TOPICAL REPORT

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Magnetotelluric Investigations at the
Roosevelt Hot Springs KGRA and
Mineral Mountains, Utah

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Abstract

During the summer of 1976, twenty-five magnetotelluric sites were monitored for the Department of Geology and Geophysics by Geotronics Corp. of Austin, Texas. Amongst other MT functions, the transverse electric (TE) and transverse magnetic (TM) apparent resistivity and impedance phase data were provided for the frequency range 3×10^{-3} Hz to 100 Hz.

Some one-dimensional inversion results for this area have yielded very low values of estimated true resistivity. Such values are unrealistic in light of established notions about conductivity mechanisms in earth materials. Furthermore, the assembly of such inversions to form a crude two-dimensional model has yielded a calculated 2-D pseudosection far removed from the observed pseudosection. Trial-and-error modeling has provided a better fit although strong differences between observed and modeled data remain and cannot be overcome by any purely two-dimensional model. The most noteworthy difficulty is the presence of exaggerated contrasts in apparent resistivity persisting to the lowest frequency of observation for both modes of wave excitation.

Single-conductor, 2-D, TE and TM modeling may explain such problems in terms of three-dimensional effects. Discontinuities in electric fields from preservation of normal current density will result in the above-stated persistent apparent resistivity contrasts. This boundary condition must be obliged down to zero frequency.

Electrical strike estimation may be a meaningless endeavour in a strongly three-dimensional area. The total fields do not decompose into

the standard principal modes (TE and TM) and H_z depends on horizontal derivatives of both electric field components. Multiple symmetry axes result in multiple estimated strike directions depending upon where the observer is located. When derivatives of electric field are relatively small, noise may be the determining factor. The estimated strike directions for the Roosevelt stations are, however, quite consistent. The elongate resistive horst structure of the Mineral Mts. situated in conductive valley fill is felt to be the overwhelming reason for such a consistency.

Introduction

Magnetotelluric measurements constitute an electromagnetic method of estimating the conductivity structure of the earth's crust, potentially to depths of 20 kilometers or more. On the basis of previous DC resistivity and active EM measurements (Ward and Sill, 1976; Tripp and Ward, 1976), ranges of interpreted true electrical resistivity spanning 3.0 to $10^3 \Omega\text{-m}$ are known to exist at the Roosevelt Hot Springs KGRA. Contour pattern lows of first separation (near-surface) dipole-dipole apparent resistivity values are roughly coincident with highs of near-surface (30-60 m) thermal gradient measurements (see Figures 1 and 2).

During the summer of 1976, twenty-five magnetotelluric (MT) soundings were obtained in the central Mineral Mts. and Milford Valley in the vicinity of the Roosevelt Hot Springs. The data collection, processing, and presentation were contracted to Geotronics Corp. of Austin, Texas. This report describes these twenty-five preliminary sites in terms of 1-D, 2-D and 3-D models. The emphasis will be on the effects of shallow conductive 3-D prisms on the interpretation of deeper structures and the effects of the three-dimensionality on the electrical strike estimation.

FIGURE 1: Contours of first-separation dipole-dipole apparent resistivity results over the Roosevelt Hot Springs. Units of contours are $\Omega\text{-m}$. Reproduced from Ward and Sill, 1976.

FIGURE 2: Contours of near-surface (30-60m) thermal gradient observations over the Roosevelt Hot Springs. Units of contours are $^{\circ}\text{C}/\text{km}$. Modified from Sill and Bodell, 1977.

This topographic map depicts the Roosevelt Hot Springs area in Oregon. The map features contour lines indicating elevation, with labels ranging from 100 to 900 feet. Key locations marked include Roosevelt Hot Springs, Early Steam Well, and several numbered points (e.g., 36, 43, 63, 135, 200, 300, 400, 500, 600, 700, 800, 900). The map also shows a dashed line representing a boundary or road, and a scale bar indicating distances in miles (0 to 2) and kilometers (0 to 3). A compass rose indicates True North and Magnetic North, with a 18.5° difference. The map is framed by latitude and longitude coordinates: 38°25' to 38°30' N and 112°45' to 112°55' W.

Conduction Mechanisms in the Roosevelt Area

Electrical techniques of remote sensing may yield good estimates of subsurface resistivity structure but do not by themselves indicate the intrinsic reasons for it. It remains for the interpreter to decide on the basis of independent geological, geochemical, and geophysical considerations which mechanisms are most important in a given environment. This section will outline which conduction processes must be considered in the Basin and Range tectonic province and what constraints on each are applicable in the Roosevelt Hot Springs area.

The importance of electrolytic conduction through pore passages and fractures and of surface conduction along mineral surfaces has been well described by Ward and Sill (1976) in another volume of this series. Electrolytic conduction can be expected to obey Archies Law

$$\rho_r = \rho_w \phi^{-m} \quad (1)$$

where ρ_r is the resistivity of the rock, ρ_w is that of the electrolyte, ϕ is the fractional porosity, and m is an exponent (usually near 2.0) labelled the cementation factor (Ward and Fraser, 1967). Porosities and solution conductivities both have wide ranges of values in the Roosevelt Hot Springs area. The former lie mostly within 0.25 (uncemented alluvium) to 0.035 (unaltered granite). Parry (1976) reports that ionic strengths around the hot springs are as high as 0.2 N(NaCl) yielding a resistivity of electrolyte of about 0.5 Ω -m. The essentially fresh waters encountered within the Mineral Mts. would average 30 Ω -m (Sill, pers. comm., 1978). These combined values suggest possible earth resistivities as low as 8 Ω -m

in the thermal anomaly area and upwards of $10^4 \Omega\text{-m}$ in the granitic rocks. Surface conduction, on the other hand, depends on the mobility of solution cations adsorbed at mineral surfaces. It is especially important in areas of clay alteration and where microcracks comprise a sizeable percentage of overall porosity. Ward and Sill (1976) estimate that clay alteration may reduce resistivities by a factor of 2 to 4. Geochemical (Parry, 1976) and geophysical (Ward and Sill, 1976) studies show that the high conductivity region associated with the clay alteration along the Dome Fault fracture zone may extend no deeper than 500 m. Surface conduction is also most important in rocks with low solution ionic strengths. That, along with the knowledge that the Mineral Mts. granitic rocks are somewhat weathered to greater than 500 ft depth, suggests the observed near-surface resistivities of 200 to 500 $\Omega\text{-m}$ in the mountains are the result of surface conduction effects.

Both temperature and pressure increase with depth. In a review of experimental results by many authors, Brace (1971) derived resistivity vs depth profiles for three American tectonic provinces. Water-saturation is assumed. Figure 3 is an adaptation of his Basin and Range province model. The effect of increased temperature on solution conductivity is to increase conductivity up to some pressure-dependent limit. The effect of increased effective pressure is to decrease porosity. The combination of the two trends results in a nearly tenfold increase in rock resistivity up to a pressure of around 1.5 kb (5 km depth). As one looks deeper, the resistivity remains high ($\sim 10^4 \Omega\text{-m}$) for some distance, perhaps down to 15 to 25 km. Pore conduction is still dominant but porosities are very low

(0.001 or so).

Thereafter, temperature dependent mineral semiconduction becomes more important. The accurate description of thermally-activated conduction processes is very difficult since the mobility of charge carriers through a crystal lattice may depend strongly on a variety of parameters (oxygen fugacity). The majority of the transported charge is probably the result of motion of ionic impurities through crystals due to lattice defects (Sill, pers. comm., 1978). If we consider temperature variations alone, one may expect an $\exp(-E/kT)$ dependence where T is absolute temperature and k is Boltzmann's constant. E involves the energies required to both liberate and move impurities. Results published by Brace (1971) indicate that semiconduction-controlled resistivities may be as low as $100 \Omega\text{-m}$ for a temperature of 700°C but are on average likely to exceed $1000 \Omega\text{-m}$. Semiconduction will remain dominant until partial melting is initiated.

Brace stopped short of discussing conductivities of partial melts. Petrological evidence reported by Nash (1976) demonstrates a substantial magma chamber(s) existed under the central Mineral Mts. as recently as 0.5 m.y. ago. The evidence consists of at least 9 viscous rhyolite domes spread for 15 km along the crest and western flank of the pluton. Water fugacity calculations indicate a series of sources at depths probably greater than about 3 km (Nash, pers. comm., 1978). It is indeed questionable whether any such bodies remain molten today. If so, however, they may be very conductive electrically and are perhaps detectable by the magnetotelluric method. Lebedev and Khitarov (1964) measured the conductivities of granite over a wide range of temperatures and partial

FIG. 3: Proposed range of resistivities vs depth for the Basin and Range tectonic province. Modified from Brace (1971).

FIG. 4: Electrical conductivity of granite as a function of partial pressure of water vapour and temperature. Adapted from Lebedev and Khitarov (1964).

pressures of water. Their results are reproduced in Figure 4. Two major inflections lie on each curve. Break 1 belies the first formation of alkalic alluminosilicate melts from reaction between water and granite. Break 2 corresponds to homogenization of the melt. The curves indicate that resistivities as low as $0.03 \Omega\text{-m}$ are possible for wet melts. However, the petrological work of Evans and Nash (1978) indicates that P_{H_2O} lay between 200 and 1000 bars for the rhyolite melts. Geothermometry estimators show a maximum magmatic temperature of 700°C . Hence, one expects that the resistivity of the proposed melt lay in the 100 to $5 \Omega\text{-m}$ range 0.5 m.y. ago.

Based on petrological P_{H_2O} and temperature estimates, this author concludes that a significant low resistivity anomaly does not likely accompany a dry heat source where semiconduction effects would dominate. However, any present-day subsurface melts might be quite conductive and detectable by additional magnetotelluric interpretation. It appears, unfortunately, that by far the greatest resistivity contrasts are near-surface (wet, altered alluvium - unaltered, low porosity granite) and their electrical consequences may badly mask those of the deeper structures in which we are interested.

For completeness' sake, it should be mentioned that the occurrence of massive sulphides or graphitic rocks in the geologic section could lead to resistivities as low as $0.10 \Omega\text{-m}$. However, this author is ignoring this possibility as there is no surface evidence for their presence and hence can only be considered as an unlikely last resort.

MT Sounding Interpretation

Figure 5 indicates the distribution of the 25 stations in the Roosevelt Hot Springs vicinity. The basic layout consists of a single, east-west, twelve-station profile across the Opal Mound Fault straddling the thermal anomaly plus 2 minor lines and some scattered single sites. The distant, isolated soundings are intended to identify a "background" crustal resistivity profile upon which any conductive anomalies accompanying the heat source for the convective hydrothermal system at Roosevelt Hot Springs may be imposed. The 12-station line was intended to detect any such deep conductive zone (see Figure 6).

The source of excitation for MT soundings is treated universally as a vertically downward propagating electromagnetic plane wave. This assumption has been questioned in the past but the high conductivity of earth materials of concern and the strong coherency of signals at widely separated stations has been considered to be adequate (Madden and Nelson, 1964; Orange and Bostick, 1965). The theory of EM plane wave behaviour and its applications to magnetotelluric soundings is well discussed in the literature (eg. Ward, 1967; Swift, 1967; Ward et al, 1971; Vozoff, 1972).

High-quality, broadband (3×10^{-3} Hz to 100 Hz) values of total EM field components, E_x , E_y , H_x , H_y and H_z , were measured at each magnetotelluric sounding site. In the field, the positive x-axis was assigned to magnetic north. Later data processing by Geotronics Corp. yielded the 4-element impedance tensor that was subsequently rotated into the principal electric excitation directions for each site. These two

FIGURE 5: Site locations for twenty-five broad-band magnetotelluric observations in the Roosevelt Hot Springs and Mineral Mts. region. Scale is 1:125,000. True north is towards top of figure. The boundary separating outcrop from alluvium may be surmised from the break in topographic contour gradient which occurs between 6000' and 7000' above sea level. The steep gradients correspond to granitic and metasedimentary exposure.

FIGURE 6: Interpreted near-surface geology underlying 12-station magnetotelluric profile in the Roosevelt Hot Springs area. Sediment distribution is determined by surface exposure, MT and dipole-dipole resistivity surveys, and deep water wells. Rock type occurrences are from surface geological mapping, aeromagnetic interpretation, and drilling. Faults are from gravity and photogeology studies. For detailed lithologic descriptions, see Evans (1978) and Ballantyne and Parry (1978).

directions are parallel (transverse electric) and perpendicular (transverse magnetic) to apparent electrical strike. Such an approach assumes that the earth is at worst approximately two-dimensional; the effects of finite strike length will be addressed later in this report. The two earth response functions of primary interest for each principal orientation are the apparent resistivity [$\rho_a(\omega)$] and the impedance phase [$\phi(\omega)$].

1-D Results

Again using the assumption of approximate two-dimensionality, it has been the habit to perform any 1-D interpretation on the transverse electric (TE) mode of $\rho_a(\omega)$ and $\phi(\omega)$ (Swift, 1967; Ward, 1971; Vozoff, 1972; Strangway, 1973). Continuity of the tangential electric fields emphasizes broader wavelength, deeper conductivity anomalies while small scale, shallow geological noise is attenuated. Figures 7 and 8 present TE apparent resistivity and phase curves (along with best 3-layer fits) for stations 1 and 11. Station 1 lies on the west end of the 12-station profile on conductive valley fill of the Milford Valley. The nearest outcrops are the opal-siliceous sinter-cemented alluvium-clay mineral alteration assemblages along the Opal Mound Fault 7 km to the east. Station 11 lies on Tertiary (?) granite in the east-central Mineral Mts. about 3 km from conductive alluvium.

The $\rho_a(\omega)$ and $\phi(\omega)$ curves for the one-dimensional modeling were interpreted in two ways: discrete layer and continuous variation inversion to an interpreted true resistivity profile. The first method involves iteratively fitting the analytic solution for the impedance of an n-layered

FIGURE 7: Apparent resistivity and impedance phase data for MT sounding RSU 1. The transverse electric mode of excitation was chosen. Resistivities are in Ω -m and thicknesses are in meters. Parameter subscripts refer to layer number with subscript one being the top layer and subscript three being the basal half-space. Limits (one standard deviation) on a particular parameter are obtained by multiplying and dividing parameter by its particular D_E .

FIGURE 8: Transverse electric apparent resistivity and impedance phase data for MT sounding RSU 11. Conventions are as in Figure 7.

isotropic earth via the generalized inverse (Ward, 1967; Inman, 1975; Petrick et al, 1977). Its advantages are division of the earth into distinct resistivity units and the yielding of statistical estimates of parameter confidence. Discrete layers are especially appropriate for determining depth to water table and depth to bedrock in conductive valley fill. The second approach has been popularized by Francis X. Bostick, Jr. of the University of Texas at Austin (Ward et al., 1977). The method is simple and inexpensive but the statistical confidence of resistivity variations is unknown. A continuous profile may be more suitable for deeper crustal soundings where pressure-dependent porosity and temperature-dependent semiconduction effects vary smoothly over substantial vertical distances. Results in this form were provided for the TE mode for all stations in the Roosevelt area by the contractor.

The resistivity profiles obtained by each procedure are contained in Figures 9a and b. The agreement between both methods, here and for other stations, is generally very good. For station 1, both suggest three major resistivity units. The upper 200 m or so likely represents wet, surficial, sandy alluvium with a resistivity of about 7 Ω -m. Subsequently, the sounding detects a substantial thickness (>1000 m) of probably saline, clay-rich valley fill of resistivity 1 Ω -m or so. An examination of deep water well data (Mower and Cordova, 1974) for a site about 4 miles south of station 1 indicates a surficial alluvium layer of predominantly coarse sand, gravel, and boulders exists with a thickness of about 500 ft (160 m). Beyond this, the well bottoms out at ~280 m in clay overburden with minor sand. Below 1200 m, an apparently unrealistically conductive base is

FIGURE 9a: Comparison of 3-layer and continuous inversion interpretations for MT sounding RSU 1. Dashed line is continuous case.

FIGURE 9b: Comparison of 3-layer and continuous inversion interpretation for MT sounding RSU 11. Dashed line is continuous case.

encountered ($0.02 \Omega\text{-m}$ and less). Dipole-dipole surveys (Ward and Sill, 1976) indicate that conductive valley fill in this vicinity is at least 1000 m thick and a resistive basement was not encountered. Gravity interpretation (Crebs and Cook, 1976) using a rock-alluvium density contrast of 0.5 gm/cm^3 yields a depth of about 1300 m. This is considered by some as the upper limit on density contrast. Water saturated alluvium with a porosity of about 20% would possess a contrast of 0.3 pushing the basement down to around 1800 m (Tripp and Ward, 1976). No resistive foundation is evident in the magnetotelluric results although, via trial-and-error insertion beneath the above conductive sequence, a base of resistant material at a depth of 1600 m appears undetectable. The reason for the very conductive material at depth is not immediately apparent. It may be partially explained by the presence of brines of higher salinity that possibly leaked westward from the hot springs. The effects of three-dimensional geometry are a stronger possibility and these will be discussed in a later section.

Station 11 lies in resistive granite and the sounding data reflect this. Ionic conduction through pores, semiconduction through minerals and perhaps partial melting are the conductivity mechanisms to bear in mind in this sort of environment. Three crude conductivity units are again apparent. A surficial layer about 1 to 4 km thick of average resistivity $400 \Omega\text{-m}$ probably represents the regime dominated by pore-space and surface conduction. A 10 to 20 km thick layer of intermediate ($\sim 1000 \Omega\text{-m}$) resistivity follows. In this range, contributions from both pore and surface conduction (igneous mineral surfaces only) are still most important

although porosities are quite small (.001 and less). As depth and temperature increase, semiconduction does become important especially for depths greater than 20 km. For normal Basin and Range thermal gradient values ($\sim 30^{\circ}\text{C km}$), temperatures would then exceed 600°C . Values of resistivity may drop to $100 \Omega\text{-m}$ (Brace, 1971) and the continuous inversion results especially suggest that this very phenomenon is going on. Past 40 km, the continuous interpretation keeps decreasing down to the lowest frequency of observation. One may speculate that a partial melting zone is being encountered but neither the raw data nor the continuous results indicate any sharp break in slope such as would be expected. The trend of inversion results generally mimics the Basin and Range model diagrammed earlier although the intrinsic resistivities appear 5 to 10 times too low while interface depths are shallow by a factor of about 2.

This was merely a cursory examination of sample one-dimensional results from the Roosevelt area. Twenty-five separate conclusions would have been reached had all twenty-five stations been considered. The consequences of lateral inhomogeneity upon the results of a particular site may be extreme and these will be addressed in subsequent sections.

2-D Results:

Contours of DC apparent resistivity, mapped and inferred fault directions, and topography all indicate a north-south preferred orientation to the near surface ($< 500 \text{ m}$) structure in the Roosevelt area. A profile of soundings perpendicular to this orientation is required to gain any knowledge of gross two-dimensional inhomogeneities. The east-west trending

stations 1 through 12 form such a profile.

The most concise way to present multi-frequency, 2-D data is in the form of a pseudosection. Using frequency as the ordinate and horizontal distance as the abscissa, contours of TE and TM apparent resistivity are displayed in Figures 10 and 11. The two plots are very similar in several respects. Values for stations 1 and 2 to the west are almost exclusively the result of conductive valley fill. No resistive basement is evident. A few hundred meters west of the Opal Mound Fault, aeromagnetics, gravity, and dipole-dipole resistivity infer near-surface Precambrian (?) gneiss. Station 3 for both plane wave modes is detecting such bedrock but more careful two-dimensional modeling is required to determine the true resistivity. Station 4 lies within the conductive fracture zone bounded on the west by the Opal Mound Fault (Parry, 1976; Ward and Sill, 1976). Its low values of resistivity reflect this. The Mineral Mts. igneous rocks are sampled by soundings 5 through 10 and the relatively high values of $\rho_a(\omega)$ are therefore not surprising. One notable interior anomaly occurs at station 8. For the transverse electric mode especially, a pronounced ($>10:1$) contrast in apparent resistivity persists down to the lowest observed frequency. This phenomenon also occurs at station 4 and, on the basis of results in later sections, is likely to be met often in magnetotelluric surveys. A final distinguishing feature between the two wave-mode pseudosections involves the general magnitude of apparent resistivity values. With the exception perhaps of sites 1 and 2, the TM resistivities are generally larger than those of TE by a factor of ten.

The University of Utah has developed a versatile, reliable

FIGURE 10: Observed transverse electric apparent resistivity pseudosection for MT stations 1 through 12. Values of contours are in $\Omega\text{-m}$.

FIGURE 11: Observed transverse magnetic apparent resistivity pseudosection for MT stations 1 through 12. Values of contours are in Ω -m.

finite-element algorithm for modeling MT field observations using either propagation mode for arbitrary two-dimensional geometries (Rijo, 1977). A very important consideration in electrical soundings of any sort is the validity of assembling a group of one-dimensional inversion results to form a crude picture of the 2-D structure. This approach is common (eg. Word, 1970; Vozoff, 1972; Stanley et al, 1977; Jiracek et al, 1977). For each of the twelve stations in the profile, the best-fit discrete-layer inversion results were stitched together as in Figure 12. Boundaries are set half-way between stations. Some lumping of parameters in the model was necessary since only nine unique values of resistivity may be input into the modeling program. For example, the extremely conductive basal material apparent under the westernmost stations was constrained at $\rho = 0.10 \Omega\text{-m}$. Optimum layer thicknesses were calculated via the generalized inverse routine for the fixed conductivities and this group of compromised parameters was utilized for the finite element program. However, the fit of these new values to the original sounding data remained very good.

The computed TE apparent resistivity pseudosection for this ensemble appears in Figure 13. Only the results for stations 1 and 2 and the very high frequency values for the other sites provide an acceptable fit. Notably absent are the high, enduring, station-to-station contrasts in apparent resistivity at soundings 4 and 8. Trial-and-error improvements in the basic model are possible. After several iterations, the final best 2-D fit to the transverse electric section appears in Figure 14 and its pseudosection in Figure 15. The comparison is adequate down to about 0.5 Hz after which it degenerates rapidly. The sampling problem and the

FIGURE 12: Assembly of best-fit, discrete-layer inversion results (TE mode) for stations 1 through 12. Resistivities are in Ω -m.

FIGURE 13: Transverse electric 2-D finite element pseudosection calculated for preceding one-dimensional assembly.

FIGURE 14: Trial-and-error best-fit model for observed transverse electric pseudosection of Figure 9. Resistivities are in $\Omega\text{-m}$.

FIGURE 15: Calculated apparent resistivity pseudosection for previous trial-and-error best-fit model. Contours are in $\Omega\text{-m}$.

importance of shallow conductivity contrasts raise their heads. The relatively small number of soundings allows the higher frequency values to be modeled by near-surface anomalies only. The low frequency values cannot be fit by any two-dimensional TE arrangement.

The transverse magnetic mode of excitation was also examined for the one-dimensional stitch model (Figure 16). Very surprisingly, the fit between TM modelled and TE observed is excellent. Especially, observe the appearance of marked contrasts in $\rho_a(\omega)$ down to the lowest observed frequency. Note, however, that TE modeled does not agree at all with TM observed so a mere misidentification of wave-excitation modes is not the answer. Hence, this author by no means wishes to imply by this that the stitched group of 1-D interpretations may be valid. Instead, let's step back a bit and examine some simple prismatic models for both wave modes.

2-D MODEL STUDIES AND 3-D IMPLICATIONS

Single Conductor Discussion:

Figure 17 shows the transverse electric and magnetic profiles for a simple, outcropping conductive 2-D body in a resistive environment. Such a geometry might very crudely represent the hydrothermally altered fracture zone at Roosevelt Hot Springs KGRA as delineated by previous work (Parry et al, 1976; Bryant and Parry, 1977; Ward and Sill, 1976; Tripp and Ward, 1976). The TE values are no surprise. Continuity of electric fields tangential to media contacts requires that the $\rho_a(\omega)$ anomaly die away as frequencies are lowered. No discontinuities in the apparent resistivity function are possible. The TM results are very different, however, since

FIGURE 16: Transverse magnetic 2-D pseudosection for the one-dimensional assembly of Figure 11.

FIGURE 17: TM and TE multifrequency profiles for single, outcropping, shallow, 2-D conductor.

the applied electric vector is instead normal to the strike direction. Note the strong discontinuity in $\rho_a(\omega)$ at the contacts. The boundary condition requiring preservation of normal current density ($\vec{J}$) is responsible. At this boundary, for the parameters listed in Figure 17, $\vec{E}$ inside the prism will be one-tenth of that outside. Now, by definition, $\rho_a(\omega) = \frac{1}{i\omega\mu_0} |E_y/H_x|^2$. Maxwell's equations state that, for this mode, $\frac{\partial H_x}{\partial y} = i\omega\epsilon_0 E_z \approx 0$ in the air. Hence, H_x is a constant and $\rho_a(\omega) \sim E^2$ leading to the observed discontinuity of 100. For arbitrary resistivity contrasts and vertical contacts, the observed discontinuity has the value $(\rho_1/\rho_2)^2$. Since normal $\vec{J}$ must be continuous even as $\omega \rightarrow 0$, this marked anomaly must persist through all frequencies. Of course as frequencies become high, the values of ρ_a towards the centre of the conductive prism will approach the true value of resistivity. Evidence that this is happening appears for the 35 Hz profile.

One may surmise the behaviour of a simple 3-D rectangular prism, however, based on the two-dimensional models above. Figure 18 illustrates the basic anomaly shape possessing characteristics of both TE and TM 2-D models. Depending upon the location of the observer, he will observe that the incident electric vector may be either normal or parallel to an interface. Referring to the geometry of the figure, measurements along line A-A' (with the electric vector normal to the resistivity discontinuity) will yield a profile resembling a TM excitation. Continuity of normal $\vec{J}$ requires that the $(\rho_1/\rho_2)^2$ discontinuity in ρ_a be present *for all frequencies*. Measurements along line B-B' (with the electric vector parallel to the resistivity discontinuity) yield a profile resembling a TE

FIGURE 18: Conductive rectangular prism in resistive environment plus proposed apparent resistivity signatures for single polarization of electric vector.

excitation. Continuity of tangential $\vec{E}$ requires a smooth ρ_a curve. It is obvious that analogous $\rho_a(\omega)$ profiles will appear for an $\vec{E}$ vector polarization orthogonal to that depicted. Line A-A' would be "TE" and line B-B' would be "TM". Hence, finally, the typical 3-D conductivity anomaly will be one of pronounced ρ_a contours lasting down to the lowest frequency measured. Because of discontinuities such as those along "TM" profiles, the values of contours within the prism could be substantially lower than the true value of resistivity. Regardless of which pseudosection (TE or TM) is examined, a profile across a conductive prism of finite strike length will show such exaggerated, persisting contrasts in apparent resistivity since E_x and E_y will both be present. Referring again to Figures 10 and 11, it is this author's opinion that station 4 and probably station 8 are good examples of this phenomenon and that there is no two-dimensional model that can be made to fit the data.

The question of depth of resolution for 3-D bodies also arises. Figure 19 displays multi-frequency TE and TM profiles for another single outcropping conductive dike of much greater depth extent than the previous example. While the TE anomaly has increased by perhaps 60%, the TM results around the body change by only about 20%. One may again estimate the 3-D response as before and end up with a signature very similar to that of the shallow prism. The important conclusion to draw from this is that MT soundings within such 3-D conductive prisms may provide no meaningful information about deeper structure.

FIGURE 19: TM and TE multifrequency profiles for single, outcropping, deeply extending, 2-D conductor.

The Mode Identification Problem:

In MT, wave mode identification is synonymous with estimation of electrical strike. The logic behind this estimation applies only for two-dimensional geometries and the effects of finite strike length on the results may be quite adverse. Consider the purely 2-D model in Figure 20. Any incident electric vector may be resolved into a component parallel to and a component perpendicular to true electrical strike. If x is the strike direction, then Maxwell's equations tell us in general that

$$H_z = \frac{-1}{z} \left[\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} \right] \quad (2)$$

with $z = i\omega\mu_0$. Since $\partial/\partial x = 0$ in the 2-D case, the above boils down to

$$H_z = \frac{-1}{z} \left[\frac{\partial E_x}{\partial y} \right]. \quad (3)$$

The vertical component of H is linearly related to, or completely coherent with, only the component of electric field parallel to strike. Hence we may write

$$H_z = Y_{zx} E_x \quad (4)$$

where $Y_{zx} = \frac{-1}{z} \partial/\partial y$ is the AC admittance for this field pair. When one sets up his orthogonal sets of electrodes and coils in the field, one has no idea which direction is strike and the sensor orientations are expected to be oblique. Components of E_x will be recorded by both electrodes. If x' and y' are the measurements axes and θ is the angle between x and x' as in Figure 20, then we must write

FIGURE 20: Co-ordinate and rotation conventions for two-dimensional mode identification discussion.

$$H_z = Y_{zx}' E_x' + Y_{zy}' E_y' \quad (5)$$

where Y_{zx}' and Y_{zy}' are the relevant admittance functions. These coefficients are gleaned from the field records of E_x' and E_y' using patent spectral analysis techniques (Bendat and Piersol, 1971; Sims, 1971; Word, 1971; Vozoff, 1972; Vozoff, 1974). The measurement axes are mathematically rotated to maximize Y_{zx}' and the corresponding x' -direction is estimated strike.

This is all fine for the strictly two-dimensional case. In 3-D, however, $\partial/\partial x \neq 0$ and H_z in general depends on both E_x and E_y (equation 2). Referring again to Figure 18, observe that along line A-A', $\partial/\partial y = 0$ and H_z will be wholly coherent with E_y . The estimated strike direction will be along the y-axis. Along line B-B', $\partial/\partial x = 0$, H_z will be dependent upon E_x , and the estimated strike direction will be along the x-axis. Along diagonals of the prism, both derivatives are important and an oblique strike estimation will result. The addition of noise to the data is a further complication, especially near the center of the prism. Here, both derivatives are small and the mode identification may vary strikingly between two close frequencies or between two stations a short distance apart.

Generalizing, wherever a strong axis of symmetry is present in a 3-D body, the estimated electrical strike direction along said axis will be normal to it. Furthermore, when the spatial derivatives of both electric field components are relatively small, noise is the determining factor in mode identification.

In spite of the potential 3-D complications, the mode identification for the Roosevelt stations is pretty consistent (see Figure 21). In this author's opinion, regional structure is responsible. The Mineral Mts. form a very elongate, north-south trending resistive body flanked on the west by deep, very conductive alluvium and to a minor extent on the east by the same. Especially for east-west profiles across the central portions of this range, $\partial/\partial y \gg \partial/\partial x$ where x is the north-south axis of the mountains. Hence, the consistency in the electrical strike estimation does not appear related to smaller-scale hot-spring structure but instead to the gross topography of the region.

FIGURE 21: Dip-axis estimates [A(YZ) is contractor's notation] as a function of depth for several stations in the Roosevelt area. The dip-axis is normal to estimated electrical strike and the blackened area indicates the scatter in the calculated axes. The depth is a product of the continuous inversion algorithm which provides an approximate depth-frequency correspondence listing.

CONCLUSIONS AND FUTURE CONSIDERATIONS

During the spring months of 1978, Geotronics Corp. will obtain measurements at another fifty magnetotelluric sites. These, coupled with the previous stations, afford an unprecedented test of the MT method in crustal conductivity sounding. The simple model studies to date bring us to the realization that the area may be complexly three-dimensional and suitable precautions must be taken. Three-dimensional geometries exist at all scales.

Based on the simple 2-D model studies and the decisions about 3-D anomaly shapes, a few conclusions may be made about future interpretation.

1) The popular habit of assembling a series of one-dimensional inversions at single sites to form a picture of the two-dimensional electric structure may be grossly inadequate. The presence of 3-D bodies, with their associated electric field discontinuities, may give rise to pseudosections that cannot be fit by any two-dimensional model. The range of observed apparent and interpreted resistivities may greatly exceed the range of true resistivities. The pseudosections presented herein are examples.

2) Near surface conductivity structures may impose a strong bias upon the effects of deeper structures. Anomalies for surficial 3-D bodies do not attenuate with lower frequencies (see Fig. 18) and may superimpose themselves upon nearby soundings to yield false intrinsic resistivities and false depths to interfaces. The TM mode of excitation is very insensitive to the depth extent of conductive prisms and one may generalize to say that prisms of finite-strike length have the same problem. It follows that MT

soundings within said bodies may provide no meaningful information about deeper structures.

3) Mode identification is a risky process. Three-dimensional geometries with more than one plane of symmetry will produce varied directions of estimated electrical strike depending on the location of the observer. Noise may sometimes be the determining factor. For the Roosevelt Hot Springs area, it is felt that the elongate resistive structure of the Mineral Mts. in the conductive valley fill results in the consistent mode identification at the twenty-five sites.

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APPENDIX

Corrections to previously released data for MT stations RSU-22 and 23.

Appendix

When the data for the twenty-five magnetotelluric soundings were originally made public, errors in the continuous inversion results existed for stations RSU-22 and 23. The original true resistivities were too low by a factor of ten while the corresponding depths to a particular resistivity value were too shallow by a factor of about three. The following is a tabulation of the corrected depth to an intrinsic resistivity value (d) and the corresponding true resistivity value (ρ_t).

RSU-22

d (m)	ρt (Ω -m)
732	573.4
805	952.6
921	1318
1050	1424
1195	1275
1350	1312
1530	1568
1745	1567
1960	1300
2195	1217
2450	1315
2745	1326
3060	1189
3385	971.7
3710	770.6
4030	772.2
4410	952.6
4855	928.8
5305	693.3
5740	599.4
6215	625.1
6715	545.2
7200	390.5
7670	349.8
8180	390.0
8755	350.3
9310	248.8
9820	208.3
10370	224.2
11020	246.2
11770	256.1
12580	231.3
13400	182.2
14190	149.0
14960	136.6
15870	148.6
16910	165.7
18080	118
18860	46
19290	15
19460	9
19610	2
19870	1

RSU-23

d (m)	ρt (Ω -m)
2000	2203
2250	2034
2545	1666
2120	1278
3105	1125
3410	1160
3745	1243
4130	1299
4545	1117
4945	802.4
5325	657.7
5720	648.9
6150	615.6
6590	546.5
7065	527.8
7595	556.8
8180	550.4
8820	498.7
9460	538.8
10130	380.0
10800	327.6
11460	285.4
12150	263.6
12900	251.9
13660	210.8
14380	145.2
14940	80.1
15310	36.1
15670	40.3
16150	71.1
16840	66.5
17380	33
17740	16
17970	10
18140	4
19590	2

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