DOE/ID/13453-7T1

EXPLORATION OF THE
EL HOYO - MONTE GALAN
GEOTHERMAL CONCESSION

FINAL REPORT

December 1997

SUBCONTRACT DE-FG07-96ID13453

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GEOPHYSICAL FIELD CREW
MEMBERS OF ONE OF TGC'S GEOSCIENTIFIC SURVEY CREWS
AT EL HOYO - MONTE GALAN

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1 EXECUTIVE SUMMARY

- 1.1 During the period April 1996 to February 1997 Trans-Pacific Geothermal Corporation (TGC) performed several geologic and geophysical investigations within the TGC El Hoyo-Monte Galán Geothermal Concession. These investigations included analyses of satellite and aerial photo imagery, microearthquake studies, ground magnetic (GM) survey, self potential (SP) survey, MT/CSAMT survey, one-meter temperature survey, geologic mapping and gas geochemistry. The GM, SP, MT/CSAMT and one-meter temperature surveys, data integration and final report were funded in part by U.S. Department of Energy Grant No. DE-FG07-ID13453.
- 1.2 Several geophysically anomalous areas indicative of high geothermal potential were identified by the studies. The anomalous areas were characterized by a coincidence of shallow seismicity, fumarolic activity, surface fracturing, high soil and groundwater temperatures, and intense and extensive GM, SP, and MT/CSAMT anomalies.
- 1.3 Four distinct areas of high geothermal potential were confirmed and defined by the TGC exploration program. The total area characterized by intense geophysical anomalies is large, covering a minimum of 20 square kilometers within the 89 square kilometer Concession area. The entire Concession area contains moderately to highly elevated ground water temperatures. Because of the large areal extent of the anomalies as compared with proven geothermal resources within the Central American volcanic arc, it is highly likely that the Concession contains at least 150 to 200 MWe of geothermal reserves.
- 1.4 Four separate target areas for slimhole drilling were identified based on the intensity and strong correlation of the various geophysical anomalies. These sites include the upper flanks of Volcán El Hoyo and Picacho, the east northeast base of El Hoyo, Cerro Colorado, and the ring fracture system of the Monte Galán Caldera. Eight specific slimhole drill sites are tentatively recommended for the purpose of assessing the four target areas.

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- 1.5 Slimhole drilling activity for the purpose of testing the target areas is expected to commence upon signature of a power sales agreement between TGC and its joint partner with ENEL.
- 1.6 Based on volumetric calculations and an integrated analysis of all of the geoscientific studies conducted within the Concession, the potential for economic development of geothermal resources within the TGC Concession is estimated as:

El Hoyo 120-150 megawatts for 30 years.

Cerro Colorado 40-50 megawatts for 30 years.

Monte Galán Not yet determined.

The actual developable capacity will be determined based on the slimhole and full diameter exploration well drilling and testing.

2 INTRODUCTION

2.1 Background

In January 1996 Trans-Pacific Geothermal Corporation (TGC) was granted a geothermal concession of 114 square kilometers from the Instituto Nicaragüense de Energía (INE) for the purpose of developing between 50 and 150 MWe of geothermal electrical generating capacity. The Concession Agreement required TGC to perform geological, geophysical, and geochemical studies as part of the development program.

TGC commenced the geotechnical studies in January 1996 with a comprehensive review of all existing data and surveys. Based on this review, TGC formulated an exploration plan and executed that plan commencing in April, 1996. The ground magnetic (GM), self potential (SP), magnetotelluric\controlled source audio magnetotelluric (MT/CSAMT) and one-meter temperature surveys, data integration, synthesis of a hydrogeologic model and this final report were funded in part by U.S. Department of Energy Grant No. DE-FG07-ID13453.

Field work was completed in February 1997 and analysis of data derived from that work is now complete. Based on results of the geophysical program, the Concession was modified to its current configuration of 89 square kilometers as shown in Figure 2.

2.2 Purpose

The purpose of this report is to present a compilation of all data gathered from the geophysical exploration program and to provide an integrated interpretation of that data. The geophysical program was designed primarily to identify and map faults and fractures that may host active hydrothermal systems. The geophysical surveys were then integrated with other geologic data including remote sensing and microearthquake studies to produce an hydrogeologic model. This model is then used

as the basis for: (1) the siting of slimhole exploration wells, and (2) a preliminary assessment of geoelectric generating capacity based on volumetric calculations.

2.3 Scope

This report presents a compilation all data collected during the TGC exploration program executed within the Concession area. The exploration program consisted of the following studies and surveys:

2.3.1 Ground Magnetic Survey

2.3.2 Self Potential Survey

2.3.3 One-Meter Temperature Survey

2.3.4 MT/CSAMT Survey

2.3.5 Remote Sensing

2.3.6 Microearthquake Surveys

2.3.7 Gas Geochemistry

2.4 Previous Reports Relating to the TGC Concession

Detailed data reports by TGC and its subcontractors and affiliates were submitted separately. These reports include MT/CSAMT (Zonge, 1997), Remote Sensing (TGC, 1996), and a microearthquake study (Smith and Kassameyer, 1997) as listed below;

Smith, Albert T. and Paul Kassameyer, 1997, Microseismicity study of the El Hoyo-Monte Galán Geothermal Prospect, Nicaragua, Lawrence Livermore Lab, UCRL-ID-127876.

TGC, November 11, 1997, Preliminary Data Report, El Hoyo-Monte Galán Geophysical Exploration Program.

TGC, 1996, "Remote Sensing for Geothermal Exploration in the El Hoyo-Monte Galán Geothermal Concession, Nicaragua: Image Processing and Interpretation", proprietary report.

Zonge Engineering, 1997, "CSAMT/MT Surveys, El Hoyo-Monte Galán Project, Leon, Nicaragua" proprietary report for TGC.

The results of these studies are included in this report in the form summary figures and discussions.

3 REGIONAL GEOLOGIC SETTING OF THE TGC CONCESSION

The TGC El Hoyo-Monte Galán geothermal prospect is located within the Marabios Range, an active volcanic chain in western Nicaragua. The volcanic chain is a product of plate tectonic processes characteristic of the Pacific Rim, in which basaltic oceanic crust and accompanying sedimentary covering are subducted beneath the relatively static continental

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margin. Offshore of western Nicaragua, the northeastward moving Cocos Plate subducts beneath the Caribbean Plate along the Middle America Trench at the rate of 8.4 cm/year (Figure 1) (Pardo and Suarez, 1995), a subduction rate which is considerably greater than in other segments of the Cocos Plate. The underthrust plate fault plane dips 26-28 degrees to the NE under the Nicaraguan volcanic arc (Dean and Drake, 1978). At a depth of approximately 100 km, partial melting of the subducting plate produces magma which migrates upward and erupts at the surface, giving rise to the ongoing volcanism of the Nicaraguan volcanic arc. This volcanic process is accompanied by a high level of shallow (<15 km depth) seismicity along the volcanic arc. The earthquake records for the period 1975-80 (White, 1995) clearly show the correlation between seismicity and volcanism within the Nicaraguan volcanic arc (Figure 1). The TGC El Hoyo-Monte Galán Geothermal Concession straddles the axis of this volcanic arc.

The Nicaraguan volcanic arc is one of the most active along the subducting eastern Pacific margin, possibly due to its relatively high subduction rate. More than 150 historically documented eruptions have occurred within the last 500 years (Simkin and Siebert). During the last two years Volcán Cerro Negro, which is adjacent to the western boundary of the TGC Concession, has been undergoing periodic eruptions. Within the Masaya Caldera southeast of Managua, the constant injection of magma from depth maintains a molten lava lake, along with vigorous gas and steam emissions.

The geology of western Nicaragua consists primarily of Late Cretaceous to Pliocene sediments interbedded, intruded and overlain by Tertiary and Quaternary volcanics. The sediments consist mainly of tuffaceous shales, sandstone, and graywackes which reach a combined thickness of up to 10,000 m (McBirney and Williams, 1965).

Structurally, western Nicaragua is dominated by a WNW-trending graben, the Nicaraguan Depression (Figure 1). Volcanoes making up the Marabios Range have erupted along the central axis of the graben. Several N and NE trending strike slip faults cause offsets and segmentation of the volcanic range. One of these NE-trending left-lateral strike-slip faults caused the Managua earthquake of December 23, 1972. The Managua quake had a hypocenter depth of less than 7 km (Algermissen et al, 1974). The segmentation is probably caused by differential subduction rates and directions of movement within the subducting plate, resulting in shearing and segmentation of the overthrusting crust. (Stoiber and Carr, 1973). These transverse shear zones may be critical to the development of the fracture permeability necessary to sustain commercial geothermal resources. They are evidenced by clusters of shallow earthquakes which were distributed at intervals of 5-15 km along the Nicaraguan Depression (Figure 1)(OLADE, 1982).

Numerous hydrothermal systems of commercial grade have been discovered within the Central America volcanic belt. At least 18 sites have confirmed high-temperature (>180°C) commercial resources and four of those sites currently support commercial electrical production (Huttrer, 1995). The total installed geothermal capacity is currently 230 MWe (Dickson and Fanelli, 1993). Nicaragua contains a commercially developed geothermal field at Momotombo with an installed capacity of 70 MWe. In addition, several prospective sites have been identified. Exploration drilling at the San Jacinto field, NW of the El Hoyo prospect, has confirmed at least twenty megawatts of geothermal capacity.

WILLIAM TELOW
TGC GEOTHERMAL PROJECT MANAGER
STANDING AT A STEAM VENT NEAR THE SUMMIT OF EL HOYO

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The El Hoyo Geothermal Concession is located along the axis of the Marabios Range and Nicaraguan Depression. The concession contains several Quaternary basaltic andesite volcanic vents that have sustained numerous historical eruption, including the ongoing activity at Cerro Negro. Cerro Negro, located in the NW corner of the El Hoyo prospect, is the most basaltic of recent volcanoes in western Nicaragua, consisting primarily of olivine-augite basalt (McBirney and Williams, 1965)(Figure 2). The concession is bounded to the SE by Volcán Momotombo which is a mature composite cone of basaltic, andesitic, and dacitic composition with the most predominant rock-type being andesitic lithic tuff (Wohletz and Heiken, 1992).

In addition to its position on the main NW trending Marabios volcanic lineament and Nicaraguan Depression, the prospect contains a major N-S trending transverse fault zone that is characterized by a lineament of basaltic vents, maars, and grabens that pass through the El Hoyo summit crater and Laguna Asososca (McBirney and Williams, 1965). This lineament is associated with an earthquake cluster located below the north flank of Volcán El Hoyo (Figure 24). Details of earthquake activity within the TGC Concession are discussed in Section 9.

Faulting and associated fracturing is critical to the development of geothermal reservoirs along the Marabios Range. This is demonstrated in the Momotombo geothermal field where fumaroles and production are directly related to NW trending, high-angle, right-lateral and reverse faults.

4 GROUND MAGNETIC SURVEY

Ground magnetic (GM) surveys normally provide information related to the location and depth of magnetizable geologic units. The location of faults is often indicated by the change in the relative depth of buried strata with common magnetic rock properties. Fault locations may be significant in the search for porous and permeable channels for hot water, because faults are typically characterized by fractures and hence permeable zones. However, the existence of a fault zone is not, in itself, a certain indication of existence of an active hydrothermal system contained within the fault. Other lines of evidence are required to make any fault zone an attractive target for drilling.

Oftentimes, magnetizable rocks which have been subjected to hot fluids circulating through them lose part or all of their magnetic properties. This is because hot water circulating through rocks will often convert magnetic minerals, typically magnetite, into non-magnetic minerals such as limonite or hematite. Negative anomalies in a geothermal area may be indicative of present or past intense high-temperature fluid circulation.

A total of 74.3 kilometers of ground magnetic (GM) profiles were executed in the Concession area as shown in Figure 3. Readings were taken at either 25 or 50 meter spacings along the profile lines. Geometrics Model 856 magnetometers were used for both the roving and base station instruments. A single, centrally located base station was used, with readings taken at one-minute intervals throughout the day. Data taken by the roving instrument was corrected for diurnal drift by using the base station readings.

Results of the magnetic survey are shown as profiles of total magnetic field strength deviation from the base station value of 37706 gammas (Figures 7 through 20). The raw field data has been smoothed through a double five point running average. A contour map of the smoothed total field strength is shown in Figure 21. Several distinct negative anomalies were observed throughout the survey area. In particular, the fumarolic area on the summit bulge of El Hoyo showed a very large bipolar anomaly with a width of approximately one kilometer. This anomaly trends generally N-S and correlates closely to a large north-trending steaming fracture which cuts the northern flank of El Hoyo. The anomaly may be due to the intense hydrothermal alteration and destruction of magnetite caused by the hydrothermal system within the central conduit and fractures of the El Hoyo massif. This relatively narrow and intense anomaly correlates very closely with a large negative SP anomalies as seen in Figure 8.

An additional sharp bipolar magnetic anomaly is also seen at the eastern edge of the El Hoyo complex (Figure 8 and 21). This anomaly is closely associated with high temperature (135°C) ground water which was encountered during shallow temperature gradient drilling program in 1976. Surface outcrops within this anomaly contain chalcedony-filled vein and fracture filling in young lava flows. This indicates that the hydrothermal system producing the hot ground water was discharging at the surface fairly recently.

The magnetic anomalies associated with Cerro Colorado are relatively subdued and are not easily distinguished from the general level of variation seen throughout the profiles. However, when compared with the SP and MT/CSAMT profiles (Figures 7-10) a strong correlation is evident. The magnetic gradient cut by profiles 1-4 shows a distinct NNE trend which is evident in the contour map (Figure 21).

A separate and very sharp negative magnetic anomaly is seen along the southern rim of the Monte Galán caldera (Figure 20 and 21). This anomaly is centered around station +3000 on line 14 (Figure 20). This anomaly correlates very precisely with a significant negative SP anomaly. This particular feature may be an indication of hydrothermal activity associated with ring fractures along the rim of the Monte Galán caldera. Since the rim of Monte Galán was transected by only one geophysical profile line, it is not possible to draw conclusions regarding the continuity of this anomaly around the entire rim.

5 SELF POTENTIAL SURVEY

Self potential (SP) is the natural voltage that can be measured between two points on the earth's surface. SP anomalies are usually generated by one of two primary causes: subsurface oxidation of large sulfide bodies or high temperature and pressure gradients within hydrothermal systems. The latter cause makes SP an important tool for geothermal exploration. Vertically circulating hot fluid can produce voltages as great as 1.5 volts in large geothermal systems. The shape, amplitude and width of the SP profiles can be used to map single hydrothermally active fractures within a large geothermal system and is therefore an important method for specific drill target determination. The method is also effective in differentiating between hydrothermally active and inactive faults that have been identified by other methods, such as magnetics or gravity.

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A total of 65.3 kilometers of SP profiles were completed as shown in Figure 4. The raw field data has been smoothed through a double five point running average. Analysis of the data shows several very significant negative SP anomalies that correlate closely with the MT/CSAMT, ground magnetic, and temperature anomalies. The largest of these anomalies, reaching as low as -370 mV, is seen in profiles 2, 3, and 4, located within the fumarolic area on the summit of El Hoyo. Lesser negative anomalies ranging from -80 to -180 mV are observed in the vicinity of Cerro Colorado (Figures 7, 8, 9 and 10) and at the southern rim of the Monte Galán caldera (Figure 22). These anomalies correlate closely with GM anomalies discussed above.

The anomaly in the Cerro Colorado area is seen on Lines 1 through 4 between stations +1000 and +2500 and appears to form a strong NNE trending lineament which closely corresponds to the surface fracture pattern mapped within Cerro Colorado (Figure 24). The relatively subdued amplitude of the SP anomaly within the Cerro Colorado fumarolic area may be due to the extremely low surface resistivity that prevails in this area. This low resistivity was documented by both the MT/CSAMT survey and by the contact resistance readings made during the SP survey.

6 ONE-METER TEMPERATURE SURVEY

Shallow temperature surveys can be used to detect zones of shallow convective heat leakage to the surface or near-surface, even when they are no surface manifestations. The technique is inexpensive and can be rapidly deployed over a large area where vehicular traffic is impossible. It can be used to test whether large geophysical anomalies have associated anomalous heat flow when surface manifestations are absent.

A total of 31 kilometers of profile were completed at an average spacing of 200 meters between data points. A total of 178 measurements were made. In addition, several sensitivity, equilibration time, and calibration studies were carried out. The one-meter temperature survey was only partially completed due to equipment failure. The locations of the completed temperature profiles are shown in Figure 5.

The survey was performed by driving half-inch diameter galvanized electrical conduit pipe, 1.5 meters in length, to a depth of 1 meter. The installed pipes were sealed with tape at the top and allowed to equilibrate for approximately 24 hours. Temperature measurements were made at the bottom of the pipe, using a thermistor probe with digital readout. Generally, an equilibration time of 7 minutes was sufficient to obtain a stable reading. Air temperature was also recorded at each station. The survey was performed during the dry season and no rain fell during or immediately prior to the survey.

Variations in the intensity of sun light falling on bare ground produced a noise level of about $\pm 3^{\circ}\text{C}$. Generally pipes were installed in areas of permanent shade such as on the north side of trees or tall brush in attempt to reduce the solar effect. The observed one-meter temperature showed good correlation with temperature anomalies identified from previous gradient drilling and water well measurements. The method was also effective in observing the extents of hydrothermally active areas where surface manifestations such as

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alteration and steaming ground were absent. Correlation of the one-meter temperature anomalies with SP and GM anomalies is shown in Figures 7 through 10.

7 MT/CSAMT SURVEY

Measurement of changes of electrical resistivity as a function of depth have been successfully employed in geothermal exploration in many parts of the world. Rocks containing hot water in their pore spaces are characterized by lower resistivity than colder rocks. The advantage of electrical resistivity methods is that they permit the measurement of the change of resistivity with depth. The disadvantage of resistivity methods is that changes in resistivity can also be due to change in rock type, change in salinity of the saturating fluid, and other factors. Hence, resistivity measurements alone are not reliable for determining that the low resistivity bodies are necessarily due to a hot water reservoir at any given depth. It is necessary to correlate the resistivity data with other geoscientific data to ascertain that the mapped resistivity features are indeed due to a change in temperature within a geothermal reservoir.

In our survey we have utilized two electromagnetic techniques known as magnetotellurics (MT) and controlled source audiomagnetotellurics (CSAMT). The CSAMT method permits rapid determination of ground resistivities from the surface down to a depth which is determined by the local earth's resistivity, typically from one hundred to several hundred meters. The MT method utilizes the natural electromagnetic signals which are generated by solar activity and lightning storms to probe the earth to a much greater depth. The great advantage of the MT/CSAMT technique over the older DC resistivity methods is that the rate of production is much higher with the electromagnetic techniques. Hence, we were able to generate a very dense data set along the selected profiles, which was not possible before the introduction of those techniques into geothermal exploration.

Zonge Engineering performed an MT/CSAMT resistivity survey in the Concession starting in August, 1996. Thirty-three and six-tenths kilometers of profile line were surveyed at an inline station spacing of 200 meters. The distribution of survey lines is shown in Figure 6. A frequency range of 1 Hz to 2048 Hz was used for the CSAMT and a range of 0.0938 Hz to 1024 Hz was used for the natural source MT. This frequency range resulted in a probing depth in excess of two kilometers for most of the survey area.

A GDP-32 receiver recording 16 channels was used to simultaneously collect 6 E-field electrode signals located at 200 meter intervals along the profile line and two E-field electrode installed perpendicular to the profile. X, Y, and Z component magnetic field measurements were taken at the center of each one-kilometer spread. A Zonge GGT-10 transmitter with 10 kW output was used to produce the controlled source signal. The transmitter employed a 1-kilometer dipole spread and was located 6-10 kilometers from the receiving electrode array.

A detailed report (Zonge, 1996) with all the resistivity sections and depth slices was transmitted to INE under separate cover. Four resistivity cross sections derived from the MT/CSAMT survey are shown in Figures 7-10. Figure 23 shows a horizontal section

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produced by contouring the various resistivity profiles at an elevation of -500 meters below ground surface.

Figure 23 shows several areas of very low resistivity (<2.0 ohm-m). In general, the N-S-trending valley between El Hoyo and Cerro Colorado exhibits low resistivity throughout. However, at the eastern margin of the valley, in the vicinity of Cerro Colorado, resistivities drop to even lower levels. As seen in the resistivity cross section along Line 3 (Figure 9), this resistivity low between stations +1500 and +2500 appears to have a deep root, as opposed to the relatively shallow resistivity low in the center of the valley (stations -1000 to +1500). This deeply penetrating resistivity low correlates well with the SP low and the area of fumarolic activity at the surface. The very sharp resistivity boundary located just to the east of Cerro Colorado is seen in both Line 3 and 4 (Figures 9 and 10). This may represent a major fault which contains hydrothermal activity and is leaking hot water westward into the valley.

Low resistivities are seen at the far eastern extent of both Profiles 3 and 4. These anomalies correspond closely to the outer rim of the Monte Galán caldera. They may be an indication of hydrothermal activity associated with caldera ring fractures. A strong SP and GM anomaly at the south edge of caldera was seen in Line 14 (Figure 20), which was not covered by the MT/CSAMT survey, but serves to show that hydrothermal systems may be present along this feature.

A similar sharp resistivity boundary was observed on the west side of the valley at stations -2500 to -2700 on both Line 3 and 4. This boundary is closely associated with a hot (135°C) shallow aquifer that was encountered in a temperature gradient hole at a depth of 20 meters. This well is located near station -1800 on Line 4 (Figure 10).

Two apparently separate low-resistivity anomalies are located at the westernmost extension of Profiles 3 and 4 (Figure 23). The western anomaly on Line 3 is closely correlated with the extensive fumarolic area on the northern flank of El Hoyo summit bulge. As seen in Figure 9, this anomaly is also correlated with a very large (-370 mV) SP anomaly. The Line 4N extension of Line 4 (Figure 23) shows very low resistivity in close proximity to an area of high shallow seismicity (Figure 24).

8 REMOTE SENSING STUDY

8.1 Types of Imagery Used in the Study

An archived LANDSAT-Thematic Mapper (TM) image covering the Concession was obtained in digital format for TGC by Earth Science Resources Institute (ESRI) of Salt Lake City, Utah. The image was shot on March 24, 1986 by LANDSAT 5.

A synthetic aperture radar image of the Concession was acquired by the RadarSat International satellite on April 11, 1996. The scene was specified and contracted by TGC from RadarSat to maximize resolution in the Concession area. The RadarSat and LANDSAT images were analyzed using the remote sensing lab facilities at ESRI.

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The digital images were processed and interpreted on a Sun Sparcstation using Arcinfo software. The image was rectified to the UTM grid.

Two sets of black and white aerial photographs were acquired from the Nicaraguan Geological Survey (INETER). The older set of photos, taken on November 28, 1986 were cloudless and of high resolution. This set provided complete coverage of the study area. The photos provided good resolution of surface fracturing and faulting as well as both recent and older, heavily vegetated, lava flows and vents. The approximate scale of the photos is 1:26,000. A second set of photos was shot by INETER in February, 1996 at a scale of 1:40,000. This set was also cloudless and of high quality. Coverage was limited to a single E-W flight line through the center of the Concession. However, because of the smaller scale, most of the important geologic features within the Concession were covered. A detailed report by TGC (TGC, 1996) covering the remote sensing study was submitted to INE in 1996.

8.2 Interpretation

Faulting and fracturing in the aerial photography was made visible due to several phenomena including (1) cross-cutting of regional dendritic drainage patterns; (2) cross-cutting of radial drainage from circular volcanic cones; (3) truncation or offset of recent volcanic features; and (4) lineaments of contrasting vegetation density and type as compared to the surrounding area. Faults and fractures, mapped using these indicators, are shown in Figure 24 (TGC, 1996).

The east flank of Volcán El Hoyo contains at least two lineaments which cross the radial drainage pattern. These features can be traced continuously for several kilometers. They are made visible primarily by slight variations in vegetation density and by a break in slope which is clearly seen when the photos are viewed stereoscopically. Likewise, Cerro Colorado is transected by at least three NNE and N-trending faults. Erosion patterns in the central part of this cinder cone appear to be controlled by the faulting.

The radar images proved valuable in identifying regional fault and fracture lineaments which, because of their relatively great length size and subtle appearance, were not readily apparent on larger scale aerial photos. The older calderas, which have been significantly eroded and partially blanketed by subsequent ash falls, are most clearly discernible in the radar imagery, as compared with the aerial photos or Landsat.

Two sets of faults, one trending NE through the Monte Galán Caldera and the other trending NNW on the NE flank of Volcán El Hoyo, are the most significant of these features. The NNW-trending faults on El Hoyo appear to be an extension of the NW-trending fault related to production at the Momotombo geothermal field located on the south flank of Volcán Momotombo at the Lago de Managua shoreline. Microearthquake records tend to support this relationship as seen in Figure 24.

The RadarSat image was very useful in differentiating between, and determining, the sequence of overlapping lava flows, particularly when covered with vegetation.

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Though the mapping of flows was not the focus of this study, it was evident that this image would be the most useful for this purpose, as compared to the other image types used in this study.

Seven frequency bands are available in the Landsat image ranging from Band 1 (blue) to Band 7 (near-mid-infrared). Two types of images were examined: images derived from various ratios of bands and images using different combinations of three of the available seven bands.

Images using various band ratios were examined for the purpose of identifying areas of hydrothermal alteration. After examining several band ratios, and comparing them with areas of known hydrothermal alteration within the study area, it was concluded that the ratio images were not effective in the soil condition of the Concession area.

Various three-band combinations were examined. The combination of bands 4, 2, and 1 proved to be highly definitive for areas of hydrothermal alteration. Band combination 7, 4, and 1 was found to be the most definitive for mapping faults and fractures. These two band combinations were used for all the TM image interpretation.

Areas of known hydrothermal alteration and active fumaroles, such as the summit craters of Volcán El Hoyo, Momotombo, and Cerro Negro, are distinguished as areas of medium dark to pale blue and white in the 4, 2, 1 band image (Figure 23). The area where soil was exposed as a result of agricultural activity had a similar color signature. These areas were generally distinguishable from the fumarolic areas by the clear indication of field boundaries, fence lines, and the large size of contiguous areas, whereas the fumarolic areas were generally small, irregularly shaped, isolated and surrounded by dense vegetation.

When compared with both the RadarSat image and aerial photos, the TM image in band combinations 4, 2, 1 and 7, 4, 1 was the most definitive image for mapping both regional and local faults and fractures. The TM-mapped faults fall into two general groupings similar to those mapped from the aerial photos (Figure 24), i.e., NW-trending and NE-trending groups. The NE-trending faults passing through Cerro Colorado are associated with active fumaroles and areas of hydrothermal alteration discussed above.

A merged image of the RadarSat and TM (bands 4, 2, 1) was made using the Arcinfo image processing software. The merged image was not as effective as the individual images in discerning faults, fractures, and hydrothermal alteration. This may be due to a slight misalignment of the rectified images causing a loss of definition of linear features. Color definition and contrast of the fumarolic areas were also lost in the merged image.

9 MICROEARTHQUAKE MONITORING

Two sets of microearthquake (MEQ) data were used for this study. A USGS survey covering all of western Nicaragua was conducted in 1975 through 1980 and recorded numerous events in the TGC Concession area. This data set was made available to TGC by Dr. Randall White of the USGS in Menlo Park.

A more precise set of MEQ data was collected with a twelve-geophone array by Dr. Paul Kassameyer of Lawrence Livermore National Laboratory (LLNL) in March and April of 1996 in the TGC El Hoyo-Monte Galán Geothermal Concession. Ninety six events were mapped during the nineteen-day deployment of the monitoring system. These events, together with the 1975-80 USGS data, are shown in Figure 24. Dr. Kassameyer's group is continuing to make more detailed analyses of this data set to define focal mechanisms and possible geothermal features that may be discernible by such parameters as P-wave delay.

Two distinct clusters of earthquakes within the TGC Concession are observed from both the USGS and Kassameyer data (Figure 24A). A third cluster is associated with the Momotombo geothermal field adjacent to the SE edge of the Concession. The most concentrated and shallowest of the clusters within the Concession is centered under the NE flank of Volcán El Hoyo, just below the NE rim of Cerro El Picacho. The second, more diffuse group, is observed below Cerro Colorado. When viewed in cross section, it appears that the Picacho group is slightly shallower (3-12 kilometer depth) than the Cerro Colorado group (5-15 kilometer depth) (Figure 25A). When viewed parallel to the main volcanic axis trending N54W, it can be seen that the seismicity correlates very closely to the expected near vertical magma conduits feeding the main eruptive centers in the Concession area (Figure 26). The seismicity for all the groups is nearly absent below a depth of 15 kilometers. This may correspond to the depth where temperature is sufficient to promote plastic deformation or partial melting.

Seismicity for both these groups seems to persist over time, with numerous events recorded by surveys that were separated by twenty years. After that 20-year interval, the 19-day survey by the Lawrence Livermore group recorded 96 events that correlated closely with the USGS clusters. This persistence over time and space shows that the fracturing is a continuous process. Figure 26 shows that the MEQ clusters correlate very closely with GM, SP and resistivity anomalies seen in Profile 3 that are clearly associated with active hydrothermal systems. The MEQ distribution indicates, therefore, that permeable fractures may not only extend to depths as great as 15 kilometers, but also that they are constantly being renewed.

10 GAS GEOCHEMISTRY

A total of six gas samples were taken from fumaroles in Cerro Colorado and from the areas of steaming ground on the upper east slope of El Hoyo. These samples were analyzed by Thermochem of Santa Rosa, California. Results from the samples taken on the upper slopes of El Hoyo showed that the samples consisted almost entirely of air and were therefore not suitable for calculation of gas geothermometers. These results are nearly identical to those

obtained in the gas study performed by OLADE in 1982. Both sets of data indicate that the source of the steam on the upper slopes of El Hoyo is meteoric water that is circulating to the shallow hot rocks within the El Hoyo volcano and then expelled as steam with the dissolved air being released at the surface. In contrast, two samples taken in Cerro Colorado, CC-1 and CC-3 had less than 0.7 percent air contamination. These samples consisted primarily of CO_2 and H_2S . The hydrogen sulfide geothermometers calculated by Thermochem indicated reservoir temperatures well in excess of 200°C for both samples.

11 HYDROGEOLOGIC MODEL

Figure 26 shows a consistent cross-correlation between the GM, SP, resistivity, ground temperature and seismicity. The GM surveys show areas of intense hydrothermal alteration at depth. The SP surveys indicate which of these areas contain currently active hydrothermal systems. The resistivities lows indicate zones of hot water upwelling and hydrothermal alteration. The seismicity shows that the shallow fracture systems identified by the surface geophysics may persist to depths of several kilometers.

A hydrogeologic model can be derived from the above observations by using data from deep drilling results in the adjacent Momotombo geothermal field. At the Momotombo field, temperatures of 250°C are reached at a depth of 500 meters and temperatures of 350°C are reached at a depth of 2 kilometers, as shown in Figure 26. The system is recharged by cool ground water which penetrates to depth from the south and east and intersects the deep fracture system which is maintained by the ongoing seismicity. The fluid is heated as it approaches the hot volcanic conduits of recently erupted magma. The fluid then rises along the near-vertical fracture system to shallow depths.

Based on these observations, it can be inferred that the adjacent areas in the TGC Concession of similar seismicity, volcanic structure and activity, geophysical anomalies and hydrothermal surface manifestations will contain similar hydrothermal plumes. In Figure 26 the isotherms are extrapolated from the Momotombo field to the TGC Concession, based on this correlation. Two major plumes within the TGC Concession are therefore inferred, one beneath Cerro Colorado and one beneath El Hoyo-Picacho. The magmatic heat source for the geothermal systems is derived from a zone of partial melting at a depth of about 15 kilometers, as defined by the lower boundary of seismicity. Narrow conduits lead upward to intermediate depth magma chambers in the 5-10 kilometer depth range. Conductive and convective heat flow from these cooling magma chambers supplies heat to power the overlying shallow hydrothermal systems. Recharge of these shallow systems comes from the valley separating the two systems and which contains an abundant ground water flow.

At depths of less than two kilometers, the hydrothermal system is controlled by fracture permeability in near-vertical faults. These faults have well defined geophysical signatures and represent the prime production and injection drilling targets. Permeable stratigraphic units and horizons within the volcanostratigraphic section provide lateral flow paths for the vertically migrating fluid, thereby creating laterally extensive plumes such as those observed at Momotombo and on the east flank of El Hoyo. These plumes also represent production drilling targets.

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According to the proposed model, at least two areas of intense vertical fracturing within the Concession are identified as potential drilling targets. The larger of the two areas is the summit and flanks of Volcán El Hoyo. This area contains surface manifestations including fumaroles and hydrothermally altered ground, which extends approximately 5 kilometers in the E-W direction and 3 kilometers in the N-S direction. Plumes of hot ground water extend from this summit area to at least the eastern base of the volcano. The internal thermal structure of the volcano is not known. However, the geophysical surveys clearly defined specific fractures within the central part of the volcano that are hydrothermally active. Drilling into the central part of the El Hoyo massif reduces the possibility of drilling through a stratigraphically controlled hydrothermal system which might produce a temperature reversal.

The second major hydrothermal system, Cerro Colorado, though much smaller at the surface as compared to El Hoyo, is nonetheless associated with a deep earthquake cluster and therefore may be vertically extensive. Surface manifestations, including fumaroles, hydrothermal alteration, and exposed fault scarps, cover an area of approximately 1.5 square kilometers. The Cerro Colorado system appears to be elongated in the NNE-SSW direction. The system projects along this trend to the El Odraje Hot Springs located 3 kilometers to the SSW. These hot springs may represent an outflow from the Cerro Colorado system.

A third hydrothermal plume may exist below the Monte Galán caldera. The very strong SP and GM anomalies seen at the southern rim of the caldera point to this possibility. Poor access to the feature prevented more extensive geophysical exploration within the allotted budget. It is therefore not known whether the hydrothermal system indicated at the south edge actually extends further around the ring fracture system associated with the topographic caldera rim. The position of the relatively young and uneroded cone, Cerro Montoso, on the western caldera rim, is evidence that there is significant structural weakness associated with the rim. This would be highly conducive to the development of shallow hydrothermal systems.

12 PRELIMINARY SLIMHOLE DRILL SITES

Preliminary slimhole drill sites were chosen to test areas with the strongest geophysical anomalies and most consistent correlation between surveys. A total of eight possible sites were chosen as shown in Figure 28. Sites 1-4 will be recommended to test the extent, continuity and depth of the thermal structure in the summit area of El Hoyo and Picacho. Site 4 is situated specifically to test for the existence of a thermal anomaly associated with the dense earthquake swarm located at that site in the depth range of 3-5 kilometers. Site 5 may be used to test a hydrothermal system associated with the inferred fault at the eastern base of El Hoyo.

The NNE-SSW trend associated with the hydrothermal and seismic activity at Cerro Colorado may be tested with holes 6 and 7. The ring fracture system of the Monte Galán caldera could be tested with hole 8. The slimholes will be drilled using a coring rig and will be drilled to a depth of approximately 1000 meters. The wells will be designed to be

flow-tested in the event that production zones are encountered. It is expected that temperatures well in excess of 200°C will be encountered at all the proposed well sites.

13 PRELIMINARY WELL FIELD DEVELOPMENT STRATEGY

13.1 Production Drilling Strategy

Initial siting of full diameter exploration wells will be based on the results from the slimhole drilling. Temperature and gradient data from the slim holes will determine the target depth and whether or not directional drilling will be used initially. For the El Hoyo geothermal system, production wells will be targeted to fractures contained in the area of the north flank of the summit, extending NE to the rim of Picacho. Initially a target depth of 2000 meters will be used.

Several areas of flat or gently sloping topography are available to the south and east of the Picacho rim for use as well pad sites. Several access road routes of relatively low grade are possible, leading up the northern flank of El Hoyo to the Picacho drilling area.

Full-diameter exploration wells in the Cerro Colorado system will be targeted to intersect the NNE-SSW trending fracture system at a depth of 2000 meters. This can be accomplished by drilling a vertical hole from the interior of the Cerro Colorado eruptive feature or by drilling a directional hole from outside the rim of the feature. The chosen strategy will be based on results of the slimhole drilling, which will determine the drilling conditions in the top 1000 meters of the section.

The Monte Galán ring fracture system can be drilled from the northeast base of Cerro Montoso, outside the caldera rim. This area can readily be reached by building an access road from El Lagartillo over low-relief terrain.

13.2 Injection strategy

Two possible injection strategies may be pursued within the Concession. Relatively shallow injection can be developed in permeable stratigraphic units and horizons that form the lateral outflow zones for the vertical hydrothermal systems of El Hoyo and Cerro Colorado. In the case of El Hoyo, the plume at the east base of the volcano may be tested, first by a slimhole and then, if warranted, by a full-diameter injection well. In the case of Cerro Colorado, shallow injection zones may be encountered in the SSW extension of the hydrothermal system in the direction of the El Obraje hot springs.

The advantage of injection into the shallow outflow plume is that the wells will be relatively inexpensive. The disadvantage is that if the hydrologic gradients are reversed due to production, as is often the case, the injectate may return to the production zone, thereby cooling it.

Injection into fractured targets, deeper than the production zones can be utilized. This has the advantage of reducing the risk of thermal breakthrough. The much denser injectate will tend to descend deeper into the reservoir from the injection zone because

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of the large density differential, as compared to the hot reservoir fluid. Nonetheless, full pressure support can be expected. Deep injection wells are relatively expensive, but some of the cost may be compensated for by shorter injection lines at the surface. This is because the production and injection wells may have the same or physically close locations.

13.3 Power Plant Siting

Possible power plant sites for the El Hoyo resource area are found in the relatively moderate slopes of the El Hoyo northern flank (Figure 29). With the power plant placed at the highest elevation possible, without getting into the steep upper slopes, gathering system piping can be kept to distance of 1.5 kilometers or less. The final power plant siting will involve a complex optimization process which will take into account surface piping costs, site excavation and road building costs, directional drilling costs and transmission line costs.

Power plant siting in the Cerro Colorado resource area will be much simpler than for El Hoyo, due to the abundance of relatively flat terrain within and surrounding the drilling target area.

14 PRELIMINARY ESTIMATE OF ELECTRICAL GENERATING CAPACITY WITHIN THE TGC CONCESSION

Computation of recoverable electrical energy is normally conducted either by (1) reservoir testing or (2) by using a volumetric reservoir analysis. The former approach is utilized when a number of production wells exist and an interference test is conducted for a sufficiently long time to assess the reservoir hydraulic characteristics and effective volume. The latter approach is utilized when no well testing data is available, but there is a sufficient body of geological and geophysical data which permits an estimate of the areal extent and depth and hence volume of the reservoir. In this report we utilize the volumetric reservoir approach, because no deep exploratory wells have yet been drilled in the Concession. However, we should add a word of caution that a volumetric analysis usually indicates a maximum potential. It serves as a useful guide to determine the maximal development that can take place, assuming that actual drilling proves that the permeability and transmissivity of the reservoir meet economic criteria.

White (1965) has stated that for the typical rocks in a geothermal reservoir, the following volumetric specific heats may be utilized: For rocks near 100° C - 0.6 cal/cm³; for rocks near 300°C - 0.7 cal/cm³. In our analysis we utilize a specific heat of 0.65. We conservatively assume that the average reservoir temperature is only 250° C. Hence, the calorific stored heat in one cubic kilometer of rocks is

$$\text{Calorific heat in } 1 \text{ km}^3 = 10^{15} \text{ cm}^3 \times 235^\circ\text{C} \times 0.65 = 1.527 \times 10^{17} \text{ calories}$$

Nathenson and Muffler (1975) utilize published data on conversion efficiencies of heat energy into electrical energy for hot-water geothermal systems. They show that this conversion efficiency is in the range of 10% for reservoirs in the 200-250°C, and 12% for

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reservoirs in the 250-300° C. They further assume that 25% of the calorific heat stored in the rocks will be extracted by the water flowing through the rock over the life of a geothermal project.

The recovery factor of the stored heat as electrical energy is the product of the conversion efficiency and the recoverable heat energy. The recovery factor for reservoirs in the 200-250° C is about 2.5%. For reservoirs in the 250°-300°C the recovery factor is 3%. This assumes that 50% of the reservoir is accessible to porosity and that half of this will be recovered, for a total recovery of 25% of the thermal energy.

The total theoretically recoverable electrical energy, E, has been defined by Nathenson and Muffler (1975) as:

$$E = 1327 \times Q \times R \quad (1)$$

Where

E = Theoretically recoverable electrical energy, in MW-centuries

Q = stored heat in the reservoir, in 10^{18} cal units

R = recovery factor.

For reservoirs in the temperature range of 250°C, and a recovery factor is 2.5%, equation (1) reduces to:

$$E = 1327 \times 0.1527 \times 0.025 = 5.06 \text{ MW-centuries per km}^3.$$

Or,

$$E = 33.175 \times Q \text{ MW-centuries per km}^3 \quad (2)$$

$$\text{Or,} \quad E = 16.87 \text{ MW for 30 years per km}^3 \quad (3)$$

14.1 Estimate for the El Hoyo Geothermal Field

Surface hydrothermal manifestations and intense geophysical anomalies have an areal extent of at least five kilometers in the E-W direction and three kilometers in the N-S direction as discussed in Section 11. The pattern of ongoing seismicity within the El Hoyo volcanic structure indicates that intense fracturing is taking place to a depth of at least five kilometers below the summit. These observations indicate a possible geothermal reservoir volume of 75 km³ within a drillable depth range. However, for the purpose of this volumetric reservoir capacity calculation, a much smaller volume is assumed. The volume used in this case is the volume which can be tapped by a single well field providing fluid to a single central power plant (Figure 29). In this case the dimensions of the reservoir volume that would be tapped are as follows:

Minimum width = 2 km

Minimum length = 2.5 km

Estimated depth of connected permeable reservoir below 1 km = 3.5 km

Estimated reservoir volume, V, below 1 km depth = 17.5 km³

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Theoretically available electrical energy in the reservoir = $V \times E$

= 295 MW for 30 years

Based upon comparison of the volumetric estimates to the actual exploitation results in developed fields, the economically developable potential has in reality proven to be about 40-50% of the theoretically available electrical energy.

Hence, the estimated economically developable potential of the initial El Hoyo geothermal wellfield is 120-150 MW for 30 years.

14.2 The Cerro Colorado Geothermal Field

For the Cerro Colorado field the following dimensions are used for the volumetric reservoir capacity estimate:

Minimum width - 1 km

Minimum length - 1.5 km

Minimum thickness - 4 km

Estimated reservoir volume, V , below 1 km depth = 3 km³

Theoretically available electrical energy in the reservoir = $V \times E$

= 100 MW for 30 years

Because of the much smaller areal extent of the Cerro Colorado hydrothermal system in comparison to El Hoyo, it is expected that only one wellfield can be developed.

Hence, the economically developable potential of the Cerro Colorado field is estimated to be in the range of 40 to 50 MW for 30 years.

14.3 The Monte Galán Geothermal Field

Due to difficult access and environmental constraints, only limited exploration has been carried out in the Monte Galán caldera. Though the SP and GM data indicate the possibility of a significant hydrothermal system associated with the ring fractures surrounding the caldera, this is not sufficient to provide a basis for a volumetric reservoir capacity estimate. Confirmation of the existence of a hydrothermal system associated with the ring fractures can be accomplished by slimhole drilling along the NW rim of the caldera at the base of Cerro Montoso. This will eliminate the necessity to perform any further drilling or exploration activities within the caldera, which is an environmentally protected area. Likewise, production drilling can be accomplished from outside the NW and SW rim of the caldera by employing standard directional drilling techniques.

14.4 Discussion

Although the above analysis indicates a rather large potential for producing electrical energy from the El Hoyo and Cerro Colorado reservoirs, it is prudent to assume that the commercial feasibility of extracting energy from the reservoirs would be lower than the values calculated above. Taking a conservative approach, we estimate that

the actual producible energy will not exceed one half the total theoretically available electrical energy in each reservoir, i.e., not more than 1.25% of the total calorific energy stored in the rocks would be economically convertible to electrical energy.

A volumetric analysis of reservoir potential is usually a first approach to estimating the potential size of a geothermal field. It serves the exploration company as a first glance at the feasibility of proceeding onwards with the drilling phase.

Actual reservoir capacity and its potential commercial viability cannot be determined until large diameter wells are drilled and tested for a sufficiently long duration, permitting the developer to conduct a long term decline analysis. However, it is clear from the exploration program results to date that the potential of the systems is large and that it justifies carrying out the exploration slimhole drilling program, followed by large diameter production drilling and long-term reservoir testing.

15 SUMMARY AND CONCLUSIONS

- 15.1 The geophysical and geological methods used in the study showed strong and consistent correlations over areas of known hydrothermal activity, in particular on the upper slopes of El Hoyo and in the Cerro Colorado area.
- 15.2 The exploration program also identified possible areas of hydrothermal activity that were previously unrecognized on the NE flank of Picacho and along the rim of the Monte Galán caldera.
- 15.3 The exploration program identified areas of proven and probable hydrothermal activity totaling at least 20 square kilometers within the Concession. Because of the very large areal extent of hydrothermal activity, it is highly probable that a resource capable of sustaining at least 150-200 MWe will be discovered within the TGC Concession. Economic feasibility of development can only be determined with certainty after completion and well testing of slimhole and full diameter exploration wells.
- 15.4 Eight preliminary slimhole drill sites were chosen based on strong correlations between geophysical surveys, surface hydrothermal manifestations, and ongoing seismicity.

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FIGURE 1: REGIONAL TECTONICS AND PROJECT LOCATION

FIGURE 3: GROUND MAGNETIC PROFILE LOCATIONS

FIGURE 4: SELF POTENTIAL PROFILE LOCATIONS

FIGURE 5: ONE METER TEMPERATURE PROFILE LOCATIONS

FIGURE 6: MTCSAMT PROFILE LOCATIONS

FIGURE 7: SP, GM, MT/CSAMT AND ONE-METER TEMPERATURE PROFILE 1

FIGURE 8: SP, GM, MTCSAMT AND ONE-METER TEMPERATURE PROFILE 2

FIGURE 9: SP, GM, MTCSAMT AND ONE-METER TEMPERATURE PROFILE 3

FIGURE 10: SP, GM, MT/CSAMT AND ONE-METER TEMPERATURE PROFILE 4

EL HOYO - MONTE GALAN
GROUND MAGNETIC PROFILE
LINE 5

FIGURE 11

EL HOYO - MONTE GALAN
SPONTANEOUS POTENTIAL AND GROUND MAGNETIC
LINE 13 AND 13A

FIGURE 12

EL HOYO - MONTE GALAN
SPONTANEOUS POTENTIAL AND GROUND MAGNETIC PROFILES
LINE 6

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FIGURE 13

EL HOYO - MONTE GALAN
SPONTANEOUS POTENTIAL, GROUND MAGNETIC, 1-M TEMPERATURE PROFILES
LINE 7

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FIGURE 14

EL HOYO - MONTE GALAN
SPONTANEOUS POTENTIAL AND GROUND MAGNETIC PROFILES
LINE 8

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FIGURE 15

EL HOYO - MONTE GALAN
SPONTANEOUS POTENTIAL, GROUND MAGNETIC, AND 1-M TEMPERATURE PROFILES
LINE 9

FIGURE 16

EL HOYO - MONTE GALAN
GROUND MAGNETIC PROFILE
LINE 10

FIGURE 17

EL HOYO - MONTE GALAN
GROUND MAGNETIC PROFILE
LINE 11

FIGURE 18

EL HOYO - MONTE GALAN
GROUND MAGNETIC PROFILE
LINE 12

FIGURE 19

EL HOYO - MONTE GALAN
SPONTANEOUS POTENTIAL AND MAGNETIC PROFILES
LINE 14

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FIGURE 20

FIGURE 21: GROUND MAGNETIC CONTOUR MAP

FIGURE 23: MTCSAMT RESISTIVITY CONTOUR MAP

FIGURE 25: SEISMICITY CROSS SECTION A-A'

FIGURE 25A: SEISMICITY CROSS SECTION B-B'

FIGURE 26: CORRELATION OF SEISMICITY WITH LINE 3 GEOPHYSICS

FIGURE 27: EL HOYO-MONTE GALAN HYDROGEOLOGIC MODEL

FIGURE 28: PRELIMINARY SLIMHOLE DRILL SITES

FIGURE 29: POSSIBLE POWER PLANT AND PRODUCTION AND INJECTION WELLFIELD SITES