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SUMMARY REPORT

ASCENSION #1 EXPLORATORY WELL AND GEOTHERMAL POWERPLANT ECONOMICS, ASCENSION ISLAND, SOUTH ATLANTIC OCEAN

Prepared For

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1.0 ABSTRACT

This report summarizes the results of geothermal exploration and drilling and testing of a deep test well on Ascension Island in the South Atlantic Ocean. The U.S. Air Force is interested in reliable, economic methods to produce power and potable water on Ascension and geothermal energy would satisfy that objective. Geothermal development would be invulnerable to disruption due to external economic or political factors, a distinct advantage for critical U.S. Air Force operations on this remote island.

The siting and drilling of the Ascension #1 well was the culmination of an exploration program that began in 1982. The well was started on August 3, 1986 and terminated on January 23, 1988. Ascension #1 intersected geothermal fluids at several levels below a depth of 8000 feet. The temperatures of these fluids are in the upper range of commercial geothermal reservoirs at similar depths. However, the volume of fluid flow was limited. While attempting to improve production by drilling a second leg, a mechanical failure resulted in loss of the well.

Economic analyses indicate that replacement of the existing diesel power generating equipment with a geothermal power plant could result in savings of as much as $112 million over the primary replacement alternative, a gas turbine. A geothermal power plant offers the additional advantage of producing about three times the current U. S. potable water demand on Ascension. On the basis of the discovery of a geothermal resource and excellent economic factors, continued drilling is recommended. An independent of panel of industry experts verified the high resource potential and recommended continued drilling.

2.0 INTRODUCTION

Ascension Island is part of the United Kingdom and is governed by an Administrator who reports to the Governor of the Island of St. Helena. The island serves as the South Atlantic Relay Station of the British Broadcasting Corporation (BBC) which is the largest British user of the island. It is also an important station of Cable and Wireless, Ltd. and several installations of the Ministry of Defense (MOD). During and since the Falklands War, the island has been an important base for Royal Air Force (RAF) operations in the South Atlantic.

The U. S. Air Force has leased a portion of Ascension and maintains the airfield and numerous tracking facilities. The base is part of the Eastern Space and Missile Center (ESMC) that is commanded from Patrick Air Force Base, Florida.

The island has no indigenous population, and it has no commerce. U. S. personnel are largely housed and fed on the U. S. base. There are two grocery stores in the British settlements of Georgetown and Two Boats. However, there are no restaurants, motels, or other services that one would expect to find in most areas of the world.

Regularly scheduled ships serve Ascension from the U. K. and South Africa. However, these ships are small. Mobilization of a drilling rig requires special shipping arrangements. The dock facilities are primative. Ships must be anchored offshore and cargo loaded onto barges for transportation to an unprotected dock. There, the cargo must be lifted by crane onto the dock. The weight limit for this operation is 30,000 pounds.

Air service to the island is provided twice a week by USAF C-141B operated out of Patrick Air Force Base, Florida. During the geothermal project, this was the primary means of moving crews and emergency supplies to the island. The island is also served once a week by an RAF L-1011 that uses Ascension as a refueling stop between the U.K. and the Falklands.

The total electrical requirement of Ascension is about 10 MW with a U. S. peak demand of about 3.5 MW. The U. S. and British maintain separate power generation facilities and different cycle distribution systems. Both use standard diesel-powered generators. However, the U. S. actually burns jet fuel that has been degraded with motor oil. The waste heat from these generators is used to desalinate sea water for domestic uses, there being no fresh water resource on the island.

3.0 RESOURCE ASSESSMENT

Ascension Island is located in the South Atlantic Ocean approximately 100 km to the west of the active spreading center of the Mid-Atlantic Ridge (Fig. 1). The island is volcanic in origin, and recent authors have characterized it as the most active volcano in the South Atlantic (Brozena, 1986). The drilling of Ascension #1 is the culmination of a geothermal exploration program which has been conducted for the U. S. Air Force by the Department of Energy since 1982.

3.1 SUMMARY OF EXPLORATION ACTIVITIES

Initial exploration efforts on the project involved the detailed geologic mapping of Ascension Island (Nielson and Sibbett, 1982). This initial work concluded that, although there were neither hot springs nor fumaroles present, the potential for discovery of a high-temperature geothermal system was high. This conclusion was based on the young age of the volcanic activity and the presence of rhyolite dome complexes which imply a viable heat source for geothermal systems at depth.

Geologic mapping was followed by geophysical exploration utilizing electrical resistivity, aeromagnetic, and temperature gradient surveys. Results of the electrical resistivity surveys are presented in Ross et al. (1984a) and Ross et al. (1984c). The second report describes supplemental

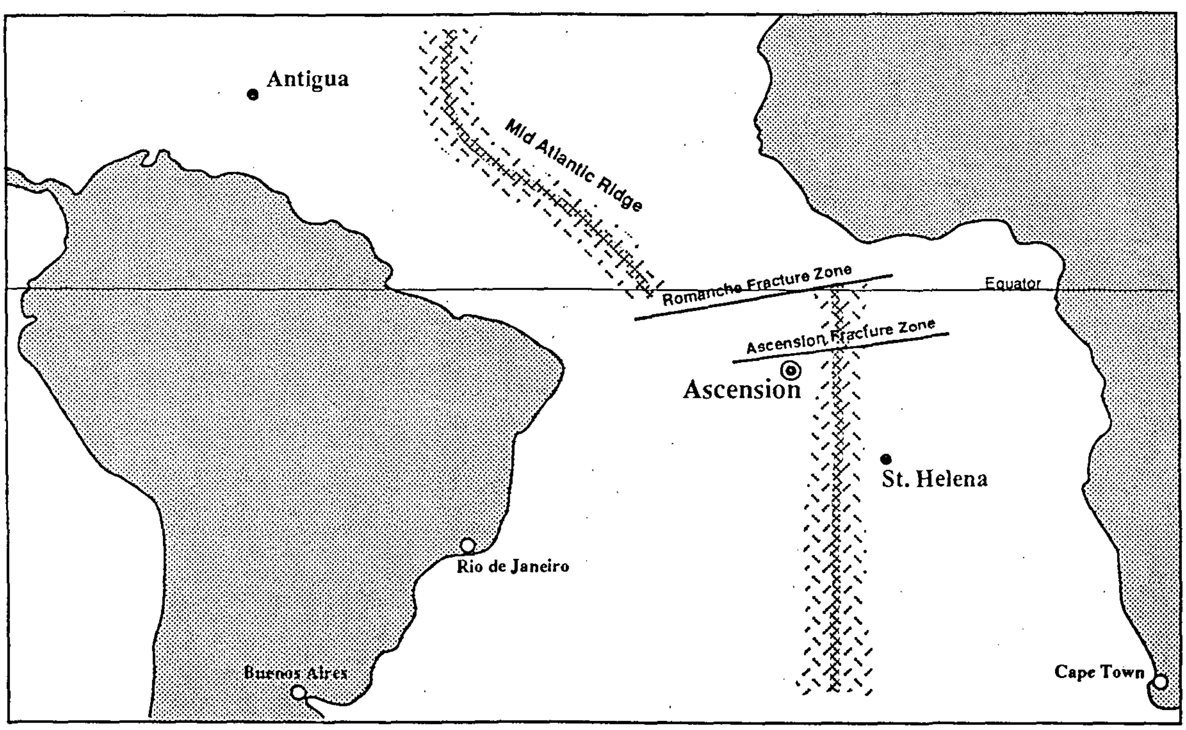

Figure 1. Location map of Ascension Island.

surveys which were completed following temperature gradient drilling. Both sets of surveys identified areas of lower electrical resistivity to the south of the present location of the Traveller's Hill RAF base (Fig. 2). Due to the small size of Ascension Island and the surrounding conductive seawater, it was not possible to model results deeper than 2500 feet.

During 1983, a detailed aeromagnetic survey was conducted over Ascension (Ross et al., 1984b). This method was used to define buried fault and dike trends and is based on variations in magnetic signature of rocks encountered. An irregular area that contained low magnetization and demonstrated considerable structural complexity was defined. This area corresponded with zones of low electrical resistivity, and it was concluded that this was the most likely place for a geothermal system in the depth range of 3000 to 9000 feet.

Results from the geologic, electrical resistivity, and aeromagnetic surveys were used to site temperature gradient holes. These holes were drilled with a Longyear 44 core rig operated by Tonto Drilling Services of Salt Lake City. The results of this drilling and subsequent temperature gradient measurements are described in Sibbett et al. (1984). The locations of the temperature gradient holes are shown in Figure 2. Figure 3 shows the thermal profiles from these holes and clearly demonstrates the higher temperature gradients in the vicinity of GH-1, 2, 6 and LDTGH. GH-2 is located in the eastern portion of the island at a much greater distance from the U. S. base and in an area with difficult access, which relegated it to

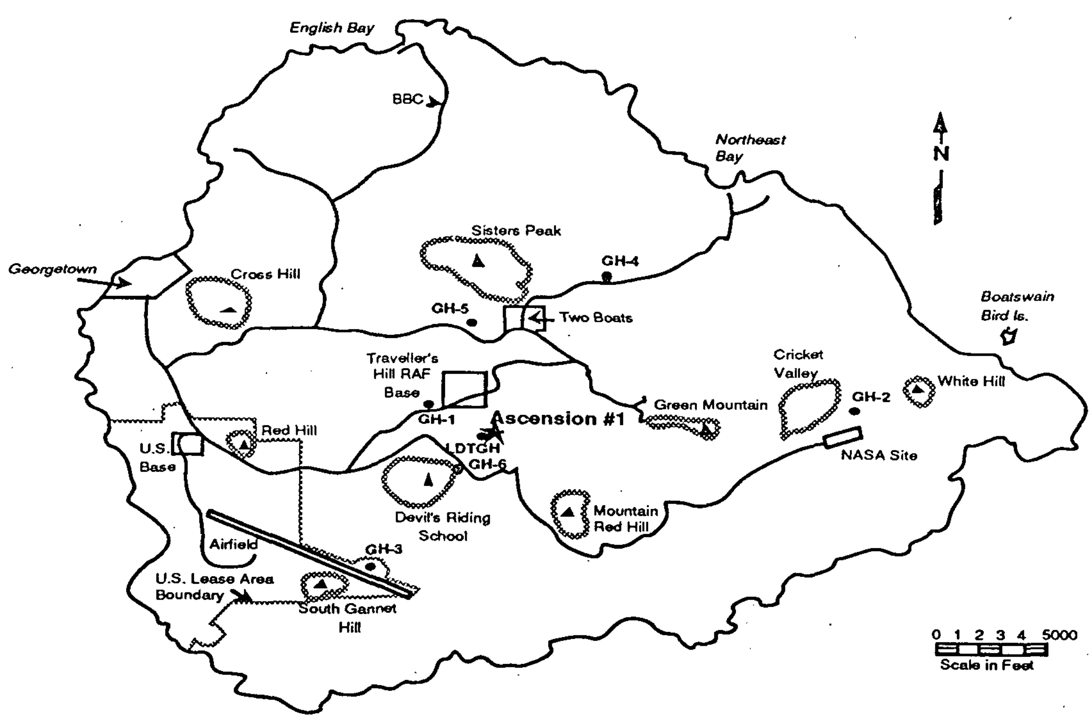

Figure 2. Map of Ascension Island. Location of temperature gradient holes are shown with solid circles.

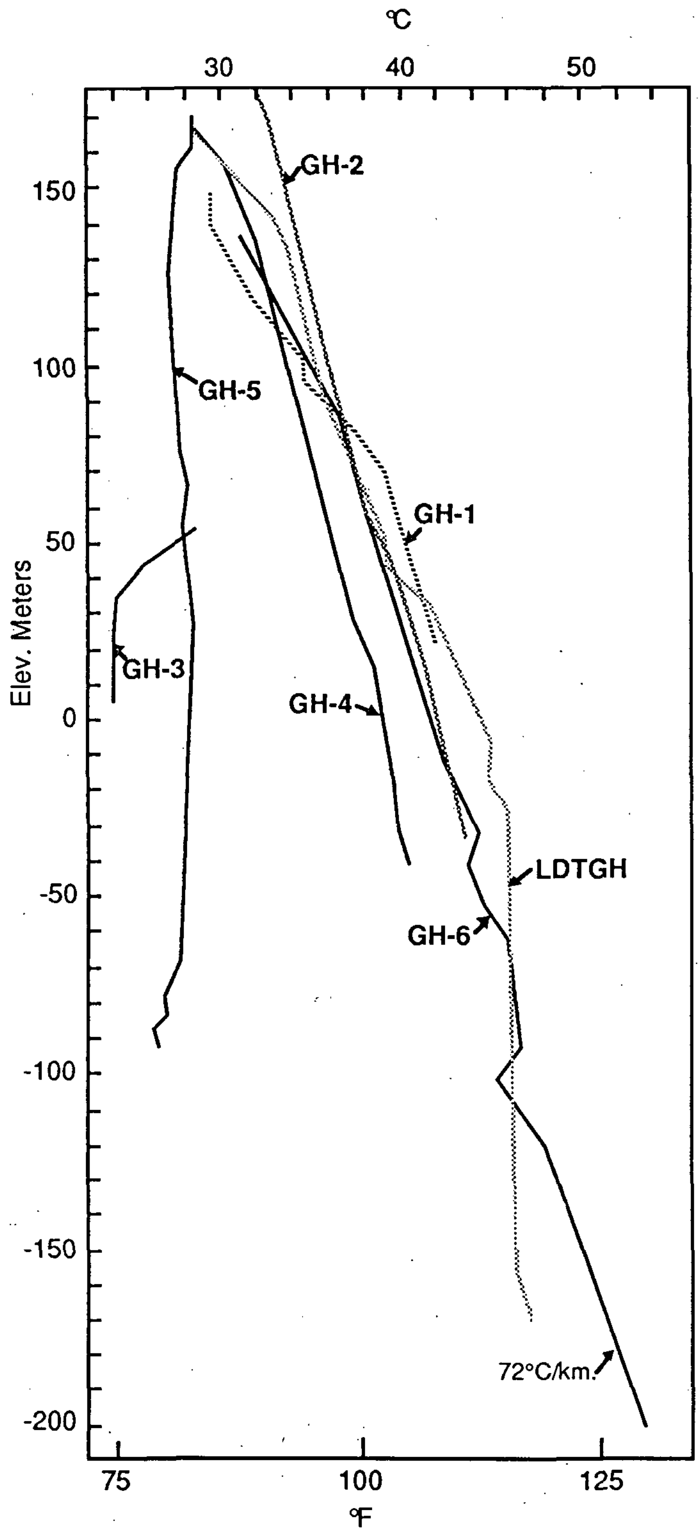

Figure 3. Temperature gradient profiles measured on Ascension Island. Depths shown as elevation with respect to sea level.

a second priority exploration site. The area around GH-1, 6, and LDTGH corresponded with low electrical resistivity anomalies, the structural complexity identified by the aeromagnetic surveys, and favorable geologic indicators, and was chosen as the site for Ascension #1. The remainder of this report discusses the results from Ascension #1.

3.2 WELL DRILLING

3.2.1 Introduction

Ascension #1 was initially planned and budgeted to be drilled to a depth of 5000 feet. It was anticipated that fluid at a temperature of 300°F would be encountered at this depth and that this fluid would require pumping to the surface. The well did achieve the predicted temperature at 5000 feet, but sufficient water was not present. Drilling continued and eventually reached a depth of 10,255 feet. The temperature at this depth was over 480°F, and fluid was present, but not in the quantities required to support geothermal power production.

A second leg of Ascension #1 was drilled to intersect the geothermal system at a deeper level and lateral to the first intersect where it was thought that more water would be encountered. This leg was being drilled at a depth of 7345 feet when a mechanical failure at 3868 feet resulted in the loss of the drill string and the abandonment of the well.

The following sections describe the drilling equipment, the drilling of the well, and the well deviation.

3.2.2 Rig Information

Ascension #1 was drilled by Parker Drilling Co. Rig #185. This rig was designed for remote operations and is helicopter transportable. This design proved useful in meeting the 30,000 pound weight limitation imposed by the dock on Ascension Island. The rig was mobilized to Ascension from Manaus, Brazil via the port of Belem.

Rig #185 has a rated capability of 15,000 feet. The rig floor is 21 feet above the ground, and the mast reaches 136 feet above the floor. The mast has a static hook load capacity of 750,000 pounds.

Most of the well was drilled using compressed air and a foam system to provide lubrication and cooling of the bit as well as to remove the cuttings from the well. Three 850 cfm, 200 psi Quincy primary compressors and a Joy 1250 psi, 2400 cfm booster were used. Nova Mud Corporation of Salt Lake City provided both the air equipment and the foam drilling fluids.

Halliburton Services were contracted for cementing operations. Cementing was required to secure casing in place as well as to plug zones of lost circulation. A cement plug was required in the original hole to allow drilling of the second leg.

EnergyLog Corporation of Sacramento, California was responsible for mud logging on the well. This service includes collection and logging of rock chips from the well, as well as continuous monitoring of injection pressure and temperatures and gas content of the outflow, or blooie, line. Monitors with warning horns were established on the rig floor and in the cellar to detect H_2S gas. EnergyLog also provided Scott air packs as a safety precaution in the event of high H_2S emissions.

3.2.3 Well Drilling

A mechanical diagram of the well is shown in Figure 4. As was stated in the Introduction, the well was originally designed to be drilled to a total depth of 5000 feet and to house a downhole pump to be used for the production of geothermal fluids. The original hole was drilled at a diameter of 20 inches to a depth of 173 feet. Casing with a diameter of 16 inches was cemented in this upper hole. The drilling then continued with a 14-3/4 inch bit to a depth of 1760 feet. Casing 11-3/4 inch in diameter was cemented in this hole from the surface to a depth of 1706 feet. During the drilling of the 14-3/4 inch hole extreme lost circulation zones were encountered. These problems resulted from the highly permeable nature of the rock, causing drilling fluid to be lost to the formation rather than circulating back to the surface. This situation required setting cement plugs in the well to seal the zones where loss of fluids was occurring. Failure to cure these problems would have resulted in a poor cement job around the casing.

Sufficient casing had originally been shipped to Ascension to set a 7-7/8 inch liner to a depth of 4000 feet. However, during drilling it was discovered that cooler water was coming into the well down to a depth of approximately 4100 feet. Additional casing was mobilized at that time in order to allow the cooler fluids to be isolated from the hole. The bottom of the 7-7/8 inch casing was set at a depth of 4548 feet. The top of this string was secured with a liner hanger within the 11-3/4 inch casing at a depth of 1406 feet. Cement was then squeezed into the annulus around the 7-7/8 inch casing to secure it in place.

Drilling continued below 4548 feet using 6-3/4 inch bits. During the shutdown in operations to allow mobilization of additional casing and other materials, the decision was made to increase the depth of the well to 6500 feet. Remaining funding for the project allowed the well to be deepened to 8706 feet, at which point the available drill pipe was exhausted. Between 8120 feet and 8545 feet several zones of geothermal production were encountered. These zones were subsequently tested, and the results of this test are discussed in a later section of this report. In general, the zone produced a mixture of CO_2 and water, but the flow was not adequate to support geothermal power production.

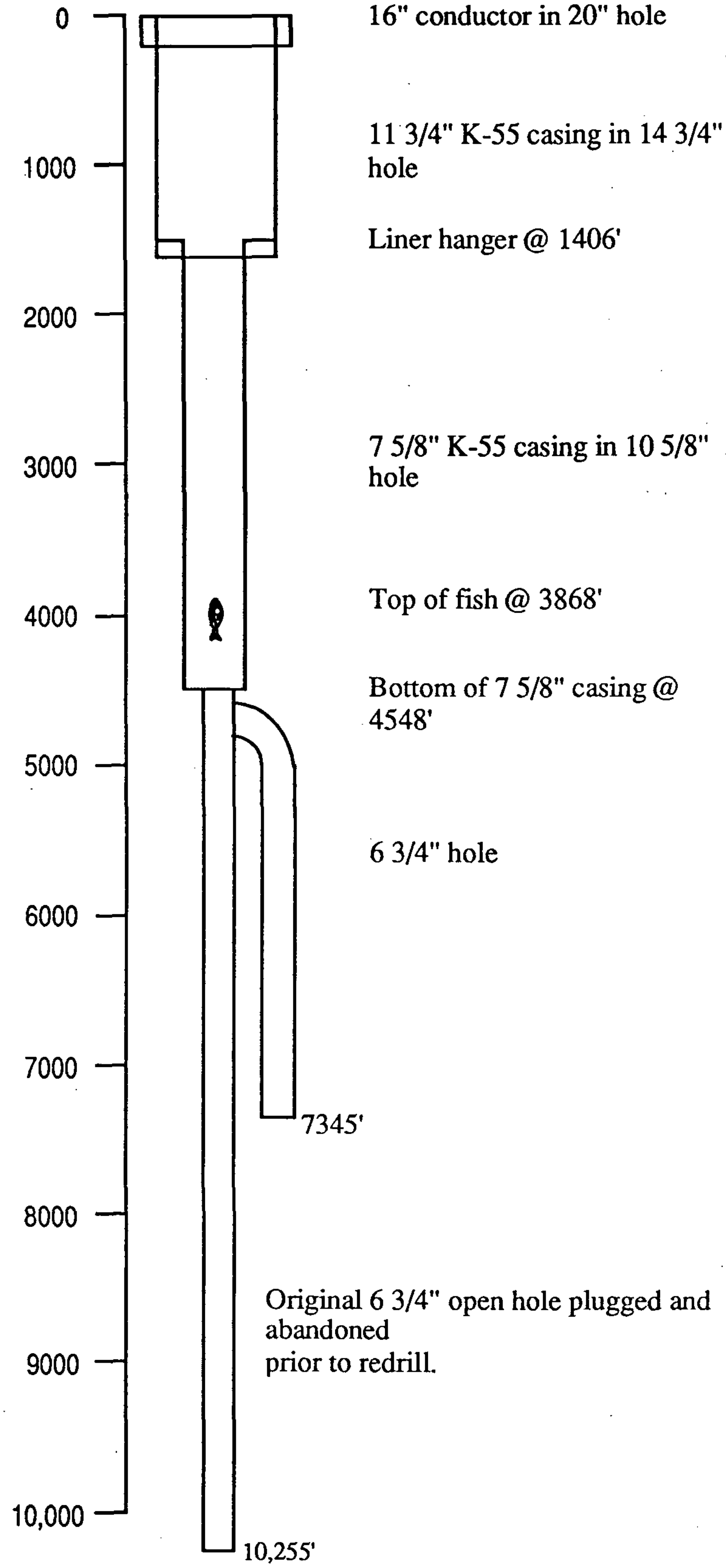

Figure 4. Mechanical diagram of Ascension #1.

Additional drilling was recommended to attempt to improve the quantity of geothermal fluid being produced. A cement plug was set to reduce the flow of CO_2 from the fractures below 8000 feet. The well was then continued at a diameter of 6-3/4 inch to a depth of 10,172 feet. Geothermal fluids were again encountered at depths below 9480 feet. Testing showed that the quantity of fluid from the deeper zones was not sufficient to support commercial production.

An independent review committee[1], whose members represented several geothermal developers, was asked to review the project at this point. The committee recommended "drilling deeper (and/or sidetracking the well) to confirm the existence of a commercial geothermal resource". The committee concluded that "the temperature, CO_2 zone, epidote mineralogy, the two low-productivity zones, and the possible rollover in temperature gradient toward a convective gradient below 8200 feet indicate that a geothermal system may exist. The most probable location for the system is at depths greater than 9700 feet."

Following a shut down in operations to resupply, drilling of the well was continued in an attempt to intersect additional fluids. At a depth of 10,255 feet cones were lost from the drilling bit. This loss of cones from a new bit was caused by extremely corrosive fluids. At this point, it was decided to abandon this particular leg of the well. As will be shown in the section on geology, the drill was probably penetrating the upper portion of a geothermal system with high gas content and low permeability as a result of hydrothermal alteration. Continued exploration of this portion of the geothermal system was felt to have a lower probability of success than drilling into a postulated underlying water-dominated zone. In addition, the corrosive fluids being encountered could have completely destroyed the drill string in a short period of time.

Two cement plugs were set in the well in order to seal it and to provide a point for kicking out of the original hole and drilling a separate leg. The objective of this new leg was to intersect the geothermal zone beneath the sealed gas-rich cap. Directional drilling services for the kick off were provided by Anadrill-Schlumberger. The well was successfully kicked off at 4733 feet using Dynadrill mudmotors. It was the objective of this phase of the drilling to keep the well as near to vertical as possible. Drilling went smoothly until a depth of 7345 feet. At this point the drill pipe broke at a depth of 3868 feet. Attempts to fish the drill pipe from the well were unsuccessful and the well had to be cemented and abandoned.

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[1] Joseph L. Iovenitti, Senior Geologist, Thermal Power Company; D. Stephen Pye, Manager, Drilling Operations, Unocal Geothermal; Anthony J. Menzies, Senior Reservoir Engineer, GeothermEx; John R. Counsil, Consultant (formerly Director, Stanford University Geothermal Program).

3.2.4 Well Deviation

A map of the deviation of both legs of Ascension #1 is shown in Figure 5. The original leg was allowed to deviate in order to explore for fracture zones that host geothermal fluids. Once the character of the reservoir had been identified, the direction of the second leg was controlled in order to intersect the geothermal reservoir in a specific area.

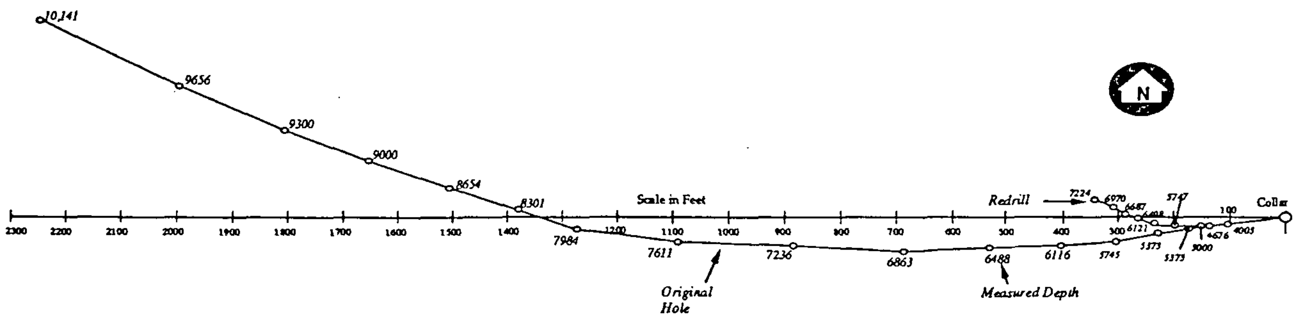

Figure 5. Ascension #1 deviation survey, Map Plan.

3.3 GEOLOGY

3.3.1 Structural Setting

Geological mapping and the aeromagnetic survey emphasized the definition of fault systems that could be the conduits for geothermal fluids. Data from these surveys have been interpreted in terms of a three-part rift system which is shown in Figure 6. Ascension #1 is located within the southwestern rift. The northern boundary of this rift is apparently buried under more recent volcanic rocks. The southern portion of the rift was identified during the geologic mapping as a series of faults and basaltic dikes intruding to the south of the drill site.

When locating Ascension #1, it was assumed that the high thermal gradients encountered in gradient holes GH-1, GH-6 and LDTGH were a result of upward circulation of geothermal fluids from faults which make up part of the rift system. Ascension #1 was located near the gradient hole with the highest temperatures (LDTGH) since no specific fault could be identified which would serve as a drilling target.

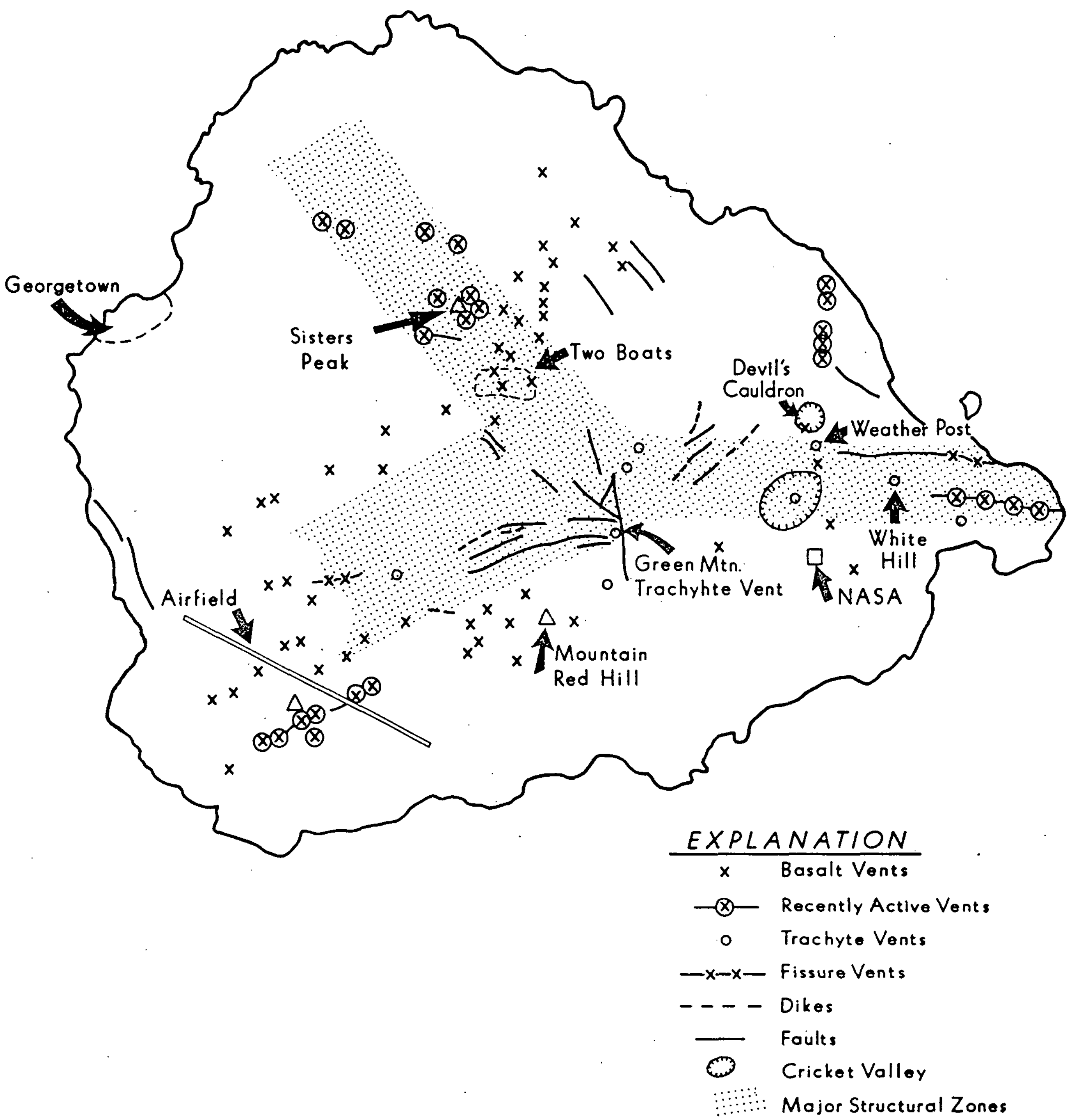

Figure 6. Summary geologic map of Ascension Island.

Figure 7 is an aeromagnetic map of the vicinity of Ascension #1 from Ross et al. (1984b). The aeromagnetic data define the boundary between an area containing rocks with a high magnetic signature to the north and an area of low magnetic signature to the south. Ross et al. modeled this boundary, and the result is shown in Figure 7. It is believed that this signature represents the northern boundary fault of the southwestern rift system. This is the fault zone that is thought to host the geothermal system at depth, and that should be the target of future exploration.

Determination of the orientation of the fault zone that hosts the geothermal fluid is open to interpretation since the faults are not exposed at the surface. Prior to drilling the second leg of Ascension #1, all available data were reviewed and it was concluded that the orientation of the fault zone was N62°E. Two diabase dikes were intersected in both the original hole and the redrill and allow additional constraints to be placed on the fracture orientation. If the dikes are vertical, they have a trend of N75° to N76°E. If the dikes were emplaced in fracture zones with a strike of N62°E as originally predicted, a dip of 52°S would be required. If the dip were 60°,the strike would be N65°E. It is most likely that the dip of the faults is 60-90°; resulting in a strike of the fault zone of N65° to N75°E.

3.3.2 Lithology of Ascension #1

The rock units encountered in Ascension #1 are summarized in Figure 8. Since the units were similar in both legs of the well, only the stratigraphy of the original hole will be described. Between the surface and a depth of 2910 feet, the well passed through a sequence of volcanic rocks that were formed in a subaerial environment. All of the primary felsic volcanic rocks found in the well occur above this point, demonstrating that the bulk of the felsic volcanism is recent in the history of the formation of the island.

Below 2910 feet, the rocks were either deposited in a submarine environment or intruded into their present positions as dikes. The submarine volcanic rocks are largely basalt flows and hyaloclastites, which are the submarine equivalents of basaltic ash. They are generally believed to be indicative of eruption within 1500 feet of the surface of the ocean. As will be discussed in a subsequent section, these rocks have been largely altered due to their contacts with seawater and position within a strong thermal gradient.

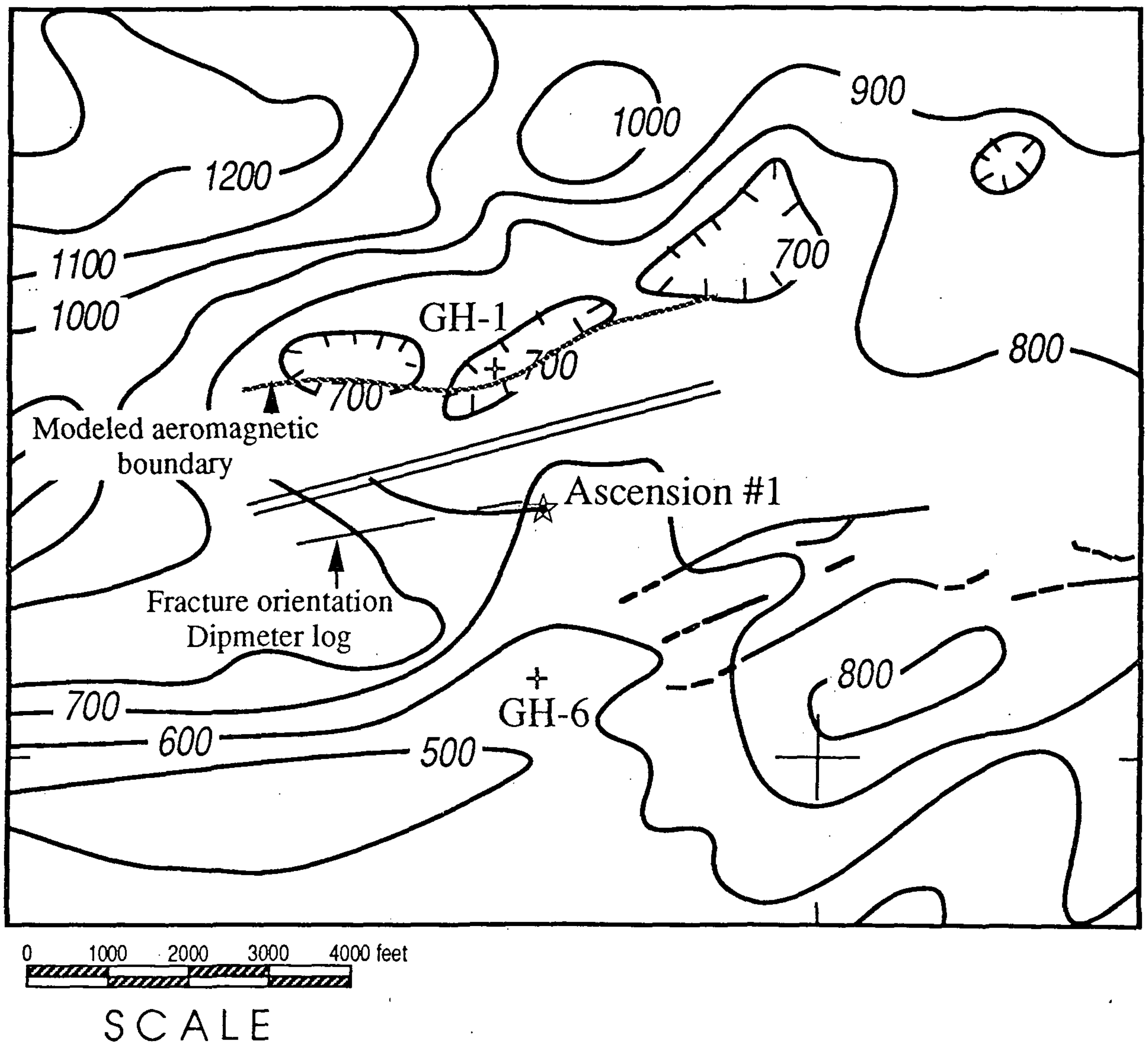

Figure 7. Structural Compilation and Aeromagnetic Map of a portion of Ascension Island.

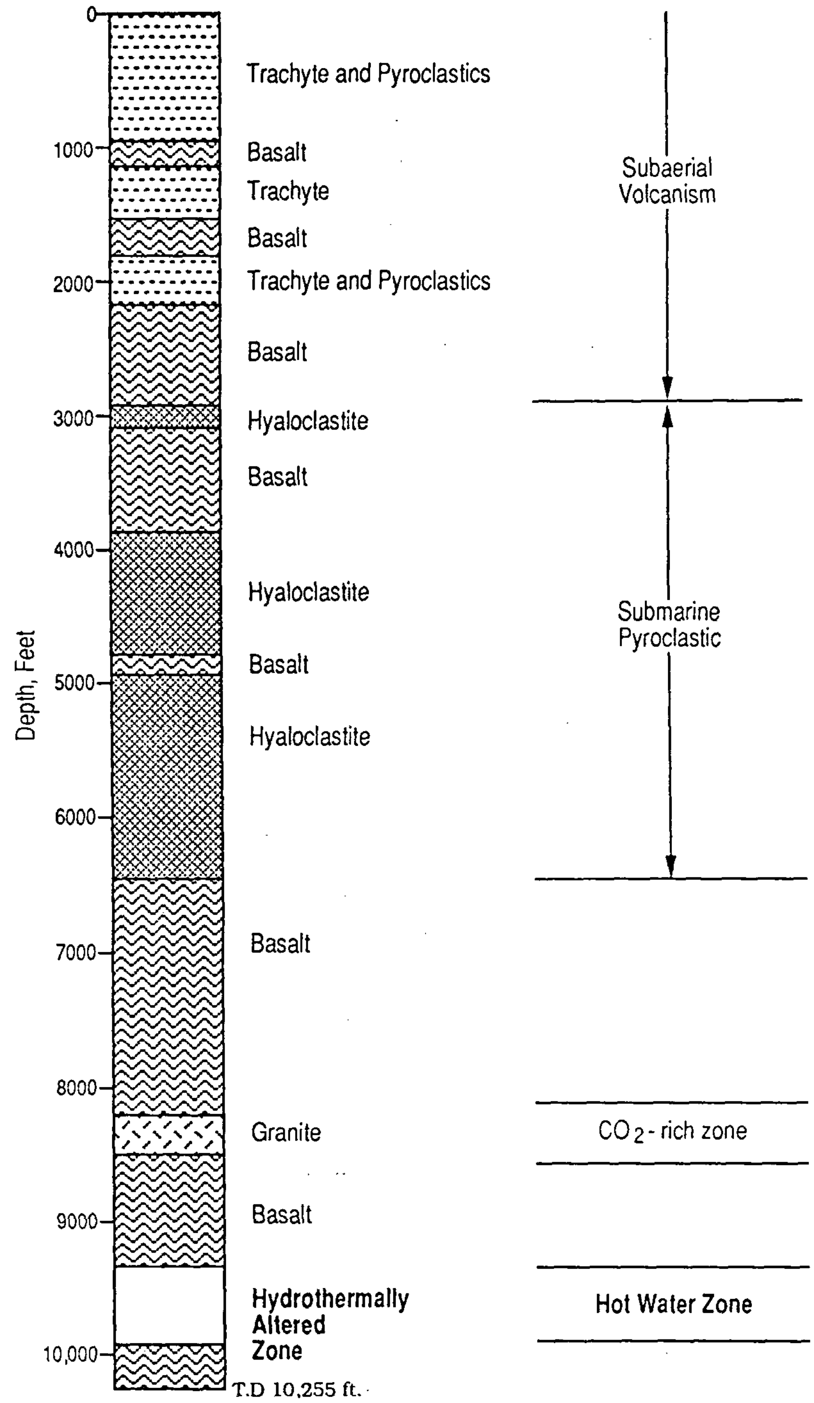

Figure 8. Generalized Stratigraphic Column - Ascension #1.

Below 6450 feet the sequence is largely basalt flows. From the cuttings samples collected, it is difficult to impossible to distinguish between dikes and flows. Therefore, on the generalized stratigraphic column, the lithologic description basalt is given rather than attempting to distinguish the origin of different units.

At 8200 feet the well intersects a dike of fine-grained granite. At the top of this unit and in the overlying fractured basalts, CO_2-rich fluid entries are present. The entries are associated with fracturing as evidenced by cuttings samples, drilling breaks, and geophysical well logs. The lower portion of the granite and underlying basalt section contain relatively few fractures.

At 9350 feet the well intersected a zone of intense hydrothermal alteration which extends to 9680 feet. From 9680 to 9770 feet there is a decrease in alteration, but hydrothermal alteration increases from 9770 to 9820 feet and from 10,200 feet to the bottom of the well at 10,255 feet.

3.3.3 Alteration Mineralogy

Minerals formed through the interaction of hydrothermal fluids with rocks provide information on both the thermal regime and the amounts of fluids present within the rocks. Samples collected at approximately 100-foot intervals were analyzed by X-ray diffractometry to determine the constituent mineral phases present. These methods were supplemented with studies of petrographic thin sections.

The distribution of mineral phases present in Ascension #1 is summarized in Figure 9. The sequence of alteration minerals found in this well is similar to that encountered in other high-temperature geothermal systems.

From the surface to about 4100 feet, alteration is dominated by smectite and calcite. The smectite is formed through the alteration of volcanic glass. The calcite is formed by precipitation from groundwater. Both occurrences are common at low temperatures, and there is little geothermal significance to their presence.

At 4100 feet the zeolite analcime forms, and the rocks enter the zeolite facies of metamorphism. At increased temperature, laumontite also forms. In addition to these principal zeolite species, thomsonite, clinoptilolite, stilbite, and mordenite were also detected in the X-ray diffraction patterns, but these minerals have a rather limited distribution. Chlorite and another smectite zone are also present with the zeolite assemblage. At about 8000 feet, both laumontite and analcime disappear.

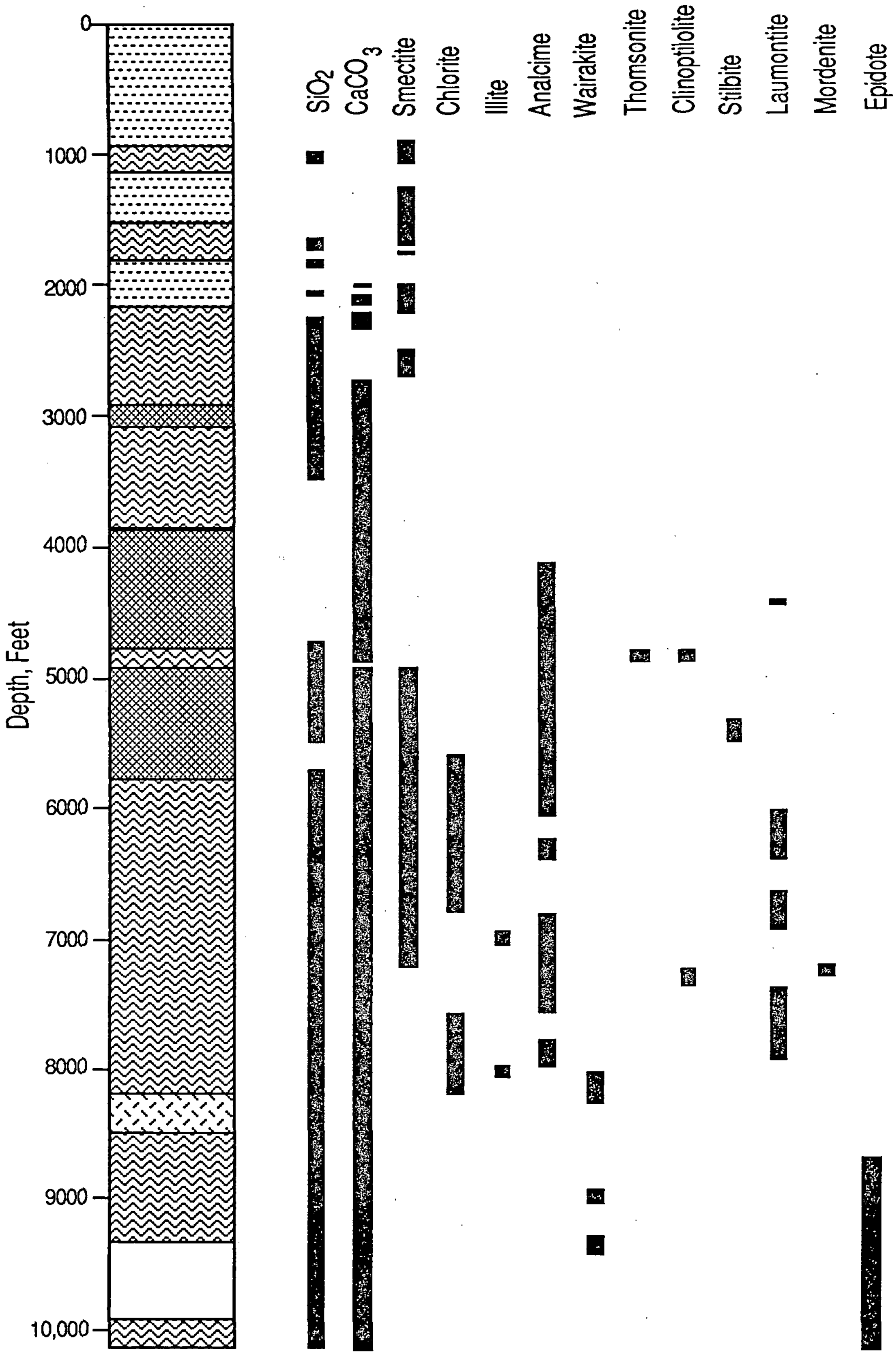

Figure 9. Hydrothermal Alteration - Ascension #1.

Wairakite is a high-temperature calcium zeolite which appears at about 8000 feet. This mineral is characteristic of high-temperature hydrothermal systems, and forms at approximately 400°F, the temperature at which the mineral is found in Ascension #1.

Epidote is first encountered at 8700 feet. This mineral has been reported from virtually every geothermal system where temperatures exceed 400°F. Epidote becomes a dominant phase in the rock at a depth of 9340 feet. Thin sections show that the epidote forms radiating crystal aggregates and is intimately intergrown with quartz. The zones containing abundant epidote show indications of extensive fracturing, and these fractures are apparently cemented by epidote.

Grains of quartz and epidote were selected from a depth of 9510 to 9520 feet and polished to allow the measurement of fluid inclusions. Primary inclusions in quartz gave homogenization temperatures averaging 431°F and those in epidote averaged 429°F. The measured temperature at this depth was 455° which is a minimum temperature considering the short amount of time the hole was allowed to equilibrate following cooling during drilling. Therefore, the zone of intense hydrothermal alteration has heated since the abundant epidote and quartz were deposited. The salinity of the inclusions was also determined through freezing measurements. Those in the quartz were determined to average 3.21 equivalent weight percent NaCl, and those from the epidote 3.53 weight percent NaCl. These measurements compare favorably with a fluid composition of 3.92 weight percent total dissolved solids measured from a sample taken at 9885 feet.

The areas of intense hydrothermal alteration are interpreted as being a partially sealed fracture zone associated with a hydrothermal reservoir which occupies the same structure. Hydrothermal minerals most often deposit at levels where the thermal gradients are steepest, since the solubility of quartz in particular is strongly temperature dependent. The fact that present temperatures are higher than when the bulk of the alteration took place is interpreted as indicating that the hydrothermal system is still active in the proximity of Ascension #1.

3.4 FLUID CHEMISTRY

Chemical samples of steam and liquid were collected from Ascension #1 during February, 1987. Twenty-nine liquid samples were analyzed for their major, minor, and trace element contents and for hydrogen, carbon, and oxygen isotopes. Five vapor samples were analyzed for their noncondensable (CO_2, H_2S, hydrocarbons, noble gases) components. Interpretation of the analytical data indicates that the fluids discharged from the well were highly modified by wellbore processes. These processes include boiling, froth formation from gas- and liquid-rich fluids, isotopic exchange of the two fluids, multiple condensation/vaporization cycles, entrainment of mixed brine/condensate in the gas flow, and spillover of the froth at the wellhead outlet. Most of the samples were taken from the gas/liquid froth at the wellhead.

Mathematical modelling of the fluid analyses indicates that the well encountered two distinct fluids within the reservoir rocks. One of these fluids appears to be modified seawater. This fluid has a salinity of about 40,000 ppm total dissolved solids. The chemical and isotopic composition of the fluid is similar to that of the Reykjanes geothermal system in Iceland. The second fluid is gas-rich and appears to be dominantly CO_2 with minor noble gases. Entry zones for the gas-rich fluid lie above the liquid-rich entry zones in the well. Both fluids first appeared at depths of about 8000 ft.

Sulfate isotope geothermometry indicates a reservoir temperature close to 500°F. The quartz geothermometer was not applicable because silica was precipitating as the fluids cooled in the wellbore. The cation geothermometer could not be applied because it is not calibrated for fluids derived from seawater, and because calcite may also have precipitated in the wellbore.

Between 10,220 feet and the bottom of the original hole at 10,255 feet a different fluid was encountered. No samples of this fluid are available, but gas analysis at the return line shows that it was 50 to 75% CO_2 with high concentrations of CH_4, H_2, and H_2S. This fluid was highly corrosive to the downhole drilling equipment and was chemically unlike other fluids from the well. It is characteristic of fluids encountered in the upper portions of many producing geothermal systems.

3.5 SEISMIC MONITORING

A network of six to eight portable earthquake seismometers recorded seismic activity on Ascension Island from September 12 to December 19, 1987 (Allison et al., 1988). The goal was to detect and locate earthquakes that define active faults. The fault locations would be considered in siting geothermal test wells.

During 92 days of active operation, 168 seismic events were recorded, averaging over 1.8 events per day. The forty-two largest and best defined events have been located, of which 11 occurred on or immediately adjacent to the island. Twenty-one events probably occurred along the nearby Mid-Atlantic Ridge, including the largest events recorded. Three events probably occurred on the Ascension Fracture Zone to the north and the remaining seven events are teleseisms of large worldwide events.

Using magnitude formulas developed for Hawaii, the largest local event detected during the survey is magnitude 0.85. The smallest events are about magnitude -1.6. These are approximately equal to Richter magnitudes. There were too few events to accurately locate active faults on the island.

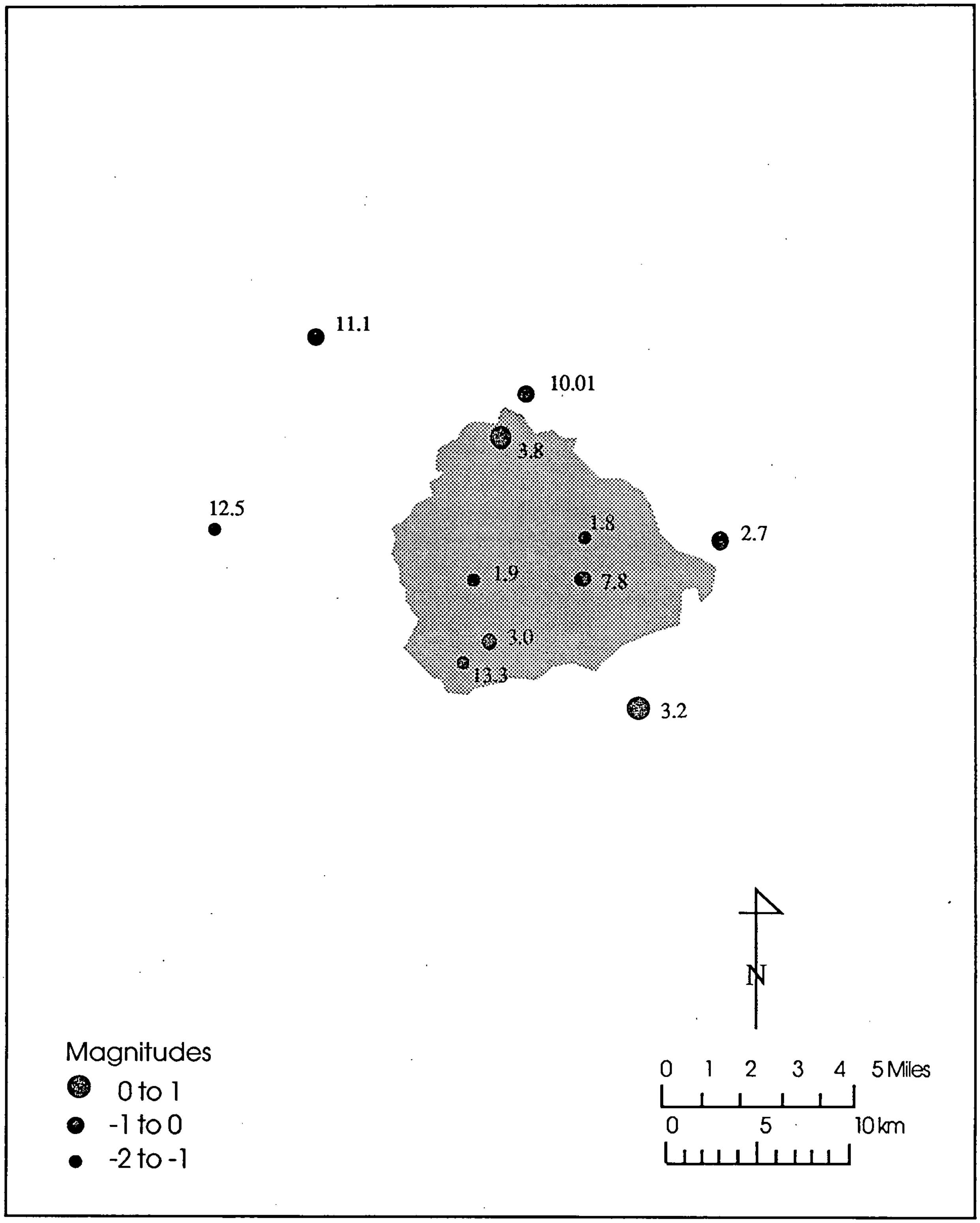

Figure 10. Hypocenter determination for local earthquakes recorded September 13 to September 19, 1987—Ascension Island, South Atlantic Ocean. Numbers next to locations are depths in km's; size of dots shows relative magnitude.

All of the events are of tectonic origin, generally indicative of brittle fracturing of rocks. Tectonic events distributed over the island pedestal argue that a system of active, brittle faults may act as a plumbing network supplying sea water to the hydrothermal heat source.

The seismic survey confirmed favorable conditions for a hydrothermal system on Ascension Island but did not clearly delineate potential reservoir areas. This may be possible with a longer monitoring period during which many more events would be recorded. Continued monitoring is also urged to better understand the volcanic and strong earthquake hazards on the island and could warn the island's inhabitants of impending danger.

3.6 WELL TESTING AND RESERVOIR ANALYSIS

3.6.1 Introduction

During drilling of Ascension #1, a series of wellbore surveys and a production test were conducted to determine the production potential of the well and to confirm geothermal reservoir conditions (temperature, pressure, fluid chemistry). Well testing and reservoir engineering support were provided by Well Production Testing, Inc. and Mesquite Group, Inc. Well logging services were provided by Earth Resources, Well Production Testing and Schlumberger. Analyses of drilling and test data indicate that Ascension #1 encountered two primary producing zones which are described in the following sections; however, neither zone was sufficiently productive to support development. The rock temperatures in the drilled zones are high and permeable fracture systems are present, indicating good potential for a viable geothermal resource in the area.

Twenty-three downhole temperature and pressure surveys were conducted during drilling and testing and provided much of the available information about reservoir conditions. Primarily because of the nature of the well's performance, data available from the surveys and testing were not sufficient to perform complete analyses of the resource using standard reservoir engineering methods. Nonetheless, the available data are adequate to derive reasonable and consistent estimates of the geothermal reservoir properties.

3.6.2 Upper Fracture Zone

Ascension #1 was first completed at a depth of 8,706 feet and encountered a low-permeability, CO_2-rich zone between 8,050 and 8,400 feet with static temperatures exceeding 400°F. The well produced a two-phase flow mixture of CO_2, brine and water vapor at rates up to 70,000 pounds per hour. A nine-day production test was conducted in late 1986, along with a series of downhole temperature and pressure surveys. After completion of the production test, the well was left open through a vent and continued to produce small volumes of fluid until drilling operations resumed the following May.

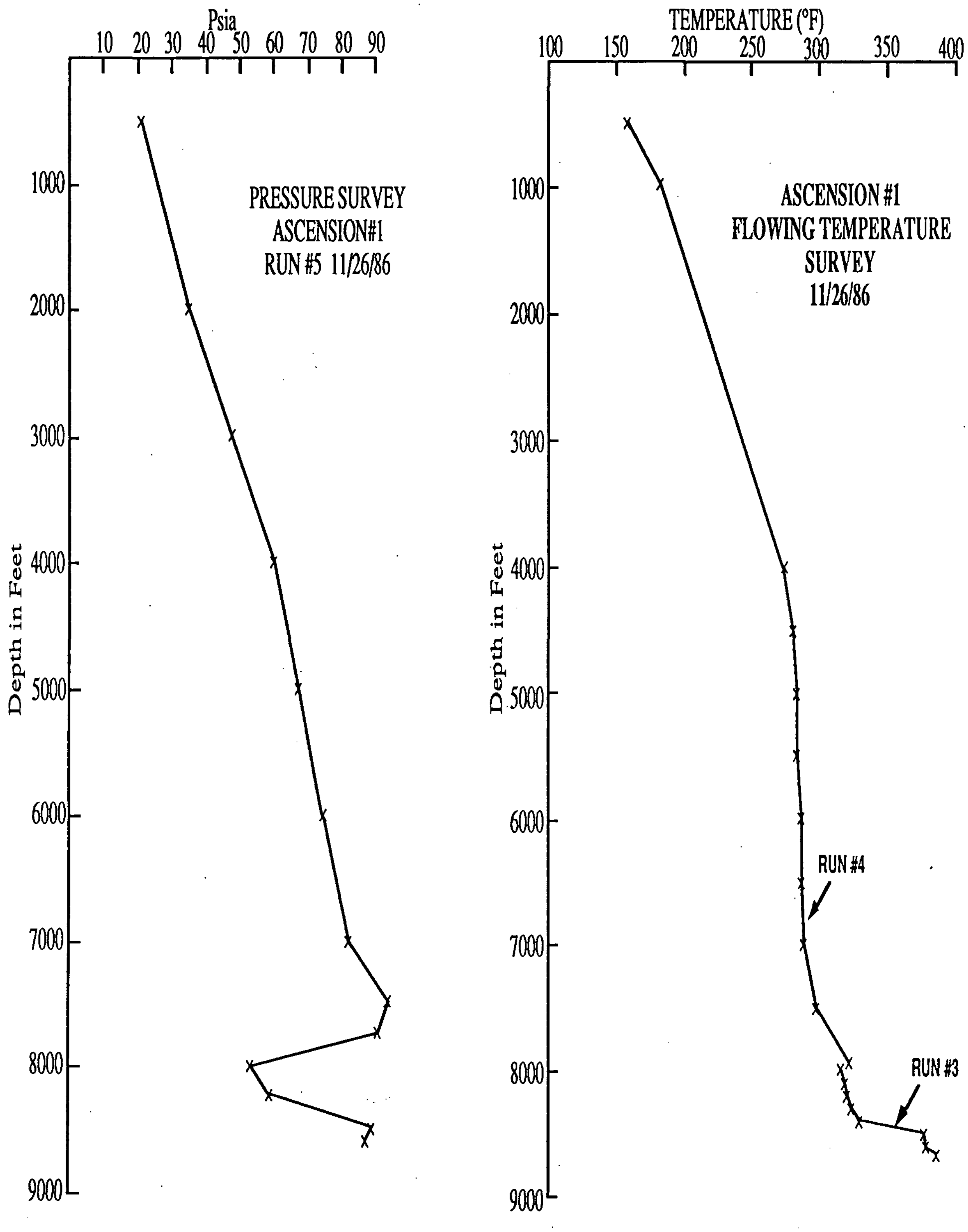

Figure 11. Flowing pressure and temperature survey data from Ascension #1, 11/26/86

Representative pressure and temperature data under flowing conditions are shown in Figure 11. During the production test, the flowing downhole pressure was in the range of 80 to 100 psia, indicating a high vapor fraction in the produced fluids. The test data also indicated separation of the liquid and vapor in the wellbore, with both brine and condensed water vapor accumulating in the wellbore at times during the test. Thus, the flow rates and fluid properties measured at the surface did not directly reflect the inflow from the reservoir. This behavior made it impractical to calculate a reliable value of reservoir transmissivity from the pressure buildup data, but an approximate value of the well's productivity could be calculated. The productivity index, which is a measure of the well's production rate per unit of wellbore pressure drawdown, was in the range of 21 to 30 pounds per hour per psi, a factor of ten lower than typical minimum commercial productivities. The low productivity index is consistent with the mineralogy which indicates significant deposition of hydrothermal minerals which have partially sealed the fractures in this zone.

3.6.3 Lower Fracture Zone

During deepening operations, drilling with air allowed maximum production from fractures encountered in the well. Temporary increases in the circulating air pressure during drilling were indications of several water inflow zones between 9,385 and 9,620 feet. The estimated sustained production from these fracture zones is on the order of 7,000 pounds per hour. Between 9,635 and 9,700 feet, another water entry was noted which resulted in a sustained inflow into the well of about 35,000 pounds per hour.

Temperature surveys during and following drilling recorded a maximum downhole temperature of 479°F (Figure 12), which is substantially above that originally expected. The higher resource temperature significantly improves the efficiency of the power cycle.

A planned production test of the well was not conducted after deepening because the well was not sufficiently productive to maintain natural flashing flow at the surface. However, the available logs, surveys and drilling data are sufficient to reach some important conclusions about the resource. Using stabilized inflow and drilling air rates at 9700 feet, a productivity index for the deeper fracture zone was determined to be on the order of 13 to 20 pounds per hour per psi, too low to be considered for commercial production.

A temperature log run after drilling to 9,885 feet indicated that brine flowing into the wellbore at 9700 feet during drilling had been flashing in the fractures near the wellbore (Figure 12, survey 5/31/87). This behavior is typical of a high-temperature, low productivity zone. After drilling to a depth of 10,172 feet, the wellbore was filled with sea water for the purposes of logging. Twenty hours later, a downhole pressure survey was run and pressure falloff data were used to determine near-wellbore transmissivity (a

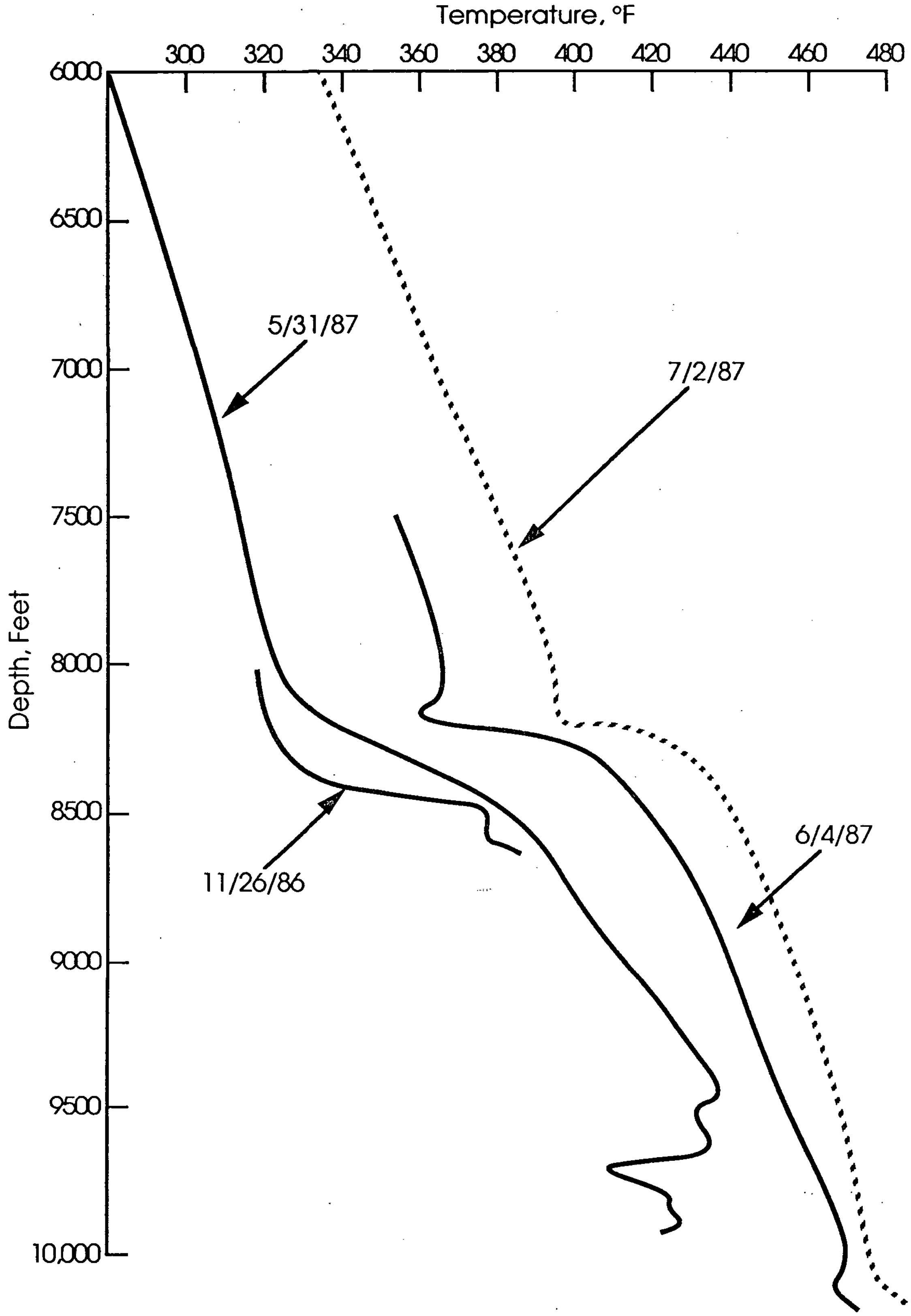

Figure 12. Temperatures versus depth measured during Ascension #1 deepening.

measure of the productive capacity of the reservoir). Analysis of the pressure response indicates a transmissivity of about 300 millidarcy-feet. This compares to transmissivities on the order of 20,000 millidarcy-ft or greater for commercial developments at similar depths and temperatures.

For the next five months, the well was left open through a small vent at the wellhead and produced only a very weak flow of CO_2. Temperature and pressure surveys were run on June 30, July 2 and November 10, 1987 to monitor the pressure and temperature recovery after drilling and to gain a better understanding of the resource conditions (see Figures 12 and 13). Downhole pressure data showed a gradual buildup over the five-month period after drilling, indicating that some limited recharge to the reservoir was occurring. From the buildup data, a value for transmissivity was calculated that agrees reasonably well with the value calculated previously.

Following the survey on November 10, 1987 the well was shutin to observe the wellhead pressure buildup and to evaluate the effect of the shut-in on the downhole temperature profile. At the time of the shut-in, the water level had risen to 2,242 feet measured depth. Over a period of 1-1/2 months, gas pressure at the wellhead built up to about 800 psig and leveled off. The gas appears to have been coming from the interval 8,050 to 8,400 feet. On January 5, 1988, a final temperature survey was run with 800 psig gas pressure on the wellhead. This survey confirmed earlier measurements of downhole temperatures.

3.6.4 Interpretation of Reservoir Data

During drilling of Ascension #1, two productive fracture intervals were encountered, but neither was sufficiently productive for useful application. The most recent downhole temperature data, which are close to the true static formation temperatures, are in the range of 405 to 433°F in the upper interval and 465 to 480°F in the lower interval. These temperatures are in the upper range of commercial geothermal reservoirs at similar depths. The latest temperature surveys show a more nearly isothermal temperature gradient in the lower 1500 feet of the well.

All temperature profiles since the well was deepened have a distinct offset between 8,200 and 8,500 feet that decreased from 40°F on July 1, 1987, to 18°F on January 5, 1988. The magnitude of this temperature offset and its abruptness suggest nonequilibrium conditions and the possibility of cross flow in the wellbore. Analyses of the survey and drilling data point to residual cooling in the rocks after drilling and production. Both of these possibilities are feasible explanations, but more sophisticated logs would have been required to confirm which was occurring.

Because a large crossflow would have important implications for the evaluation of the well, calculations were made using available data to estimate the possible magnitude of crossflow. Independent calculations based on temperature gradients and heat transfer considerations, and on

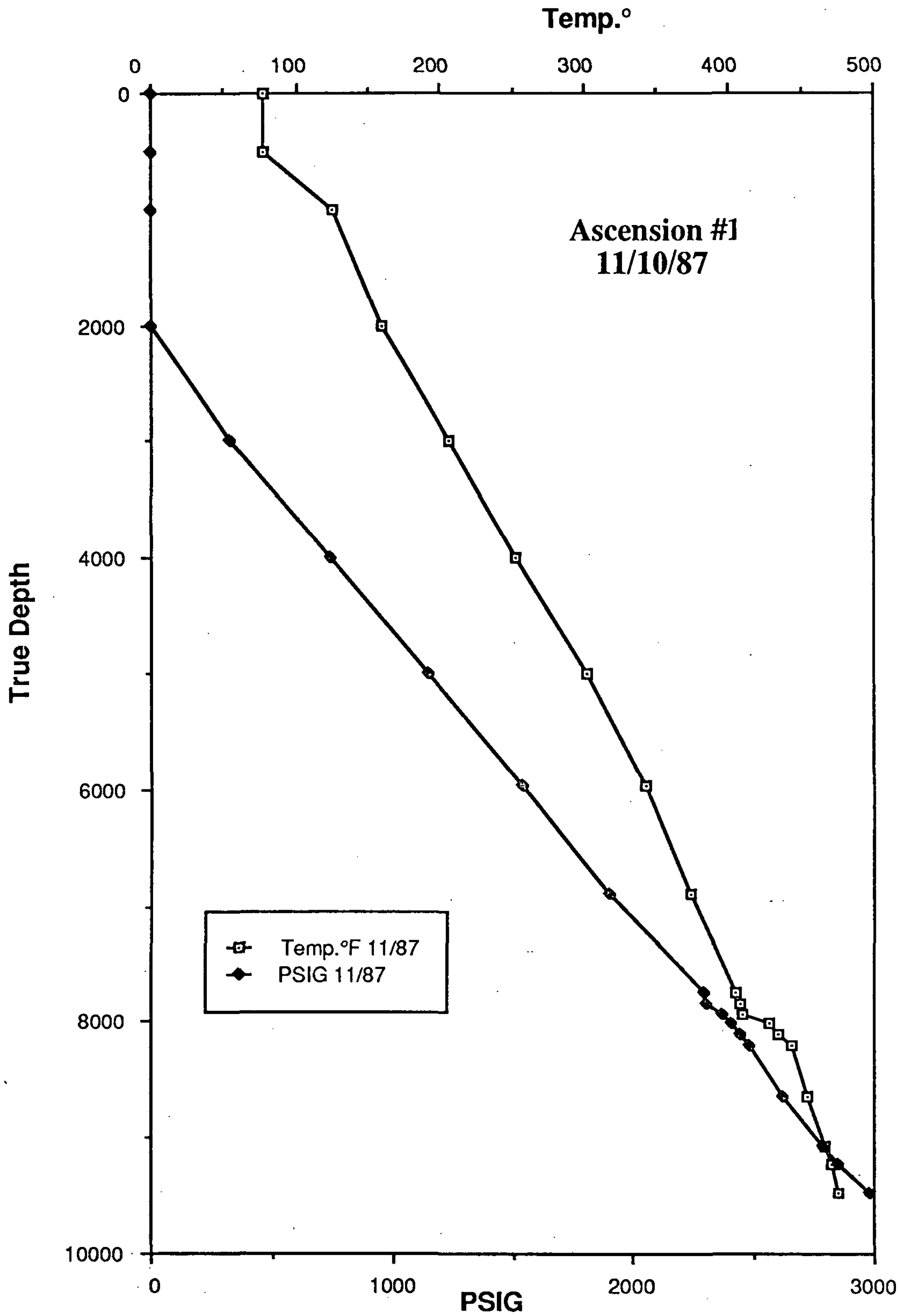

Figure 13. Temperature and pressure as a function of measured depth in Ascension #1.

wellbore pressure and productivities of the fracture zones, indicate a crossflow of about 1,400 pounds per hour could be possible. This is insignificant compared to the normal flow of a geothermal well and does not impact the resource conclusions based on reservoir analyses.

It was never possible to measure the static reservoir pressure in the upper fracture zone, but recent downhole pressure measurements indicate a pressure about 1000 psi less than ocean hydrostatic. This is an indication of reduced permeability or limited recharge to the fractures which were encountered in Ascension #1.

3.7 SYSTEM MODEL

The geothermal system discovered beneath Ascension Island is located in faults associated with a northeast-trending rift structure. The geothermal system is high-temperature with measured values approaching 500°F. The fluids present are heated seawater, and the interaction of the geothermal fluids and the wall rock of the fractures have produced minerals that have sealed the permeability, resulting in the low volumes of fluid production from the well. The sealing encountered in Ascension #1 typically occurs at the top and margins of zones of fluid circulation in geothermal systems. The redrill attempted to tap hot water beneath the sealed zone. Further evidence that the well entered the top of a geothermal reservoir is the high gas content that was observed in the deepest part of the well.

4.0 POWER PLANT DEVELOPMENT AND ECONOMIC ANALYSIS

Development of a geothermal resource on Ascension Island would reduce the use of petroleum fuels for power generation and potable water production as well as provide a self-sufficient, cost-effective energy system for mission-critical tracking facilities on the island. A key advantage of geothermal power development on Ascension Island is its invulnerability to disruption due to external economic or political factors, an important consideration for U.S. Air Force operations on this remote island.

A series of economic analyses have been conducted to determine what constitutes an economic geothermal resource on Ascension Island. The purpose of the economic analyses summarized in this report is to determine the cost of geothermal power based on the most probable resource conditions and to evaluate the sensitivity of that power cost to key resource parameters such as well production and reservoir permeability.

Geothermal economics are dependent on many parameters, including such items as power lines, switchgear, generators, etc., which are common to other types of power plants. One of the big differences, however, in predicting potential geothermal economics is the cost of obtaining the energy. In conventional diesel or coal-fired plants, input energy costs can be readily predicted based on market history. For geothermal power plants the available energy is a measure of well temperature, pressure and fluid production. For an undeveloped geothermal resource, these parameters are not well-defined. Therefore, factors which account for the geothermal resource uncertainty were incorporated in the economic analyses. These factors include the cost of unsuccessful production wells and a sinking fund to pay for well rework and redrilling during the life of the project. Inclusion of these considerations in the economic analyses results in a conservative evaluation of the project's feasibility.

The existing diesel power equipment has a remaining operating life of five to ten years. For these economic analyses, it was assumed that the existing units would require replacement no later than 1995. Two replacement alternatives are compared in this report. The first alternative being considered by the Air Force is replacement of the diesels with a gas turbine unit. The second alternative assumes the existing generators and the desalination facility are replaced with a geothermal system. The analysis of both alternatives is based on 2.7 MW average electricity production, with a peak demand of 3.5 MW.

4.1 BACKGROUND

A preliminary examination of the potential for an economic geothermal power development on Ascension Island was performed for the U.S. Air Force before Ascension #1 was drilled and the results were documented in "Final Report, Phase II Geothermal Exploration and

Geothermal Power Plant Update for Ascension Island, South Atlantic Ocean" (Nielson et al., 1984).

For the preliminary analysis, a geothermal resource temperature between 300 and 340°F was assumed. The power cycle best suited to a resource temperature in this range is a binary cycle in which heat is transferred from the geothermal fluids to a secondary fluid such as isobutane (Whitbeck et al., 1987). The preliminary economic evaluation also assumed that pumping would be required to produce geothermal fluids from the wells on the basis of the relatively low resource temperature anticipated.

Drilling of Ascension #1 has confirmed a resource temperature on the order of 480°F; however, the permeability of this resource was not confirmed. This temperature is much higher than was originally assumed and significantly improves the efficiency of the geothermal power cycle. The higher resource temperature also means that a producing geothermal well will be self-flowing and no pumps will be required.

4.2 POWER PLANT AND PORTABLE WATER SYSTEM DESIGN

4.2.1 Existing Diesel System

The present installed capacity of the 14 existing U.S. Air Force diesel units on Ascension is 5.3 MW. The current power demand averages 2.7 MW, while peak demand is 3.5 MW. It is anticipated that future power demand for U.S. operations could total 5 MW. Annual consumption of JP-8 fuel is 1,253,880 gallons. Fuel costs per unit of power produced are $0.13/kWh (1987) and annual operations and maintenance costs add another $0.02/kWh to the cost of generating power on the island. The U.S. Air Force estimates that the expected operating life of the existing diesel units ranges from five to ten years. For these analyses, it was assumed that the diesel units would have to be replaced no later than 1995.

Waste heat from the existing diesel power units is used as pre-heat to the desalination facility, which produces a nominal 47,000 gallons per day potable water. Reliable potable water supply for U.S. operations has been difficult to achieve and water shortages are not uncommon. The cost in fiscal year 1987 to produce the potable water was $17.80 per thousand gallons. This cost is lower than in previous years due to significantly reduced fuel prices.

4.2.2 Alternative #1: Gas Turbine System

To provide a consistent basis for economic comparison, it was assumed for the first alternative that the existing diesel units would be replaced at the end of their operating life (nominally 1995) with a 5 MW gas turbine. Since a single 5 MW unit does not provide the same reliability as several smaller units of equivalent total capacity, it was assumed that several of the existing diesel units would be retrofitted at that time to enable their use as backup to the gas turbine. Waste heat from the power generation system would be used as preheat to the potable water system. A new desalination facility would be purchased to increase the reliability and efficiency of the water supply system.

4.2.3 Alternative #2: Geothermal System

On the basis of the high resource temperature encountered in Ascension #1, a reevaluation of the basic design of a geothermal power plant was made. A hybrid design, developed by Barbar-Nichols, Inc., which incorporates a flashed steam and a binary cycle, is recommended. This hybrid design provides the optimum power production per pound of geothermal fluid produced.

The geothermal plant design consists of small, modular, skid-mounted units which would be fabricated stateside to reduce onsite construction. The total plant design assumes an available geothermal fluid production of 450,000 pounds per hour of 450°F saturated brine at the wellhead. In the flashed steam cycle, the brine is flashed to 70 psia as input to the steam turbine, for a net production of 2.8 MW. Brine exits the steam cycle at a temperature of about 300°F and is run through a closed, organic Rankine cycle. Net production from this binary cycle is 1.0 MW. The condenser for the power plant is assumed to be water-cooled. The geothermal brine exiting the binary cycle is then injected into a permeable zone above the geothermal reservoir.

While diesel power systems have rapid turn-down and turn-up response, the nature of geothermal wells and gas turbine power systems makes them more effective when used for base loads. On that basis, this analysis assumes that a geothermal power system with a 3.8 MW total capacity would be installed by 1990 (the analysis was conducted in 1988). The existing diesel units in the best condition would remain for backup and peaking requirements.

The analyses assume that a potable water system with an approximate capacity of 174,000 gallons per day is integrated into the geothermal plant. In the integrated design, condensed geothermal fluid from the flashed steam power cycle is treated and upgraded to meet potable water requirements.

4.3 ECONOMIC EVALUATION

The economic methodology used for these analyses includes two basic approaches: payback analysis which determines the number of years required to payback an investment given the projected savings from that investment, and life-cycle cost analysis which takes into account the relevant costs over the life of a project. The methodology assumes that the project alternatives produce identical service and have identical economic lives (twenty years for the alternatives considered). The basic analyses assume that the Air Force finances all costs for the development.

4.3.1 Economic Assumptions

All dollar values for capital costs and operating expenses are estimated in 1987 dollars. The escalation of fuel prices is based on values published by the U.S. Department of Energy (1984). All other operating variables such as labor, overhead and maintenance were assumed to inflate annually at 3 percent. The present value analysis assumes all future values are discounted to 1987 dollars using a 7 percent discount rate according to standards set by the Department of Defense.

4.3.2 Capital and Operating Costs

A summary of the capital, operating and maintenance costs used in the economic analyses is presented in Table 1. To make the gas turbine and geothermal options consistent, the life cycle analyses were run to the year 2010. At this time, it was assumed that the gas turbine had remaining economic life which was incorporated into the analyses as a salvage value.

For the geothermal development alternative, a sinking fund was established for reworking or replacing the production wells over the life of the project. This is a conservative approach which, in part, addresses the current uncertainty in the geothermal fluid supply.

4.3.3 Economic Results

A simple payback analysis of the geothermal power plant and potable water system indicates a payback of 4.5 years (discounted payback 6.2 years). The nominal life-cycle costs are $165 million for the gas turbine alternative versus $53 million for the geothermal development, a $112 million savings. Discounted life-cycle costs for the gas turbine and geothermal alternatives are $80 million and $34 million respectively.

The greatest uncertainty in these analyses is that related to the production well success. The impact of unsuccessful wells typical of geothermal developments was addressed by considering that two unsuccessful wells are drilled before successful production is achieved. The sinking fund was also increased from $250,000 to $1,000,000 per year for this case. Based on these revised assumptions, the simple payback for the development would be 8.5 years and the nominal geothermal life-cycle costs would increase to $85 million, an $80 million savings over the gas turbine alternative.

TABLE 1

Ascension Economic Analysis
cost basis
($000)

	Gas Turbine Replacement	Geothermal Replacement
Capital Costs		
Power Plant	$13,400	7,130
Construction & Auxiliaries	500	2,321
Potable Water System	710	35
Wells	--	5,823
Diesel Retrofit	2,000	0[a]
TOTAL	$16,610	$15,309
Annual O&M Costs		
Power System	$ 3,550	$ 620[b]
Diesel Backup	275	275
Potable Water System	425	55
TOTAL	$ 4,250	$ 950
Operating Life	25-30 years	20 years
Salvage Value in 2010	$ 6,820[c]	$ 0

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[a] This case assumes sufficient operating life remains in 1990 for existing diesel units to be used as backup with no retrofit.

[b] Includes $250k sinking fund for well repair and replacement.

[c] Accounts for remaining operating life of gas turbine unit.

5.0 RECOMMENDATIONS

The two primary requirements for a producible geothermal resource are temperature and productivity. Exploration activities and drilling of Ascension #1 have confirmed high resource temperatures that are in the upper range of commercial geothermal reservoirs. Although the fracture zones encountered in Ascension #1 were not sufficiently productive to warrant further development of that hole, they provided evidence that permeability does exist at drillable depths. The evidence of the geothermal resource potential and the favorable economics of resource development for power generation and potable water production warrant continued drilling.

Normally about 10% of wildcat geothermal wells actually discover a high-temperature geothermal system. Ascension #1 has discovered such a system, and what now remains is to confirm the production volumes that can be expected from the system. The second leg of Ascension #1 was intended to do this when drilling was stopped by a mechanical problem. This problem does not change the viability of the target concept. Indeed, through the drilling of Ascension #1, much of the exploration risk has been removed from the project.

6.0 ACKNOWLEDGEMENT

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7.0 REFERENCES

Allison, M. L., Ross, H. P. & Reinbold, D. R., 1988, Seismic monitoring, Ascension Island, South Atlantic: University of Utah Research Institute Earth Science Laboratory Report ESL-88011-TR, 43 p.

Brozena, J. M., 1986, Temportal and spatial variability of seafloor spreading processes in the northern South Atlantic: Journal of Geophysical Research, v. 91, p. 497-510.

Nielson, D. L. and Sibbett, B. S., 1982, Geothermal Potential of Ascension Island, South Atlantic Phase I - Preliminary Examination: University of Utah Research Institute, Earth Science Laboratory Report, 79 p.

Nielson, D.L., Sibbett, B.S., Shane, K., and Whitbeck, J.F., 1984, Final Report, Phase II Geothermal Exploration and Geothermal Power Plant Update for Ascension Island, South Atlantic Ocean.

Ross, H. P., Green, D. J., Sibbett, B. S., and Nielson, D. L., 1984a, Electrical Resistivity Surveys Ascension Island South Atlantic Ocean: University of Utah Research Institute, Earth Science Laboratory Report, 33 p.

Ross, H. P., Nielson, D. L., and Green, D. J., 1984b, Interpretation of Aeromagnetic Survey Ascension Island South Atlantic Ocean: University of Utah Research Institute, Earth Science Laboratory Report, 37 p.

Ross, H. P. Mackelprang, C. E., and Dejany, S. F., 1984c, Supplemental Electrical Resistivity Surveys Ascension Island South Atlantic Ocean: University of Utah Research Institute, Earth Science Laboratory Report, 38 p.

Sibbett, B.S., Nielson, D.L., Ramsthaler, J.H., and Shane, K., 1982, Geothermal Potential of Ascension Island, South Atlantic, Phase I Preliminary Examination: U.S. Department of Energy Report IDO-10110, 54 p.

Sibbett, B. S., Nielson, D. L., and Adams, M. C., 1984, Geothermal Gradient Drilling and Measurements Ascension Island, South Atlantic Ocean: University of Utah Research Institute, Earth Science Laboratory Report, 72 p.

Stiger, S.G., Verity, R.V., and Stiger, R.S., in preparation, Ascension #1 Well Testing and Reservoir Analysis: Idaho National Engineering Laboratory Report.

U.S. Department of Energy, 1984, Appendices A, B, and C of the Methodology or Life Cycle Cost Analysis Using Average Fuel Costs: DOE/CE-0101.

Whitbeck, J.F., Plum, M.M., Berglund, G.R., and Stiger, S.G., 1987, Ascension Island Determination of Acceptable Well Flows and Temperatures for Electrical Power: Idaho National Engineering Laboratory Report.