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AN ELECTROMAGNETIC (EM-60) SURVEY OF THE McCOY GEOTHERMAL PROSPECT, NEVADA

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ABSTRACT

A frequency-domain electromagnetic survey was conducted at 19 stations over a 200 km^2 area encompassing the McCoy geothermal prospect, Churchill County, central Nevada. The McCoy area is characterized by high heat flow, mercury mineralization, and recent volcanics. Three horizontal-loop transmitters were used with receivers from 0.5 to more than 4.0 km from the loops. Receiver stations were arranged along a pair of crossing north-south and east-west lines. Data were interpreted first with a simple apparent resistivity formula and then with a least-squares lumped-model inversion program. The rough terrain and complex geology introduce an element of uncertainty to the interpretations.

The north-south line suggests a thinning of the volcanic surface rocks northward toward the McCoy mercury mine, where a resistivity discontinuity occurs. The high-temperature gradients on the south end of the line can be correlated with a conductive zone (<10 ohm-m) at a depth of 200-500 m and occurring within the lower part of the Tertiary volcanics and the underlying Mesozoic limestones. We also see evidence for a deeper conductor, below 2 km.

The east-west line of stations indicates high resistivity associated with exposed Mesozoic rocks, a thickening ridge of lower-resistivity sediments and volcanics at the western end of the line, and a very thin alluvial cover in Antelope Valley at the eastern end of the line.

INTRODUCTION

As part of the Department of Energy's program to stimulate the development of geothermal resources by private industry, Lawrence Berkeley Laboratory (LBL) has performed a series of electromagnetic surveys with the EM-60 frequency-domain system over promising targets in Nevada. This paper describes the results of our survey over the McCoy geothermal prospect in Churchill County, central Nevada (Figure 1).

The McCoy prospect is located 72 km northwest of Austin, between Dixie and Antelope Valleys on the west and east, respectively, and at the junction of the Dan Augusta Mountains, the Clan Alpine Mountains, and the New Pass Range. Elevations within the mountainous prospect area vary between 1200 and 1900 m, and local terrain variations are severe.

The McCoy geothermal area was chosen for study for three reasons. First, preliminary work by Amax, Inc. showed a thermal anomaly of large dimensions, indicating substantial geothermal potential. Second, because very little other geophysical work had been done there previously, the EM results could be evaluated independently. Third, the area provided an opportunity to test the EM-60 system in mountainous terrain with laterally discontinuous geology.

GEOLOGY

The McCoy region has been mapped on a reconnaissance scale by Stewart and McKee (1977) and Wilden and Speed (1974), mainly in connection with potential mining resources. No detailed geologic maps are available for the prospect area. Major rock units in the area include a thick assemblage of Tertiary volcanic flows and tuffs; Triassic and Jurassic sandstones,

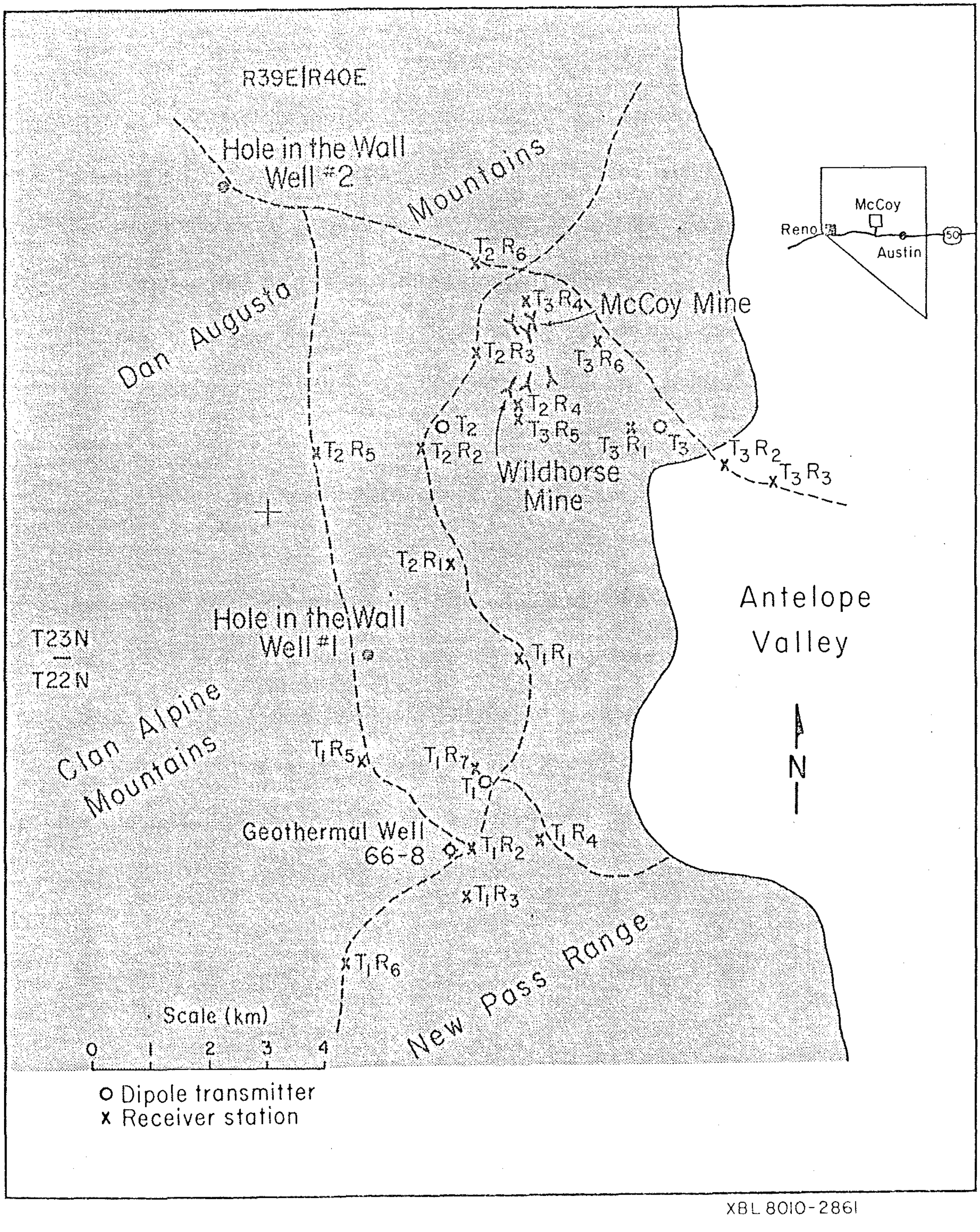

Figure 1. Survey location map of the McCoy prospect.

shale, limestone, and conglomerate; and several groups of Pennsylvanian and Permian eugeosynclinal sediments. All rocks have been extensively faulted by Basin and Range type faulting, which followed the main episode of Tertiary volcanism and continues into the present. The dominant trend of the faulting is north-northeast, parallel to the range fronts. Significant east-west faults have also been mapped, however, and several are related to ore deposits.

Hydrothermal alteration is extensive in the central part of the prospect. A fossil travertine deposit 2 km^2 in area and 10m thick occurs adjacent to and west of the McCoy mine, and may be related to the mercury mineralization there. The Wildhorse mine, located 5 km south of the McCoy mine, is also a mercury deposit, but neither site is being actively mined. There are no active hot springs in the prospect, but there is a warm well near the McCoy mine.

GEOPHYSICS

Figure 2 is a temperature gradient map of the McCoy prospect (Olson et al., 1979). Thermal gradients were computed from temperature variations in 45 holes ranging from 12 to 100 m in depth. The map indicates anomalously high gradients over an area of at least 100 km^2. Gradients are especially high near the McCoy mine and about 3 miles southeast of the Hole in the Wall water well no. 1. Heat flow values were calculated from these thermal gradients and thermal conductivity measured from collected well cuttings. The resultant heat flow data indicate values as high as 10 times the regional average, which is 2 to 2.5 heat flow units (HFU). Chemical analysis of a warm-water well near the McCoy mine suggests a minimum reservoir temperature of 186^{o}C.

TEMPERATURE GRADIENT

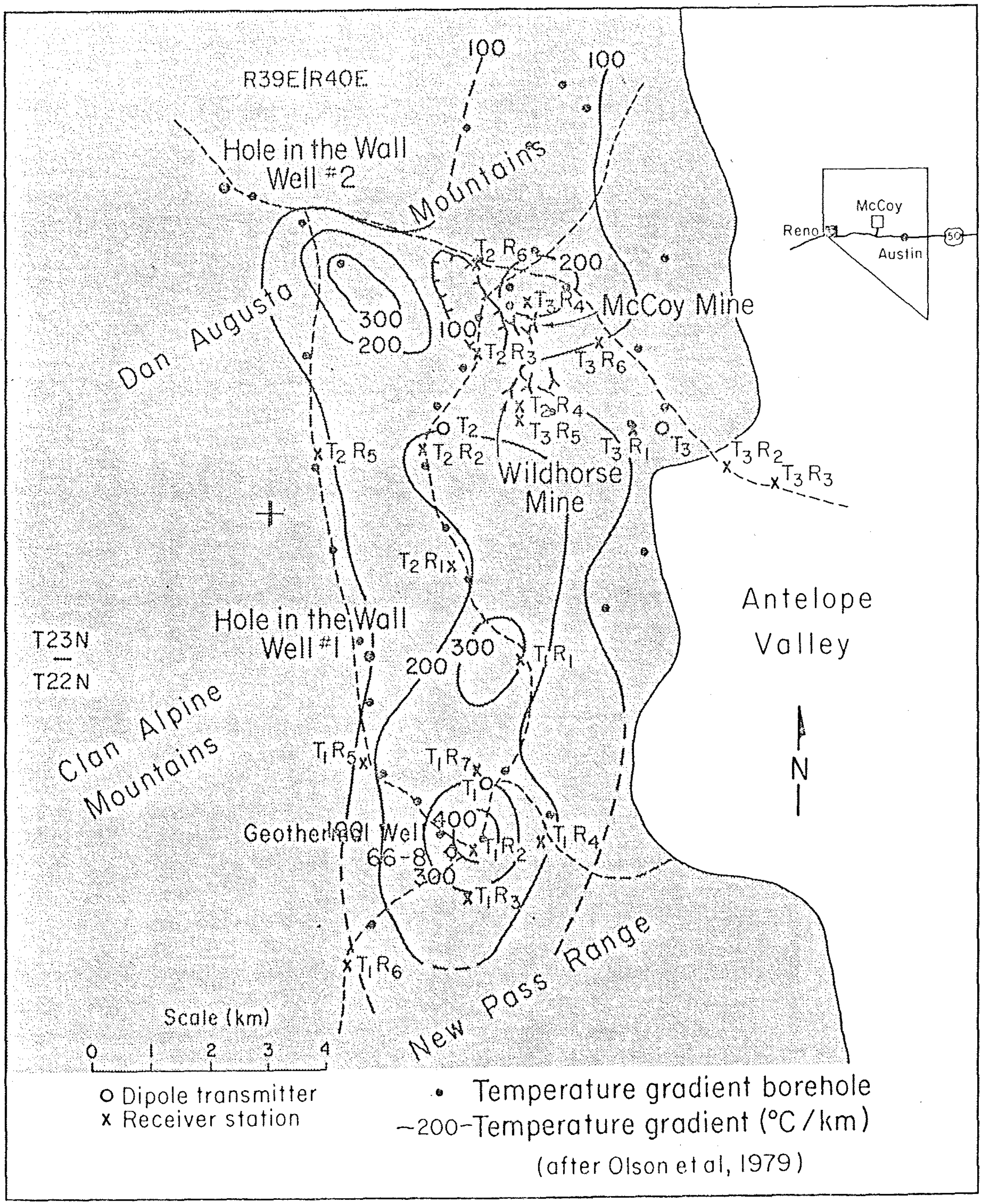

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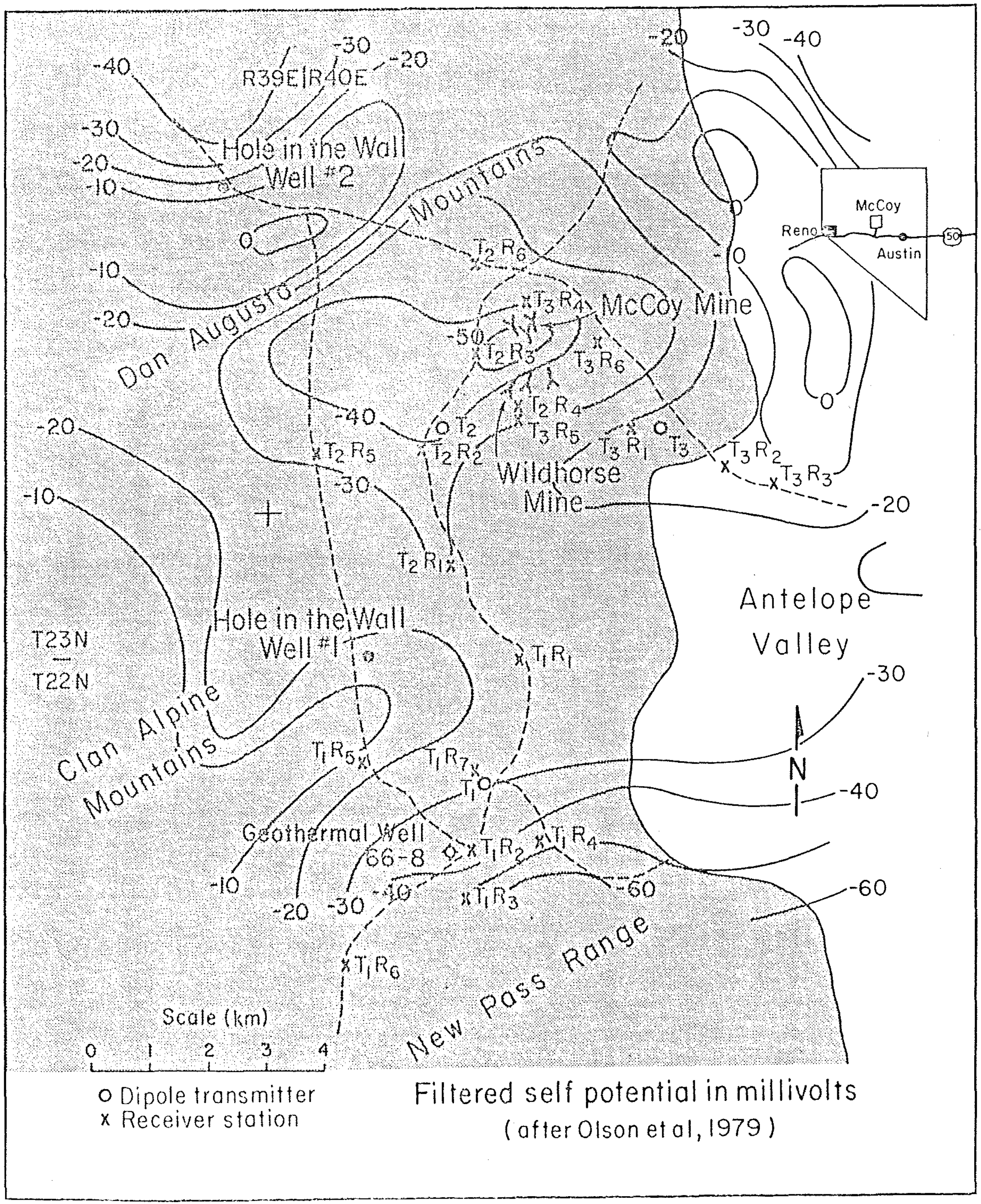
Figure 2. Temperature gradient map of the McCoy region.

Magnetic, gravity, self-potential (SP), and magnetotelluric (MT) measurements have all been made at McCoy, but so far only the SP data and some MT data have been interpreted (Olson et al., 1979). The general contour pattern of the SP data (Figure 3) is different from that of the thermal data; the SP indicates pronounced northeasterly and northwesterly orientations of equipotential contours, suggesting that regional faulting in these two directions may be an important control. In local details, however, the SP and thermal anomalies show interesting similarities and correlations, the clearest of which is in the area of the McCoy mine. This SP anomaly may be related to ore mineralization or hydrothermal alteration, but because of its elongation parallel to nearby cross faults, and because it appears to be dipolar, the SP anomaly may also be related to deep-water circulation along faults (Olson et al., 1979; Corwin and Hoover, 1978). The temperature anomaly near geothermal well 66-8 appears to be on the flank of a broad SP anomaly, as yet not completely defined by survey.

ELECTROMAGNETIC SURVEY

The transmitter and receiver stations occupied for the EM-60 survey are shown in Figure 1. The survey consisted of 19 frequency-domain electromagnetic soundings from three horizontal transmitter loops at transmitter-receiver separations ranging from 450 m to more than 4 km. The stations are grouped in three clusters, one within the area of the southern heat flow anomaly, a second northward near the Wildhorse mine, and a third at the eastern margin of the Dan Augusta Mountains. The survey was designed such that north-south and east-west trending sections could be made from interpreted soundings, but the coverage is still sparse in view of the large prospect

SELF POTENTIAL



Filtered self potential in millivolts

(after Olson et al, 1979)

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Figure 3. Self-potential map of the McCoy region.

area. Soundings were made in 11 field days during October and November, 1979, often during periods of blizzard, hail, and subfreezing temperatures.

The EM-60 soundings were made by impressing square-wave currents at frequencies within the band 0.001 to 1000 hz into a horizontal wire loop and measuring the vertical and radial magnetic fields at receiver sites. A more detailed description of the system and procedure is given in Appendix A. For this survey we took data at frequencies from 0.05 to 1000 hz, with data recorded for at least two to three frequency decades for each station.

Data quality for McCoy stations was fair to good at all sites. Recording times varied from less than an hour for the near stations to more than 4 hours for the more distant sites. Two stations could normally be obtained per 12 hour field day.

Data Analysis and Interpretation

EM sounding data at McCoy were reduced to a set of spectral plots corresponding to the observed radial and vertical magnetic fields and the ellipticity and ellipse inclination (or tilt angle) of the combined fields. The amplitude spectra are normalized by the primary magnetic field by calculating the free-space primary field due to the dipole transmitter and dividing the observed fields by this number. The reduced spectral data are given in Appendix B along with the estimated measurement errors.

After reduction, the soundings were first interpreted using an apparent resistivity formula, and later data were fitted to layered model curves by least-squares inversion. The apparent resistivity calculations were used in qualitative evaluation and for "first guess" models of the inversion routine. The inversion program can fit all or any part of observed spectral data to layered model curves and will give parameter resolution based on observed standard error of data. Plots of the results of layered-model inversions are given in Appendix C. Although successful inversions were made for all stations, not all of the observed data were used in obtaining the fits. Some data were found to be noisy and distorted, and these were deleted prior to inversion. Absolute phase data were not obtained at several stations because of the difficulty of establishing a phase-reference wire over the rough terrain. At certain stations, the phase-reference wire was removed when it was found to contaminate signals with noise -- a serious problem when signal levels were low.

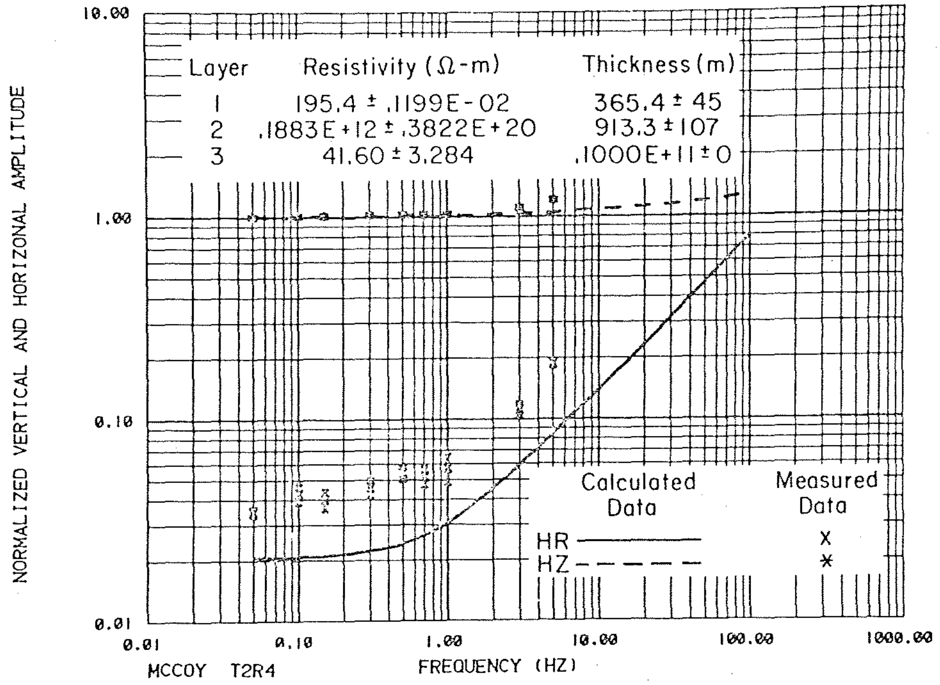
The Effect of Topography

Because of the hilly terrain at McCoy, differences in elevation between transmitter and receiver stations were significant. These differences can be accounted for in interpretation, but the effect of the intervening terrain cannot. For the McCoy region, where the near-surface resistivity is fairly high, the effect of terrain may not be a significant factor. In any case, terrain effects are ignored because we are unable to account for them in models. Another effect of terrain is that two of the transmitter loops had to be laid out on inclined surfaces. This effect also influenced data interpretation, particularly for stations in line with the tilted dipole--i.e., stations at which there is a signal from the horizontal component of the magnetic dipole. The predominant combined effect of elevation differences and inclined dipole moment is to alter the inclination of the observed primary field at the receiver site. Although differences in elevation once accurately measured can be routinely taken into account for layered-model inversion, the effect of a tilted dipole requires calculations combining vertical and horizontal magnetic dipole solutions at the appropriate strengths and inclination. The procedure is slightly more complicated and considerably more expensive in terms of computer time than the vertical dipole solutions. A computer program to perform forward model calculations of a tilted dipole over a layered media has recently been written (Haught et al., 1980), and we have tested the program with data taken at McCoy.

An example of the effect of the tilted dipole is given in Figure 4, which shows two interpretations for a set of EM sounding data at McCoy from a tilted dipole. In the top two graphs, the data set is fit to a vertical-dipole solution, ignoring the 1 degree of dipolar tilt. 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 km in depth. The bottom two graphs in Figure 4 show a layered-model fit for a two layer section with a tilted dipole source. Here the fit is superior, and with no indication of a deeply buried conductor. Ignoring the effect of dipole tilt can therefore give misleading results, particularly in regions of high resistivity, such as McCoy, where small secondary magnetic fields may easily become distorted by dipolar tilt.

Apparent Resistivity Plots

We constructed apparent resistivity spectral plots to obtain an initial model for use in the inversion code and for qualitative interpretation of well-behaved sounding data (Stark et al., 1980). The plots are made from sounding data by comparing amplitude-phase and polarization ellipse values to corresponding values on a homogeneous half-space curve. The resistivities calculated from the half-space curve are then plotted against frequency to obtain an apparent resistivity spectral plot. Such plots are useful



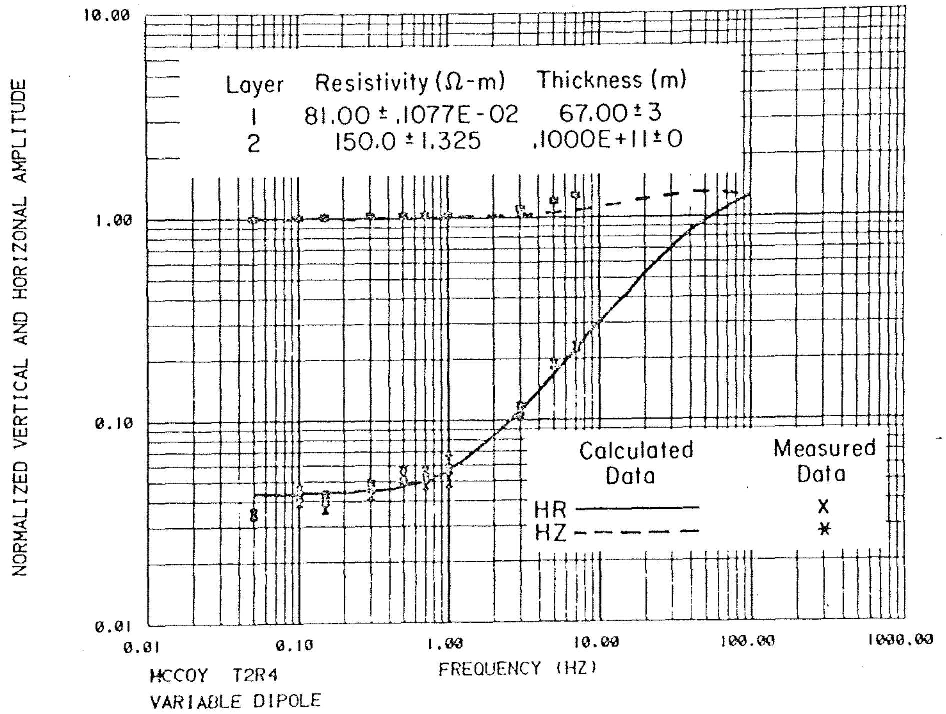


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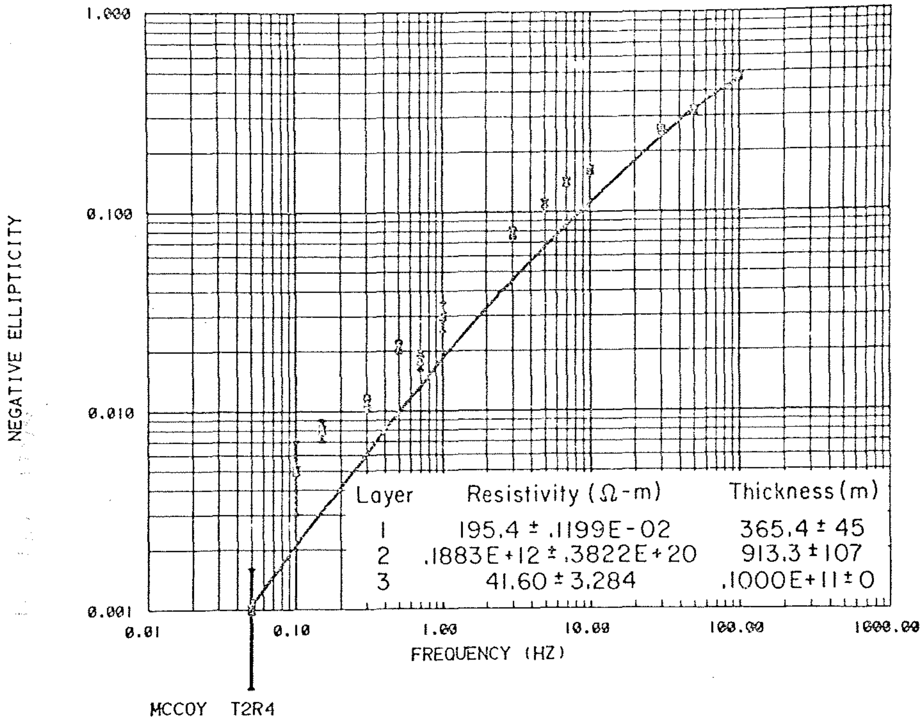
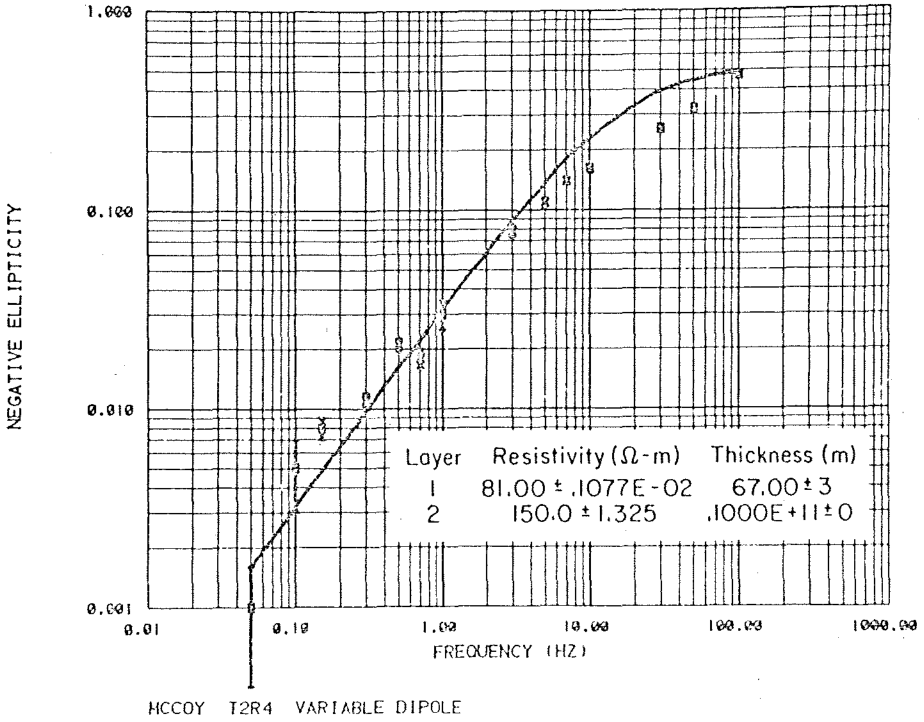
Figure 4. Comparison of inversions from a vertical dipole source (top graphs) and a variable dipole source (bottom graphs).



Layer	Resistivity (Ω-m)	Thickness (m)
1	195.4 ± .1199E-02	365.4 ± 45
2	.1883E+12 ± .3822E+20	913.3 ± 107
3	41.60 ± 3.284	.1000E+11 ± 0



Layer	Resistivity (Ω-m)	Thickness (m)
1	81.00 ± .1077E-02	67.00 ± 3
2	150.0 ± 1.325	.1000E+11 ± 0

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Figure 4. Continued.

for determining the probable number of layers, for judging data quality, and for characterizing the sounding. 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; apparent resistivity curves for these stations are given in Figures 5 to 7.

Figure 5 is an apparent resistivity spectral plot for station T_1R_1. The figure shows apparent resistivity values plotted for all six types of data; HZ is vertical amplitude, PHZ is vertical phase, HR is radial amplitude, PHR is radial phase, ELL is ellipticity, and TILT is the tilt angle of the polarization ellipse. There is considerable agreement in the shape of the curves, but substantial scatter exists among values calculated for each parameter. The curve shapes suggest a three-layer section consisting of a conductive surface layer, a resistive intermediate layer, and a conductive deeper layer. The apparent resistivity plot for sounding T_1R_7 (Figure 6), which was located closer to the transmitter, indicates a more resistive surface layer overlying the conductor, and does not suggest the presence of the deep conductor. The two sections are compatible, however, if we consider that the closer station is more sensitive to the shallow subsurface and the more distant is sensitive to the deeper parts of the section. Apparent resistivity plots (Figures 5 to 7) then indicate a four-layer section for the region near transmitter 1. This basic section was successfully tried on layered model inversions for this area.

Figure 7, an apparent resistivity plot for a large-separation sounding (T_1R_6), shows a marked decrease in apparent resistivity at low frequencies, indicating the pressure of a good conductor at depth. Although station T_1R_1 (Figure 5) indicates a similar decrease at lower frequencies, only

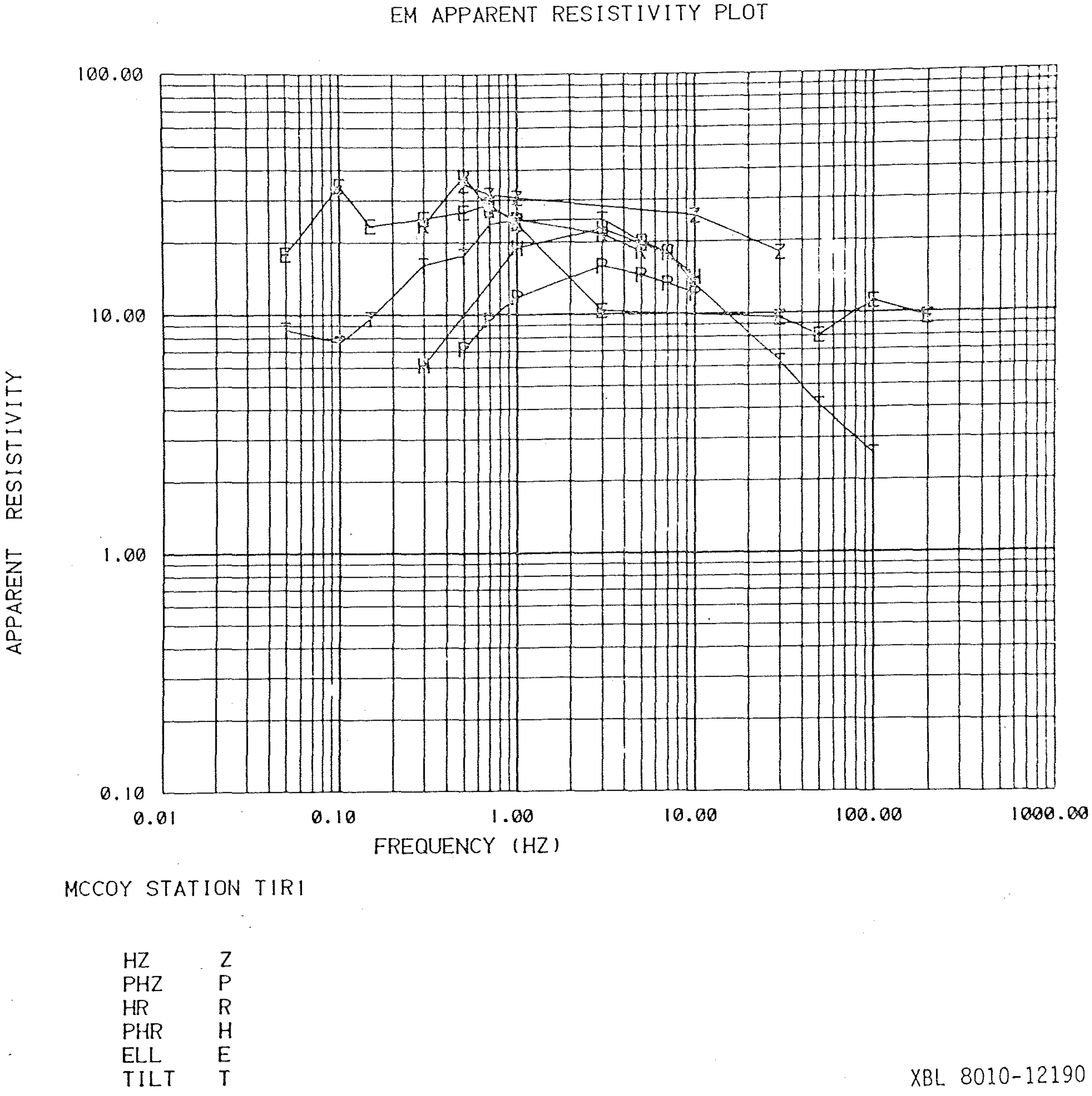

Figure 5. Apparent resistivity spectral plot for EM station T_1R_1.

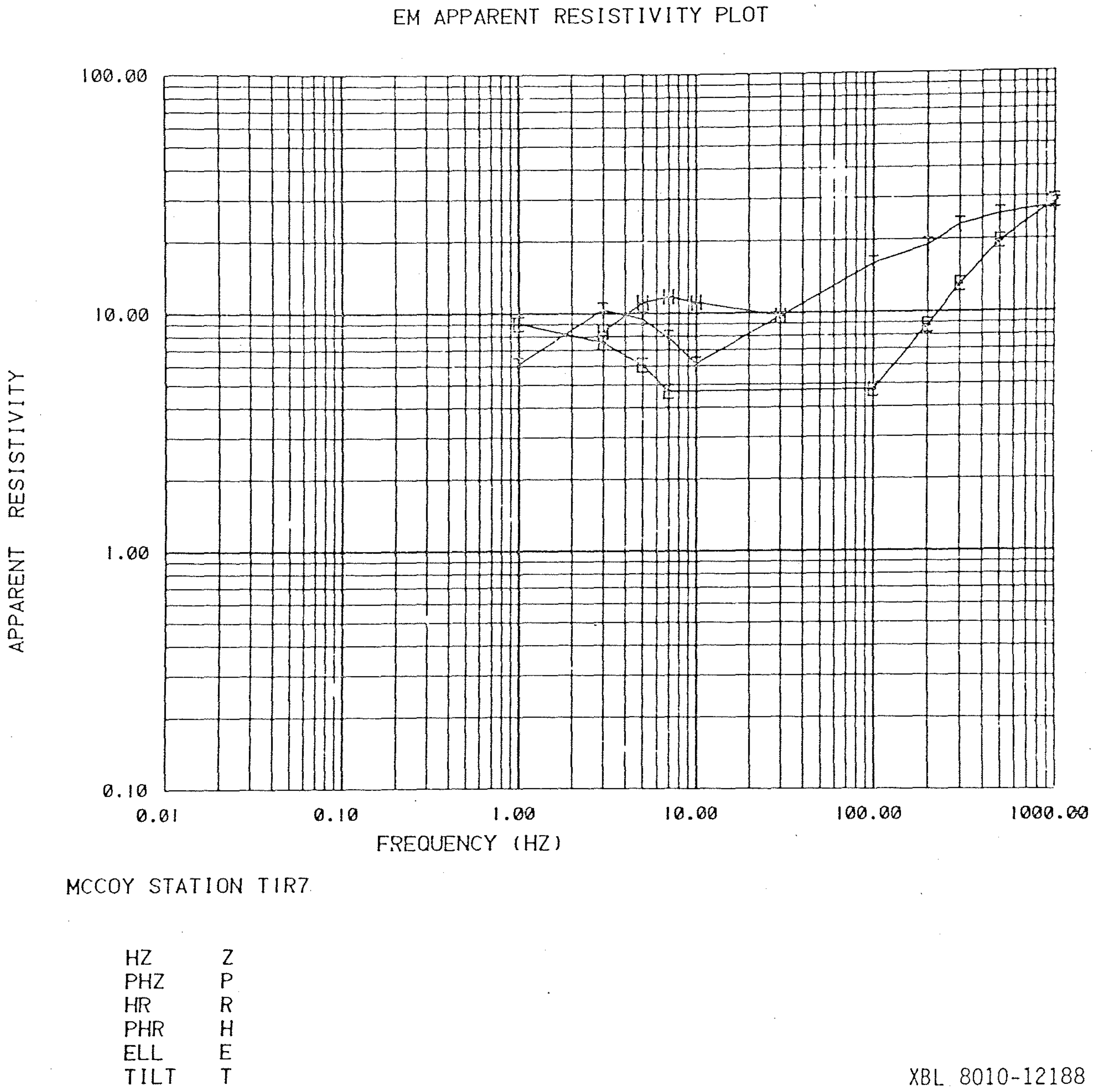

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Figure 6. Apparent resistivity spectral plot for EM station T_1R_7.

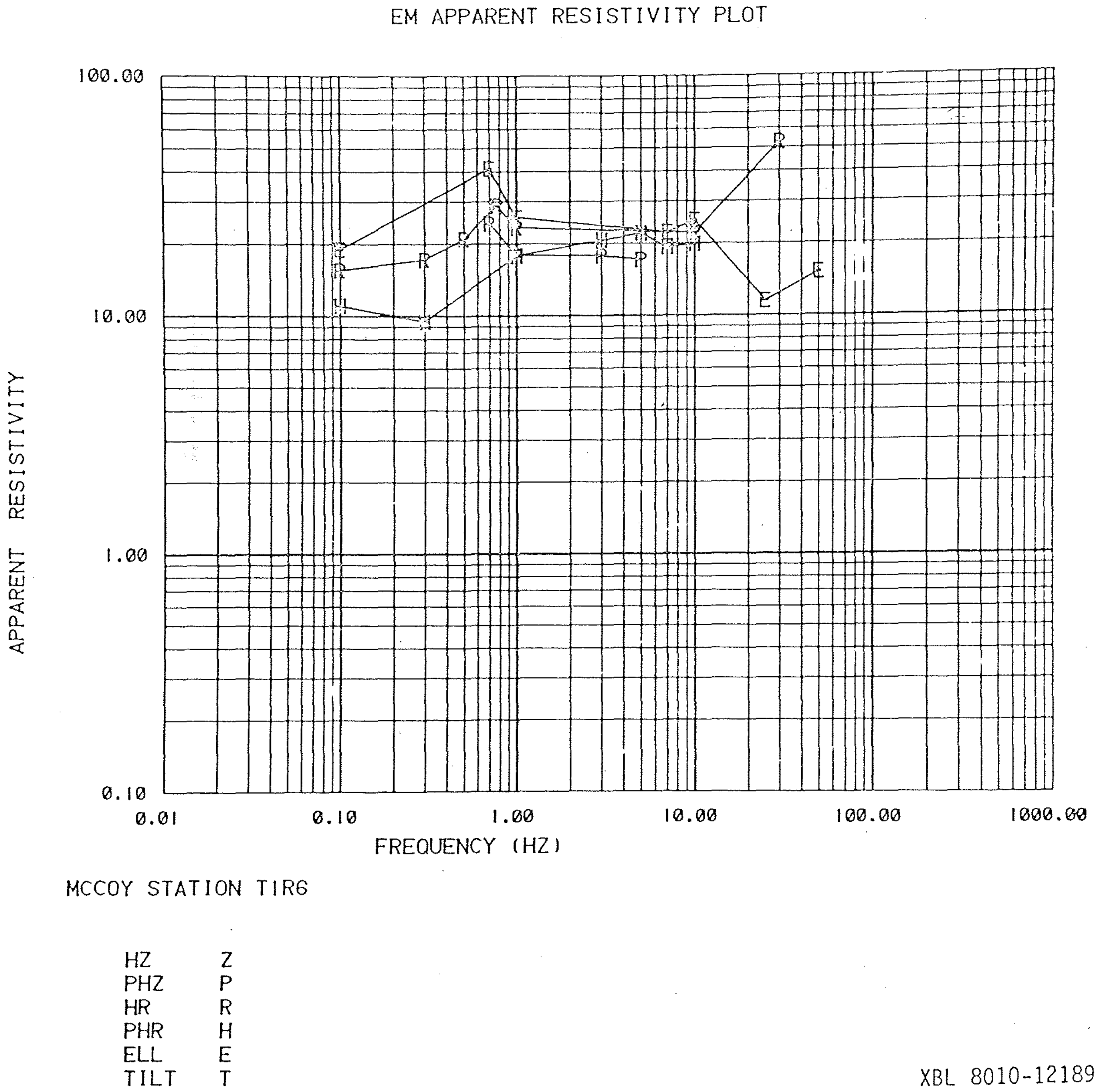

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Figure 7. Apparent resistivity spectral plot for EM station T_1R_6.

station T_1R_6 has sufficient higher-frequency data to show that the decrease was not due to geomagnetic noise contamination or some other effect. It is significant to note that had the apparent resistivity algorithm been known at the time of the survey, it is likely that additional large-separation soundings would have been made, since the results of T_1R_6 would have been known in the field.

INTERPRETED RESISTIVITY PROFILES

Layer-model inversions for all 19 stations at McCoy are given in Appendix B. Fair to good fits and reasonable one-dimensional interpretations were obtained for all sites. Because of the sparse distribution of stations, discussion is limited to results obtained along two profiles, a 13 km nine-station north-south profile that bisects the prospect in its elongate dimension (Figure 8), and a 9 km eight-station east-west profile that crosses the northern end of the prospect (Figure 10). The profiles are made by plotting layer parameters obtained from one-dimensional inversions for stations located along or close to the profile. The interpreted sections were plotted at a point halfway between source and receiver.

Figure 8 includes five soundings made from transmitter 1 and four from transmitter 2, with a gap of 4 km between the sounding groups. The gap was necessary because the difficult terrain prohibited establishing a third transmitter between the other two. The soundings from transmitter 1 differ markedly in character from soundings made from the northern loop (Figure 8). In the southern end, the sections generally indicate a resistive surface layer ranging from 100 ohm-m or more in mountainous stations to about 20 ohm-m for the lower-lying stations. The thickness of this unit is 100-300 m, and it probably represents a sequence of dry or undersaturated

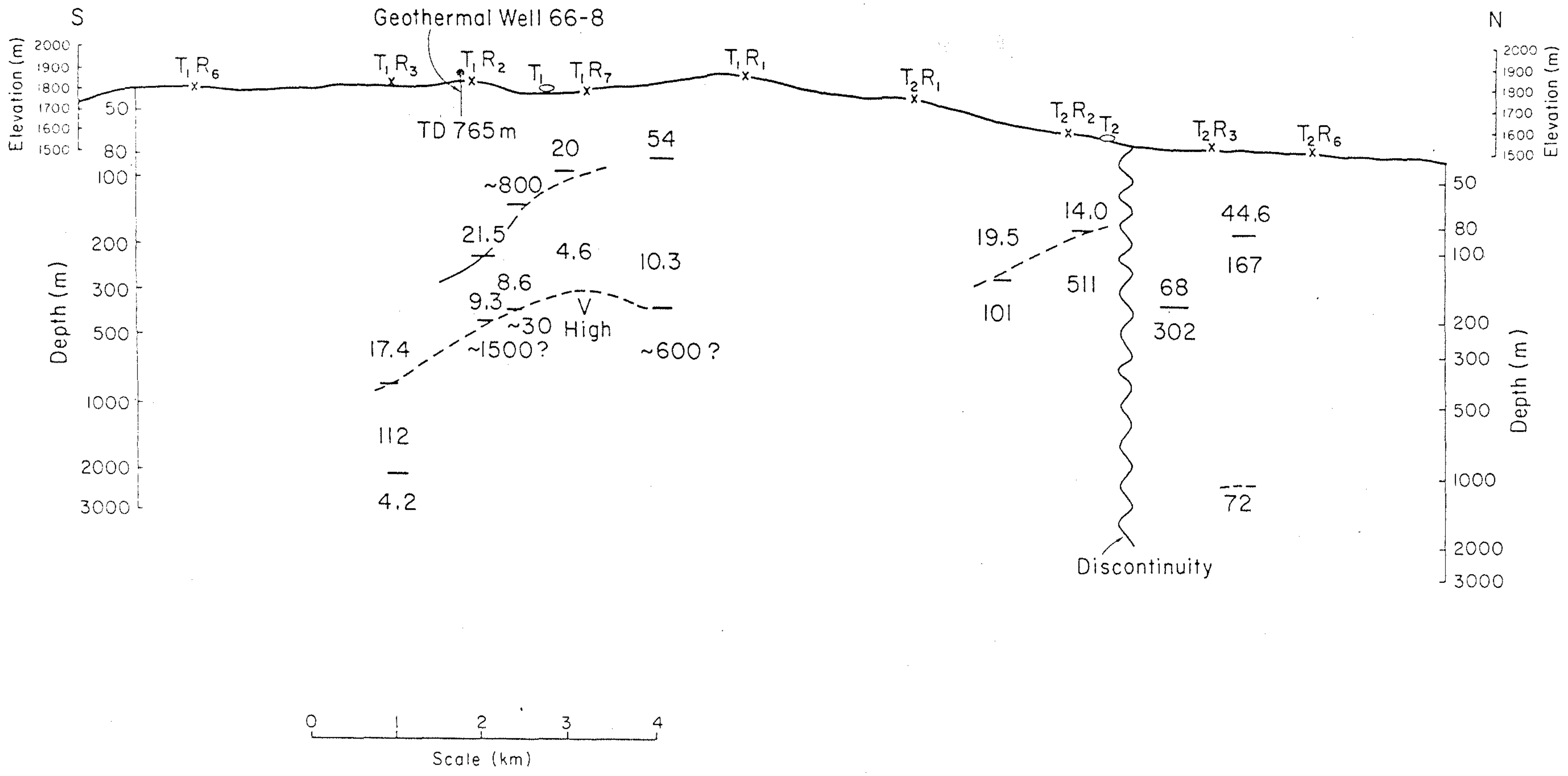

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Figure 8. North-south profile of interpreted EM soundings over the McCoy prospect; stations used are plotted at the top of the figure. Layered-model parameters, resistivity (ohm-m), and depth (m) are plotted at a point halfway between source and receiver.

Tertiary flows and tuffs. Shallow wells in the region show a deep (>100 m) water table (Olson et al., 1979). Near 200 m in depth, a conductive layer is detected from all EM soundings near transmitter 1. This layer ranges from 200 to 300 m in thickness and 5 to 10 ohm-m in resistivity and suggests either a sequence of clay-rich tuffs or perhaps a warm-water aquifer. The resistivity of 5-10 ohm-m is consistent with geothermal aquifers, and the thermal gradients could be conservatively extrapolated to more than 100°C. Beneath the conductive layer at a depth of 300-400 m, the EM soundings indicate the presence of a much more resistive formation. The calculated resistivity of this unit ranges from 100 to 1000 ohm-m, but the true value is probably closer to the lower end of this range, since the lower values are consistent with the more depth-sensitive, larger-separation soundings. Because the EM induction method is generally much less sensitive to resistive bodies than to conductors, the depth to and resistivity of this unit are poorly resolved. Fortunately, a 765 m well has been drilled in the area near EM station T_1R_3 (Figure 1), and the driller's log has been published (National Geothermal Well Report, 1980). Figure 9 indicates a generalized lithologic section from this well adjacent to an interpreted EM induction sounding. The figure indicates that the conductive layer corresponds closely to the rocks between the lower boundary of the Tertiary volcanics and the upper boundary of the Mesozoic quartz conglomerate. Boiling water was reported to be flowing in the well at depths corresponding to this conductor (Art Lange, Amax geologist, 1980, personal communication). The figure also shows that the lower, more resistive unit corresponds to the quartz conglomerate. The depth correlation, although not exact, is quite good, and the high resistivity of this part of the Mesozoic section is consistent with older, less permeable formations.

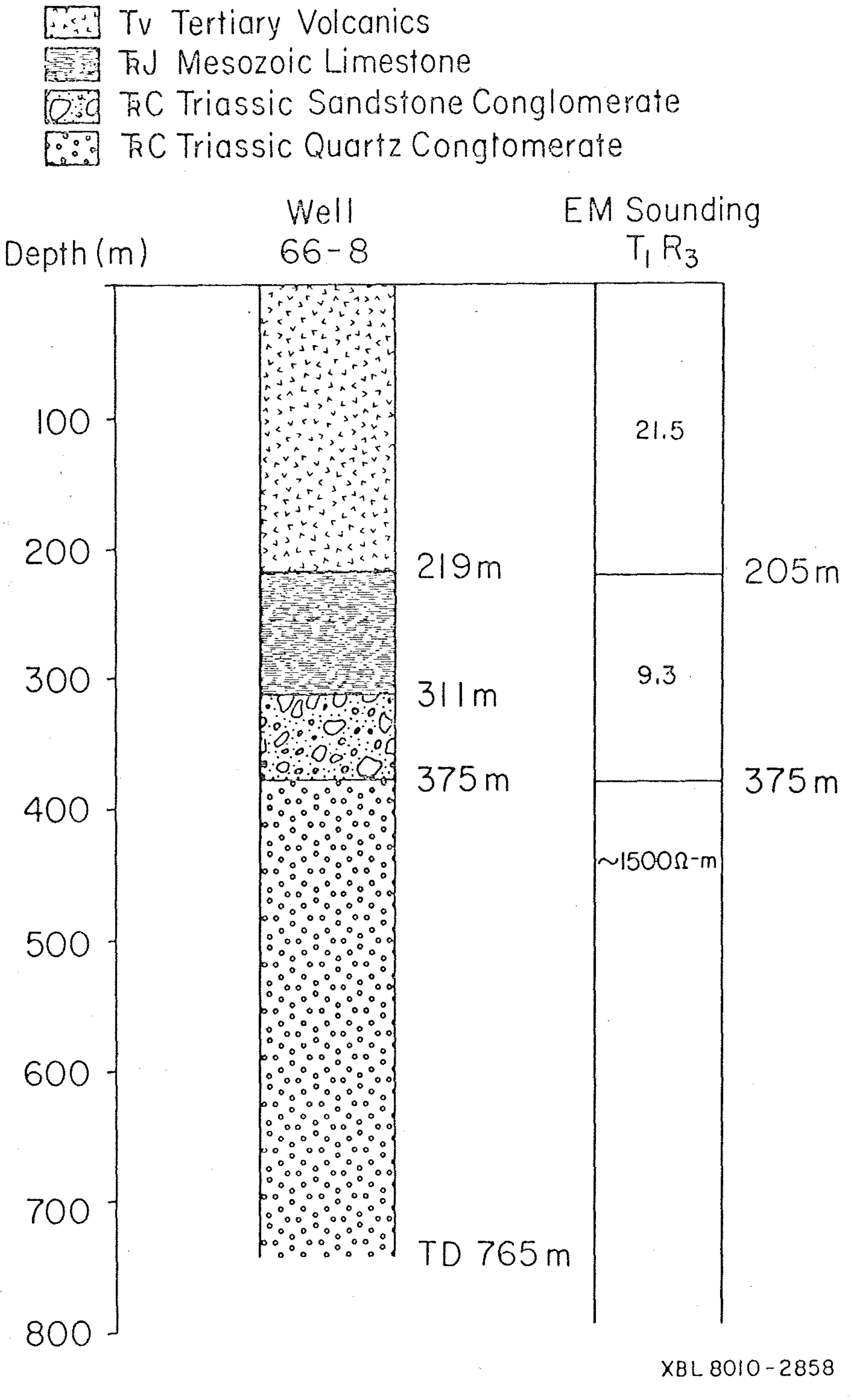

Figure 9. Generalized lithologic log from geothermal test well 66-8 compared with a layered-model inversion from EM station T_1R_3.

The inversion of sounding T_1R_6 indicates the presence of a 4 ohm-m layer at a depth exceeding 2000 m. Although no other soundings at McCoy indicate such a conductive body at depth, none of the others have sufficient transmitter-receiver separation to detect such a feature. As this conductor is detected at only one station, its delineation should be treated with some skepticism until confirmed with another set of measurements. It is possible that the field curves that detected this deep conductor are affected by the presence of a topographic ridge between the source and receiver (i.e., channeling of currents) or some other lateral effect. Because the presence of this body suggests a good geothermal target, further investigation is warranted.

Figure 8 indicates that the northern section of the profile is considerably different from the southern. The volcanic sequence is perhaps only 100 m or less thick at the north, where the section is dominated by high-resistivity Mesozoic rocks. A glance at the elevation profile in Figure 8 suggests that the thinning of the volcanics is related to the drop in elevation between southern and northern stations, since the decrease in elevation between these two stations is approximately equal to the decrease in thickness of the volcanic section. The elevation of the Mesozoic probably does not appreciably change from south to north, at least as far north as transmitter 2, indicating that the thinning of the volcanics is not related to any large vertical displacement. The variation in thickness may instead indicate that volcanic vents were located closer to the southern stations. North of transmitter 2, the resistivity at the surface layer is appreciably higher, suggesting the crossing of a lateral discontinuity near transmitter 2. The reconnaissance geologic map shows a major northwest-trending fault in this region (Wilden and Speed, 1974), and this may represent a lateral lithologic charge or a ground-water barrier.

The east-west profile is drawn from stations crossing the eastern margin of the Dan Augusta Mountains into Antelope Valley (Figure 10); stations used are located to the south of the above-mentioned northwest-trending fault. The predominant feature of this profile is the high resistivity associated with the higher-elevation eastern escarpment of the Dan Augusta Mountains. Resistivities of 500-1000 ohm-m are associated with out-cropping Mesozoic rocks in the mountains; soundings also indicate slightly lower resistivities (80-100 ohm-m) at a depth of 300-400 m. West of the eastern margin ridge, a low-resistivity surface layer overlies the Mesozoic section. This layer is from 100-200 m thick, thickens westward, and probably consists of Tertiary volcanics and alluvium. Soundings in Antelope Valley just east of the Dan Augusta Mountains indicate a fairly resistive section. Surface resistivities range from 20 to 200 ohm-m in the faults, and layered models indicate that resistivities do not appreciably change at depth. These data suggest a very shallow alluvial cover to this valley and an underlying resistivity consistent with Mesozoic basement rocks.

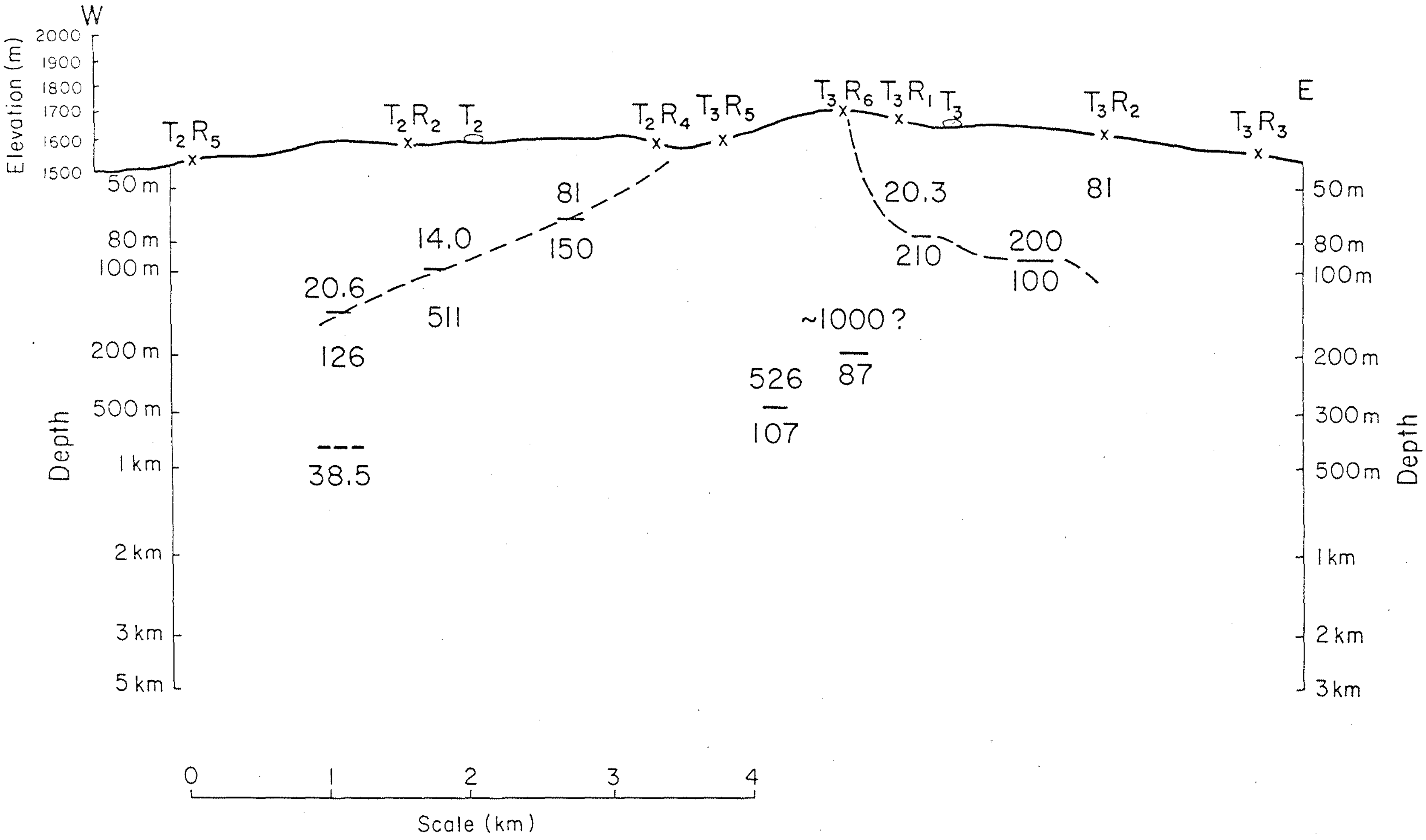

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Figure 10. East-west profile of interrupted EM soundings over the McCoy prospect; stations used are plotted at the top of the figure. Layered-model parameters, resistivity (ohm-m), and depth (m) are plotted at a point halfway between source and receiver.

ACKNOWLEDGEMENT

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