GEOTHERMAL EXPLORATION OF ASCENSION ISLAND SOUTH ATLANTIC OCEAN

Dennis L. Nielson(1) and Susan G. Stiger(2)

(1) University of Utah Research Institute
(2) Idaho National Engineering Laboratory

ABSTRACT

Exploration on Ascension Island in the South Atlantic Ocean has resulted in the discovery of high-temperature geothermal fluids. Ascension is a volcanic island that has seen eruptions within the last 1000 years. However, there are no geothermal manifestations at the surface and only limited amounts of hydrothermal alteration exposed. Exploration began with geologic mapping and was followed by geophysical investigations that included electrical resistivity and aeromagnetic surveys. These data were used to site seven core holes for temperature gradient measurements. A deep test well, Ascension #1, was drilled to a depth of 10,255 feet. Several fluid entries were encountered and tested, but they lacked the permeability required to support production. Extensive quartz + epidote alteration was responsible for sealing of the lower fracture zones. In spite of this, a bottom hole temperature of 480°F was recorded. A second leg was drilled to explore for greater permeability. This leg was terminated by a mechanical failure before the target depth was reached.

INTRODUCTION

Ascension Island is located in the South Atlantic Ocean approximately 80 km to the west of the active spreading center of the Mid-Atlantic Ridge and south of the Ascension fracture zone (Van Andel et al., 1973). Ascension is formed on oceanic crust of approximately 5.5 Ma (Brozena, 1986). There have been no recorded volcanic eruptions on the island that was occasionally visited between 1501 and 1815 and has been continuously inhabited since 1815. However, there are basalt flows present whose age has been estimated at 700 years (Atkins et al., 1969).

SUMMARY OF EXPLORATION ACTIVITIES

Initial exploration efforts on the project involved detailed geologic mapping. Previous mapping by Daly (1925) had outlined the gross lithologic types, but was not of sufficient detail to be utilized in the geothermal exploration program. Following our mapping it was concluded that, although there were neither hot springs nor fumaroles on the island, 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. The electrical resistivity surveys identified areas of lower electrical resistivity near the present location of Ascension #1 (Fig. 1). 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 to define buried fault and dike trends. An irregular area was defined in the vicinity of Ascension #1 which contained low magnetization and demonstrated considerable structural complexity. 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 (Fig. 1). High temperature gradients were found in the vicinity of GH-1, 2, 6 and LDTGH. GH-2 is located in the eastern portion of the island in an area with difficult access, which relegated it to 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.

WELL DRILLING

Introduction

Ascension #1 was initially planned and budgeted to be drilled to a depth of 5000 feet. At this depth it was anticipated that fluid at a temperature of 300°F would be encountered. It was also thought that this fluid would require pumping to the surface. Therefore, the well was designed to support a downhole pump. The well did achieve the predicted temperature at 5000 feet, but the fluid required to operate a geothermal power plant was not present. Drilling continued and eventually reached a depth of 10,260 feet. The temperature at this depth was 480°F, and fluid was present, but not in the quantities required to support geothermal power production.

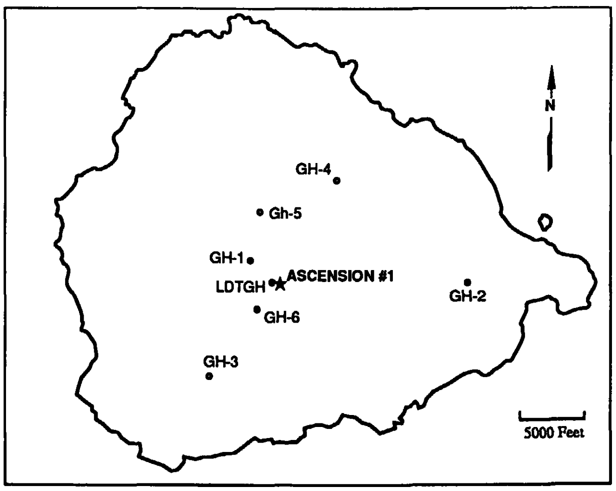

Figure 1. Map of Ascension Island showing location of temperature gradient holes and well Ascension #1.

A second leg of Ascension #1 was drilled to intersect the geothermal system along the strike of the controlling structure where it was thought that more water would be encountered. This leg was being drilled at a depth of 7346 feet when a mechanical failure at 3825 feet resulted in the loss of the drill string and the abandonment of the well.

Structural Setting

Geological mapping and the aeromagnetic survey emphasized the definition of fault systems which could be the conduits for geothermal fluids. Ascension #1 is located along a major structural zone that may be the northern portion of a NE trending rift. This structure is partially 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 exposed south of the drill site.

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.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.

Lithology of Ascension #1

The rock units encountered in Ascension #1 are summarized in Figure 2. Since the units were similar in both legs of the well, only the stratigraphy of the original hole will be described. The well passed through a sequence of volcanic rocks which were formed in a subaerial environment to a depth of 2910 feet. All of the 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.

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

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

Alteration Mineralogy

Minerals formed through the interaction of hydrothermal fluids with rocks provide information on both the thermal

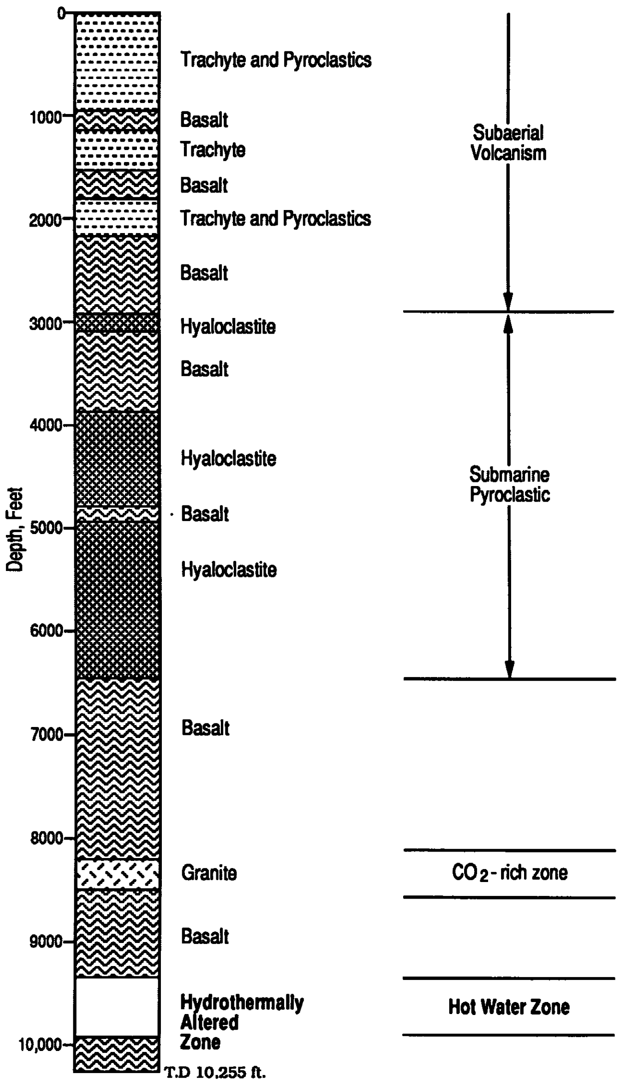

Figure 2. Generalized lithologic log of Ascension #1.

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.

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.

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

Epidote is first encountered at 8700 feet and 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 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°F which is a minimum temperature considering the short amount of time the hole was allowed to equilibrate following drilling. 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 partially sealed zones associated with a hydrothermal reservoir that 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.

FLUID CHEMISTRY

Chemical samples of steam and liquid were collected from Ascension #1 during February, 1987. 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 at the wellhead, 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, and the chemical and isotopic composition is similar to that of the Reykjanes geothermal system. 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 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 concentration of CH_4, H_2, and H_2S. This fluid was highly corrosive to the downhole drilling equipment and is chemically unlike other fluids from the well. It is characteristic of fluids encountered in the upper portions of many producing geothermal systems.

WELL TESTING AND RESERVOIR ANALYSIS

Introduction

During drilling of Ascension #1, a series of wellbore surveys and production tests were conducted to determine the production potential of the well and to confirm geothermal reservoir conditions. 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 viable resource in the area.

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 were adequate to drive reasonable and consistent estimates of the geothermal reservoir properties.

Upper Fracture Zone

Ascension #1 was first completed at 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 by natural two-phase flow a 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.

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 range of 21 to 30 pounds per hour per psi, a factor of 10 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.

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 3), which is substantially above that originally expected. The higher resource temperature significantly improves the efficiency of the power cycle.

A planned 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 rates at 9700 feet, a productivity index for 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. This behavior is typical of a high-temperature, low productivity zone. After drilling to a dept 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 was used to determine near-wellbore transmissivity. Analysis of the pressure response indicates a transmissivities on the order of 300 millidarcy feet. This compares to transmissities of 20,000 millidarcy-ft or greater for commercial developments at similar depths and temperatures.

Interpretation of Reservoir Data

During drilling of Ascension #1, two productive fracture intervals were encountered, but neither was sufficiently productive for 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 (Fig. 3). The magnitude of this offset diminished from 40°F on July 1, 1987, to 18°F on January 5, 1988. The magnitude of this

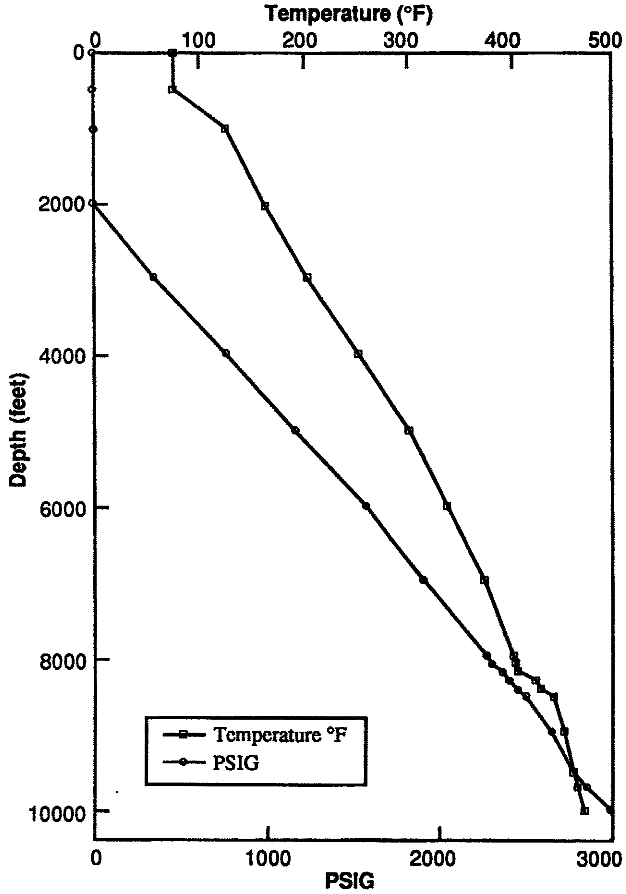

Figure 3 Pressure-Temperature logs of Ascension #1.

temperature offset and its abruptness suggest a dynamic condition in the wellbore such as crossflow from the lower to the upper fracture interval or cooling due to gas inflow from the upper interval. 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 crossflow. Independent calculations based on temperature gradients and heat transfer considerations, and on wellbore pressure and productivities of the fracture zones, indicate a crossflow of about 1,400 pounds per hour. 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.

CONCLUSION

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.

ACKNOWLEDGEMENTS

This work was sponsored by the U. S. Air Force and the U. S. Department of Energy. We thank the Eastern Space and Missile Center of Patrick Air Force base for permission to publish this paper. We acknowledge the efforts of Joe Hartnet, Mike Nasr and Bill Koslow in this project. Michael Adams, Otis Day, Howard Ross, Dale Green, Bruce Sibbett and Lee Allison of UURI, Lee Waldan, Jim Thomson, Bob Stiger of WPT and Gary Berglund of INEL and Bob Verity of Mesquiate Group have made important contributions to this project.

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