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Audiomagnetotelluric Sounding as a Reconnaissance Exploration Technique in Long Valley, California

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An audiomagnetotelluric (AMT) sounding system developed by the U.S. Geological Survey appears to be an effective technique for reconnaissance exploration to detect shallow resistivity anomalies associated with geothermal reservoirs. The equipment operates within the frequency range of 8–18,600 Hz by using nine logarithmically spaced narrow band filters. The technique has been evaluated in Long Valley, California, where the results from dc resistivity and time domain electromagnetic surveys were available for control. The AMT method outlines two linear zones of low resistivity that correlate well with known hot springs in the area. Generally, good agreement was obtained with the results of other electrical methods.

INTRODUCTION

The audiomagnetotelluric method (AMT) has recently been used by the U.S. Geological Survey as a reconnaissance technique for the evaluation of potential geothermal areas. Initial testing of the technique, using newly developed equipment, was done in the Long Valley caldera, where extensive geothermal studies by the Geological Survey were in progress. The results of those studies are reported in the other 12 companion papers in this special issue and provide a unique opportunity for evaluation of this relatively new electromagnetic technique. Of particular importance in evaluating the AMT method was the work of *Bailey et al.* [1976] and that of *Stanley et al.* [1976].

Because the AMT method is an inductive electromagnetic technique, it emphasizes conductive bodies such as are commonly associated with the hot waters and alteration zones of geothermal reservoirs. Although large errors in depth estimation can occur due to very poor resolution of intermediate high-resistivity beds, in reconnaissance work it is usually sufficient to verify the existence of conductive anomalies, measure their approximate values, and gain some idea of their lateral extent. These tasks can be carried out rather easily by using AMT techniques for conductors relatively near the surface. The depth of exploration is quite variable depending on the geoelectric section but typically ranges from 200 to as much as 2000 m.

Because commercial equipment was unavailable for purchase, the results reported here were obtained from equipment and field techniques developed by the authors. We consider these methods and techniques only preliminary, and modifications to both equipment and field methods are continuing as more experience is gained.

THEORETICAL BASIS FOR AMT METHOD

The magnetotelluric method is one of three exploration techniques which use naturally occurring electromagnetic fields. The more familiar telluric and Afmag (audiofrequency magnetics) methods are the others, and all three suffer from being dependent upon the vagaries in the natural fields, as all who have worked with these methods know. In our work, selected narrow frequency bands were employed in the range from 8 to 18,600 Hz, and the technique is accordingly called audiomagnetotelluric (AMT) exploration. An excellent discussion of the method as applied to mineral exploration is given by *Strangway et al.* [1973]. The interested reader will find a more thorough discussion of the theory and nature of the source fields in their paper and in its listed references.

Electromagnetic fields penetrate into the earth to depths which vary depending on the earth conductivity and the frequency of the signals. The skin depth δ is a measure of this penetration and an approximate measure of the depth of exploration by the AMT method. It is given by (1) for a homogeneous earth:

$$\delta = (2\rho)^{1/2}/\mu\omega \qquad (1)$$

where ρ is resistivity, μ is permeability, and ω is the angular frequency $2\pi f$.

Using our system, then, over a 100-Ωm earth, we measured the resistivity from the surface to a depth of about 37 m at 18,600 Hz and to about 1800 m at 8 Hz. One should also remember that as the depth of exploration increases at the lower frequencies, so too does the lateral extent of exploration increase.

In employing the AMT method a usual assumption is that the electromagnetic energy propagates as a plane wave nearly vertically downward into the earth. For practical purposes this condition is met when the energy source is removed several wavelengths from the point of measurement and when displacement currents in the earth can be neglected.

Associated with this downward propagating plane wave are mutually orthogonal horizontal magnetic and electric fields. In the case of a homogeneous or horizontally stratified earth the electric field in the earth is radial, and the magnetic field is tangential to the source. Under these conditions the apparent resistivity of the earth is a function of these horizontal fields and the frequency and is given by the following equation [*Cagniard*, 1953]:

$$\rho_a = \frac{1}{5f}\frac{|E|^2}{|H|^2} \qquad (2)$$

where f is frequency in hertz, E is electric field in microvolts per meter, H is magnetic field in gammas, and ρ_a is apparent resistivity in ohm meters.

Because the skin depth and apparent resistivity are both functions of frequency, one can determine the variation of resistivity with depth by surface measurements of the electric and magnetic fields as a function of frequency. Thus in measuring apparent resistivity as a function of frequency, a sounding is made in much the same way as a dc geometric sounding

[*Keller and Frischknecht,* 1966] but without the bother of expanding an electrode array.

The principal source of natural electrical energy in the AMT range of frequencies is worldwide lightning storms, particularly in tropical regions, which account for the preponderance of the energy. *Bleil* [1964], *Ward* [1967], and *Strangway et al.* [1973] discuss in detail the temporal and spatial variations of these storm-stimulated signals. Briefly, these variations principally affect the method by restricting operations to good signal periods and by introducing scatter in the data. In regard to the temporal variations the energy is weakest during winter months, when storm activity is reduced. We have operated as late as October but noticed a decided decrease in energy toward the end of the month, particularly in the higher frequencies. Also the energy, particularly in the higher frequencies, tends to increase in the afternoon as thunderstorm activity comes closer to the recording site [*Strangway et al.,* 1973].

The presence of two or more major storm centers supplying energy during a given recording period will cause some data scatter and nonrepeatability of data, particularly where lateral inhomogeneities exist. The response of two- and three-dimensional structures varies with the orientation of the source fields and the sensor array orientation [*Strangway et al.,* 1973]. Thus data scatter is due to the varying source locations during a given recording period, and nonrepeatability is due to distinctly differing source locations at different recording times. While these problems preclude very precise analysis of the data in terms of a layered structure, they clearly emphasize that the earth usually does not fit the simple horizontally stratified model that we often assume.

Propagation in the earth-ionosphere wave guide produces spectral characteristics which impose other restrictions on the method. In the low-frequency range, wave guide resonances produce energy peaks at discrete frequencies. These are the Schumann resonances, the lowest frequency being at about 8 Hz. Above this frequency the energy wave guide has a strong absorption band which severely limits data acquisition in the 2000-Hz range.

Within the AMT frequency band, manmade signals are also present. Most troublesome are the fields from power lines at both the fundamental and many of the harmonics. The large amount of energy at these discrete frequencies constitutes a difficult noise problem in most cases, as the source generally cannot be assumed to be distant enough to produce a plane wave.

In the higher AMT frequency range, VLF radio signals are present and may be employed. In our system we used stations at 10,200 Hz and 18,600 Hz as a matter of convenience. During the rare periods when these stations were not transmitting, there was sufficient natural energy for operations.

INTERPRETATION OF DATA

Where horizontal layering can safely be assumed, interpretation of data is similar to that of conventional resistivity interpretation techniques such as curve matching. For any postulated layered structure one can compute the corresponding sounding curve; thus matches to sounding curves may be made. The problem of intermediate high-resistivity layers being masked, however, seriously limits accurate depth interpretation and is discussed in detail by *Strangway et al.* [1973] and *Strangway and Vozoff* [1970]. As they point out, an intermediate high-resistivity layer must be 2–3 times as thick as the upper layer in order to be seen. In the present system the limited definition of the sounding curves also is a hindrance to interpretation. This limited definition is due, in part, to weak signal conditions near 2000 Hz, this situation being particularly bad during the winter months. In addition, with eight points typically defining the sounding over more than 3 decades, much detail is lost.

In mining and geothermal exploration, two- and three-dimensional structures are much more prevalent than are simple layered ones. Interpretation methods for this situation are severely limited, and most often simple anomaly maps are used as a basis for qualitative interpretation. We have chosen the anomaly map method to present our data. Some theoretical solutions for simple two-dimensional structures have been presented [*Strangway et al.,* 1973; *Strangway and Vozoff,* 1970; *Vozoff,* 1972; *Madden and Swift,* 1969], and limited three-dimensional data are available from model studies of *Frischknecht* [1973]. These studies permit some generalizations that are useful when AMT anomaly maps or sounding curves are examined.

For two-dimensional structures the most definitive measurements are made with the electric field oriented parallel and perpendicular to the strike of the structure. In general, '*E* perpendicular' measurements will define the boundaries very sharply, but the measured values near the boundaries will exhibit overshoot and undershoot. These edge effects can result in measured apparent resistivities both higher and lower than the actual resistivities present in the section. Near-surface conductive layers, however, tend to suppress the overshoot. In the case of '*E* parallel' measurements across a structure, the resistivity values will vary smoothly without edge effects but will only poorly define the boundaries. A common situation would involve an area in which approximately vertical conductive fault zones are present. In this case, if one were not within a fault zone, the *E* parallel measurements would be lower, and the *E* perpendicular measurements higher than the background resistivities of the area; if one were within a fault zone, just the opposite would tend to result with respect to the actual resistivities in the fault zone.

In a broad sense these same generalizations apply to three-dimensional structures. Thus measurements with the telluric line oriented perpendicular to the boundary are more definitive of that boundary than *E* parallel measurements. From these results one can conclude that spherical bodies will not give circular anomaly maps, as is evident from Frischknecht's [1973] data.

EQUIPMENT

Commercial AMT equipment is not yet available for purchase, so the equipment used was designed and fabricated by the U.S. Geological Survey. It is similar to that recently described by *Strangway et al.* [1973] except that we have provided a means of preserving phase information as well. Figure 1 is a block diagram of our instrumentation. To measure the horizontal electric field, two steel stakes, generally separated by 100 m, are used as electrodes. The voltage difference between the electrodes is amplified and prefiltered by using RC (resistance-capacitance) band-pass filters so as to prevent strong local noise sources from overdriving the first stages generating spurious signals. Narrow band active notch filters are used to remove 60- and 180-Hz power line signals, which are very strong when work is being done in the vicinity of power lines. The signals then enter a universal active filter connected in a high-*Q* band-pass configuration. Approximately constant, *Q* is maintained at all filter settings, the

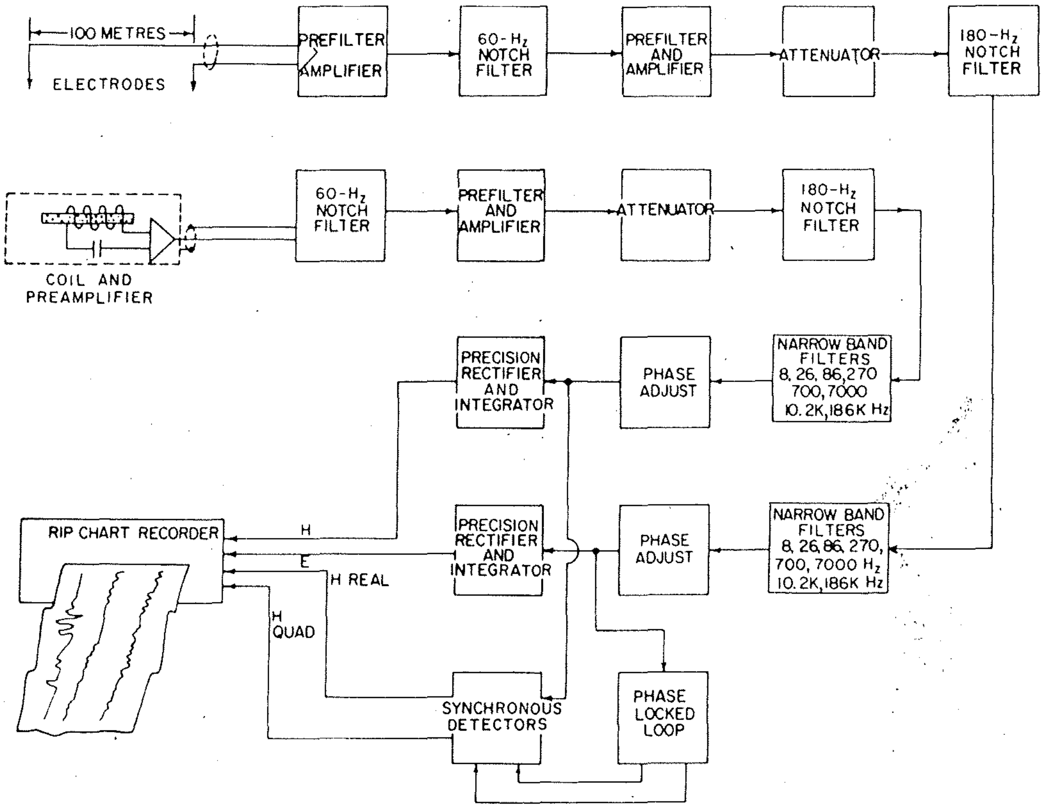

Fig. 1. Block diagram of the U.S. Geological Survey audiomagnetotelluric system.

6-dB bandwidth at 8 Hz being 0.3 Hz. To define a sounding curve, nine selected frequencies are used, these being spaced roughly logarithmically throughout the band but selected so as to avoid the midband harmonics of 60 Hz. At present, our operating frequencies are 8, 26, 86, 270, 700, 2000, 7000, 10,200 and 18,600 Hz. The output of the narrow band filter is rectified, integrated, and displayed on a strip chart recorder to show the envelope of the received energy.

An induction pickup is used for the horizontal magnetic field sensor and consists of a ferrite core upon which are wound many thousands of turns of wire. In order to span the broad range of frequencies we found it necessary to use two separate coils. One covers the frequency range from 8 to 700 Hz and the other covers from 2,000 to 18,600 Hz. The coils weigh 5.3 and 6.1 kg, respectively. The sensitivity of the large coil is 0.1 $\mu V/m\gamma$ at 8 Hz. An integral part of each sensor is a low-noise preamplifier which feeds the magnetic field signal to a second channel nearly identical to that described for recording the electric field.

Phase information is preserved by means of a phase-locked loop and synchronous detectors as shown in Figure 1. The usefulness of the phase information is still being evaluated, so it will not be discussed further here.

FIELD OPERATIONS

The strip chart recorder and high-gain selective filters were operated from the back of a carryall van. The power was supplied by an inverter connected to the truck battery. The coil and common electrode of the electric line were located 30 m from the truck to avoid electrical noise in the vicinity of the truck. Signals are brought to the truck over coaxial cable.

The electric line is laid out in either an east-west or north-south direction, and the coil placed at the right angle to the line. System gains are adjusted so as to give 20 to 40-mm chart deflection of peak energy bursts on each channel. The amplitudes of corresponding electric and magnetic signals are measured, and their ratios are computed for a sufficient number of signals to obtain a reliable average ratio. The Cagniard resistivity [*Cagniard*, 1953] is then computed by using system gain values and (2).

Data are computed and plotted in the field while recording is under way. A sounding is obtained by switching through the various frequencies. The electric dipole and coil are then rotated 90°, and a second sounding is made and plotted. This permits the operators to correct any obvious errors and to check any data points that appear aberrant. The second sounding also provides information on lateral variations in conductivity or anisotropy of the earth.

Soundings were carried out by two persons, one acting as observer and the other acting as computer. Typical production was eight soundings (four stations) per day. Most of the time is spent waiting for a sufficient number of strong signals so as to provide a good statistical sample for the E/H ratio. Our experience has shown that the 8-Hz signals are often insufficient to provide strong samples; 700-Hz signals tend to be variable in strength, 2000-Hz signals are virtually nonexistent, and at 7000 Hz and greater the signals provide very good samples.

Figure 2 shows the locations of the 25 sounding stations used in this survey as well as the major faults and hot springs in the area, as adapted from *Bailey et al.* [1976]. Inasmuch as the AMT technique is being used for reconnaissance exploration, the object was to define the major conductive anomalies and not to detail them precisely. No attempt will be made here to review the geological setting or other pertinent geophysical data, as these are given in accompanying papers. The results reported here were obtained by two persons during 1 week of field work in June 1973.

Typical sounding curves are shown in Figures 3 and 4,

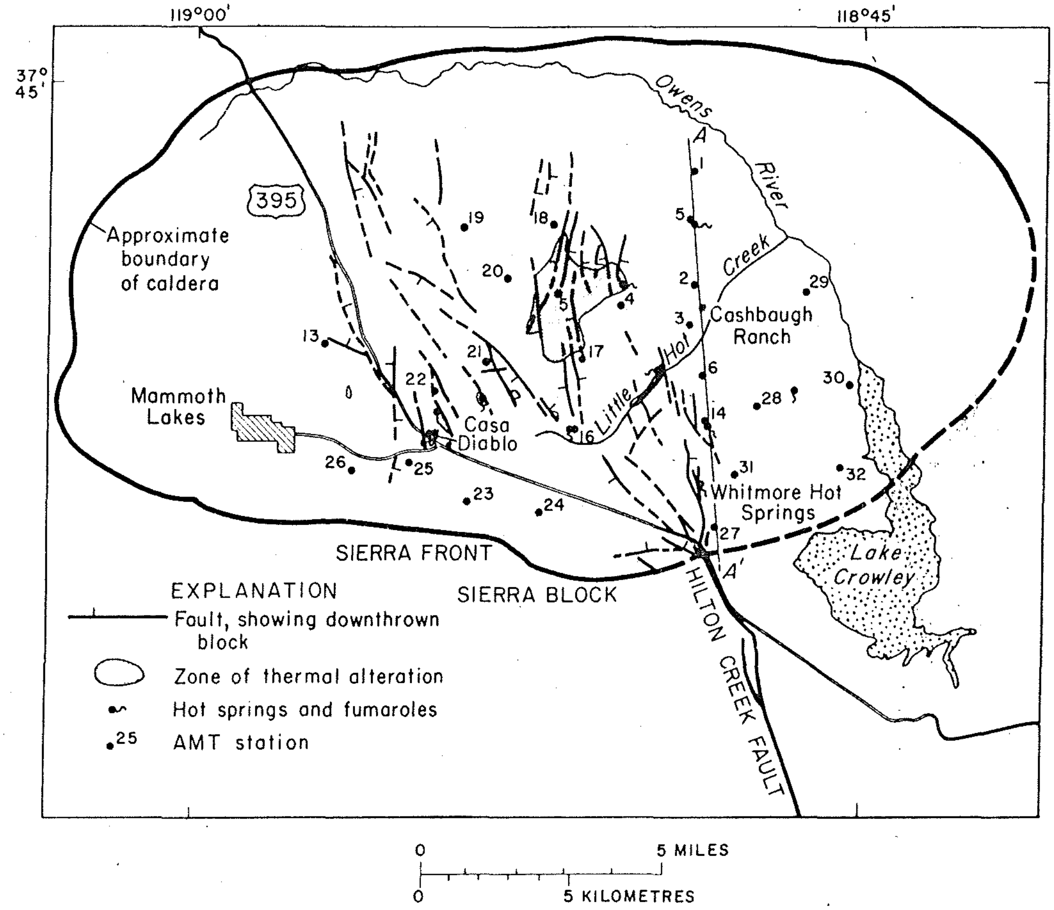

Fig. 2. AMT station location map, Long Valley, California.

which give data from stations 1, 14, and 16. Soundings for station 1 (Figure 3) show the typical reproducibility of the two soundings in which lateral effects are not pronounced. The soundings are plotted on a logarithmic base with frequencies increasing to the left. Although this is contrary to conventional presentation, it produces a sounding similar in appearance to Schlumberger sounding curves, thus providing easier reference to the work of *Stanley et al.* [1976].

Stations 14 and 16 are beside two hot springs associated with approximately north-trending faults, as shown in Figure

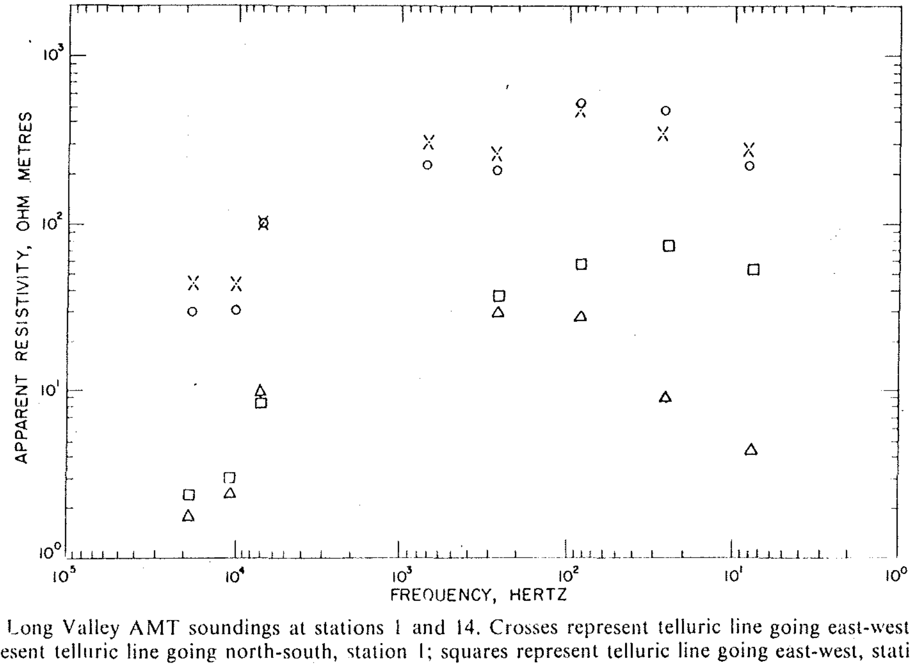

Fig. 3. Long Valley AMT soundings at stations 1 and 14. Crosses represent telluric line going east-west, station 1; circles represent telluric line going north-south, station 1; squares represent telluric line going east-west, station 14; and triangles represent telluric line going north-south, station 14.

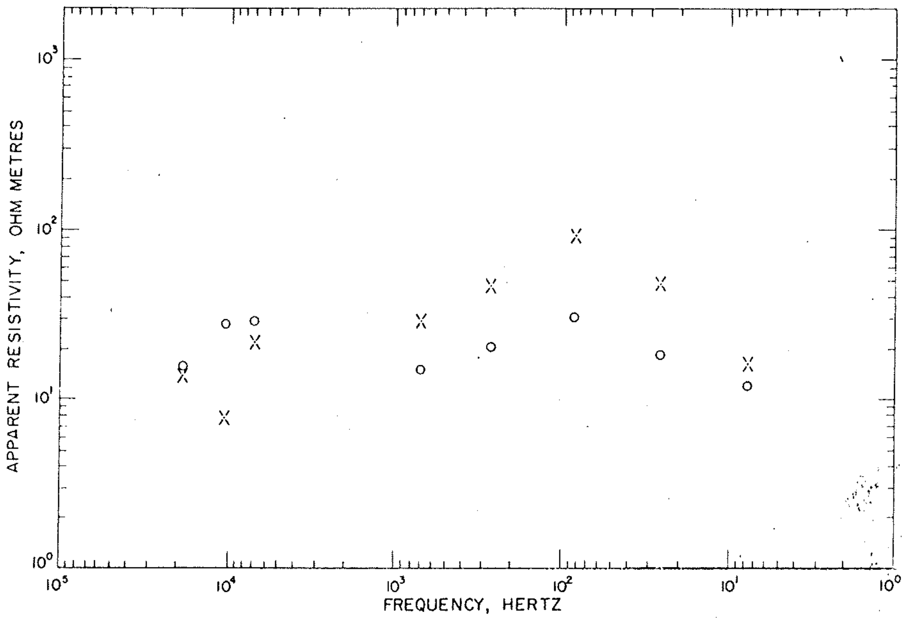

Fig. 4. Long Valley AMT soundings at station 16. Crosses represent telluric line going east-west, and circles represent telluric line going north-south.

2. These soundings (Figure 4) show very clearly the effect of lateral resistivity variations, the north-south (*E* parallel) orientation of the telluric line giving significantly lower apparent resistivities. At station 14, which was about 100 m west of the fault, the data begin to diverge significantly, showing the influence of the fault when the skin depth is greater than the offset. This type of behavior is to be expected outside of the conductive zone. The variation in apparent resistivity with orientation is not as great at station 16. Although this could be due to the relative orientation of the fault, these less pronounced variations at 16 are probably associated with less intensive alteration of the rocks, as the activity of the hot springs is considerably less there than at station 14.

Strangway and Vozoff [1970] note that in practice many more lateral variations are noted in this type of data than one might expect. This is quite evident in the Long Valley data, and, in fact, the north-south orientation of the telluric sensor usually, but not always, gives the lower resistivity values. This would be expected in Long Valley, where the predominant faulting is north to northwest trending and is of minor width; thus measurements would generally be made near but outside of the narrow conductive zones.

Because it is an inductive technique, the AMT method is excellent for locating conductors because it tends to 'look through' high-resistivity materials, and this is one of the principal reasons we are employing it in our geothermal program. However, its depth resolution is often poor, as was pointed out earlier. Because of both this problem and the evidence for lateral variations in the soundings themselves, interpretation in terms of horizontally layered structures was not attempted. Instead, the data presentation was limited to a set of anomaly maps at each frequency and some pseudosections.

Figure 5 is a map of apparent resistivity at 8 Hz. Where differences in apparent resistivity were obtained for the two sensor orientations, an average of the two values was used. Contouring of the data is logarithmic with four intervals per decade. This map represents information obtained at greatest depth in our survey, but the reader is cautioned not to think of the measurements as representing resistivity at a fixed depth across the map.

Despite the low station density, Figure 5 shows an anomaly pattern remarkably similar to the total-field resistivity anomaly of *Stanley et al.* [1976, Figure 6]. A small low, under 10 Ωm, is seen just south of the Cashbaugh Ranch, enclosed within a broader, V-shaped low under 100 Ωm. This V-shaped low encloses most of the hot springs in the caldera from Casa Diablo on the west and Whitmore Hot Springs on the east, to the head of Little Hot Creek in the northwest. In terms of reconnaissance, surveying the high-conductivity region has been adequately defined.

On the southern border of the caldera the 8-Hz map shows steep resistivity gradients as the Sierra front is approached. Resistivities of several thousand ohm meters are associated with the Sierra batholith and Paleozoic metasediments present in a nearby roof pendent. Intermediate resistivity values within the caldera are associated with volcanic fill, where there has evidently been little hydrothermal activity.

The total-field map of *Stanley et al.* [1976, Figure 6] shows a broader resistivity low in the vicinity of the Cashbaugh Ranch than is indicated by Figure 5. This discrepancy is due in part to the contour interval chosen and also to the differences in depth of exploration obtained with the two techniques. A 50-Ωm contour at 8 Hz would have included all of the anomalous area outlined by Stanley et al. near the Cashbaugh Ranch. Evidence to be discussed later indicates that the northern part of this conductive zone is slightly deeper than the rest of the zone and thus does not appear as prominently in Figure 5. Deepening of this zone is more clearly seen in the pseudosections across the anomaly (Figures 9 and 10).

At 26 Hz the signals are sufficiently strong, and so quite reliable data are obtained for both east-west and north-south orientations of the telluric line. To show the differences produced by lateral inhomogeneities, two maps have been prepared (Figures 6 and 7), one for each orientation. The two maps are generally similar to the 8-Hz map, showing the same V-shaped low centered on the hot springs and the steep resistivity gradient on the south. Either of the two maps adequately defines the anomalous area.

One major difference between the two maps lies in the significantly lower resistivity values associated with the north-

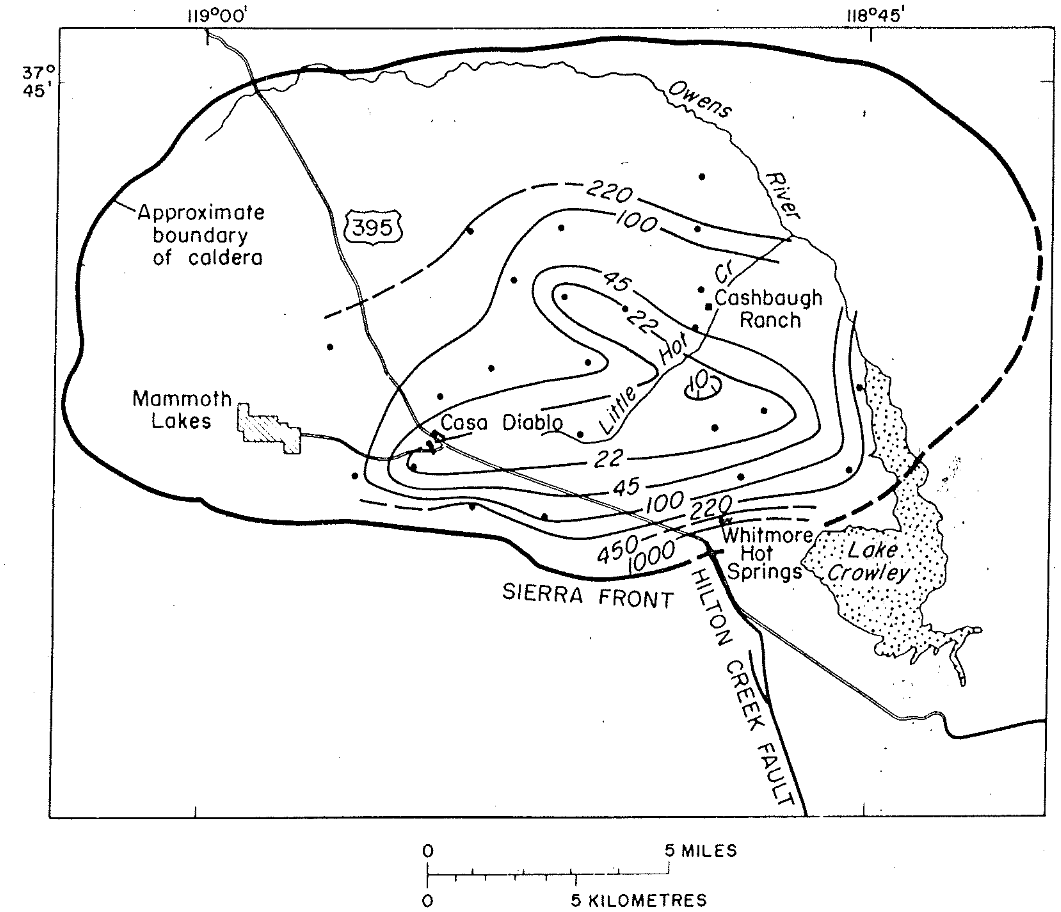

Fig. 5. The 8-Hz apparent resistivity map, Long Valley, California. Values are in ohm meters; contours are dashed where they are approximate.

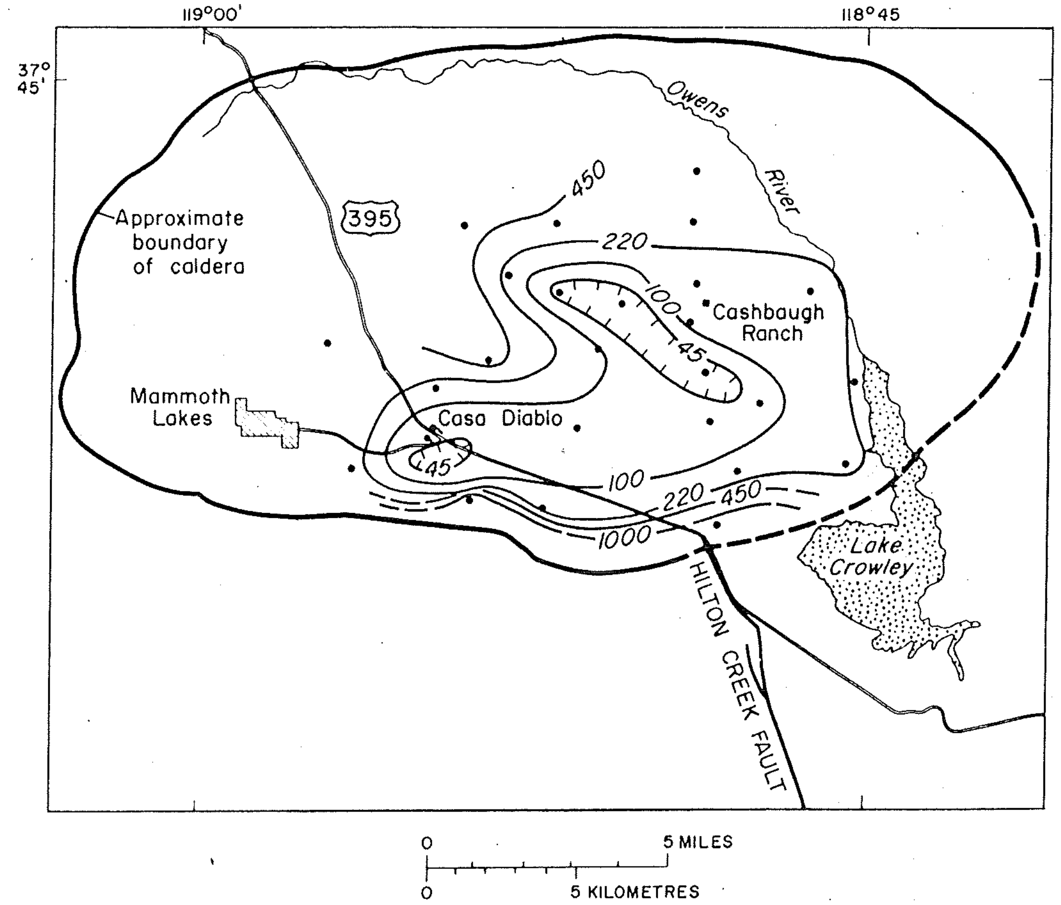

Fig. 6. The 26-Hz apparent resistivity map, Long Valley, California (electric line east-west). Values are in ohm meters; contours are dashed where they are approximate.

south telluric line orientation in the region of the anomaly. These lower values are believed to reflect the predominant north to northwest fault trend within the caldera, as was explained in the discussion of soundings at stations 14 and 16. Other differences between these two maps also are the result of lateral resistivity variations, but the low station density makes specific explanation or description of these variations impossible.

Mapped data at the higher frequencies continue to show the same general trends as the maps previously presented but with a smaller change in apparent resistivity across the map. Figure 8, the apparent resistivity at 7000 Hz, shows the near-surface resistivity variations in a general way. Although at the high frequency the volume of rock sampled at each station is quite small in comparison to the station spacing, the correlation of resistivity data with surface geology is quite good. The resistivity low now appears as a broad trough from Casa Diablo Hot Springs to the head of Lake Crowley. This is interpreted as the zone of most pervasive near-surface alteration and the region in which the saline hot spring waters discharge at the surface. The resistivities associated with the Sierra front are lower than those noted in the deeper data, showing the effect of weathering. On the 7000-Hz map the resurgent dome to the north of Casa Diablo has the highest resistivities in the mapped area; these resistivities do not differ much from values obtained at the lower frequencies. Rocks near the surface of the dome are young volcanics which have undergone little weathering.

In magnetotelluric work, electrical cross sections are often used as interpretational aids. These are called pseudosections and are usually plotted with frequency decreasing downward on a logarithmic scale. An obvious disadvantage of this type of pseudosection is the distorted idea of depth of exploration that is gives in areas where large changes in resistivity exist. We prefer a pseudosection plotted in terms of skin depth, which gives a better idea of the variation in exploration depth in complex areas. Figures 9 and 10 show skin depth pseudosections on a line oriented approximately north-south through Whitmore Hot Springs. Figure 9 was plotted for an east-west orientation of the telluric line. The major conductor is evident near Whitmore Hot Springs between stations 14 and 6 but continues somewhat deeper to the north under the Cashbaugh Ranch area. It is interesting to compare this figure with the total-field map which shows that the major low along the AMT line extends from station 31 to midpoint between stations 2 and 15. Figure 9 also shows clearly the large variation in exploration depth.

SUMMARY

The described AMT technique was developed for use as a reconnaissance geothermal exploration tool to search for conductive anomalies associated with hot saline waters and related altered rock. The exploration philosophy is that a survey using a relatively inexpensive technique such as AMT would be followed by a more definitive electrical surveying program in promising areas. Long Valley was used as a test area for the technique because of the extensive supporting studies.

The correlation of AMT results with other detailed electrical work in Long Valley is considered very good and provides evidence for the effectiveness of the technique. In fact, if the

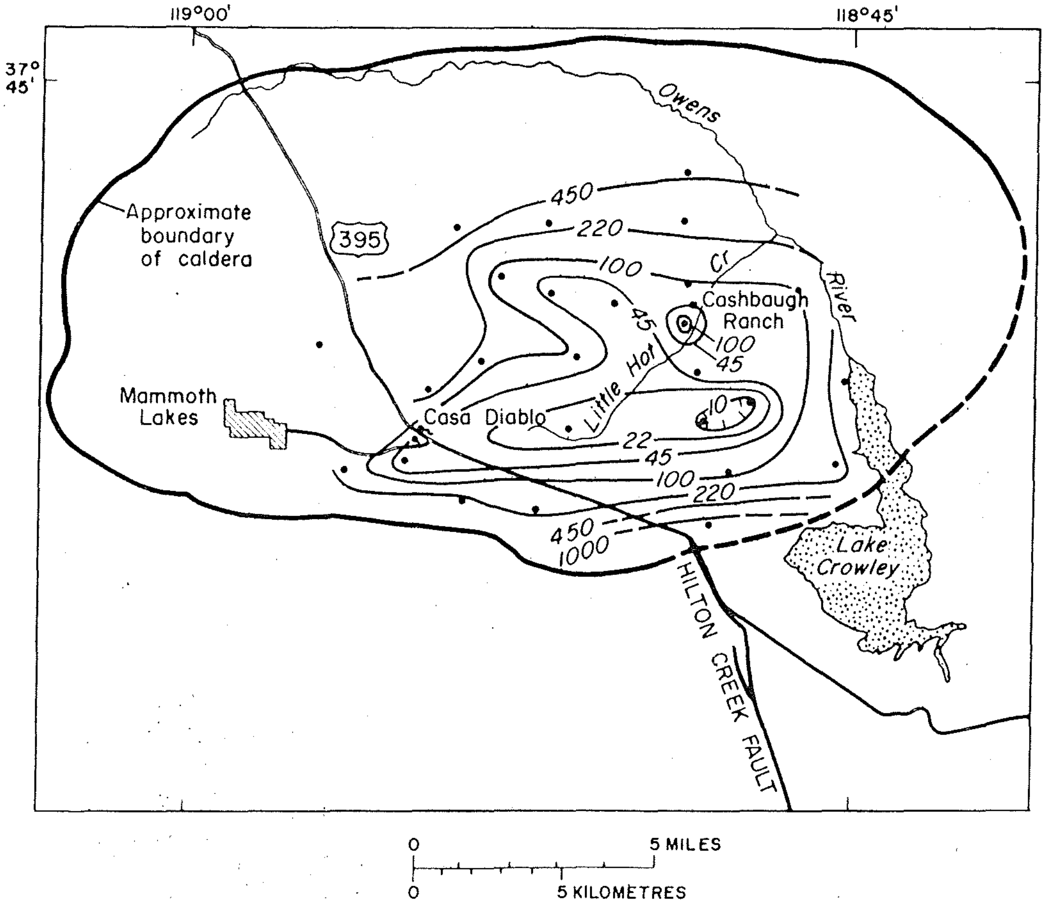

Fig. 7. The 26-Hz apparent resistivity map, Long Valley, California (electric line north-south). Values are in ohm meters; contours are dashed where they are approximate.

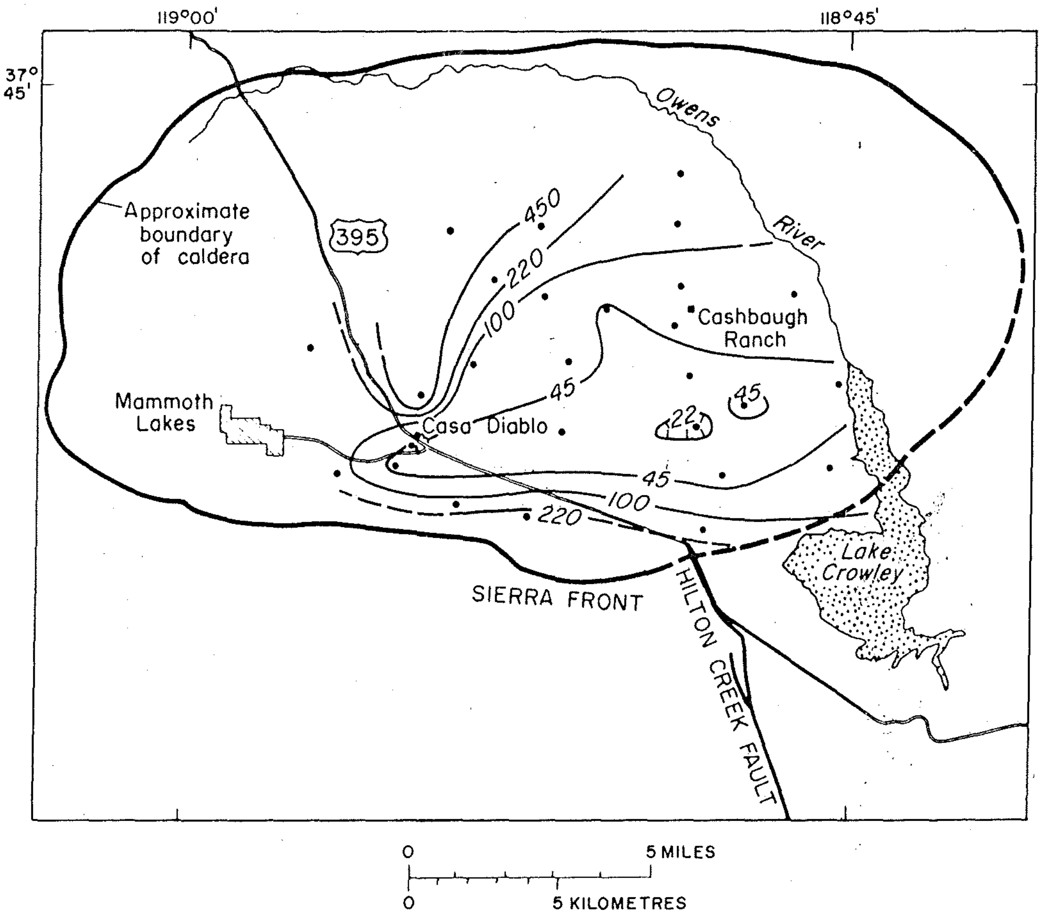

Fig. 8. The 7000-Hz apparent resistivity map, Long Valley, California. Values are in ohm meters; contours are dashed where they are approximate.

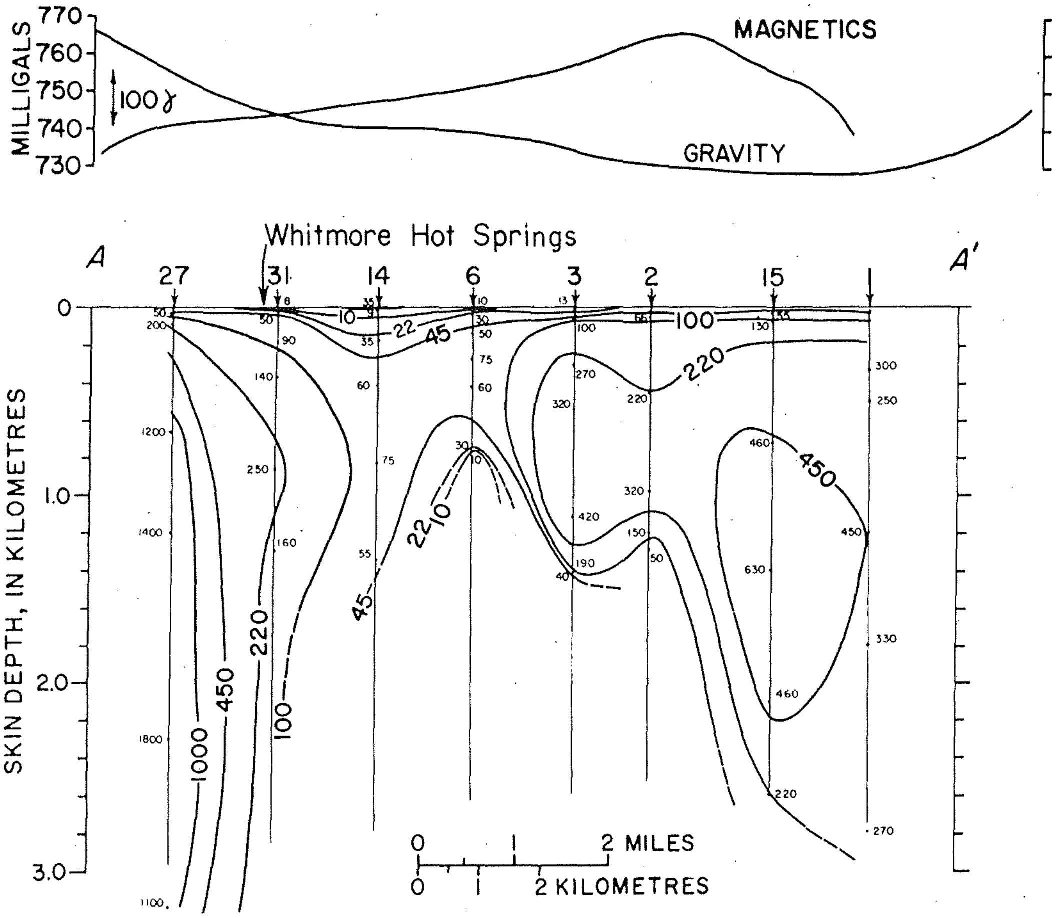

Fig. 9. Skin depth pseudosection along AA′ (electric line east-west), Long Valley, California. Line of section is shown in Figure 2. Values are in ohm meters.

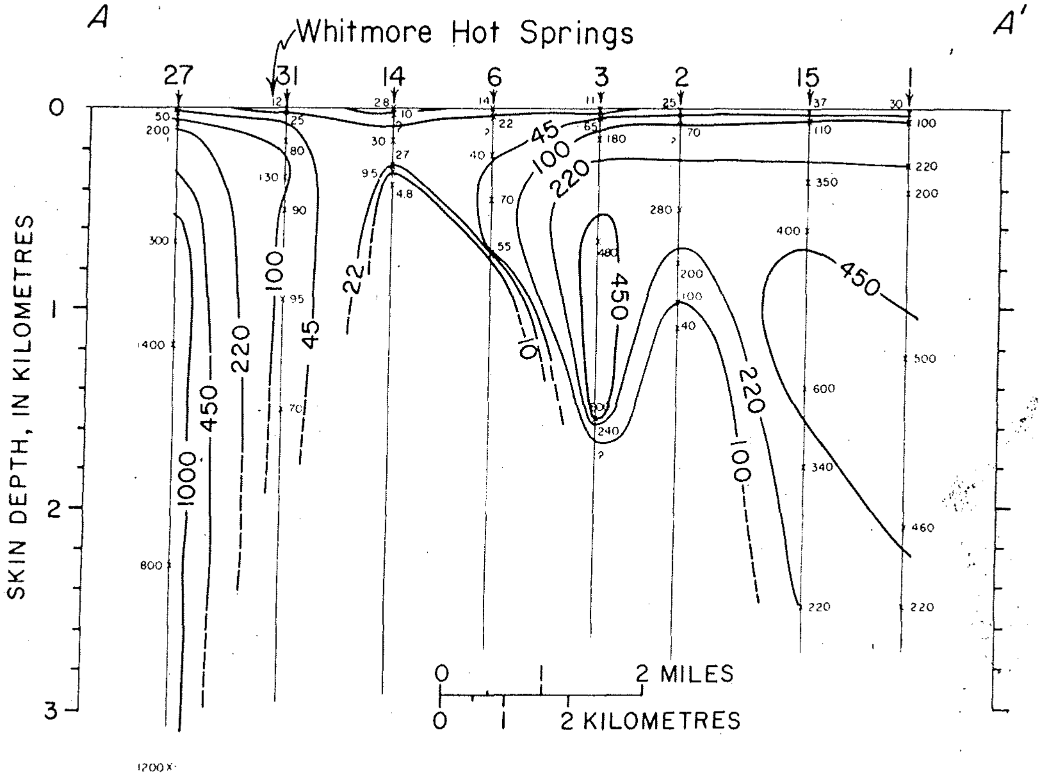

Fig. 10. Skin depth pseudosection along AA' (electric line north-south), Long Valley, California. Line of section is shown in Figure 2. Values are in ohm meters.

AMT survey had been used to pinpoint an area for an intensive exploration program, the area selected would not have differed significantly from that identified by the more detailed surveys. The 2 man weeks of work involved in the field survey and the good correlation obtained with conventional techniques clearly demonstrate the effectiveness of AMT for reconnaissance exploration.

In terms of the geothermal potential of Long Valley the hot waters and associated alteration zones in near-surface materials appear from the geological and electrical data to be restricted to a V-shaped area extending from Casa Diablo, east to Whitmore Hot Springs, and then northwest to the head of Little Hot Creek. Within this region the thermal waters are concentrated along the fault zones, which act as channels along which hot water leaks from a poorly defined reservoir at depth. The AMT data thus imply that shallow exploration should be confined to faults within the V-shaped region encompassing the known hot springs.

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