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SUMMARY EVALUATION OF GEOPHYSICAL SURVEY RESULTS

NICARAGUAN GEOTHERMAL RESOURCES PROJECT-STAGE I

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The economical development of electrical power from naturally-occurring hot water in the ground requires that large volumes of steam be produced from underground water at a steam pressure adequate to operate an electrical generating plant. There are at least three primary requirements to be met by underground resources of hot water before an area can be considered to have potential for the production of geothermal power; these are, a reservoir with adequate hot water reserves to last the proposed plant over its projected lifetime, a sufficiently high temperature so that the thermal energy can be converted to electrical energy efficiently, and a sufficiently great permeability so that the heated water can be removed from the reservoir with a reasonable investment in drill holes. In addition to these main requirements, there may also be subsidiary considerations about the economic potential of a geothermal power source related to the convenience of the source to power markets or possible difficulties in handling the water produced from the ground if it contains a large amount of impurities. The program of geophysical surveys carried out in northwestern Nicaragua had three parallel objectives related to these questions; they were directed toward regional evaluation of geological structure and its control over the occurrence of geothermal reservoirs, they were directed toward the location and delineation of several specific reservoirs, and they were directed toward the evaluation of the probable productivity of these reservoirs once they had been adequately located. In conjunction with the geological and geochemical studies and drilling tests, they provide a reasonably reliable estimate of the amount of power producing capacity that may be

available in two geothermal reservoirs in northwestern Nicaragua, the one at the village of San Jacinto, and the one on the southern flank of Volcan Momotombo. I shall review here the conclusions that may be drawn from the geophysical studies in each of these three applications.

1. Regional tectonic setting

Large reserves of heated ground water may be found in several types of geological environment. These include the cases of an igneous intrusion into porous water-bearing rocks, deep burial of water-rich sediments in sedimentary basins, and downfaulting of porous water-filled rocks to great depth. Of these three types of hot-water occurrence, the one which has been most easy to exploit is that associated with intrusion of molten rock into water-bearing rocks. Molten rock intruded into the upper part of the earth's crust causes fracturing in the overlying rock so that commonly there is permeability for the vertical movement of heated ground water. Being of relatively low density, heated water rises toward the surface, forming a convection cell. The heat transport in such a hydrothermal system is mainly by mass transfer, with relatively little contribution from conduction through the surrounding rocks.

Geothermal systems associated with intrusives appear most commonly to be a feature of areas with well expressed modern volcanic or tectonic activity, for reasons that may be explained by modern concepts of crustal mobility and plate tectonics. According to these concepts, lithospheric plates of rock move laterally away from mid-ocean ridges, leaving behind a gap which is filled by repeated intrusions of mantle material. At a continental margin, the lithospheric plate is sometimes thrust under the continental crust and into the upper part of the mantle. In its descent, the downgoing slab carries with it water-rich rocks, the addition

of this water to the upper mantle rocks lowers the melting point, and phase changes occur. A volcanic cycle is thus initiated, starting with andesitic to basaltic volcanism, and followed by rhyolitic ignimbrite eruptions and intrusion of granitic plutons in turn. The leading edge of the downthrust slab may drag with it the edge of the continental crust, giving rise to linear tensile fractures in the crust over the slab. The surface manifestations of these tensile fractures can be grabens and linear composite volcanoes.

The Middle-America trench, lying off the west coast of Mexico and Central America, bounds the northeast spreading Cocos plate on the northeast. The axis of this trench lies 160 kilometers southwest of the Nicaraguan coast. Epicentral data from earthquakes for the period 1961-1967 (Barazangi and Dorman, 1969) show that the landward side of this trench is one of the most active downthrusting zones in the world. The seismic activity extends from the west end of the Trans-Mexican volcanic belt into Costa Rica, an area which is also the site of extended volcanism from Miocene time to the present. It appears that the rhyolitic ignimbrite phase of activity listed above is currently in progress or has just finished. The abundance of highly porous pyroclastic rocks from this phase of activity and of intrusions accompanying the volcanic activity make the area extremely favorable for the occurrence of geothermal convection cell systems.

Geophysical surveys related to regional investigation of the tectonics of the volcanic belt in northwestern Nicaragua included some of the gravity measurements and the electromagnetic sounding surveys, both described in preceding parts of this report. Assuming that the subsurface structure giving rise to the character of the gravity profile from Poneloya to

San Isidro (Part 2, Fig. 3) is basically two-dimensional in origin, some idea of the depth extent of the volcanic pile and the size of the intrusions in the crust may be derived. Volcanic rocks may be expected to give rise to two anomalies in gravity; one will be a negative anomaly, or reduction in the strength of gravity, over areas underlain by low density pyroclastic and extrusive rocks, and the other will be a positive anomaly, or increase in the strength of gravity, over areas beneath which high density igneous rocks have been intruded into the crust.

The highest observed values for gravity were noted on the profile at the location of the village of San Jacinto (see Part 2, Fig. 3). The effect of the mass contributing to this gravity high seems to be removed quite well by subtracting the effect for a cylinder of circular cross section, centered at a depth of 13.5 kilometers. The amplitude of the anomaly so subtracted is 31.5 milligals. On the residual gravity profile obtained after removing the effects of such a deeply buried cylinder, there is a marked decrease in gravity at each end of the Poneloya-San Isidro traverse; it is assumed that these features are related to geological structure outside of the volcanic belt and not of immediate concern to us. The effect of low-density pyroclastic rocks is apparently present on the residual profile from a location of a few kilometers southwest of Leon to a point about 22 kilometers northeast of Malpaisillo. Over this interval, the gravity is depressed uniformly by about 10 milligals. In addition, there are three local anomalies with amplitudes of 2 to 4 milligals between San Jacinto and Malpaisillo.

These data may be used with the electromagnetic sounding data to obtain some information on the properties of the pyroclastic rocks. The electromagnetic soundings provided a depth of close to 500 meters for the pyroclastic rocks relatively uniformly across the region of

depressed gravity values. Using an expression given by Nettleton (1940) for the gravity of a slab, the density contrast between the slab and the underlying rock was found to be 0.48. This is quite a large density contrast between the surficial pyroclastic deposits and the older volcanic rocks beneath.

Both the resistivity and density contrasts affirm that there is a major change in properties between the surficial porous pyroclastics and the underlying rocks. If we assume that the surficial rocks have a porosity of 35 to 40 percent by volume, a value that is compatible with the resistivities of 1.1 to 3.0 ohm-meters observed with the electromagnetic soundings, and a grain density of 2.4, a value that is typical for a volcanic glass rich in ferromagnesian minerals, the density of the pyroclastic pile will be 1.95 to 2.00 when saturated with water. The surrounding and underlying rocks must therefore have a density of 2.45 to 2.50, representing a very marked decrease in porosity or an increase in grain density, or both. If there is to be any significant reservoir capacity in a hydrothermal system, it must be found in the surficial pyroclastic rocks.

The center of mass of the high density material giving rise to the high gravity values near San Jacinto probably lies at a depth of 13.5 kilometers, if it is a cylinder of circular cross section. The apparent radius of such a cylinder may be estimated from an assumed density contrast between the intrusive rocks and the host rocks, assumed to have a density of 2.5 to 2.7. Basic intrusions in the crust should have a density of 2.7 to 2.9, providing a contrast of 0.20. Again, using a simple formula by Nettleton (1940), it is possible to find the radius of a

circular cylinder which might give rise to the observed gravity anomaly as 3000 meters.

These figures cannot be considered to be very precise because of the paucity of data on which they are based. However, if the subsurface structure shows the same marked lineation as the surface features, the calculations should be roughly correct with respect to order of magnitude. The source of heat driving the geothermal systems could be an intrusion with a volume of the order of 20 cubic kilometers per kilometer of distance along the strike of the volcanic zone. The enthalpy available on cooling of such a rock amounts to about 400 calories per gram in the anhydrous state, and perhaps a hundred calories per gram more if the melt is water-rich (Keller, 1960). The total energy from the intruded rock mass is then of the order of 10^{21} calories per kilometer of length. This is a very crude figure, but indicates that the scale of the geological phenomena is appropriate for the development of significant amounts of geothermal power.

2. Delineation and Evaluation of Geothermal Systems

Detailed geophysical surveys were done about two areas, one near the village of San Jacinto and the other along the shore of Lake Managua on the south flank of Volcan Momotombo. These two areas were selected on the basis of surface geology and the occurrence of hot springs as being favorable for the existence of geothermal systems at depth. Geophysical surveys were carried out to determine the size of these geothermal systems and locate the boundaries. Most of the geophysical surveying was done with a variety of electrical prospecting methods; some of the surveying was done also with the gravity method. Selection of the electrical methods as

a primary tool was based on the fact that an increase in temperature may affect the electrical properties of a rock to a greater degree than any of the other physical properties.

It has been well established that the resistivity of a rock depends on several factors, primarily the amount of water present in a rock and the conductivity of that water (Keller, 1971). In turn, the conductivity of the water in a rock is a function of the salinity and of the temperature. As a consequence, the resistivity of a rock cannot be used to estimate the temperature unless variations in porosity and of water salinity can be taken into account.

The variation of resistivity in volcanic rock as a function of water content should be similar to that shown in Figure 1, which was taken from a compilation of data for volcanic rocks in the southwestern United States (Keller, 1960). Not enough samples were recovered from the holes drilled in the course of the present project to improve on this relationship.

Water resistivity may be estimated from salinity. Numerous data were acquired with respect to the salinity of water samples taken from the holes drilled at both San Jacinto and Momotombo (see Part 8 of this report), and these are summarized statistically for our purposes in Figure 2. On this figure, the cumulative frequency of occurrence for total cation salinity has been plotted separately for samples taken from the wells at San Jacinto and at Momotombo. A conversion scale for converting cation salinity to approximate water resistivity is also given on this plot. From this, it may be seen that the median water resistivities for these two locations are:

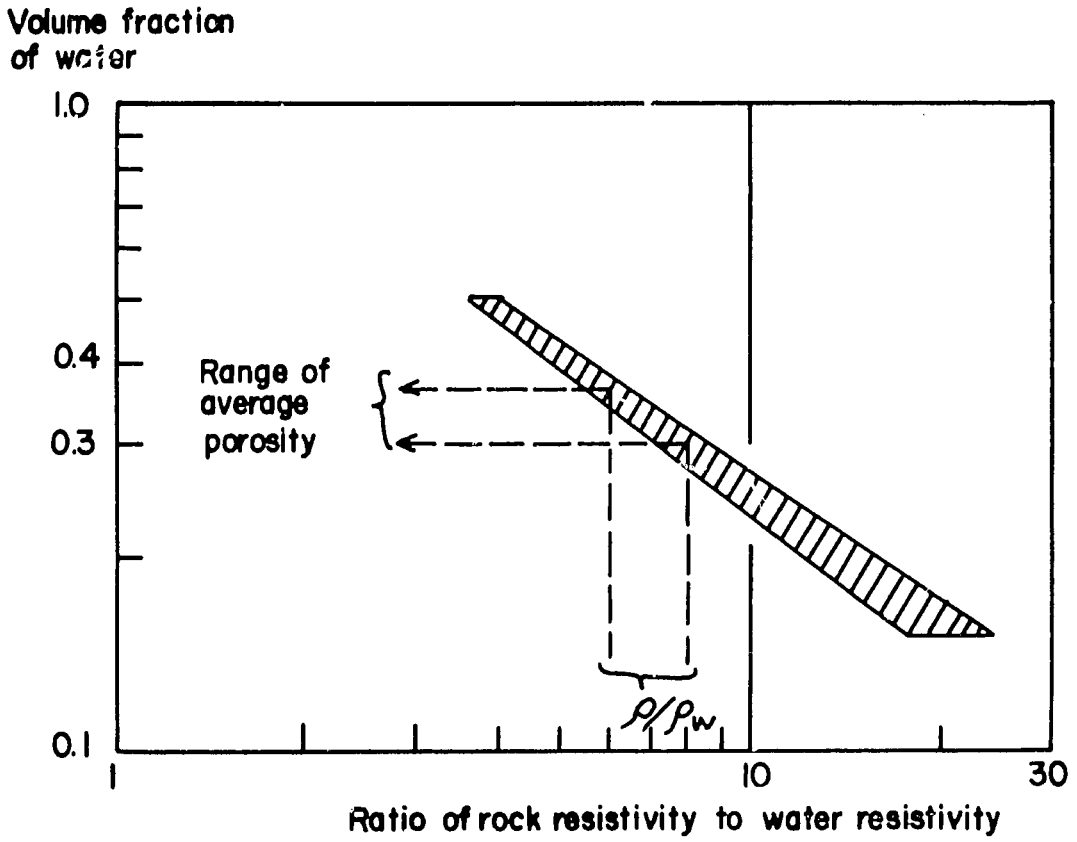

Figure 1. Empirical relationship between rock resistivity and water content for typical pyroclastic rocks.

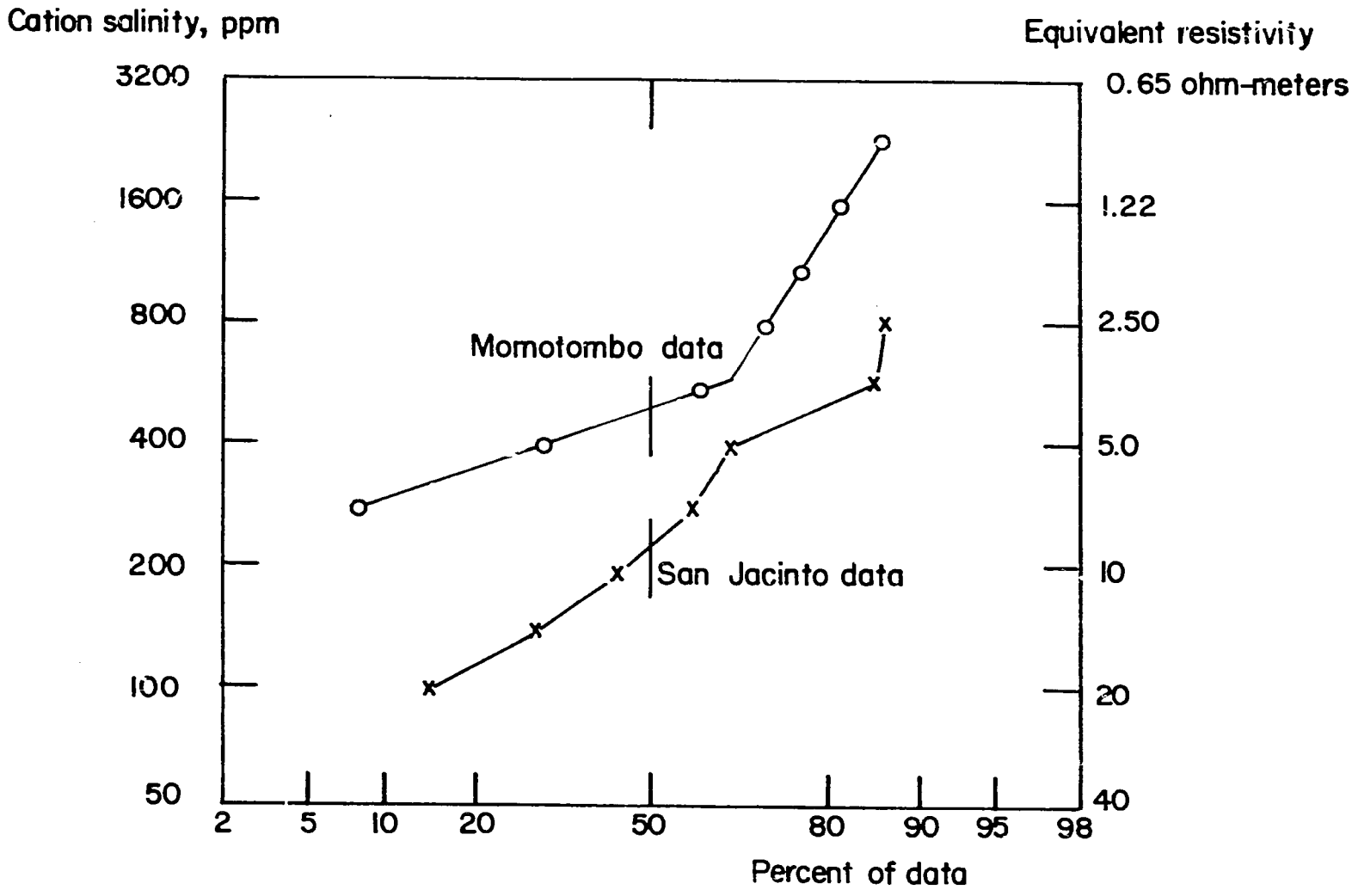

Figure 2. Cumulative frequency of occurence for salinities determined on samples taken from the wells at San Jacinto and Momotombo.

San Jacinto -- 8 ohm-meters

Momotombo -- 3.5 ohm-meters

These resistivities are computed for a water temperature of 20° C. The variation of electrical resistivity with temperature in dilute solutions of sodium chloride has been studied by Quist and Marshall (1966, 1968), and on the basis of their data, the correction chart for the effect of temperature on water resistivity shown in Figure 3 may be prepared. The two curves shown apply for ambient pressures of 0.5 and 1.0 kilobars, as indicated. In volcanic rocks with a density of 2.0, pressure increases at the rate of 1 kilobar per 5 kilometers of burial; the pressures of interest in a geothermal system should be 0.1 to 0.5 kilobars. At these pressures, the resistivity of water passes through a minimum value at a temperature of 280° to 300° C, with the minimum resistivity being less than the resistivity at 20° C, by a factor of approximately 7. The increase of resistivity at higher temperatures is associated with the development of a gas phase in the water.

To make use of these data, we need to select representative values of resistivity from the field data. One approach to this is through the use of cumulative frequency curves for the apparent resistivity values measured in the dipole mapping surveys (see Part 6 of this report). Cumulative frequency of occurrence curves for the dipole data acquired at San Jacinto and at Momotombo are shown separately on Figure 4. Resistivity values for a single rock type commonly show a log-normal statistical distribution (Keller, 1968), which would plot as a straight, rising

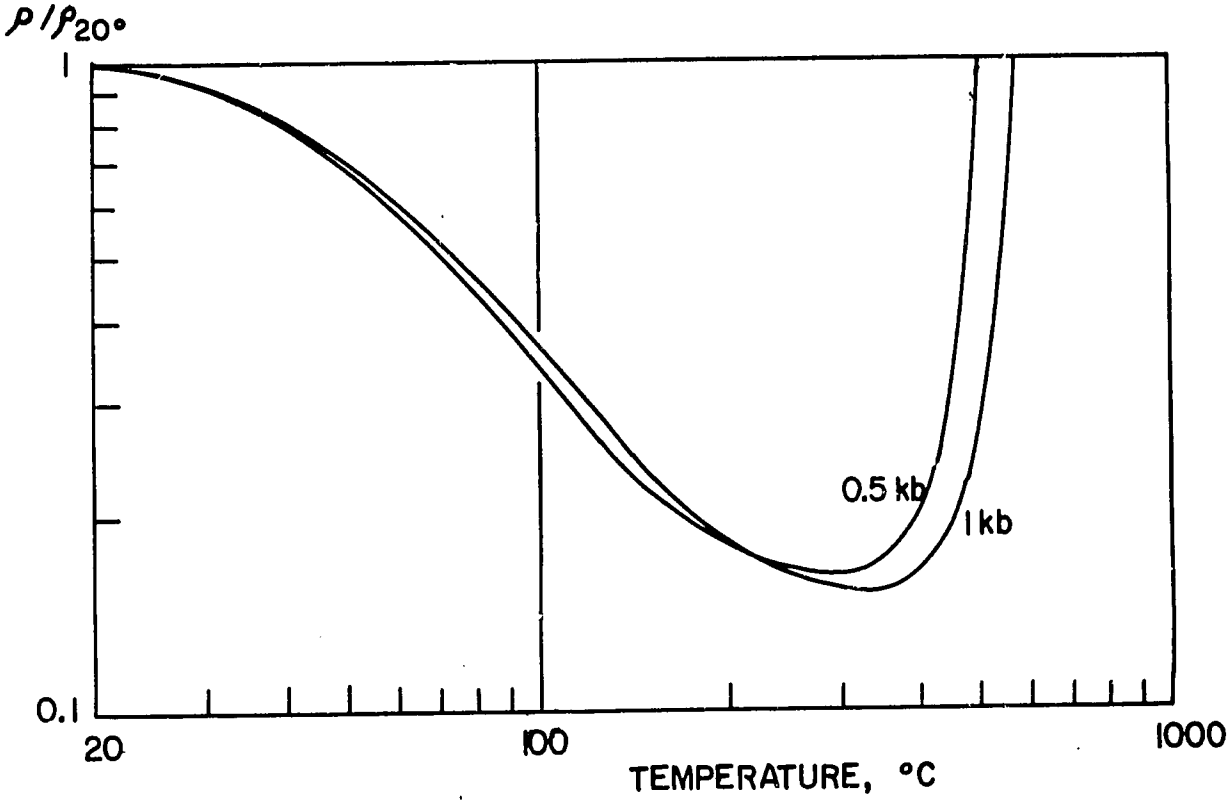

Figure 3. Variation of the resistivity of a dilute solution of sodium chloride with pressure and temperature.

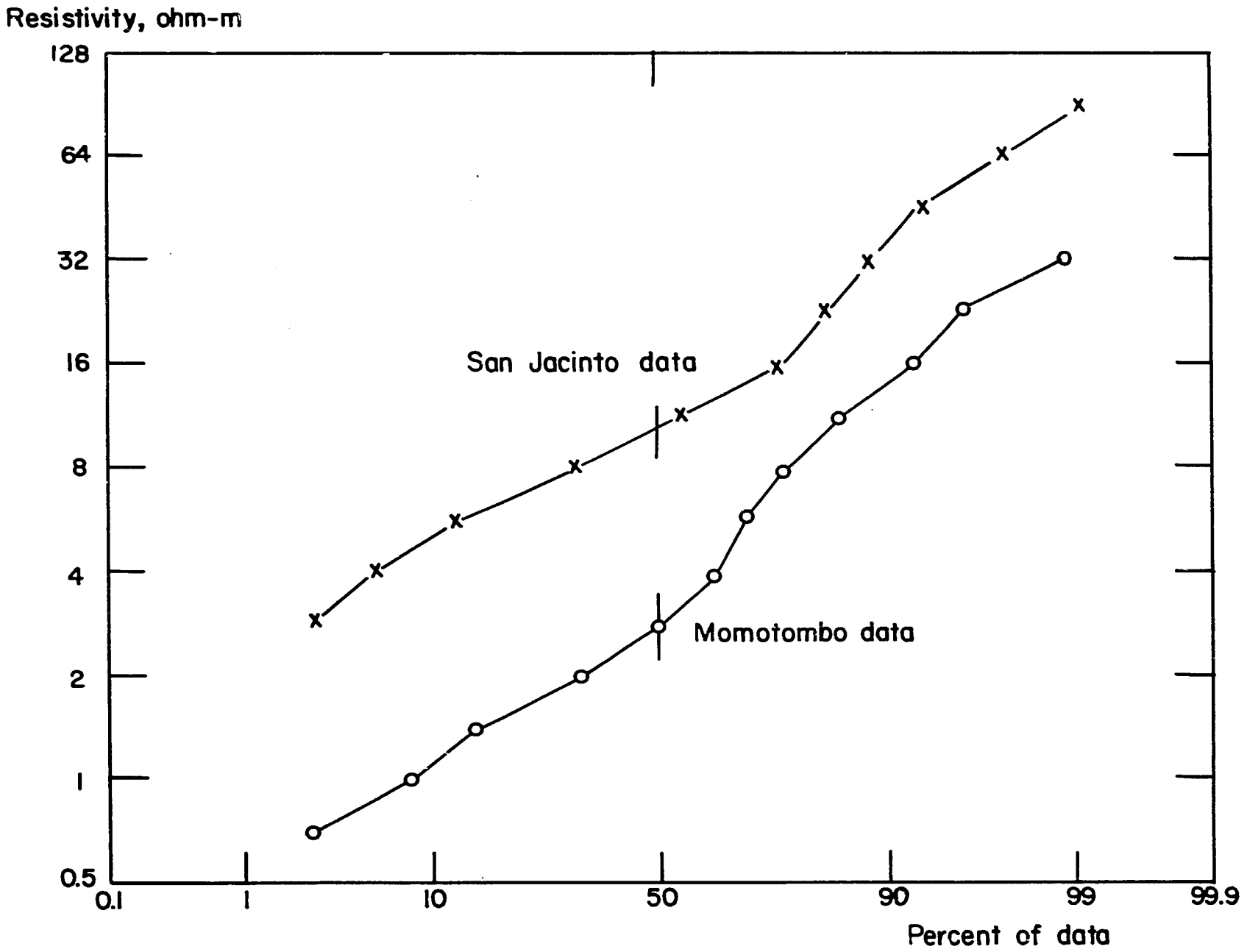

Figure 4. Cumulative frequency of occurence plots for dipole mapping data. The percent of the measurements of resistivity less than a given value is plotted against that value.

line in a presentation such as that in Figure 4. The actual data in Figure 4 appear to be the sums of two such log-normal distributions. The median values for each of the sub-distributions in each area are:

San Jacinto -- 8.0 ohm-meters and 24 ohm-meters

Momotombo -- 2.0 ohm-meters and 8.0 ohm-meters

It is reasonable to conclude that the median values of 8.0 and 2.0 ohm-meters in San Jacinto and Momotombo respectively represent hot-water-saturated rocks, while the median values of 24 and 8.0 ohm-meters, respectively, for these two areas apply to "normal" volcanic rocks outside the areas appreciably affected by the thermal activity. These distributions allow us to draw boundaries on the dipole mapping survey results for the limits of the geothermal systems. In the case of San Jacinto, if the boundary is taken as the 9 ohm-meter contour (see Part 6), the area enclosed amounts to 7.6 square kilometers, of a total area surveyed of 36.4 square kilometers. In the case of Momotombo, if the boundary is taken as the 3 ohm-meter contour, the area amounts to 3.8 square kilometers, out of a total area surveyed of 15.0 square kilometers. A significant difference in the results from the two areas, though, is the fact that the 9 ohm-meter contour at San Jacinto is closed, and the entire area within it is known reasonably accurately, while at Momotombo, there is a strong suggestion that the area within the 3 ohm-meter contour may be much larger than that actually mapped.

The depth extent of each geothermal cell is required to estimate the volume. At San Jacinto, the electromagnetic sounding data indicate that the depth to more resistant rock, presumably the "basement" for the reservoir, is about 700 meters. The maximum volume of the

porous reservoir is thus about 5.3 cubic kilometers. At Momotombo, the electromagnetic sounding data indicate a much greater depth to basement, at least greater than 2 kilometers. At a depth of one kilometer, the rock becomes even more conductive than it is at shallower depths, perhaps indicating the transition from brackish to saline water. The volume of the porous reservoir at Momotombo is thus mapped as 7.6 cubic kilometers, with no limit given to the boundaries in any direction except to the west.

The apparent resistivities from the dipole mapping surveys are not "true" resistivities for the rock in the geothermal systems, but represent averages over considerable volumes of ground. Model studies and computer studies may be used to convert such apparent resistivities to the correct values for underground structures of specific types (Furgerson, 1970). Considering the results from such model studies, it is probable that the resistivity of the geothermal system at San Jacinto is between 2.0 and 3.0 ohm-meters, and at Momotombo, between 0.7 and 1.0 ohm-meters. The ratios between the "normal" resistivities in these two areas and these values for the geothermal systems are:

San Jacinto -- geothermal resistivity ratio = 8 to 12

Momotombo -- geothermal resistivity ratio = 8 to 11

In both cases, the ratio is larger than that which is theoretically possible, as shown in Figure 3, to a minor extent. This greater contrast probably represents the fact that the reservoirs may be somewhat more saline and somewhat more porous than the host rocks, as a consequence of the upward convection of ground water. However, it is reassuring that the resistivity data are

compatible with the existence of high temperatures in the geothermal systems, and do not preclude the existence of temperatures as high as 250 to 300° C.

All of these data and inferences may be combined to provide an estimate of the power producing potential of the geothermal systems at San Jacinto and Momotombo. According to Banwell (1970), the heat energy available on cooling the geothermal fluid to 50° C is of the order of 3500 megawatt-years per cubic kilometer of reservoir. Not all this energy is available for the generation of electricity because of inefficiencies in production of steam and conversion; Banwell gives a realizable yield as being 900 megawatt-years per cubic kilometer of reservoir. On this basis, the energies available at San Jacinto and Momotombo should be:

San Jacinto -- 4800 megawatt years

Momotombo -- 6800 megawatt-years

These estimates must be regarded as very rough, and it is better to conclude merely that the geophysical evidence does not contradict the possible existence of power sources of this size at these two locations. Whether they actually exist and may be produced cannot be determined until an extensive drilling program has been undertaken.

Recommendations for future use of Geophysics

Numerous geophysical techniques were used, many briefly, in the survey of northwestern Nicaragua. Some of these were standard and conventional techniques, others were less standard. It is appropriate here to summarize the conclusions we have drawn concerning

the merits of specific techniques for prospecting for geothermal systems under the conditions prevailing in northwestern Nicaragua.

1. Resistivity profiling and sounding, using either the Schlumberger or Wenner arrays. These techniques are widely used in other areas of the world for reconnaissance for geothermal cells. However, in Nicaragua, these methods were found to be less effective than we had hoped, primarily because high surface resistivity in the volcanic rocks led to erratic measurements of resistivity, and difficulty in driving sufficient current into the ground to make accurate measurements.

2. Dipole mapping surveys were found to be extremely effective in delineating the boundaries of geothermal systems, as in other parts of the world. Some effort is required to find a location where the dipole source can be sited. On the basis of our results, it is not clear whether it is preferable to have one end of the source line in the geothermal area of interest, or to have both ends outside the area. Siting one end of the source line in the geothermal area makes it difficult to detect the boundaries of the system within about 0.5 kilometers distance from the electrode. On the other hand, for elongate cells such as exist at Momotombo and San Jacinto, the boundary away from the source cannot be located accurately when both ends of the source are located outside the conductive area. In most cases, the location of one end of the source line inside or outside the target geothermal cell is an academic problem, because the boundaries are not known beforehand so this choice can be made.

3. Electromagnetic soundings proved to be quite effective in determining the thickness of conductive rocks, both in the Nicaraguan Depression, and in the thermal areas. This technique can be recommended as being superior to resistivity sounding because of its insensitivity to problems caused by resistant surface rocks.

4. The magneto-telluric method appears to offer promise as a reconnaissance technique for a rapid evaluation of surface manifestations of geothermal activity, as indicated by the results reported in Part 6. However, the method will have to be evaluated further to determine whether or not the limited accuracy with which resistivity can be determined is a serious limitation.

5. The "slingram" or two-loop electromagnetic profiling method was found to be quite useless for two reasons; first, because of the difficulty involved in traversing with the two loops in heavily vegetated terrain, and second, because the method did not provide sufficient penetration to reach through the highly resistant surface lavas to detect conductive rock beneath.

Our recommended approach for further search for geothermal systems would include the use of the magneto-telluric method as a reconnaissance tool to evaluate areas with geothermal manifestations such as hot springs, followed by dipole mapping surveys to determine the dimensions of the systems. The dipole mapping surveys should be supplemented by electromagnetic soundings to determine the depth extent of conductive rock. If drilling is decided upon, resistivity surveys with the Schlumberger method will be useful in picking suitable drilling sites.

Summary

In summary, the conclusions which may be drawn from the geophysical data are as follows. The volcanic belt of northwestern Nicaragua is a particularly favorable area in which to prospect for geothermal reservoirs because of its tectonic setting, the modern volcanism and the existence of porous pyroclastics in the Nicaraguan Depression. Geophysical surveys of two areas with surface geothermal manifestations, San Jacinto and Momotombo, provided results which would not be incompatible with an energy production capacity of 4800 megawatt-years at San Jacinto and 6800 megawatt years at Momotombo. The system at San Jacinto was well defined, while the system at Momotombo was not, and may extend eastward under Lake Managua and northward under Volcan Momotombo. The Momotombo system may also be considerably more saline than the one at San Jacinto, especially at depths greater than 1000 meters. Either system is worthy of further investigation by development drilling.

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