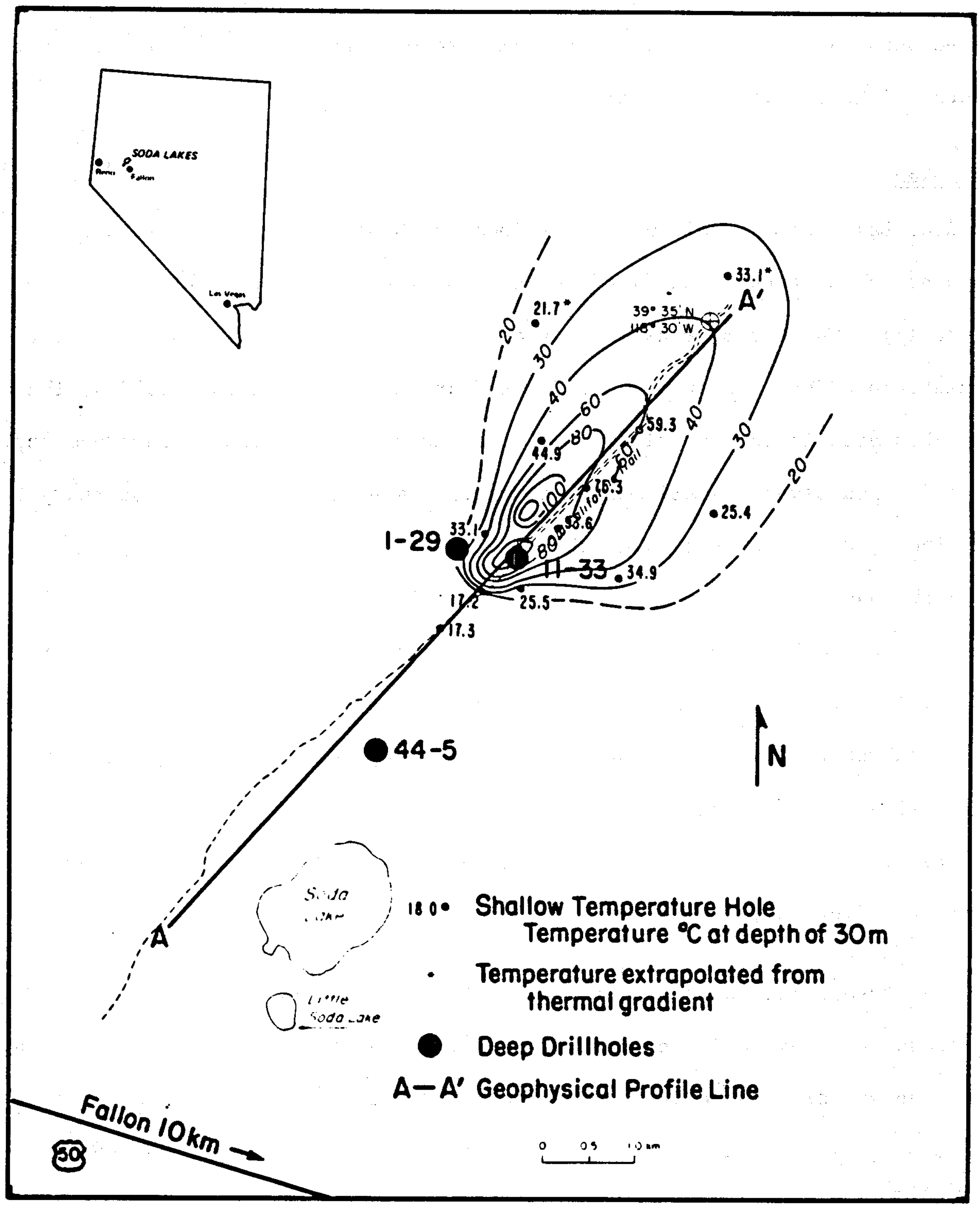

Figure 11. Location map and shallow temperature survey results, Soda Lakes geothermal anomaly.

layer is approximately 10 ohm-m in resistivity and varies from 100 to 400 m in thickness. The second layer is 2 ohm-m or less in resistivity and 400 to 1000 m in thickness. Well logs show that the top layer consists predominantly of sand and the second predominantly of shale. Higher temperatures and some evidence of hydrothermal alteration are observed locally in the second layer, and in some areas the geothermal activity may be partly responsible for the low resistivity. For most of the region the predominant cause for the low resistivity is probably the thick shaly sequence. MT soundings show a high-resistivity basement at a depth of 1 to 2 km. Well logs indicate that the upper part of this layer consists mostly of sandstone and volcaniclastic and volcanic rocks. MT data also show a regional conductor at a depth of nearly 10 km but coming to within only 3 km of the surface beneath Soda Lake. This shallowing of the deep conductor is as yet unexplained. A seismic reflection survey indicates the predominance of northeast-trending normal faulting in the area and suggests that the thermal anomaly lies within a deep northeast-trending graben. The seismic data also show numerous shallow northwest-trending faults with displacements of a few meters. At the time of the EM-60 survey, three deep geothermal wells had been drilled (Figure 9). None of these were good producers, but temperatures in excess of 170°C at 700 m depth were reported in well 11-33 in the vicinity of the shallow temperature maximum (Hill et al., 1979)(Figure 11).

The EM survey at Soda Lakes was made to better define the resistivity structure and to compare the results with other data. The survey consisted of 13 soundings from 2 transmitter loops with transmitter-receiver separations ranging from 500 m to about 3 km (Figure 12). Good quality data were collected at all sites within a one-week period by a crew of four, which attests to the

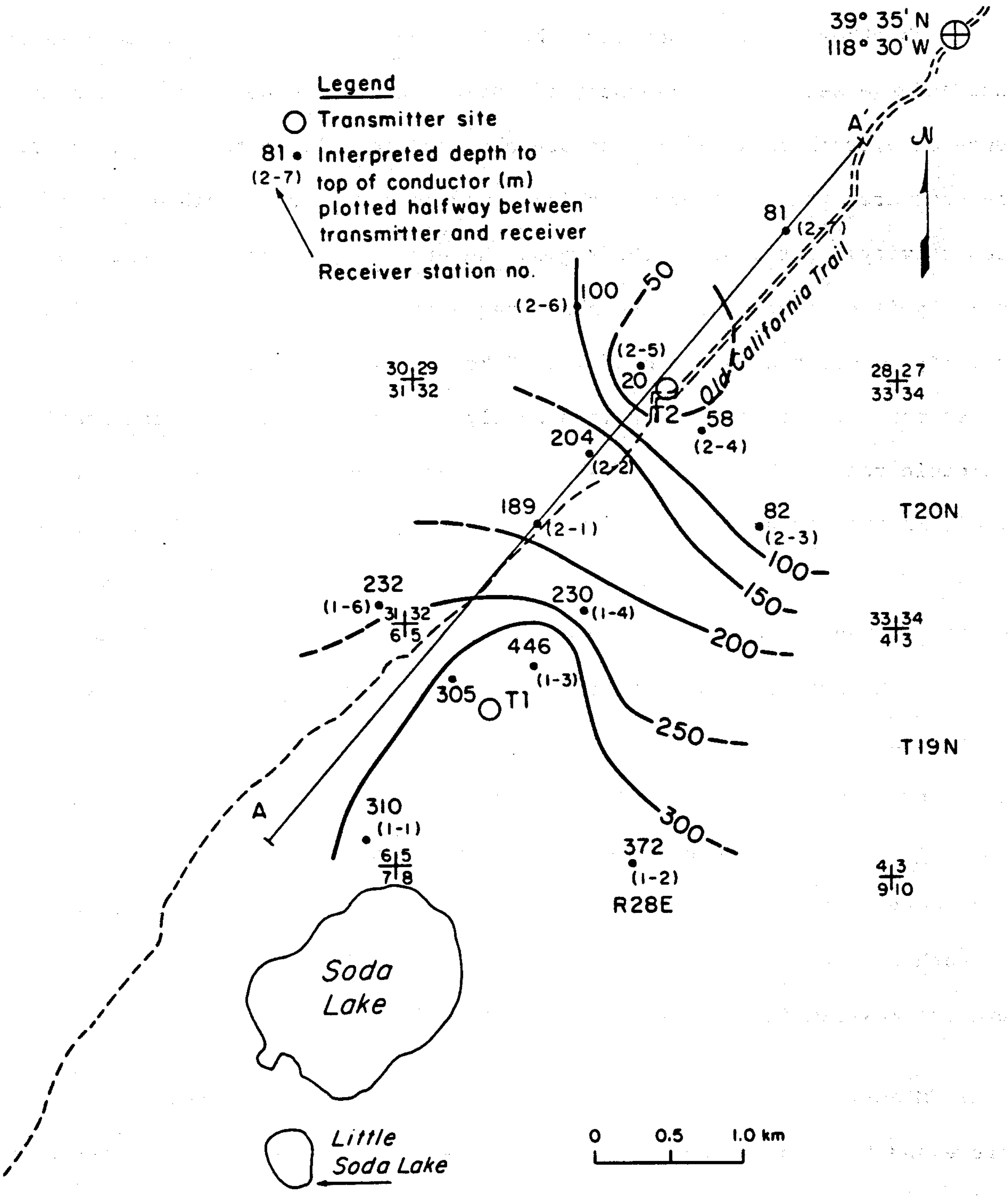

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Figure 12. Contours on interpreted depth to the top of conductive second layer, Soda Lake geothermal anomaly.

speed of the method under good field conditions. The survey was designed to map the configuration of the conductive layer associated with high temperatures. The interpreted depth to the top of this conductive layer is shown in Figure 12. EM station coverage included areas near existing boreholes so that interpretations could be compared with well data. A series of soundings was made along a northeast-trending profile (A-A′) connecting the deep test wells so that subsurface structure could be mapped between the wells.

Figure 13 is a resistivity cross section comparing one-dimensional MT interpretations, one-dimensional EM interpretations, and lithologic logs from wells along the profile A-A′. The EM and MT resistivity cross sections are remarkably similar, both indicating a three-layer section with similar layer parameters. The sections differ most near the southwestern end where the MT data indicate a shallow basement layer and the EM data show no basal resistive layer. Since there are no drill holes in this region and no other geophysical data, the discrepancy remains unresolved. Both methods indicate a shallowing and thinning of the conductive second layer near wells 1-29 and 11-33. The EM data show a significant resistivity decrease in the second layer near these wells that may be due to an increase in temperature or the presence of hot fluid. EM soundings also suggest that a northwest-trending fault in this region is controlling the shallow thermal system. The offset on this fault is not clear, however, since the resistivity boundaries do not match well with the lithologic units.

McCoy

The remote and mountainous McCoy region is located about 40 miles west of Austin, within the Augusta and Clan Alpine mountain ranges. Geologically, the area is characterized by Tertiary volcanics overlying Mesozoic limestones

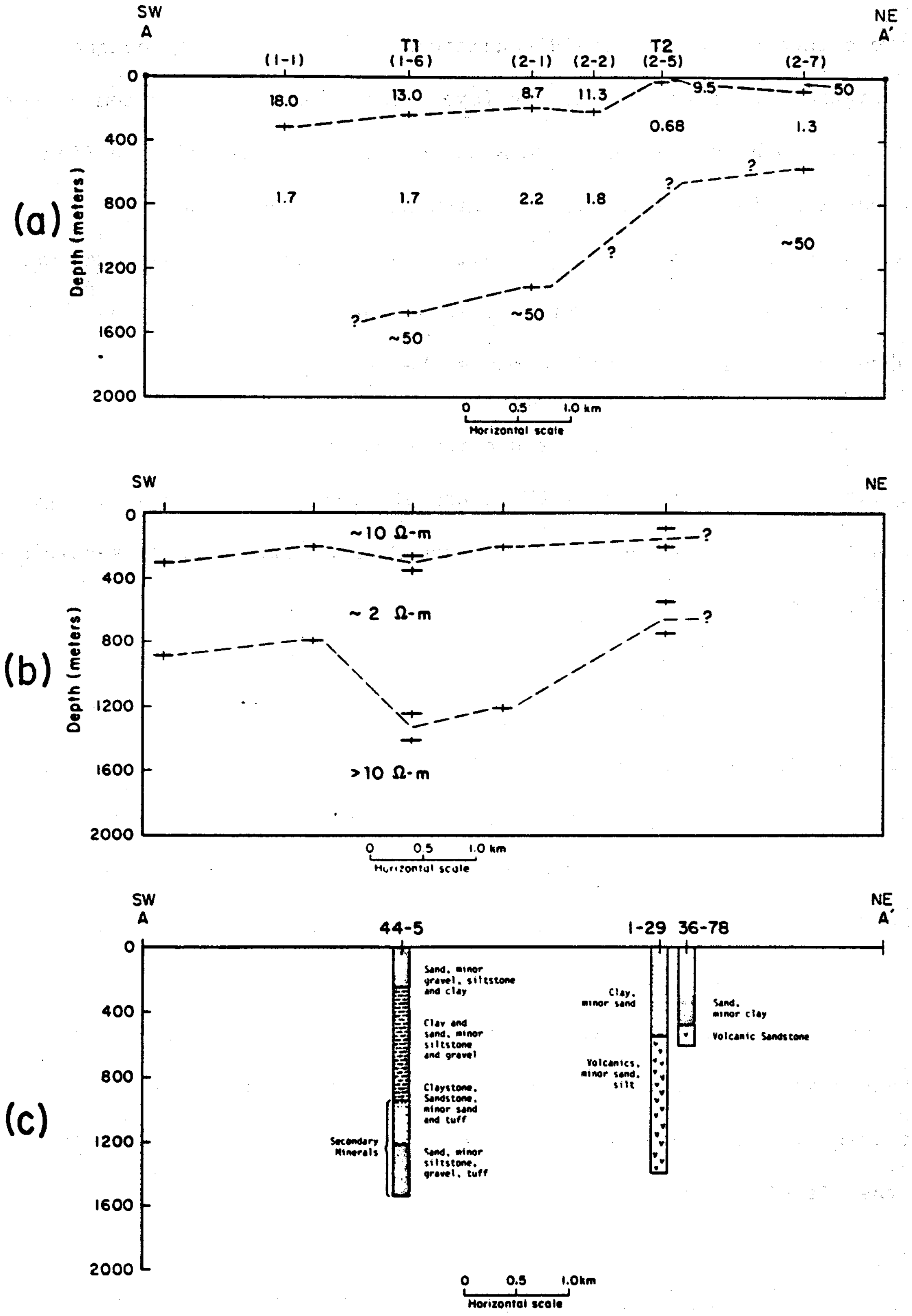

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Figure 13 (a) Interpreted EM resistivity cross section; (b) interpreted MT resistivity cross section; and (c) generalized lithologic logs for three wells (bottom) along Profile A-A'.

and other sedimentary rocks. Several mercury deposits within the volcanics have been mined. There are no surface thermal discharges, but a 2 km^2 fossilized travertine mound, located near the McCoy mercury mine, indicates former geothermal activity (Figure 14). When the EM survey was conducted, Amax, Inc., the principal leaseholder, was at an early stage of prospect evaluation. Some temperature gradient surveying, self-potential measurements, and water sampling had been done, but little other data were available to supplement the EM results. Temperature gradient measurements indicated a 100-km^2 region of anomalously high thermal gradients within which three maxima were located (Figure 14). Self-potential (SP) measurements show elongation of contours in a northwesterly direction, although there are indications of dipolar-type anomalies near a thermal gradient maximum at the McCoy mine and near geothermal well 66-8. Dipolar SP anomalies have been linked to active geothermal systems in several cases (Corwin and Hoover, 1979).

Nineteen electromagnetic soundings were made at McCoy from three loop transmitters; transmitter-receiver separations ranged from 400 m to more than 4050 m. The survey was designed such that north-south and east-west trending sections could be made from interpreted soundings. The McCoy area provided significant challenges for crew and equipment. Because the area is mountainous and access is difficult, soundings could be made only where it was convenient, thus limiting areal coverage. Moreover, there were few flat places on which to lay out the transmitter loops, and therefore most soundings were made from inclined loops, making data interpretation much more difficult. For most stations there was a significant difference between transmitter and receiver elevations. This made it imperative to determine

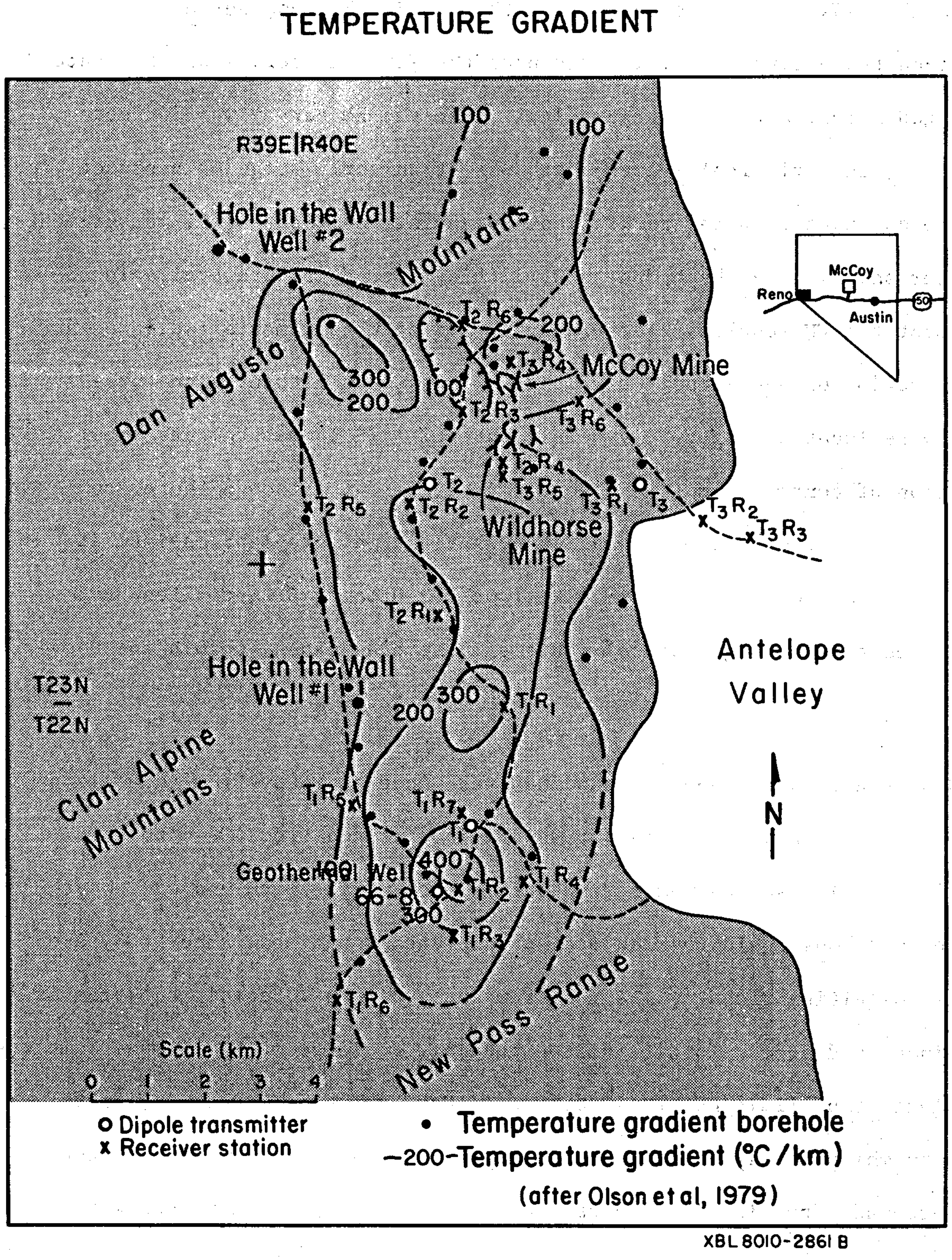

Figure 14. Temperature gradient map of the McCoy region.

correct elevations for proper interpretation; the effect of the intervening topography could not, however, be determined.

We constructed apparent resistivity spectral plots to obtain an initial model for use in the inversion program and for qualitative interpretation of well-behaved sounding data. The apparent resistivity curves can be used effectively only if there is no elevation difference between source and receiver and no tilting of the transmitter dipole. Only 4 of the 19 soundings at McCoy, all from transmitter 1, satisfy these criteria.

Figure 15 is an apparent resistivity spectral plot for station T_1R_1. The figure shows apparent resistivity values plotted for all six types of data. There is considerable agreement in the shape of the curves, but substantial scatter among values calculated for each parameter. The curves suggest a three-layer section consisting of a conductive surface layer, a resistive intermediate layer, and a conductive deeper layer. Apparent resistivity plots for stations located closer to the transmitter indicate a resistive surface layer. Combining the apparent resistivity plots, we find evidence for a four-layer section for the region near transmitter 1. This basic section was successfully tried on layered-model inversions for this area.

Figure 16 is a north-south resistivity cross section made from interpreted EM soundings located near the southern thermal gradient maximum and geothermal test well 66-8. The section gives resistivities and depths of the various layers as well as an elevation profile. The soundings generally indicate a three- or four-layer section which includes a shallow conductive layer and a deep basal conductor. The surface layer is generally resistive and probably represents undersaturated Tertiary flows and tuffs. Shallow

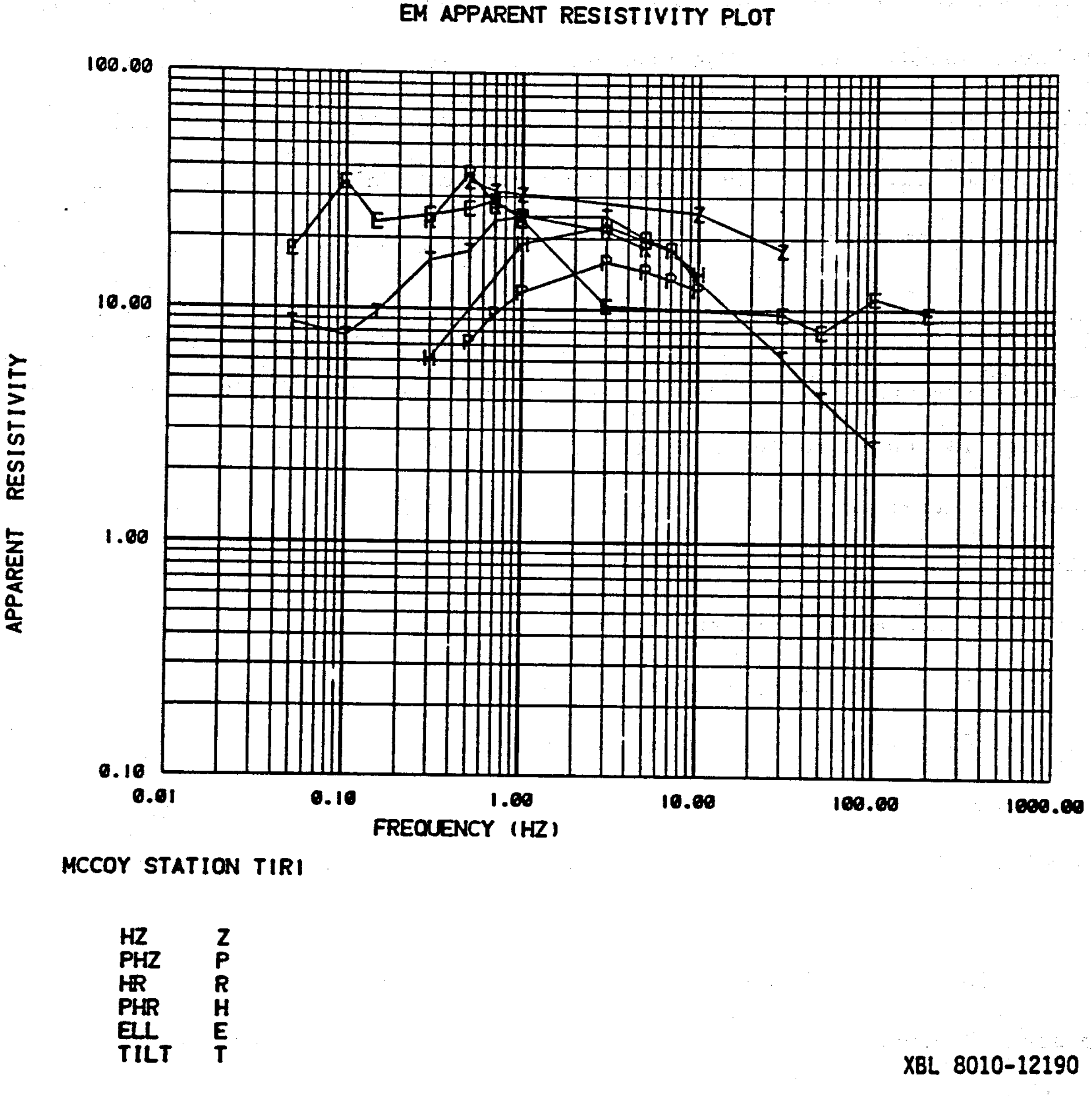

Figure 15. Apparent resistivity spectral plot for EM station T_1R_1.

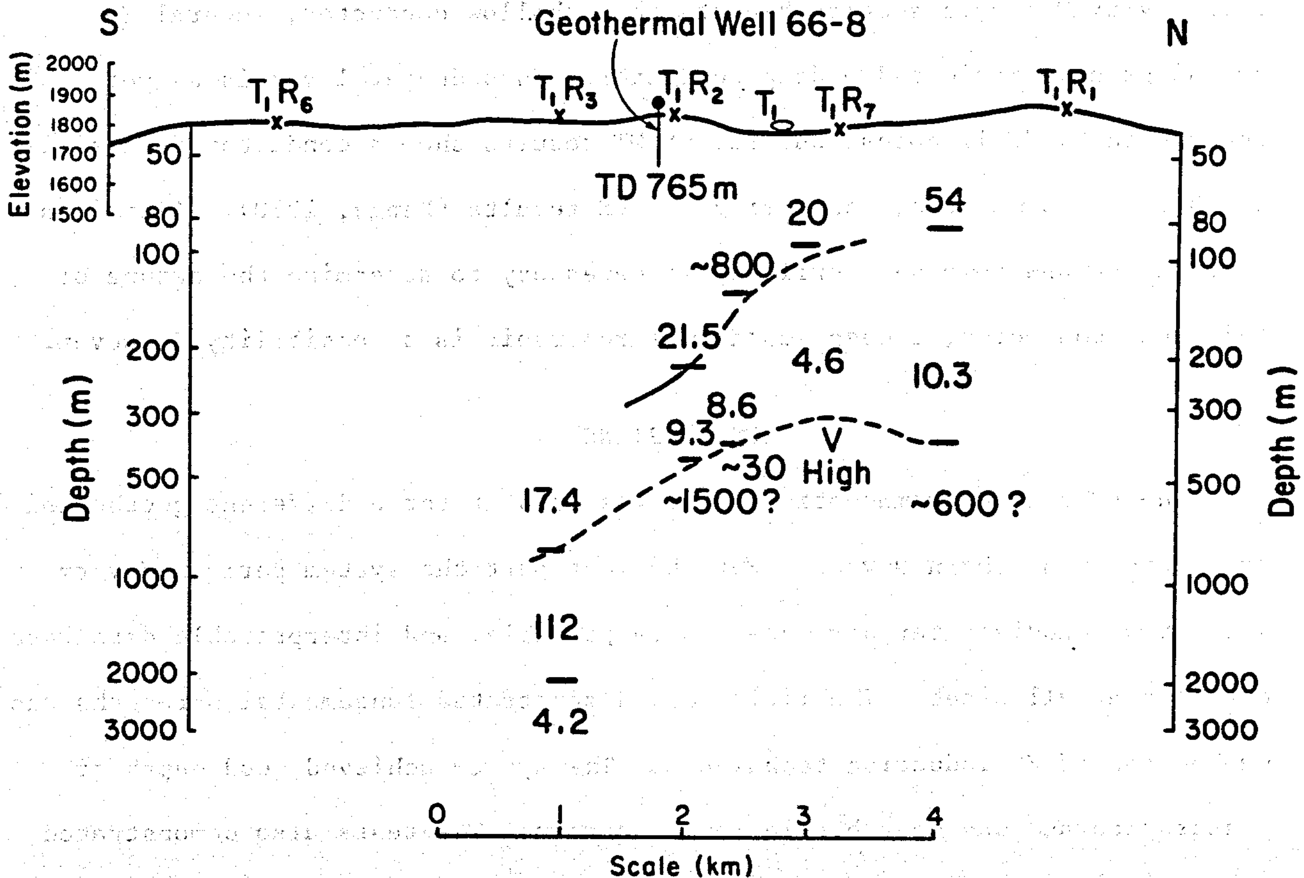

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Figure 16. North-south profile of interpreted EM soundings over the McCoy prospect. Layered-model parameters, resistivity (ohm·m) and depth (m) are plotted at points midway between source and receiver positions.

wells in this area indicate that the water table depth exceeds 100 m (Olson et al., 1979). The depth of the shallow conductive layer corresponds well to that of a zone of warm-water inflow marked in geothermal test well 66-8 and is probably indicative of a shallow, warm-water aquifer. Within the high-resistivity Mesozoic section beneath this shallow conductor, several EM soundings have indicated a deep conductor. This deeper layer is as yet unexplored by drill holes, but recent MT results show a conductor at a similar depth in the same area, confirming the EM results (Lange, 1980). Additional exploration and some deep drilling is necessary to determine the nature of this deep conductor; a deep geothermal reservoir is a possibility, however.

CONCLUSIONS

The EM-60 electromagnetic system was used at three different geothermal prospects in northern Nevada. For the most part the system performed very well; two soundings per day were easily possible, and interpretable data were obtained at all sites. The field work demonstrated fundamental strengths and weaknesses of EM induction techniques. The system achieved good depth of penetration and was operable in rough terrain. The tests also demonstrated the ability of the EM-60 to accurately locate buried conductive bodies. The limitations lie in the present difficulty of interpretation using two-dimensional and three-dimensional computer modeling and in the insensitivity of the technique to resistive bodies. Until improved computer algorithms are developed, two-dimensional and three-dimensional interpretations will be impractical. However, because of the spatial decaying of the source field, one-dimensional interpretations seem to be providing reliable results.

Although the method is in an early stage of development, our experience has indicated that it has the potential to become a powerful exploration tool.

Future applications may include basin studies, petroleum exploration, and large-scale geothermal prospecting.

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