PN-AEK-976
ISN 75316

FINAL REPORT

GEOTHERMAL RESOURCES PROJECT-STAGE ONE

PART 6

ELECTRICAL GEOPHYSICAL SURVEYS

Prepared for

GOVERNMENT OF NICARAGUA

Ministry of Economy, Industry and Commerce

By

George Keller and Norman Harthill

GROUP SEVEN

For

TEXAS INSTRUMENTS INCORPORATED
Services Group

December 1970

A.I.D.
Reference Center
Room 1656 NS

PREFACE

This Final Report on STAGE ONE of the Nicaraguan GEOTHERMAL RESOURCES PROJECT is submitted to the Government of Nicaragua by TEXAS INSTRUMENTS INCORPORATED in Spanish and English versions.

The report is the work of several authors and consists of ten parts, or chapters, each of which is bound separately, as follows:

Part 1 - PROJECT SUMMARY, by D. E. Heilner and L. T. Braun

Part 2 - REGIONAL GEOLOGY: Thermal Manifestations of Western Nicaragua, by John B. Thigpen

Part 3 - SURFACE GEOLOGY: San Jacinto-Tisate-Najo Area, by John B. Thigpen

Part 4 - SURFACE GEOLOGY: South Volcan Momotombo Fumaroles, by John B. Thigpen

Part 5 - GRAVITY AND MAGNETIC SURVEYS, by Mario Mazzolini

Part 6 - ELECTRICAL GEOPHYSICAL SURVEYS in Relation to the Location of Geothermal Power Resources in Northwestern Nicaragua, by George Keller and Norman Harthill

Part 7 - GEOCHEMISTRY of the Nicaraguan Geothermal Project Area, by R. Bennett

Part 8 - TEMPERATURE GRADIENT WELLS at San Jacinto and South Volcan Momotombo, by R. Bennett

Part 9 - DEEP BOREHOLE TEST at the South Volcan Momotombo Fumarole Area, by John B. Thigpen

Part 10 - CONCLUSIONS AND RECOMMENDATIONS, by Texas Instruments Staff and Consultants

CONTENTS

	Page
Abstract	
Introduction	1
Resistivity Profiling	2
Resistivity Depth Sounding	4
Dipole Mapping Surveys	6
Extended Depth Sounding	13
Electromagnetic Soundings	16
Audio-Magneto-Telluric Surveys	23

Table 1. Interpretation of Schlumberger resistivity soundings

Table 2. Apparent resistivities for dipole mapping surveys

Table G3. Summary of interpretations of electromagnetic soundings

ILLUSTRATIONS
(folded in pocket)

FIGURE

G1 Apparent resistivities measured with a 150 meter Schlumberger array in the San Jacinto-Tisate area
G2 Examples of depth soundings from the San Jacinto-Tisate area
G3 Summary of depth-sounding interpretations in the San Jacinto-Tisate area
G4 Interpretations of resistivity soundings along the Mina El Limon road
G5 Summary of depth-sounding interpretations in vicinity of V. Momotombo
G6 General scheme of a dipole mapping survey
G7 Map 1 - Dipole resistivities measured from Dipole SJ1
G8 Map 2 - Dipole resistivities measured from Dipole SJ2
G9 Dipole mapping survey from dipole source M1
G10 Dipole mapping survey about source dipole M2
G11 Extended resistivity-depth soundings
G12 Components of system used in electromagnetic sounding
G13 Transient voltage recorded as electromagnetic sounding LI/5
G14 Locations of electromagnetic soundings in Northwestern Nicaragua
G15 Electromagnetic sounding SJ2/2
G16 Curves for electromagnetic sounding-lower layer more resistant
G17 Curves for electromagnetic sounding-lower layer more conductive
G18 Electromagnetic soundings in the San Jacinto-Tisate area
G19 Electromagnetic soundings near V. Momotombo
G20 Profile of electromagnetic sounding results
G21 Audio-magneto-telluric surveying system
G22 Skin-depth chart
G23 AMT profile, Momotombo shoreline of Lago de Managua
G24 AMT profile, Ocoton-Las Grietas

ABSTRACT

Four types of electrical geophysical surveys were conducted in northwestern Nicaragua to assist in the location of areas suitable for the development of geothermal power:

1. Resistivity profiling delineated the extent of surficial ground saturated with hot water in the San Jacinto-Tisate area.

2. Resistivity depth soundings determined the depth of hot-water-saturated rock at San Jacinto-Tisate, along the road to Mina Limon and along the shoreline of Lake Managua near Volcan Momotombo.

3. Dipole resistivity mapping delineated the region of conductive rock associated with the occurrence of hot water in greater detail and to greater depths.

4. Electromagnetic sounding provided more definitive information about the depth to which porous, hot-water-saturated rocks probably occurs in the geothermal systems at San Jacinto-Tisate and South Volcan Momotombo.

The electromagnetic survey was extended to obtain information about the regional setting of the geothermal activity, along a traverse from El Sauce to the Pacific Coast near Leon.

Evaluation of the results of the electrical geophysical surveys is presented in Part 10 of the Final Report.

GROUP SEVEN

ELECTRICAL GEOPHYSICAL SURVEYS IN RELATION TO THE LOCATION OF GEOTHERMAL POWER RESOURCES IN NORTHWESTERN NICARAGUA

Introduction

Various types of electrical geophysical surveys were carried out in northwestern Nicaragua to assist in the location of areas suitable for the development of geothermal power. In the early stages of exploration, the resistivity profiling technique was used to delineate the extent of surficial ground saturated with hot water about the fumaroles and hot springs in the San Jacinto-Tisate area. This was followed by a series of resistivity depth soundings in an effort to determine the depth extent of hot-water-saturated rock beneath the surface manifestations at San Jacinto-Tisate. Additional resistivity depth soundings were made along the road to Mina Limon and along the edge of Lake Managua near Volcan Momotombo. This effort was followed in turn by the use of the dipole resistivity mapping technique for the purpose of delineating the region of conductive rock associated with the occurrence of hot water in greater detail and to even greater depths. The last major stage in electrical surveying was the use of an electromagnetic sounding method to provide more definitive information about the depth to which porous, hot-water-saturated rocks probably occurs in the geothermal systems at San Jacinto-Tisate and Volcan Momotombo. The electromagnetic survey was extended beyond the immediate vicinities of the two geothermal systems to obtain information about the

regional setting of the geothermal activity. Soundings were made generally about a traverse extending from the vicinity of El Sauce to the Pacific coast near Leon. One additional electrical surveying technique, the audio-frequency magneto-telluric method, was used briefly at two locations to evaluate its merits in comparison with the resistivity sounding method for surveying the extent of shallow conductive ground associated with geothermal systems.

The following sections describe each of these techniques and the results obtained. The evaluation of these results in terms of development of geothermal power in northwestern Nicaragua is contained in a later chapter of this report.

Resistivity profiling

Reasons for considering the thermal manifestations about the village of San Jacinto as the first target in this exploration program have been described elsewhere in this report. It is well known that rock saturated with hot water is considerably more conductive than the same rock at normal temperature, so that the measurement of electrical resistivity is a logical approach to exploring for hot-water-saturated rocks. The first step in the survey in the San Jacinto-Tisate area was the use of the resistivity profiling method along trails, to provide information on the variations of resistivity within the first few hundred meters of depth from the surface.

In resistivity profiling, a fixed electrode array is used. Measurements are made as the array is moved along a profile or

traverse, and computed values for apparent resistivity are then plotted on a map or profile at the array location. In the work at San Jacinto, the Schlumberger array was used in the profiling; that is, the electrode array consisted of four colinear electrodes placed along the profile direction. The two outer electrodes, separated by a distance of 300 meters, were used as current electrodes, while the pair of electrodes at the center of the array, separated by 20 meters, were used to detect the voltage drop caused by the current. With the Schlumberger array, the depth to which resistivity is said to be measured is one-half of the current electrode separation, or 150 meters in this survey. However, any statement of the depth of penetration for an electrode array must be considered to be only a rough guide, until a detailed interpretation of the data verifies that such a penetration is actually achieved.

Apparent resistivities were computed from the measurements, using the standard formula for the Schlumberger array, and the resulting numbers are compiled on the base map of the San Jacinto Tisate area in Figure G1.

The range of values for apparent resistivity on Figure G1 is quite large, from less than 1 ohm-meter to more than 10,000 ohm-meters. The lowest values are observed immediately about the surficial geothermal manifestations, while generally low resistivities are found in a region trending north-south from the fumarole and hervidero at San Jacinto to the hervidero at Hda. Santa Clara, and then westward to the hervidero at Najo. In general, however, the shallow Schlumberger profiling does not

appear to provide information beyond that which can be obtained by a visual inspection of hot springs, altered rock areas and other manifestations of geothermal activity at the surface. As a consequence, the profiling method was not used in other areas where geothermal prospects were to be evaluated.

Resistivity Depth Sounding

The second stage in electrical surveying was the use of resistivity depth soundings to determine the resistivity beneath the highly variable surface materials mapped with the profiling method. The Schlumberger array was used for the resistivity depth soundings, but in this case, the spacing between the current electrodes was increased gradually about the midpoint of a sounding. The basis for calling such a set of measurements a depth sounding is that as the current electrodes are moved to greater separations, the current from them flows to greater depths, and so, the voltage measured at the receiving electrodes at the center of the array is affected by the resistivity at progressively greater depths. Measurements of voltage and current are converted to apparent resistivity values for each spacing, and a plot of apparent resistivity as a function of current electrode separation, as shown by the examples in Figure G2, is termed a resistivity sounding curve.

In interpretation, such plots are compared with families of curves previously computed for simple models, such as a sequence of several horizontal layers. Approximate values for the resistivities and thicknesses of layers are estimated by noting which

of the model curves matches most closely with the field data. The interpretation is then refined by computing new model curves iteratively on a computer, adjusting the properties of each layer by a small amount each time until the best possible agreement between the field data and the final model curve is obtained. The results obtained with this interpretation are listed in Table 1.

Thirty-one of the soundings were made generally along the north-south trend of low resistivities found with the earlier profiling survey at the San Jacinto-Tisate area. The interpreted resistivity vs depth profiles are plotted on the San Jacinto-Tisate base map in Figure G2. It should be noted that the coordinates for these plots are the logarithms of resistivities and depths, a method of plotting which emphasizes the decreasing resolution which is obtained with the resistivity sounding method as greater depths are reached. It is obvious from these interpretations that the high resistivity layers present within the first few tens of meters of depth are not individually continuous for significant distances. Resistivities below ten ohm-meters, which are believed to be indicative of a geothermal reservoir, are found on relatively few of the soundings, mainly those immediately around and south of the hervidero in the village of San Jacinto. In a number of cases, the layer with resistivity less than 10 ohm-meters lies beneath 100 to 200 meters of material having considerably higher resistivity.

Twelve soundings were carried out on the road to, and in the vicinity of Mina El Limon. The resistivities determined

from these soundings are shown plotted as vertical sections on Figure G4. The results obtained in the vicinity of the mine show high values of resistivity, which are probably not of interest in terms of geothermal activity. However, soundings 34 and 35 show a considerable thickness of rock with a resistivity of approximately 4 ohm-meters, and sounding 30 shows a resistivity of approximately 7 ohm-meters beneath the surface cover. This area might be of some interest in further exploration.

Eight soundings were completed along the coast of Lake Managua on the south slope of Volcan Momotombo, and the results of interpretation are compiled on the map in Figure G5. Some very low resistivities, less than one ohm-meter, were found in the areas where surface geothermal activity is most abundant. On the other hand, quite high resistivities were found in the tree-covered areas along the shoreline to the west of the hervideros.

Dipole Mapping Surveys

In a dipole mapping survey, as the expression is used here, a large amount of electric current is caused to flow in the earth between two electrode contacts situated within a kilometer or two of the target area. As the current flows through the ground, its flow pattern will be governed in detail by variations in resistivity in the ground to a depth comparable to the offset distance at which the measurements are being made. Inasmuch as the dipole source is left fixed as many measurements of electric field are made about it, any electrical peculiarities about the

source will affect all the measurements in a similar way, and the variation in electric field from observation point to observation point will be indicative of the electrical structure in the vicinity of the measuring point. Having the source fixed in location for many measurements simplifies greatly the patterns of resistivity which may be mapped, in comparison with the profiling and resistivity sounding techniques described in the preceding sections.

The general scheme of a dipole mapping survey is indicated on Figure G6. The source dipole is several kilometers long, with contact to the ground normally being made with 40 to 80 feet of pipe standing in a drill hole or water well. Power was provided to the source dipole from a 40 KVA motor-generator set. The 220-volt 60Hz three-phase output of the generator was stepped up to 600 or 800 volts with a transformer, rectified to form direct current, and alternately switched to cause current to flow first one way and then the other in the line connecting the source electrodes. The periodicity of reversal of current flow was selected to be 10 or 20 seconds, so that the frequencies contained in the waveform of the current to the source would be sufficiently low to avoid problems with electromagnetic attenuation of the current field and lack of penetration caused by skin-depth effects. The amount of current was monitored with a meter, and on occasion, it was recorded graphically. Normally, currents of 10 to 20 amperes were used, so that the amplitude of a current step on reversal was 20 to 40 amperes.

In mapping the current field from such a source dipole, voltages between electrode pairs were measured at many points about the source dipole. Inasmuch as the direction of current flow at a measurement site is somewhat unpredictable, the total voltage drop is measured using two electrode pairs oriented at right angles to one another, and adding the voltage drops vectorially. The electric field is merely the voltage drop per meter of separation between the measuring electrodes. Measurements were made with receiving electrode separations ranging from 50 meters to 300 meters, the longer separations being used in areas where the signal strength was low. The receiver equipment was a simple DC voltmeter, on which the deflection as the current flow reversed was measured. At its maximum sensitivity, deflections as small as 5 to 10 microvolts could be detected on the voltmeter. Readings of less than 100 microvolts were rarely taken, to assure that the data were meaningful.

Electric fields were measured at distances from the source dipole ranging to 5 kilometers and more. Some measurements were made close to the ends of the source dipoles, but the principal advantage in using the dipole mapping technique lies in the capacity to make measurements at distances of several kilometers from the source. At these distances, the current from the source penetrates to considerable depths, and the resultant electric field measurements characterize the properties of the rocks about the measurement sites to depths of the order of one or two kilometers, typically.

The measurements made in a dipole mapping survey may be converted to apparent resistivity values using several different formulas. A parallel-field apparent resistivity may be computed using only the component of electric field intensity measured in the direction parallel to the source dipole (the formulas for these calculations are listed on Figure G6). A perpendicular-field apparent resistivity may be computed using only the component of electric field intensity measured in the direction perpendicular to the source dipole. A total-field apparent resistivity may be computed using the magnitude of the electric field intensity, assuming that the direction of the total field is the same as in a uniform earth. Finally, the amount of rotation of the direction of the total electric field from the direction it should have in a uniform earth may be computed.

It should be recalled that an apparent resistivity is the actual resistivity of the earth only if the earth is completely uniform. When the earth is non-uniform, each of the apparent resistivity values described above may be affected in a different way, and so, each may be useful in studying different types of earth structure. For the kinds of resistivity distributions observed about geothermal systems, the more meaningful apparent resistivity values appear to be those computed from the magnitude of the electric field, because these values come closer to the actual resistivity at the measurement site when there are strong lateral changes in resistivity than do the parallel-field and perpendicular-field values. These latter apparent resistivities are useful in accentuating variations in an area where the actual

resistivity is relatively uniform.

Four dipole mapping surveys were carried out, two in the San Jacinto-Tisate area, and two in the Volcan Momotombo area. The San Jacinto-Tisate area was mapped using the two source dipoles SJ1 and SJ2 as shown on Figures G7 and G8. Dipole SJ1 stretched to the east of San Jacinto along Highway 26 for a distance of two kilometers while dipole SJ2 stretched north from the junction of the Mina El Limon road with Highway 26 for a distance of 2.6 kilometers. The values for the various apparent resistivities from these sources are listed in Table 2.

Measurements were made at some 200 locations in the San Jacinto-Tisate area, using dipole SJ1 as a source. The locations and the computed total-field apparent resistivities are shown on the map in Figure G7, which was prepared using the Geophoto Services, Inc. 1:10 000 photo mosaic of the San Jacinto area as a base. Perhaps the most striking feature of the dipole maps is the existence of areas of quite low apparent resistivity, in contrast to the very limited areas of low resistivity mapped with the profiling and Schlumberger sounding techniques. The five ohm-meter contour, which defines an elliptical area about three kilometers from north to south by one and one-half kilometer from east to west lying generally to the north and west of the village of San Jacinto, most probably encloses the focus of thermal activity in the region. The 10 ohm-meter contour encloses and tends to parallel the five ohm-meter contour, but is extended to the north by northeast direction, forming a distinct linear trend. The Tisate hervidero lies on the western boundary of the

trend. North of Highway 26, the apparent resistivity values increase to the to the east and west of this trend, reaching values of 20 ohm-meters to the west, and values over 100 ohm-meters to the east. The high values to the east probably represent a steep-sided volume of electrically resistant rock, possibly an intrusion. Although the dominant linear trend is the north-south feature, there are obvious subsidiary east-west trends in the resistivity patterns to the south of Highway 26. Because the apparent resistivities are less than 2.5 ohm-meters here, these trends may represent fault-controlled elongations of the main thermal area at San Jacinto.

It cannot be definitely established from the resistivity patterns shown in Figure G7 that the north-south trend of low resistivities terminates at the north edge of the mapped area. The gradual increase in apparent resistivity northward along the trend may be caused by the presence of a resistant basement at a depth of about one kilometer such that measurements made at distances greater than several kilometers incorporate a significant effect from such a basment. Moreover, the distance from the source is too great to permit measurements beyond the 10 ohm-meter contour to the north. In view of this, it was deemed necessary to make measurements in this area using a second dipole, SJ2, situated more advantageously for measurements in this area. The resistivity values computed from these measurements are tabulated on the map in Figure G8, and it may be seen that the area mapped has resistivities considerably above those found in the main thermal areas.

For the dipole mapping surveys on the south slopes of Volcan Momotombo, two source dipoles were used, M1 and M2, as indicated on the maps in Figures G9 and G10. Dipole source M2, some 2000 meters long, was located along the shore of Lake Managua between Puerto Momotombo and San Cayetano such that the distance to the geothermal activity at Punta Las Salinitas on the south slope of Volcan Momotombo was about six kilometers. Because of the extremely low resistivities in this area, signal levels were not high enough to permit accurate detection beyond about four kilometers from the source dipole. Source dipole M1, which was 2650 meters long, was located closer to the geothermal area with one electrode being positioned at Punta Las Salinitas. Because of this, the measurements made in the hervidero at Punta Las Salinitas were made too close to the source to represent the electrical character of the ground to significant depths, but this source location did permit measurements to be made in the thermal areas higher on the slopes of Volcan Momotombo.

The contours of total-field apparent resistivity shown in Figures G9 and G10 are rather complicated in character, and show considerably lower values than were observed at San Jacinto. There appear to be two east-west trends to the regions with low apparent resistivity, one roughly paralleling the coast of Lake Managua, and intersecting it near Punta Las Salinitas, and the other, parallel to the first, lying about one and one-half kilometers up the slope of Volcan Momotombo from the lake shore. The lake-side boundary of the first trend is quite sharp, with

apparent resistivity increasing by a factor of ten or more in a distance of a few hundred meters along the shoreline. The northern limit of the upslope trend is not well established, primarily because the northern edge must lie under the upper reaches of Volcan Momotombo, which are relatively inaccessible.

It is important to point out that no indication of closure of the low resistivity contours, which most probably define the limits of thermal activity, was obtained. A considerable effort was made to obtain electric field measurements in Lake Managua near Punta Las Salinitas, with little or no success. The difficulty was not technical in nature, but logistic. What few measurements that were attempted suggest that the low resistivity zone at Punta Las Salinitas must extend under Lake Managua for a significant distance -- no measurable electric field could be detected several hundred meters offshore, indicating a very low apparent resistivity.

Extended Depth Sounding

The data obtained in profiling, shallow Schlumberger resistivity soundings and dipole mapping surveys may be combined to provide an extended resistivity depth sounding. This was done with the data in an attempt to determine the depth extent of the subsurface reservoirs feeding the surface expressions of geothermal activity at San Jacinto and Volcan Momotombo.

The primary difficulty in compiling the various forms of apparent resistivity on a single resistivity vs spacing plot is in choosing a comparable measure of spacing for the dipole data

and the Schlumberger data. The convention which was used here was as follows:

1. For measurements made with a Schlumberger array -- that is, the profiling data and the shallow resistivity sounding data -- the spacing was taken to be half the separation between current electrodes, as is conventional.

2. For dipole measurements made at locations lying more than 15° away from either the equatorial or polar axis of the source dipole, the perpendicular-field apparent resistivity was used, with the spacing taken to be the distance to the nearer end of the source dipole.

3. For dipole measurements made at locations lying within 15° of either the equatorial or polar axis of the source dipole, the total-field apparent resistivity was used, with the spacing taken to be the distance to the nearer end of the source dipole.

The data from the San Jacinto-Tisate area were divided into two groups, one consisting of measurements made within the area of low resistivity and the other for measurements made outside this area. The line dividing these two regions is shown on the map in Figure G7. The purpose of this procedure was to reduce the problem of confusing the effects of lateral changes in resistivity with the effects of vertical changes in resistivity in the interpretation of the composite depth sounding curve.

Three extended depth sounding curves were prepared, and the results are shown in Figure G11. The individual values for apparent resistivity are not plotted, but rather, histograms showing the distributions of apparent resistivity values for

narrow ranges of spacing are given. This form of presentation permits a smooth curve to be drawn through the data representing a likely average resistivity sounding curve.

The two extended sounding curves for the San Jacinto Tisate area both show a relatively high near-surface resistivity, probably extending to a depth of 100 meters over most of the area. Beneath this, the resistivity of the rock decreases to a few tens of ohm-meters for the areas not within the region of thermal activity. Within the thermal area, the resistivity decreases to 2 to 3 ohm-meters for spacings of 1.0 to 1.5 kilometers, and then increases towards values of a few tens of ohm-meters at greater spacings. This behavior might be interpreted as indicating the existence of basement at about 1.0 to 1.5 kilometers depth beneath the thermal areas.

The data used in compiling the extended sounding curve for the Volcan Momotombo area were not subdivided in the same manner, because so few measurements were made outside of the low resistivity region. Rather, a few of the measurements along the shore of Lake Managua were deleted from the compilation because they are the only ones obviously outside the thermal areas. The resulting extended sounding curve shows high resistivity in the near surface rocks, followed by low resistivities apparently extending to great depths. There is no assured indication of resistant basement rocks, even with spacings of two kilometers.

Electromagnetic Soundings

In electromagnetic sounding, current flow is generated in the earth by creating a time-varying magnetic field. The amount of current flow so generated depends in part on the conductivity of the earth. A series of such electromagnetic soundings was carried out as part of the exploration program for geothermal systems in northwestern Nicaragua. These soundings were located within the thermal areas at San Jacinto and Volcan Momotombo, for the purpose of determining the depth extent of the geothermal reservoirs at these locations, and along a traverse line extending along Highway 26 from the intersection of the road to El Sauce to the area south of Leon. These additional soundings outside the area of main thermal activity were intended to provide information on the regional setting of the geothermal systems.

The essential components of the system used in electromagnetic sounding are shown in Figure G12. The electromagnetic field was generated by driving a current step through a grounded length of wire, using the same source equipment as was used in the dipole mapping surveys. The vertical component of magnetic induction was recorded at a measurement site using an induction loop as a detector. The induction loop consisted of one or two 500-meter lengths of 26-conductor wire laid on the ground in the form of a square, with the conductors connected in series to form a continuous loop. The transient voltage induced in this loop by the magnetic induction as the current reversed direction

in the grounded wire source was recorded graphically. An example of a record of transient magnetic induction is shown in Figure G13.

Electromagnetic soundings were recorded at 36 locations, as indicated on the map in Figure G14. These 36 receiver locations were distributed about 6 electromagnetic source locations, of which 4 were the same as those used for dipole mapping surveys. Two additional source locations, one west of Leon and one at the intersection of the El Sauce road with Highway 26, were also used.

The transient electromagnetic coupling at a receiver site, such as the data shown in the example in Figure G13, is interpreted in a manner analogous to that used in interpreting the Schlumberger sounding data. The field data are first converted to values of apparent resistivity, and then these data are compared with theoretically derived model curves for a series of layers with differing resistivity contrasts to determine what the probable resistivity layering beneath the receiver site is. However, the procedures used in doing this are less straightforward than in the case of Schlumberger sounding curves.

The signals that are recorded in the field are not precisely those required for comparison with theoretical curves. The transient coupling as recorded is distorted by the response characteristics of the recording equipment, with the distortion being most severe in the early part of the coupling. In addition to this problem, extraneous noise added to the recorded signals makes recognition of the signals with the desired accuracy

difficult. Four stages were required in processing the field data before they were ready for comparison with theoretical curves:

1. Synchronous stacking, to reduce the level of random noise in relation to signal amplitude;

2. Deconvolution, to minimize the effect of distortion by the recording equipment;

3. Smoothing with an exponentially time-varying filter to further reduce uncorrelated noise; and

4. Conversion to values of apparent resistivity, using the formulas shown in Figure G12.

The synchronous stacking procedure was not used with all the recorded signals, but only with those in which the ratio of signal amplitude to noise amplitude was not good. As the initial step, from 10 to 20 similar signals were selected from a record and converted to digital form for input to the computer. These signals were added synchronously, with values which were abnormal being discarded from the stacking process on a statistical basis. With the stacking of a given number of signals, n, the random noise level should be reduced by a factor $(n-1)^{\frac{1}{2}}$, or by factors ranging from 3 to 5 for the numbers of signals used here.

In accomplishing the deconvolution of the equipment response from the field data, the spectral response of the recording equipment was first computed from the step response. The amplitude and phase spectrum of a stacked signal or a single low-noise signal was then computed and this data spectrum was divided by the spectrum for the equipment response. The compensated data

spectrum was then transformed back into the time domain.

The non-linear filtering scheme applied to the data was based on the property of transient coupling curves that they are shape-invariant when plotted to logarithmic coordinates. When linearly sampled field data are plotted to logarithmic coordinates, the early part of the transient coupling appears to be sparsely sampled, while the late part appears to be densely sampled. The remaining noise in the data appears to increase in frequency for progressively later parts of the transient, when data are plotted to logarithmic coordinates. Because the noise is relatively larger in comparison with signal strength during the later part of the transient, this provides a basis for separating the signal from the noise during the late part of the transient without undoing the effects of deconvolution on the early part. In filtering, the field data were interpolated at equal intervals after conversion to a logarithmic scale. The interpolated data set was smoothed by performing a moving average. For the parameters chosen for this smoothing filter, the effect is to average the last six points of the original data set, and to interpolate additional points between the first few of the original data set. After smoothing, the data are converted back to antilogs.

These processed data are then converted to apparent resistivity values. Because electromagnetic theory is so complex, there is no simple formula which will convert the recorded voltage directly to resistivity, even if the earth is uniform. Instead, one must be satisfied with asymptotic formulas which

convert the measurements to the proper resistivity for a uniform earth either for the very early part of the transient coupling or for the late part only. These formulas are listed in Figure G12. The apparent resistivity computed with the early-time formula should then represent the properties of the upper part of a sequence of layers, while the apparent resistivity computed with the late-time formula should represent the properties of the lower part of the sequence. A set of apparent resistivities computed with these formulas is shown in the example in Figure G15.

The theoretical curves used in interpreting field data such as those shown in Figure G15 must be presented in exactly the same format as the field data. Two families of theoretical curves meeting this requirement are shown in Figures G16 and G17. The first of these sets of curves, in Figure G16, is for an earth with two layers, with the lower layer being more resistant than the upper layer. The horizontal scale is the time following the beginning of the transient, normalized in terms of the properties of the upper layer. The vertical scale is apparent resistivity, normalized to the resistivity of the first layer, computed from the early-time formula for the set of curves to the left and from the late-time formula for the set of curves to the right. Each curve represents a single value for the ratio of the thickness of the first layer to the distance between the source and the receiver. The curves in Figure G17 are exactly similar, except that the underlying layer is more conductive than the upper layer.

Several generalizations about the behavior of apparent resistivity plots may be made from these two examples of families of theoretical curves. If resistivity increases at depth, the apparent resistivity increases with increasing time for a while, with the amount of rise being greater when the surface layer is thin with respect to the offset distance between the source and receiver. If resistivity decreases with depth, the apparent resistivity begins to decrease even at early times. It should also be noted that theoretically there is no limit to the depth at which an interface may be detected, if the transient coupling can be recorded at sufficiently late times. Realistically, limitations in the accuracy of recording make it impossible to detect boundaries beyond a depth equal to about half the offset distance between the source and the receiver.

The interpretations which were made of the electromagnetic sounding data by comparing the field measurements of voltages with theoretical curves such as those in Figures G16 and G17 are listed in Table G3, and some of them are shown in geographical perspective in Figures G18, G19 and G20. All but three of the soundings were interpreted in terms of more resistive rock lying beneath a surface layer of low resistivity; the three soundings made in the Volcan Momotombo thermal area all show more conductive rock to lie beneath a surface layer, which itself has a low resistivity.

The electromagnetic sounding locations in the immediate vicinity of the San Jacinto- Tisate thermal activity are indicated on Figure G18, along with a summary of the interpretations. The

resistivity of the surface rocks is seen as 1.5 to 3.0 ohm-meters, with the electromagnetic soundings, with more resistant rock being present at a depth of 500 to 600 meters under much of the thermal area. The resistivities seen with an electromagnetic sounding method are normally somewhat lower than those measured with direct-current sounding, because the average resistivity measured with induction currents is less sensitive to the presence of resistant beds in the section, such as basalt flows, than is the average resistivity seen with a direct current method.

The soundings at Volcan Momotombo are quite different in character than any of the others. The locations and interpretations are shown on Figure G19. These data indicate that there is an extensive zone or layer with a resistivity near 0.5 ohm-meters lying at a depth of about one kilometer beneath the surveyed area. The electromagnetic soundings did not reach deep enough to detect more resistant rock beneath this zone.

Most of the electromagnetic soundings were made outside the two thermal areas, and were intended to provide information on the regional character of the rocks in which the thermal systems are present. A cross section, running along Highway 26 from near the coast at Poneloya to the northeastern boundary of the Nicaraguan depression is shown in Figure G20. These data indicate that the thickness of conductive rocks at the surface is fairly uniform over this entire section, with the thickness ranging from about 300 meters at either end of the line, to over 600 meters in the San Jacinto area. The resistivities are uniformly low in the surface layer, from 1.1 to 6 ohm-meters.

Audio-Magneto-Telluric Surveys

The electromagnetic coupling measurements described in the preceding section are of such large scale that they provide no resolution in measuring the electrical properties of rocks within the first few hundred meters of the earth's surface. The Schlumberger sounding method, described earlier, is used for this purpose, but the existence of resistive rocks at the surface makes interpretation of such soundings uncertain to some degree. An induction method for measuring resistivity within a few hundred meters of the surface would be helpful in place of the Schlumberger method because induction methods are insensitive to a resistive surface cover. A brief field trial was given to one electromagnetic method, the "audio-magneto-telluric" method, to evaluate how it might be used in further exploration of the type described in this report.

The audio-frequency magneto-telluric method is identical in theory with the better known magneto-telluric method, and the reasons for distinguishing the two methods are practical rather than theoretical. In a magneto-telluric determination of earth resistivity, one measures the simultaneous magnitudes of orthogonal electric and magnetic field components, normally present as electrical noise. By assuming that these components belong to a planar electromagnetic wave propagating vertically into the earth, the earth resistivity can be computed quite simply. The essential elements of the field system and the formula for computing resistivity are shown in Figure G21.

In the audio-magneto-telluric method, measurements are made at a sequence of discrete frequencies, ranging from 20 Hz to to 850 Hz in the surveys to be described here. For a specific frequency, the resistivity so determined is an average for rocks to a depth of about one skin depth. The skin depth of an electromagnetic wave is determined from the frequency and the resistivity of the rock through which it is passing. Skin depth may be determined from a chart such as the on shown in Figure G22.

When magneto-telluric measurements are made at audio frequencies, the source of the energy is usually either current flowing in power mains or energy arriving from distant lightning strokes. The wave-lengths involved range from a few tens of meters to some hundreds of meters when measured in the earth.

The instrumentation used in the surveys described here was simple. The electric field component was detected using copper electrodes driven about six inches into the soil, with a separation between them of 20 meters. The separation of the electrodes was selected quite arbitrarily to provide a measurable signal level. The horizontal component of magnetic induction at right angles to the electrode line was detected with an induction coil. This coil consisted of 14,000 turns of wire wound on a permeable core with dimensions of 0.75 meters (length) by 0.125 meters (diameter). The outputs of the electrode pair and the induction coil were measured using a pair of General Radio nullmeters. These instruments are high-gain amplifiers with a variable-frequency narrow-notch pass filter, which indicate on a visual meter. In making

a measurement, the gains of the two nullmeters were set equal, the filters were set at the desired frequency, and the ratio of the outputs appearing on the meters was recorded. This was then repeated for each of the frequencies at which measurements were to be made.

Two brief surveys were made using this system, one along the shore of Lake Managua near Volcan Momotombo, and the other along the road from Ocoton to Las Grietas, where numerous warm springs are noted. The data from each of these surveys are presented in the form of equivalent sections in Figures G23 and G24. In these equivalent sections, frequency is plotted as the vertical scale, rather than depth; otherwise, the sections are similar to a normal section plot. The relationship between frequency and depth of penetration is given in the skin-depth chart in Figure G22. The observed values of apparent resistivity, computed with the formula given on Figure G21, are contoured.

Locations for the measurements made near Volcan Momotombo are indicated on Figure G9, so that the resistivities may be compared with values obtained in the dipole mapping and Schlumberger sounding surveys.

Table 1. Interpretations of Schlumberger resistivity soundings

Sounding number	Layer number+	Thickness (meters)	Resistivity (ohm-meters)	Error measure++
1	1	6.	12.0	255.
	2	>400	740.	
2	1	2.6	9.0	144.
	2	24.	29.5	
	3	>300	0.94	
3	1	1.4	7.5	196.
	2	140.	7.9	
	3	50.	0.55	
	4	>200	55.	
4	1	10.	14.	1410.
	2	30	3.7	
	3	30	1.4	
	4	>200	90.	
5	1	9.	400.	7.4
	2	22.	5.0	
	3	40.	1.3	
	4	>200	54.	
6	1	47	20.	1520.
	2	>400	2.3	
7	1	1.2	130.	3.7
	2	40.	52.	
	3	140.	54.	
	4	>200	200.	
8	1	12.	1700.	57.
	2	25.	8.5	
	3	>200	135.	
9	1	12.	23.	1460.
	2	30.	2.7	
	3	20.	3.0	
	4	>200	60.	

+ Layers are counted from the surface down.

++ Arbitrary units. A good visual curve match provides error measures of about 2000 units.

Table 1 (Continued)

Sounding number	Layer number	Thickness (meters)	Resistivity (ohm-meters)	Error measure
11	1	9.0	8.7	11.
	2	24.	40.	
	3	>300	16.	
12	1	3.6	20	379.
	2	33.	610.	
	3	>200	12.	
13	1	10.	64.	19.
	2	77.	880.	
	3	>200	19.	
14	1	3.0	43.	12.5
	2	7.8	256	
	3	310.	94.	
15	1	2.5	15.	378
	2	2.0	85.	
	3	>280	42.	
16	1	1.2	30	11.6
	2	4.8	150.	
	3	68.	380.	
	4	>200	21.	
17	1	2.8	2500.	1.9
	2	30.	700.	
	3	>200	200.	
18	1	1.2	80.	225.
	2	2.1	410.	
	3	82.	140.	
	4	>200	85.	
19	1	6.2	25.	1040.
	2	105.	120.	
	3	>100	260.	
20	1	1.8	100.	109.
	2	8.7	59.	
	3	22.	880.	
	4	22.	150.	
	5	70.	600.	
	6	>100	60.	

Table 1 (Continued)

Sounding number	Layer number	Thickness (meters)	Resistivity (ohm-meters)	Error measure
21	1	2.4	42.	138.
	2	7.0	280.	
	3	45.	1130.	
	4	>200	8.	
22	1	3.6	20.	483.
	2	8.5	240.	
	3	73.	4.9	
	4	>200	240.	
23	1	1.9	9.0	66.
	2	2.6	13.5	
	3	250.	16.	
	4	>200	8.9	
24	1	24.	4.1	4.6
	2	69	80.	
	3	105.	21.	
	4	>200	120.	
25	1	12.	42.	1590.
	2	37.	124.	
	3	62	12.4	
	4	>200	124.	
26	1	3.2	25.	473.
	2	24.	98.	
	3	106.	110.	
	4	>200	24.	
27	1	0.7	5.0	5.6
	2	5.6	18.	
	3	44.	130.	
	4	76.	35.	
	5	>200	24.	
28	1	0.4	12.	2.1
	2	2.5	280.	
	3	7.3	39.	
	4	130.	110.	
	5	>200	14.	
29	1	0.6	13.	0.9
	2	6.2	47.	
	3	180.	49.	
	4	>200	17.	

Table 1 (Continued)

Sounding number	Layer number	Thickness (meters)	Resistivity (ohm-meters)	Error measure
30	1	9.3	20.	1260.
	2	130.	6.8	
	3	>200	160.	
31	1	0.8	5.0	4.1
	2	6.1	96.	
	3	24.	260.	
	4	>300	6.2	
32	1	5.7	9.2	13.
	2	12.	75.	
	3	41.	51.	
	4	>200	8.0	
33	1	1.1	47.	1.8
	2	3.5	18.	
	3	11.	41.	
	4	130.	10.	
	5	>200	170.	
34	1	0.5	4.0	5.0
	2	2.1	300.	
	3	6.6	73.	
	4	55.	4.6	
	5	>200	16.	
35	1	2.7	10.	185.
	2	2.2	65.	
	3	70.	8.1	
	4	120.	3.8	
	5	>200	50.	
36	1	3.4	6.0	682.
	2	4.1	15.	
	3	5.7	76.	
	4	>300	11.	
37	1	1.0	17.	8.8
	2	4.9	65.	
	3	>300	82.	
38	1	6.5	9.0	1490.
	2	7.4	21.	
	3	36	93.	
	4	>100	300.	

Table 1 (Continued)

Sounding number	Layer number	Thickness (meters)	Resistivity (ohm-meters)	Error measure
39	1	1.8	46.	199.
	2	1.7	30.	
	3	11.	120.	
	4	>200	43.	
40	1	1.2	12.	26.
	2	4.0	64.	
	3	34.	11.	
	4	>200	140.	
41	1	4.3	25.	910
	2	3.1	370.	
	3	>200	180.	
42	1	2.0	320.	78.
	2	8.2	66.	
	3	12.	2500.	
	4	>200	750.	
43	1	2.6	100.	115
	2	2.2	1080.	
	3	35.	260.	
	4	>200	120.	
44	1	2.1	100.	94.
	2	1.5	1000.	
	3	60.	210.	
	4	>200	80.	
45	1	2.9	50.	500.
	2	5.8	17.	
	3	13.	230.	
	4	>200	140.	
46	1	4.3	40.	491.
	2	12.	670.	
	3	>200	104.	
47	1	1.4	60.	98.
	2	2.7	250.	
	3	2.5	1250.	
	4	53.	100.	
	5	>200	12.	
48	1	1.7	90.	16.
	2	16.	4.1	
	3	64.	250.	
	4	>200	3.8	

Table 1 (Continued)

Sounding number	Layer number	Thickness (meters)	Resistivity (ohm-meters)	Error measure
49	1	4.2	80.	218.
	2	116.	14.	
	3	>200	11.	
M1+	1	1.3	1.5	13.
	2	38.	4.3	
	3	19.	1.4	
	4	>200	2.0	
M2	1	1.2	30.	13.
	2	8.4	20.	
	3	180.	17.	
	4	>200	9.3	
M3	1	1.0	100.	8.6
	2	4.4	2.1	
	3	>300	26.	
M4	1	1.2	24.	13.
	2	1.8	9.1	
	3	265.	19.	
	4	>200	5.8	
M5	1	1.3	7.0	28.
	2	20.	3.5	
	3	33.	0.83	
	4	>200	8.1	
M6	1	1.8	150.	22.
	2	130.	42.	
	3	>200	33.	
M7	1	1.7	40.	796
	2	30.	230.	
	3	50.	5.9	
	4	>200	0.3	
M8	1	4.0	225.	2.3
	2	225.	99.	
	3	>200	32.	

+ These soundings are located on the south flank of Volcan Momotombo.

Table 2. Apparent resistivities for dipole mapping surveys

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field rotation
		A. Source dipole SJ1		
1	12.7 ohm-meters	0 ohm-meters	3.1 ohm-m.	-1.3 radians
2	12.7	3.9	4.3	-0.3
3	9.9	7.4	7.5	0.1
4	5.2	8.6	8.3	-0.1
5	1.1	7.1	6.6	-0.3
6	9.5	8.9	9.0	0
7	17.4	9.3	12.0	0.3
8	6.2	14.1	12.0	-0.3
9	19.5	1.6	11.6	0.8
10	8.3	9.0	8.7	0
11	15.1	14.6	14.7	0
12	4.7	16.3	13.7	-0.4
13	5.1	8.0	7.2	-0.2
14	5.2	68.8	61.2	-0.4
15	-31.9	-451.	34.0	0.3
16	-16.1	-14.4	16.1	0
17	-18.1	0	18.0	-0.1
18	-36.5	0	36.1	-0.2
19	-17.9	0	17.6	-0.2
20	2.6	9.1	6.2	0.5
21	2.8	11.1	7.3	0.6
22	1.8	136	4.9	1.2
23	8.1	18.5	12.6	0.4

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field rotation
24	6.6	9.7	7.8	0.2
25	7.0	14.5	9.8	0.4
26	4.4	14.2	8.3	0.5
27	8.1	48.7	25.9	0.8
28	5.8	21.4	11.8	0.6
29	8.8	15.1	10.7	0.3
30	5.5	7.2	6.0	0.1
31	3.6	3.8	3.6	0
32	29.9	48.3	35.9	0.2
33	11.8	17.8	14.6	0.2
34	9.4	30.5	25.2	0.4
35	1.7	14.9	11.3	0.6
36	0.5	11.2	7.3	0.8
37	1.2	16.2	10.5	0.8
38	0.7	18.5	11.6	0.8
39	1.1	20.3	10.5	0.9
40	0.9	38.6	14.7	1.1
41	1.0	38.1	11.8	1.2
42	19.9	1140.	20.2	0.2
43	11.6	22.8	11.8	0.1
44	24.1	26.5	24.3	0
45	15.5	13.2	15.2	0
46	11.0	6.6	10.2	-0.2
47	10.5	16.1	12.1	0.2

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field resistivity
48	17.3	0	17.3	0
49	14.1	14.9	14.1	0
50	14.6	0.2	13.7	0.3
51	16.0	16.7	16.1	0
52	9.0	3.1	8.0	0.5
53	10.7	5.5	9.1	0.3
54	17.5	7.0	12.9	0.4
55	15.0	3.0	11.0	0.6
56	9.4	13.5	11.7	-0.2
57	9.8	2.9	8.0	0.4
58	27.0	612.	28.7	-0.3
59	-22.1	-563.	22.5	0.2
60	-45.0	-148.	45.5	0.1
61	9.3	10.5	10.0	0.1
62	13.8	24.4	19.5	0.3
63	17.7	9.3	15.2	-0.3
64	10.0	4.2	8.9	-0.3
65	13.4	5.2	11.9	-0.3
66	18.2	14.5	17.3	-0.1
67	13.7	25.4	17.8	0.3
69	9.8	8.5	9.6	-0.1
70	7.1	6.2	7.0	0
71	7.3	12.0	7.4	0.1
71A	7.4	7.8	7.5	0
72	6.4	14.7	7.1	0.3

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field rotation
73	9.2	18.3	9.6	0.2
74	8.3	5.0	7.1	-0.2
75	617.	8.0	10.5	-0.7
76	49.4	5.0	7.1	-0.7
77	15.6	5.9	7.0	-0.4
78	11.1	5.4	6.7	-0.3
79	7.2	6.0	6.6	-0.1
80	8.4	5.4	7.2	-0.2
81	11.7	8.2	9.1	-0.2
82	65.0	10.9	12.3	-0.4
84	-26.7	-14.2	16.0	0.2
85	-41.8	-15.8	23.7	0.4
86	-30.7	-12.9	19.3	0.4
87	-14.9	-8.2	11.0	0.3
88	-16.0	-13.1	14.3	0.1
89	-17.4	-5.8	11.7	0.5
90	-24.6	-17.0	21.0	0.2
91	-23.0	-8.6	16.1	0.5
92	-17.8	-9.5	15.2	0.3
93	-17.0	-16.8	17.0	0
94	-7.5	-8.5	7.7	-0.1
95	-13.6	-19.9	16.3	-0.2
96	-31.2	-38.6	32.5	-0.1
97	-16.8	-14.0	15.3	0.1
98	-17.6	-3.9	13.0	0.6

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field rotation
99	-22.1	-17.2	19.6	0.1
100	-16.5	-16.5	16.5	0
101	-21.0	-8.9	15.9	0.4
102	-16.4	-14.0	15.6	0.1
103	-19.2	-112.	22.9	-0.5
104	-23.0	-86.1	28.2	-0.4
105	-33.4	-11.3	13.6	0.4
106	-37.2	-8.1	13.9	0.7
107	-55.5	-23.7	27.7	0.3
108	-27.3	-12.7	14.7	0.3
109	-203.	-18.7	20.7	0.4
110	-41.9	-21.8	27.1	0.3
111	-17.6	-41.3	30.5	-0.4
112	-16.7	-23.7	18.9	-0.2
113	-7.4	-27.9	12.9	-0.6
114	-8.1	-33.4	11.2	-0.5
115	-4.0	-42.2	40.5	-0.3
116	22.1	30.3	23.3	-0.1
117	13.7	21.2	14.8	-0.2
118	11.3	31.1	15.0	-0.4
119	8.8	30.2	12.7	-0.5
120	5.6	7.1	5.8	-0.1
121	4.2	12.0	5.4	-0.4
122	5.2	0.5	4.3	0.5
123	5.0	5.6	5.2	0

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field rotation
124	6.7	12.9	7.4	-0.2
125	3.6	12.7	4.2	-0.4
126	3.9	3.4	3.8	0
127	0.9	11.1	2.9	1.0
128	-4.4	-0.9	4.1	-0.3
129	-11.9	-3.7	9.9	0.4
130	-8.3	-3.6	7.8	0.2
131	-7.3	-8.2	7.3	0
132	-9.1	-4.6	9.0	0.1
133	-11.8	-3.8	11.7	0.1
134	-13.9	-119.	14.9	-0.3
135	9.8	6.4	9.6	-0.1
136	8.1	5.1	7.9	-0.1
137	8.1	14.4	8.7	0.2
138	6.3	3.2	5.6	-0.3
139	5.0	7.0	6.3	0.1
140	20.2	9.6	10.8	-0.3
141	4.7	18.6	8.0	0.6
142	8.4	2.4	6.4	-0.5
143	-11.8	0	12.7	0.4
144	-6.9	0	7.4	0.4
145	3.8	11.3	3.8	0.1
146	4.2	14.0	4.5	-0.3
147	13.8	6.4	13.6	0.1
148	2.8	2.8	2.8	0

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field rotation
149	4.3	2.6	4.3	-0.1
150	7.0	4.5	5.9	0.2
151	13.0	1.6	6.0	-0.9
152	15.6	7.4	8.1	-0.3
153	25.8	0	25.8	0
154	7.7	0	7.7	0
155	1.5	0	1.5	0
156	-22.1	-251.	24.3	-0.4
157	-43.6	-50.8	44.0	0
158	19.8	4.2	6.6	0.6
159	1.0	6.0	6.0	0.1
160	0	1.8	1.8	0.2
161	0	3.0	2.7	0.5
162	0.7	13.5	10.6	0.6
163	1.0	4.6	3.3	0.6
164	0.8	0.8	0.8	0
165	1.1	8.9	8.1	0.4
166	2.6	10.7	10.2	0.2
167	7.7	13.1	11.1	-0.2
168	35.4	8.8	9.0	-0.2
169	49.3	9.5	10.4	0.3
170	24.9	10.4	11.8	0.3
171	2.3	2.3	2.3	0
172	25.1	11.3	12.5	0.3
173	15.8	7.6	8.2	0.2

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	electric-field rotation
174	13.2	11.8	11.4	-0.2
175	12.2	5.4	6.6	0.3
176	-38.0	-42.0	42.0	0
177	-61.7	-95.7	95.5	0
178	-93.2	-116.	115.	0
179	-59.2	-63.0	61.8	0
180	2.6	0.7	2.2	0.4
181	10.3	1.2	3.6	0.9
182	12.5	6.7	6.8	0.1
183	10.2	12.6	12.3	-0.1
184	63.7	17.2	19.3	0.3
185	13.4	11.5	11.5	0
186	11.1	6.0	9.6	-0.3
187	10.2	11.0	10.4	0
188	10.1	2.6	8.8	-0.4
189	4.2	6.1	3.7	-0.4
190	-11.4	-6.1	10.6	-0.2
192	33.8	77.9	39.4	-0.3
193	11.8	11.3	11.6	0
194	0	5.6	4.4	-0.9
195	2.3	11.4	10.1	0.4

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field rotation
		B. Source dipole SJ2		
1	219.	140.	140.	0
2	27.8	178.	178.	0
3	122.	61.5	62.1	-0.1
4	73.9	57.5	58.2	-0.1
5	7.0	36.8	35.5	0.2
6	57.9	5.3	10.6	-0.9
7	299.	7.4	8.0	0.3
8	44.2	60.5	51.2	0.2
9	14.7	10.4	10.8	-0.1
10	54.9	3.5	24.9	-1.0
11	3.9	17.7	17.1	0.2
12	40.5	31.6	38.1	-0.1
13	48.8	70.7	53.8	0.2
14	60.0	130.	72.2	0.3
15	60.8	180.	65.3	0.3
16	32.7	239.	33.7	-0.2
17	-64.2	-31.1	64.2	0
18	27.2	4.7	15.2	-0.7
19	-19.8	-28.9	20.6	-0.1
20	-21.4	-45.2	24.3	-0.3
21	-32.8	-53.0	35.6	-0.2
22	-21.0	-45.5	24.7	-0.3
23	-54.2	-13.0	51.5	0.2
24	-10.8	-46.5	39.2	-0.4
25	0	-72.7	63.2	0.1

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field rotation
		C. Source dipole M1		
1	3.0	0	9.4	0.1
2	0.8	3.7	1.2	0.6
3	3.9	2.8	3.7	-0.1
4	1.4	1.0	1.3	-0.1
5	4.4	5.9	5.0	0.1
6	3.6	0.3	2.4	-0.8
7	3.3	1.3	2.4	-0.4
8	1.0	1.8	1.5	0.2
9	2.4	1.0	1.7	-0.4
10	1.1	0	0.44	-1.2
11	-58.0	0	66.6	0.5
12	-27.2	-22.1	26.8	-0.1
13	36.3	181	40.7	-0.4
14	-0.13	-0.67	0.15	-0.4
15	4.6	12.5	4.7	0.1
16	3.2	2.7	3.2	0
17	1.6	0.42	1.6	-0.2
18	11.2	0.98	10.2	-0.4
19	1.8	3.0	2.3	0.2
20	2.6	2.2	2.5	-0.1
21	0.56	0	0.56	-0.1
22	0	- 3.6	0.21	0.1
23	-2.9	-2.1	2.6	0.3
24	-2.4	-3.6	2.9	-0.2

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field rotation
25	-5.3	-8.9	6.4	-0.2
26	-1.1	-3.5	1.9	-0.5
27	-1.8	-11.2	4.8	-0.8
28	-12.6	-8.6	12.6	0
29	22.1	0	22.5	0.2
30	-39.3	-4.7	16.4	0.9
31	-0.74	-1.1	1.0	0.1
32	0.97	3.6	1.3	-0.5
33	3.6	5.2	4.0	-0.2
34	2.5	3.0	2.7	-0.1
35	2.4	11.6	3.7	-0.6
36	-8.5	0	12.8	0.8
37	-4.6	-90.0	4.7	-0.1
38	4.2	21.7	4.3	0.1
39	-39.7	0	39.7	0
40	0.58	10.0	2.5	-1.1
41	2.9	4.6	3.4	-0.2
42	5.7	4.3	5.2	0.1
43	1.5	3.2	2.6	-0.3
44	3.0	4.6	3.2	-0.2
45	94.5	15.5	18.9	0.5
46	4.8	15.1	14.3	-0.2
47	99.9	9.8	17.9	-0.8
48	28.1	3.2	3.8	0.5
49	69.5	2.5	3.7	0.8

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field rotation
50	3.2	3.5	3.5	0
51	2.3	2.9	2.7	-0.1
52	22.2	6.5	16.2	0.5
53	9.9	2.2	6.0	0.7
54	2.3	2.0	2.1	0.1
55	3.0	4.2	3.2	-0.1
56	-2.7	-2.3	2.4	-0.1
57	-4.4	-2.4	3.2	-0.3
58	-6.3	-5.2	5.8	-0.1
59	-5.4	-1.5	3.8	-0.5
60	-15.6	-13.1	14.6	-0.1
61	-1.8	-1.5	1.6	-0.1
62	-2.4	-2.8	2.8	0
63	-5.0	-2.3	2.5	-0.2
64	-12.8	-8.7	9.0	-0.1
65	-31.7	-3.2	6.6	-0.9
66	-276.	-0.97	2.7	1.2
68	-98.6	-4.1	5.2	-0.6
69	0	-8.6	8.4	1.4
70	0	-10.6	10.2	1.3
71	-2.4	-1.9	2.0	0.2
72	-2.5	-2.0	2.2	0.1
73	0.52	9.2	1.0	0.9
74	-4.5	-4.3	4.4	0
75	-6.8	-10.3	9.0	-0.2

Table 2 (Continued)

Station number	Parallel-field resistivity	Perpendicular-field resistivity	Total-field resistivity	Electric-field rotation
76	-7.5	-4.0	5.6	0.3
77	-10.0	-2.2	6.6	0.6
78	7.2	0	4.6	0.9
79	-4.4	-14.1	6.4	-0.5
80	-4.0	-2.4	3.8	0.3
		D. Source dipole M2		
1	20.8	58.3	48.9	-0.4
2	44.5	12.6	15.3	0.4
3	1.9	26.5	25.6	0.1
4	34.5	3.5	4.9	0.7
5	31.9	14.6	15.2	-0.2
6	30.6	8.3	14.4	0.6
7	32.4	12.6	29.1	0.3
8	2.1	8.3	6.7	0.5
9	3.9	0.75	1.2	-0.7
10	101.	7.8	9.4	-0.5
11	22.1	19.8	20.0	0.3
12	3.5	18.9	17.7	0.3

Table G3. Summary of interpretations of electromagnetic soundings.

Sounding number	Layer number	Thickness (meters)	Resistivity (ohm-meters)
SJ1/1	1	490	1.3
	2		>10
SJ1/3	1	1590	1.1
	2		>10
SJ1/5	1	2700	2.4
	2		>10
SJ1/6	1	800	1.2
	2		>50
SJ1/7	1	310	1.5
	2		>20
SJ1/8	1	310	1.7
	2		>20
SJ2/2	1	590	7.4
	2		>20
SJ2/3	1	480	1.2
	2		>10
SJ2/4, SJ2/12	1	550	1.5
	2		>30
SJ2/5	1	1900	40.
	2		>120.
SJ2/6	1	170	1.5
	2		>20
SJ2/7	1	670	15.
	2		>300
SJ2/11	1	430	3.0
	2		>30
SJ2/12	1	540	2.9
	2		>30
SJ2/13	1	510	1.5
	2		>20.

Table G2 (Continued)

Sounding number	Layer number	Thickness (meters)	Resistivity (ohm-meters)
SJ2/14	1	450	2.6
	2		>20
SJ2/15	1	470	1.8
	2		>20
SJ2/16	1	350	5.2
	2		>20
M1/1	1	830	1.2
	2		>40
M1/2	1	670	1.1
	2		>40
M1/3	1	1050	1.2
	2		>40
M2/1	1	600	6.9
	2	1100	>20
	3		0.5
M2/2	1	1650	1.6
	2		0.4
M2/3	1	1400	1.5
	2		0.4
M2/4	1	500	1.5
	2		>5
L1/1	1	460	1.1
	2		>20
L1/2	1	460	1.5
	2		>100
L1/3	1	410	1.1
	2		>40
L1/4	1	310	1.0
	2		>40
L1/5	1	520	1.0
	2		>30

Table G3 (Continued)

Sounding number	Layer number	Thickness (meters)	Resistivity (ohm-meters)
ES1/1	1	360	1.0
	2		>30
ES1/3	1	670	3.3
	2		>50