Geothermal Exploration on Nevis: A Caribbean Success Story

Joe LaFleur[1] and Roland Hoag, PhD[2]

[1]Geologist Extraordinaire and Chief Geologist, West Indies Power Company
[2]Executive Vice President, BEAD, LLC

Keywords

Caribbean, Lesser Antilles, geothermal, drilling, CSAMT, magnetotellurics, helium, Nevis, geophysics, slim-hole

ABSTRACT

The island of Nevis is in the northern part of the Lesser Antilles volcanic island arc in the Caribbean. It is the next island northwest of Montserrat at a distance of approximately 35 miles (56 km). Nevis has a primary central cone, Nevis Peak, which had its last major eruption about 100,000 years ago.

West Indies Power (WIP) initiated a geothermal exploration program on Nevis in January 2007. Previous studies had been conducted but no extensive geophysical surveys had been run and no exploration drilling had taken place. Although the entire island was evaluated for geothermal potential, it was apparent from geothermal indicators that the western side of the island is where detailed exploration activities should be conducted.

The first phase of the exploration program for West Indies Power consisted of field mapping, geochemical sampling, sampling of noncondensible gasses, a digital elevation model analysis, and remote sensing analysis of satellite imagery and airphotos. These data were used to delineate the areal extent of the geothermal system and to map the apparent faulting on the flanks of the island's central volcano, Nevis Peak.

The second phase consisted of magnetotelluric (MT) and controlled-source audio-frequency magnetotelluric (CSAMT) geophysical surveys. Transects were run in order to map the subsurface clay cap, delineate the reservoir, identify fault and fracture zones, and to estimate the orientation and dip of these structures. Drill sites were selected near faults that appeared to be conduits for ascending hydrothermal fluids. Drilling next to upflow faults improves the chances of identifying high-temperature resources at shallower depths.

The third phase consisted of drilling three slim-holes to depths of 2,500 to 3,700 feet and elevations below sea level (bsl) of 1,800 to 3,200 feet. Fluid samples and temperature measurements from the top of the reservoir were obtained. These holes identified a hydrothermal system with temperatures of over 500°F (260°C) that extends for at least 3.5 miles in a north-south direction on the western side of the island. Chemical analyses of the reservoir show it to be a mixture of meteoric water and seawater with fairly neutral pH and relatively moderate noncondensible gas content for a young volcanic system. This may reflect passive degassing since the last eruption. Subsequent production wells will be drilled directionally to target suspected "upflow" faults at depths of approximately 5,000 to 6,000 feet.

Our drill sites were selected on the basis of regional faulting, surface manifestations, thermal domestic wells, geophysical surveying, and conceptualization of the potential configuration of the hydrothermal system. All three slim-holes measured temperatures near 500°F (260°C). Two of the three slim-holes flow on their own, one quite impressively. Nevis-3 was estimated to flow 76,000 lb/hr through a 3-½ inch drill pipe. It's a screamer.

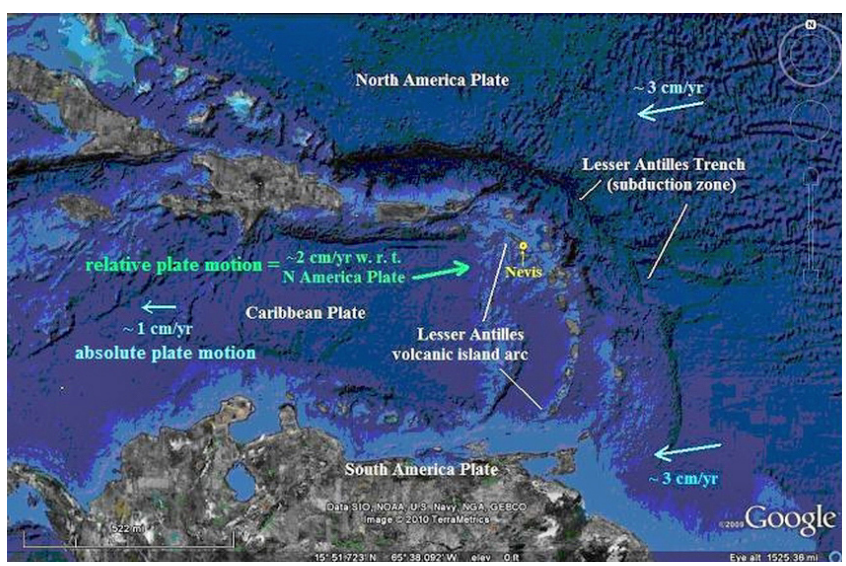

Figure 1. Location map showing Nevis and the Lesser Antilles.

Introduction

Since 2007 a geothermal exploration program has been conducted on the island of Nevis for West Indies Power Ltd. Nevis is the smaller of the two island nation of St. Kitts and Nevis located in the Lesser Antilles. Previous investigations were summarized in a study conducted in 2005 for The Organization of American States (OAS) (GeothermEx, 2005). The OAS project included geological and geochemical investigations and provided a wealth of information on the past geothermal investigations on Nevis. The investigation described here builds upon the OAS study and will describe the results of remote sensing analysis, geochemical sampling, geological investigations, geophysical surveying, slim-hole drilling, and a preliminary reservoir analysis.

Geology

Since Cretaceous time, at least, the North Atlantic Crustal Plate has been moving westward and subducting beneath the Caribbean Crustal Plate. The Lesser Antilles chain of volcanic islands is a back-arc response to this subduction (Figure 1).

The island of Nevis is composed almost exclusively of volcanic rocks. Radiometric age dating of the volcanic rocks comprising Nevis shows that the history of island-forming eruptions began at least 3.4 million years ago and the youngest only 0.1 million years before present (Figure 2). The dominant rock types are pyroclastic rocks with a dacite composition suggesting the presence of a high-level, evolved magmatic center of the type that maintains high heat flux in the near-surface.

The fact that the last eruption was about 100,000 years ago has some rather positive implications. For one, it shows that the volcano is not presently in an eruptive mode, thus providing assurance that the anticipated geothermal investment will not be buried by a volcanic flow. Secondly, that amount of lapsed time should have allowed degassing of the most recent shallow magma emplacements. Hence, there should be a reduced concentration of corrosive volcanic gases, such as hydrogen chloride and di-hydrogen sulfide, in the hydrothermal fluids. This contention is supported by the observation that the fumarolic activity was far greater in the recent geologic past and by the fact that the slim-hole drilling did not encounter highly acidic reservoir fluids, as will be discussed later.

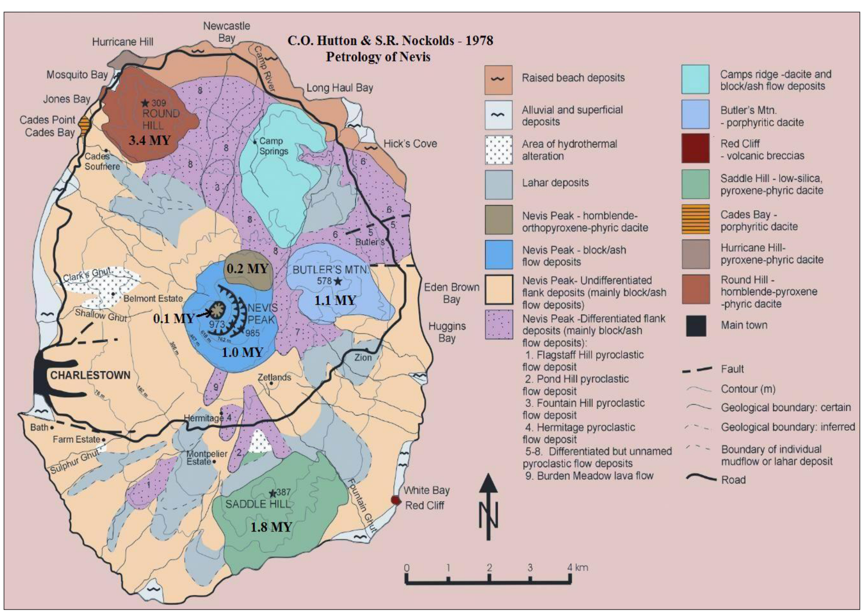

Figure 2. Ages of eruptions. Geological map modified from Hutton & Nockolds (1978).

Sector Collapse

It appears from the topography that the western side of Nevis has experienced a large sector collapse event. Sector collapse is a gravity failure of a section of the volcano. Incompetent clay-rich layers, such as a weathered volcanic ash or a hydrothermally altered zone, can facilitate collapse. The apparent collapse feature on Nevis is bounded north and south by large fault zones identified by the WIP exploration team. The northern boundary of the feature is coincident with the Spring Hill Fault Zone and the southern boundary is coincident with the Grandee Ghut Fault. This feature is observable on the satellite imagery and is seemingly reflected in

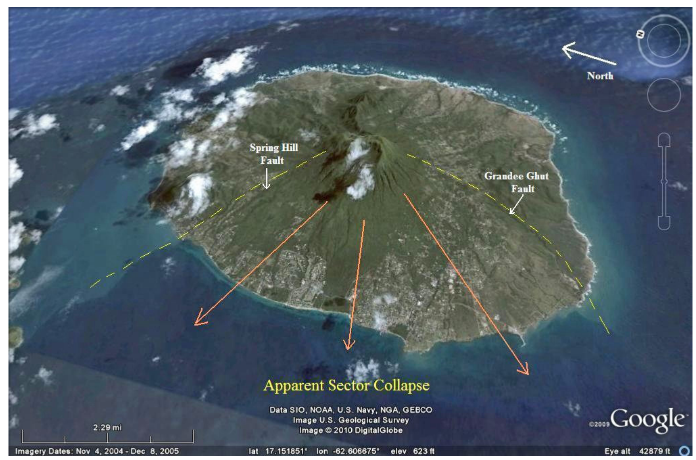

Figure 3. Apparent Sector Collapse on west side of Nevis.

the seafloor morphology that shows down-dropped shoreline within the apparent collapse feature (Figure 3). The sector collapse is most apparent in the digital elevation model and almost all of the hydrothermal surface manifestations on Nevis are located within this apparent collapse feature (Figure 4). Perhaps hydrothermal clay alteration, as identified in the CSAMT surveys, facilitated the gravity collapse of the west side of Nevis Peak.

Surface Manifestations

The hydrothermal manifestations of Nevis are all located on the western side of the island within the apparent sector collapse feature, with the one exception of the Camps warm spring which is located on the north end. These manifestations include fumarole areas, thermal springs, gas seeps, and anomalously thermal domestic water wells (Figure 4). A brief description of these manifestations follows:

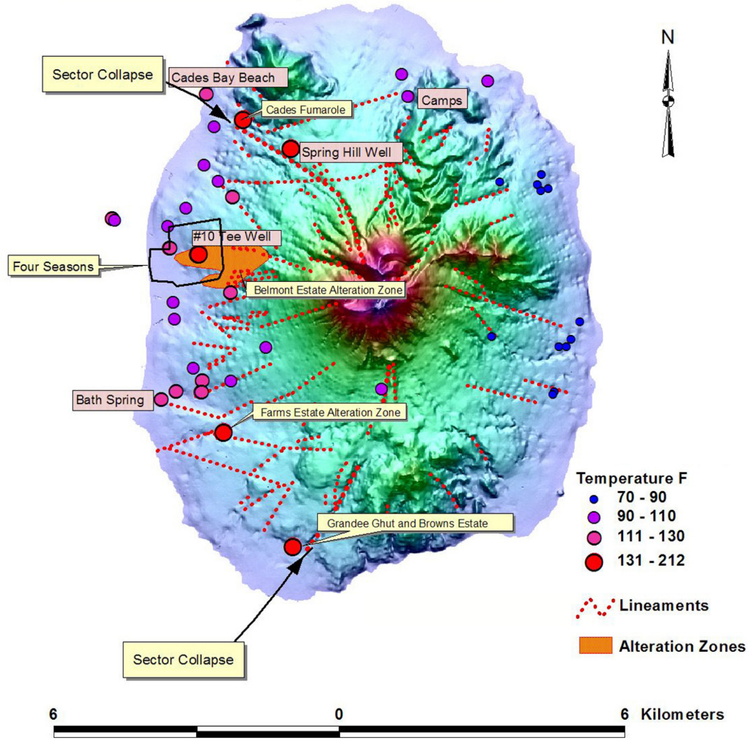

Figure 4. Temperature distribution of thermal manifestations shown on the digital elevation model.

Cades Estate Area

The Cades Estate fumarole (Figure 4) developed in the early 1950's following seismic activity beneath Nevis Peak. It consists of an area of sulfateric alteration about 30 meters across, in which minor deposition of native sulfur and discrete occurrences of near boiling temperatures can still be found. Outflow from the hydrothermal system discharges from the sand in the shallows at Cades Bay with temperatures recorded of 126°F (52°C). Also in this area to the east (Springhill) is a test well that was drilled by the Nevis water department that has a temperature of 181°F (83°C).

Bath Springs and Farm Estate Area

Bath Springs, located on the Bath fault south of Charlestown, are fed by hot springs that flow at temperatures up to 118°F (48°C). The Bath fault trends to the east and appears to be truncated by an ENE-trending fault that intersects with the Farm Estate fumarole; thus, it appears to be hydraulically connected to those fumaroles (Figure 5).

The Farm Estate fumarole was much more active in the past. Presently there are only small locations of limited venting within a much larger area of bare, altered ground. There are only a few active vents within approximately 8 acres that has experienced a high degree of sulfateric and argillaceous hydrothermal alteration. It is still actively depositing pneumatolytic sulfur crystals in a few steam vents with surface temperatures about 100°C indicating that it is underlain by a relatively shallow boiling water table. The degree of steam venting is dependent on current rainfall conditions. The extensive size and high degree of vapor phase alteration displayed in this fumarole area suggest that it has been active for a relatively long time.

Belmont Estate Alteration Area

An extensive zone of hydrothermal alteration was mapped by Hutton and Nockolds (1978) in the area now partially occupied by the Four Seasons golf course (Figure 4). Chunks of anhydrite and an abandoned gypsum mine are found in the creek bed. Although no longer leaking to the surface, the hydrothermal system is still present at depth, as evidenced in the 220 feet deep water well adjacent to the # 10 tee with a temperature of 167°F (75°C) and by the 31 feet deep Jessup well which has a pH of 3.4 and a temperature of 118°F (48°C).

Brown Estate Area

Evidence of active hydrothermal outflow was also documented on the south end of Nevis when a water well drilled by the Nevis water department encountered hot water on the Brown Estate (Figure 4). The well, drilled adjacent to the linear drainage known as Grandee Ghut, was reported to have a temperature of at least 154°F (68°C). In mapping the entire length of Grandee Ghut, we found no compelling evidence of hydrothermal surface manifestation.

Interpretation of Manifestations

We concur with the OAS study (GeothermEx, 2005) that promoted the concept that there is a centralized magmatic source area beneath the island that has fed the various volcanic vent areas throughout its eruptive history. The perception of a large and continuous heat source centralized beneath Nevis Peak influences the hydrothermal model concepts and exploration strategy.

We consider that the active and recently active fumaroles mentioned above are reflective of local leakage from a shallow outflow of thermal water, rather than local deep upflow. The data and observations best support the concept that deep upflow occurs within faults and fracture systems closer to the hot center of the island. When the ascending thermal water encounters permeable sub-horizontal aquifers in the upper volcanic units, it mixes with cool groundwater, spreads outward, and flows towards the coast. As a result of the above surface indicators, exploration activities were focused on the western side of the island.

Nevis Geochemistry

Among the most useful information in the OAS report (GeothermEx, 2005) was a summary of existing geochemical data from prior studies combined with additional analyses that they conducted. In order to fill in the data gaps we collected additional samples for noble gas analysis.

The geochemistry of Nevis is predominated by fluids that are of the acid sulfate and the sodium chloride types. These have been largely neutralized by their passage through thick volcanoclastic rocks mixing with shallow groundwater on their way to the surface. Of the existing water wells, there are two that provide insight into defining the conceptual model of the Nevis geothermal system. Those two wells, the Spring Hill well and the #10 tee well on thee Four Seasons golf course (Figure 4), have chemistries consistent with the outflow and the upflow zones respectively. The high chloride concentration of the Spring Hill well and its high temperature (181°F, 83°C) and relatively high concentration of boron and lithium indicate that some of the fluid in this well originates from the outflow of fluids from a deep geothermal system. The high sulfate and temperature (165°F, 74°C) in the #10 tee well and the low pH's of adjacent wells (Jessup well) is indicative of gas rich fluids rising along an upflow zone.

To assist in flow-path determinations we sampled the mixed-water thermal outflows and had the samples analyzed for the helium isotope ratios (He^3/He^4) as well as other noble gases at the University of Rochester, NY rare gas laboratory. Studies have shown that the He^3/He^4 ratio is higher in fluids that have a large magmatic component than in the atmosphere. All of the samples clearly have a significant magmatic helium signature (1.5 to 7.8 times the atmospheric ratio) with the lower ratio due to mixing with shallow groundwater. The results of the helium isotopic data are shown graphically on Figure 5. It is clear that the distribution of high helium ratios occurs in almost every sample taken on the western part of the island indicating a magmatic source for the helium.

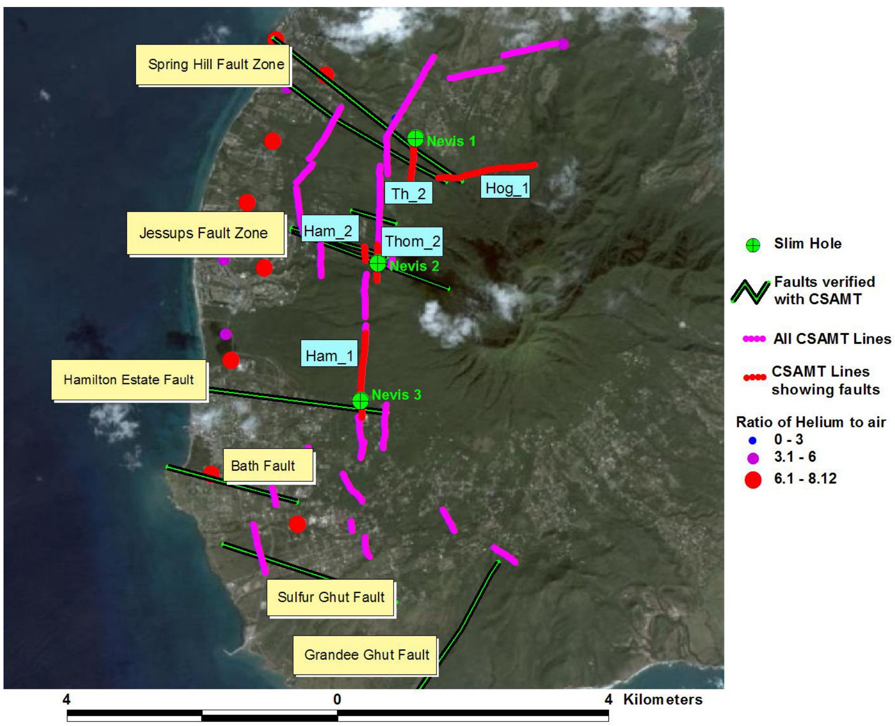

Figure 5. Helium ratio, CSAMT lines, faults and slim-hole locations.

Conceptual Model Development

The shallow groundwater sources that were sampled vary in temperature depending upon the input from the upflow zone, the degree of cool water mixing, and variable parameters of the outflow path. Hence, the absolute temperatures measured in the various shallow thermal wells are not as important as knowing where the anomalously thermal waters occur. The challenge is determining the location of the upflow zones providing the high temperature input. The identification of potential upflow faults and the selection of drill site locations relative to these faults is the objective of exploration activities.

Enhanced satellite imagery, digital elevation model, and aerial photography were used to identify observable faults and linear features considered to be permeable geologic structures. These structures were investigated in the field in order to map hydrothermal surface manifestations and indications of faulting. The high permeability and semi-consolidated nature of the young volcanic surface deposits tends to preclude the occurrence of such features so their absence does not eliminate the potential for underlying hydrothermal fluid.

It appears that the Spring Hill Fault Zone and the Grandee Ghut Fault (Figure 5) constrain most of the hydrothermal system on the north and south respectively. The geochemical and geological data seem to indicate that the location of the magma source may underlie the western part of the island. This would be consistent with the high sulfate and low pH of the wells in the Clark's Ghut/Belmont Estate area (Figure 4) appearing to be near to the up-flow zone.

Figure 5 shows the structures verified by geophysical surveys that might be of sufficient size to propagate to the necessary depths for geothermal development. The geophysical surveying was also used to image these structures to depths of several thousand feet.

Geophysical Surveying

Most high temperature hydrothermal systems are associated with a low resistivity layer over the geothermal reservoir due to clay mineral alteration. Because resistivity methods can be used to infer hydrothermal alteration, and permeability, they offer a means for interpretation of geothermal reservoir configuration and fracture zone distribution. Resistivity variations are usually related to salinity, water saturation, porosity, and cation exchange capacity in hydrated clays.

Resistivity techniques using electromagnetics have the capability of profiling to a depth of several thousand meters. The electromagnetic method that gives the greatest resolution over the upper 1000 meters of depth is the controlled-source audio-frequency magnetotelluric method (CSAMT). Approximately 20,000 meters of CSAMT surveys were conducted on the western side of the Island (Figure 5).

The other method that was used in Nevis was the magnetotelluric (MT) method. This method estimates the resistivity to depths of several kilometers from the measurements of orthogonal components of the natural time-varying electrical and magnetic (EM) fields. These fields are created by worldwide lightning strikes and from solar flares.

CSAMT Results

The major structures identified during the geological exploration phase and some less apparent lineaments were targeted with the CSAMT surveying in order to verify the location of the structure and to estimate its direction and angle of dip. A series of N-S oriented lines extending south of Spring Hill to Prospect Estate give an excellent cross section of the upper several hundred meters of the western flank of Nevis Peak. Ubiquitous along all these profiles is the existence of a highly conductive zone (5 ohm/m and less) that varies in depth from just under the surface to a depth of 200 meters below the surface. The area where this layer is disrupted usually coincides with or is adjacent to major faulting. This zone is shallowest in the vicinity of the mapped Belmont Estate hydrothermal alteration area (Figure 4), indicating that the high conductivity of this extensive zone is caused by the effects of the hydrothermal system. Figure 5 shows the relationship between the CSAMT lines and the identified structures. The CSAMT results crossing the main structural features of interest for defining the geothermal system are described below starting from north to south.

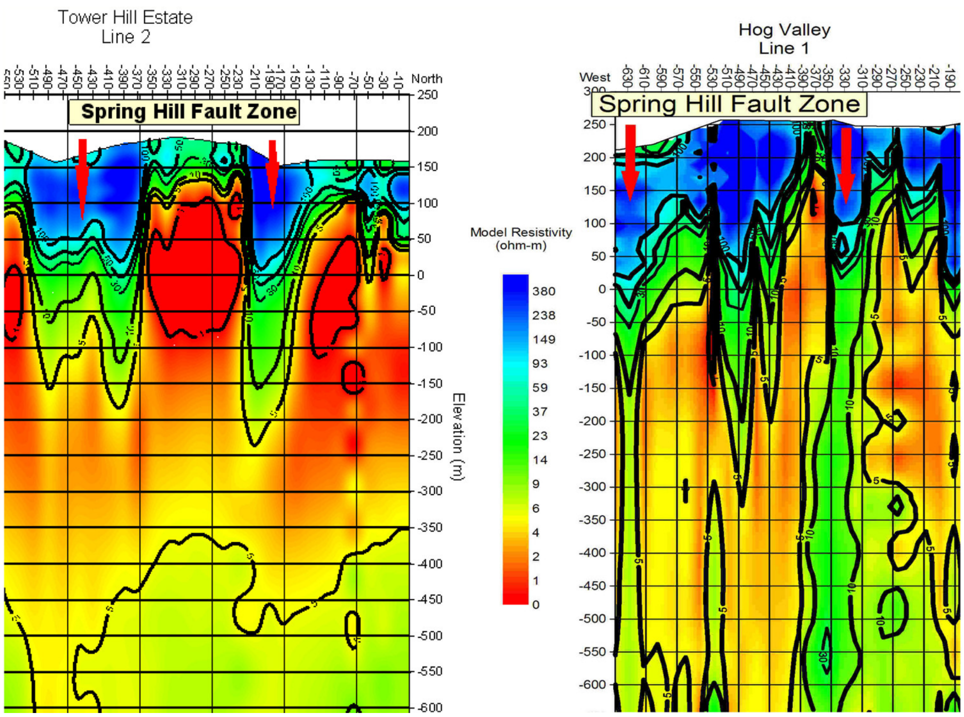

Figure 6. Hog Valley line 1 and Tower Hill Estates line 2 showing the location of the Spring Hill fault zone.

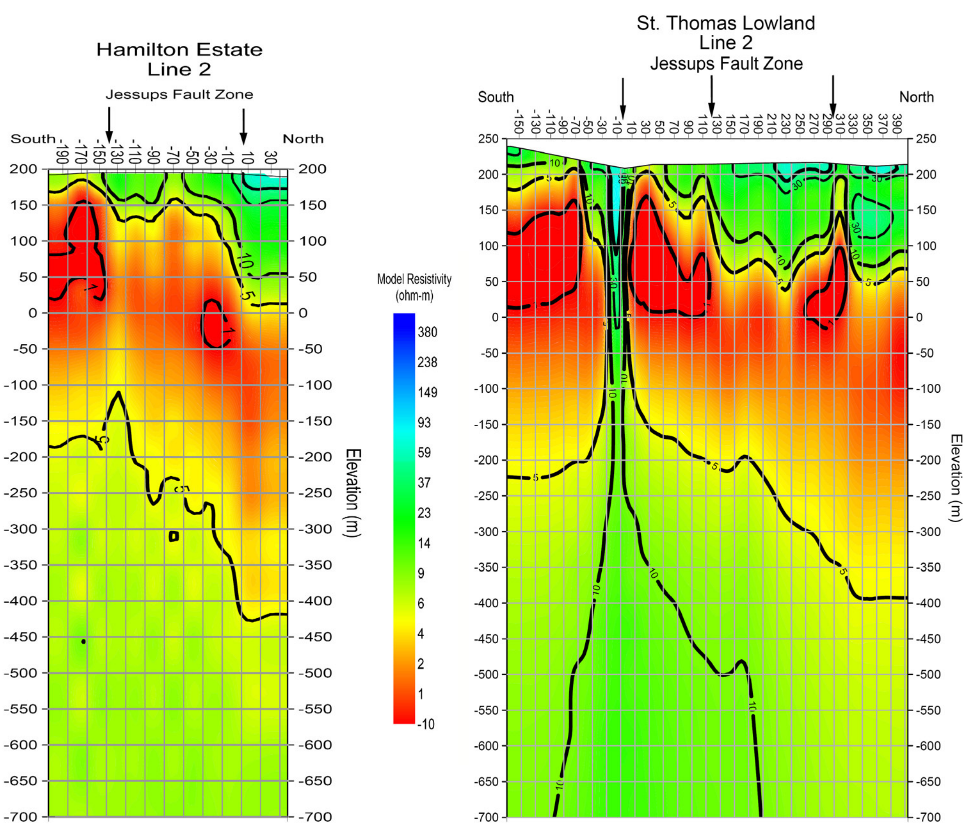

Figure 7. Hamilton Estates line 2 and 3 showing the Jessup's fault zone and the conductive zone close to the surface.

Spring Hill Fault

This feature was first identified from a lineament analysis of several sources of imagery and is proximal to the Cades Bay Fumarole and appears to form the southern boundary of Round Hill. The CSAMT data from line HOG_1 and line TH_2 (Figure 5) show the fault zone (Figure 6). Since there are no clearly defined horizontal beds on each side of the fault, the offset of the fault is not known. The higher resistivity evident along the fault plane probably shows the higher water content within the zone associated with downward migration of infiltrating groundwater.

Jessup Fault Zone

This structure was identified from the initial photo lineament analysis (Figure 4) and has been confirmed with the CSAMT. The CSAMT profile across this structure is not as dramatic as the profiles in Hog Valley or Tower Hill Estates, partially due to the homogenously low-resistivity volcanic deposits evident all along this portion of the western flank of Nevis Peak. However, the offset in the shallow conductive zone shows the vertical displacement to be about 100 to 150 meters (Figure 7). Also evident on this profile is that the conductive zone is very close to the surface in the Ham_2 and Thom_2 lines. These lines are located upslope from the Belmont Estates hydrothermally altered zone, implying that the shallow conductive zone is the same one that is exposed in outcrop and is due to hydrothermal alteration.

Hamilton Estate Fault

This fault is oriented WNW and is parallel to the Bath Fault (Figure 5). It is subtly evident on the aerial photographs and was mapped by Geothermix Inc. (2005) as part of the OAS geothermal project. The seaward extension of this fault appears to be the source of the offshore bubbles that were sampled and analyzed. The CSAMT survey clearly shows the shallow conductor being disrupted by this fault (Figure 8). The more resistive rocks to the south may

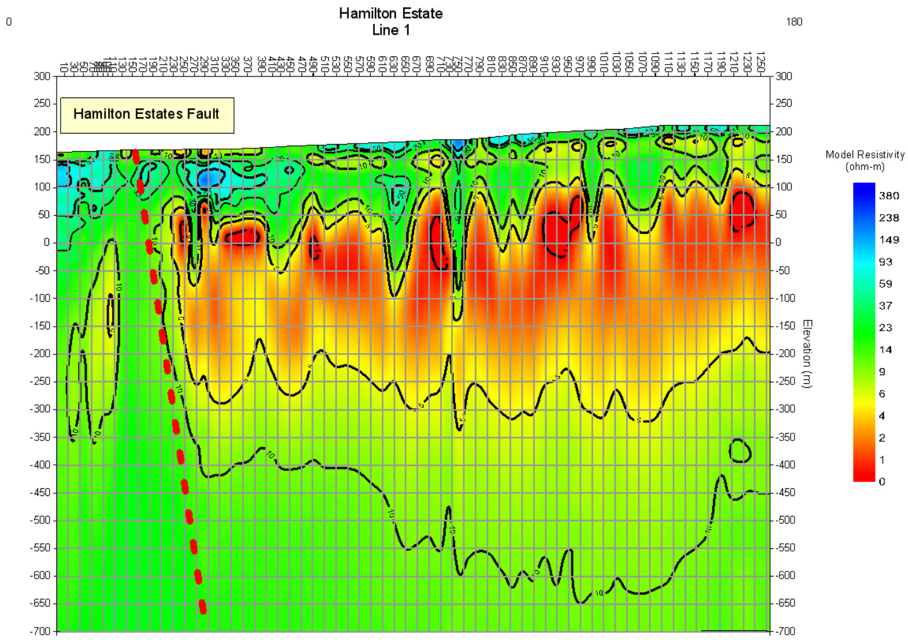

Figure 8. CSAMT profile showing the Hamilton Estate fault and the higher resistivity volcanic flow and possible intrusive.

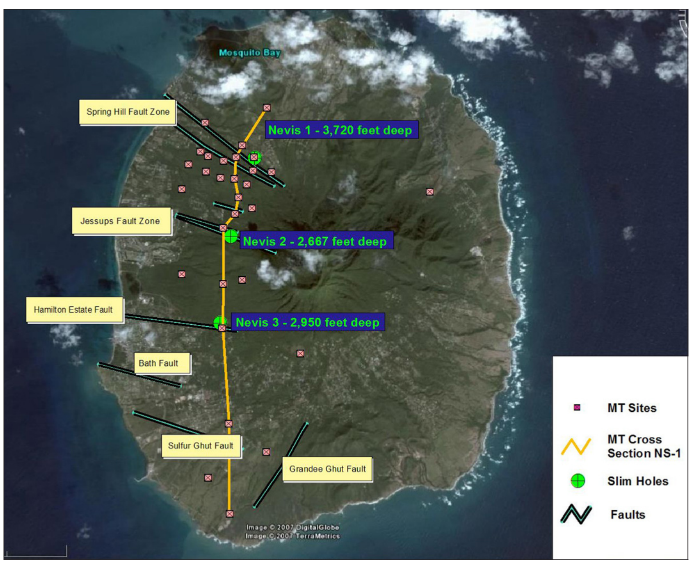

Figure 9. MT stations, cross section N-S 1, faults and drill site locations.

represent a shallow intrusive that is responsible for the lava flow apparent in the Hamilton Estates area.

Magnetotelluric Results

Magnetotelluric surveying was conducted over three separate periods. The effects of near-surface inhomogeneities which can cause a shift in the resistivity (static shift) were nullified using the standard practice of acquiring transient electromagnetic (TEM) data in close proximity to the MT station points. The assumption is that TEM data is less affected by static shift errors because it does not use in-ground electrodes to measure the electric field; rather, it utilizes an inductive loop on the surface of the ground and a magnetic coil for collecting measurements.

Initially MT data were collected from 12 stations widely distributed on the western side of the island and one station on the eastern side providing reconnaissance level resistivity data. In addition TEM data were collected at 7 of those sites in order to correct for "static shift". This data was then processed and interpreted by Dr. Stephen Onacha of Sondi and Consultants to provide an overview of the Nevis geothermal system. The interpretation of this data assisted in the construction of a conceptual geothermal model and was used to plan additional MT sites. Figure 9 shows the location of these initial stations and the stations used to create a N-S profile.

A total of 17 additional MT soundings and 12 TEM soundings were made in proximity to selected MT sites in order to correct the MT soundings for "static shift". The primary objective of the additional two rounds of MT/TEM surveying was to pinpoint the locations of buried fluid-filled fault zones so that these could be targeted with slim-holes to characterize the geothermal system. The characterization and analysis of both the shallow and deep resistivity structures assisted in developing a conceptual model that was used as a guide to exploration and will assist in targeting deep production wells. The locations of the MT stations within this area of interest are shown in Figure 9.

A series of cross sections and maps were prepared based on the data acquired in all three phases of exploration. The cross section NS-1 was one of the more critical cross sections. The 1d profile of NS-1 shows the Springhill and Jessup's Fault zones and the Hamilton Estate Fault. The CSAMT data has been merged with the MT data to produce the profile in Figure 10. It appears that the Springhill Fault Zone is near vertical, possibly dipping to the

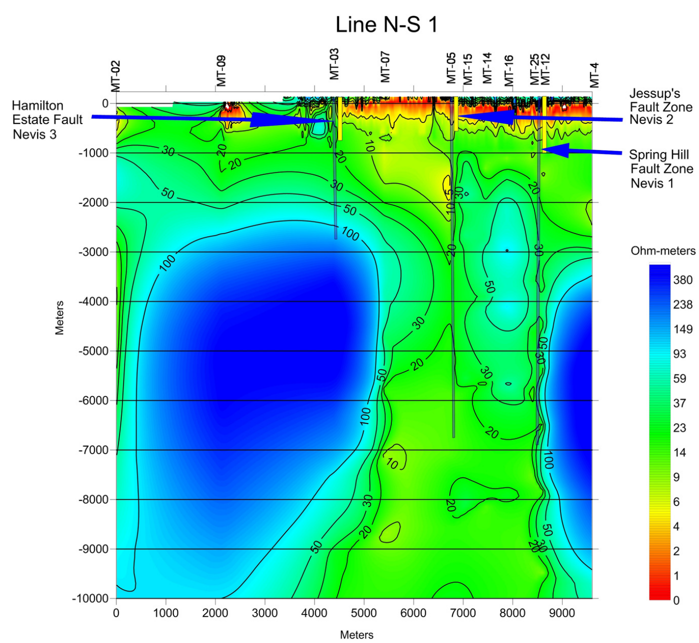

Figure 10. North-South Profile of 1d MT data merged with CSAMT data showing the faults and slim-holes.

south as the CSAMT data suggested. A more detailed survey with closer spaced MT soundings across the faults may help to better estimate the detailed geometry of the fault zone. The NS-1 1d Model cross section also shows the detailed image of the Jessup Fault Zone which is very steeply dipping but there are far too few data points to confirm that it dips to the north as suggested by the CSAMT survey.

Drill Site Selection

The objective of the slim-hole drilling project was to verify the presence and extent of the apparent high-temperature hydrothermal system in the west and northwest quadrant of Nevis. As discussed above, locations adjacent to potential upflow faults were sought. As indicated by the geophysics (Figure 10) and linear nature of the fault traces, most of the faulting is near-vertical.

Some geothermal fields are totally dependent on fault-produced fracture permeability (e.g. the Coso Field in California which produces entirely from fractured granitic rock); however, the layered volcanic units in Nevis will undoubtedly afford some sub-horizontal hydrothermal aquifers as well. Brittle units such as lava flows and welded tuffs often provide such aquifers in a volcanic pile, but their lateral extent is highly variable and often limited. Hence, the chances of encountering a high-temperature sub-horizontal aquifer increase in closer proximity to upflow faults.

The elevation of the drill sites was selected based on land availability, drill rig access, and the desire to drill on the mid flank of the volcano. Locations too low on the volcano's flanks may encounter only distal outflow from the hydrothermal system; whereas, locations higher on the volcano would have increasing potential of encountering volcanic gasses as one approaches the most recent volcanic eruptive center of Nevis Peak (0.1 mybp). So, drill sites mid way up the flanks of Nevis Peak were selected.

The spacing of the slim-holes and the number of slim-holes drilled were a consequence of the drilling results. The high temperature at relatively shallow depth measured in the N-1 slim-hole well encouraged a fairly large "step-out" distance of about 2 km for siting of the N-2 slim-hole. Likewise, the high temperature at shallow depth recorded in the N-2 slim-hole justified another approximately 2 km step-out for the N-3 slim-hole well. The gratifying results of the drilling and spatial distribution of the surface manifestations allowed for a generous spacing of the slim-holes and reduced the number of holes required to identify the resource.

The Nevis 1 Drill Site

The first geothermal test well drilled on the Island of Nevis, the N-1 slim-hole well, was sited adjacent to a large NW-trending fault zone that we call the "Spring Hill Fault Zone" (Figure 9, Figure 10). Although not previously mapped, this fault zone is quite apparent on the aerial photography, digital elevation model and satellite imagery and was verified by the geophysical surveys as being near vertical.

The Nevis 2 Drill Site

The N-2 slim-hole was sited adjacent to the Jessups Fault zone (Figure 9, Figure 10). Downhill from N-2 is the Belmont Estate extensive area of sulfateric alteration that includes small occurrences of native sulfur and significant deposits of secondary anhydrite and gypsum. Within this alteration area is the second hottest domestic water well on the island 167°F (75°C), which was drilled on the Four Seasons golf course for irrigation.

The Nevis 3 Drill Site

The N-3 slim-hole well was sited adjacent to the Hamilton Estate fault (Figure 9, Figure 10). This fault is the southern boundary of the conductive zone in the northwestern quadrant of Nevis. The resistive zone south of the Hamilton Estate fault may represent the volcanic source of the lava flow evident along Pump Road. The initial drill site was used as an exploration water well test hole that was drilled by BEAD, LLC for the Nevis Water Department. Its location was selected to intersect the fault zone with the hope of developing potable water. The well produced about 70 gallons per minute, however the iron concentration was high (3.5 ppm) and the water was effervescent with carbon dioxide. The temperature was slightly thermal at 100°F (38°C) and therefore was not a worthwhile municipal well. Because the location was ideally located to intersect the fault at depth and it was a ten-inch diameter hole to a depth of 607 feet it was perfect for the conversion to a slim-hole. Examination of the well cuttings revealed argillic and sulfateric alteration, and the occurrence of secondary, "vapor-phase" pyrite. With the encouragement of these observations, it was decided to cement surface casing to a depth of 607 feet thereby using the well as a deep slim-hole. The results of this decision were stunning.

Drilling Results

West Indies Power selected a core rig for its deep slim-hole drilling on Nevis; however, the sticky volcanic clays that were encountered created problems. Therefore, core was only available for part of Nevis 1. The other two slim-holes were drilled with a rotary drilling technique.

Results of the Nevis-1 Slim-hole

The N-1 slim-hole was drilled to a total depth of 3,720 feet (-3,190 feet bsl). The formations penetrated were predominantly volcanoclastic deposits of hornblende-bearing dacite with lesser amounts of andesite.

At a depth of 3,500 ft, the N-1 well experienced a notable hot water entry. Drilling was temporarily suspended and a temperature/pressure survey was performed by Tiger Wireline Services. The temperature profile measured in the N-1 well showed no reversals and was approaching isothermal conditions with a maximum bottom hole temperature of 484°F (251°C) (Figure 11).

The well was deepened to 3,720 feet, but in attempting to retrieve a core sample, the HQ drill string became stuck with the bit 50 feet off the bottom. Drilling was abandoned after much effort to retrieve the tools. The well was airlifted for 72 hours and surface temperature and pH were recorded. The outflow fluid temperature was measured to increase from 197ºF (92°C) to 207ºF (97°C) with dubious accuracy because the fluid was flashing. The pH varied between 5.5 and 7.9 but stabilized at a pH of 6.4 for the last 25 hours of air lifting. It was later observed that N-1 will develop a shut-in wellhead pressure of 80-100 psi and will flow a small volume on its own when opened quickly.

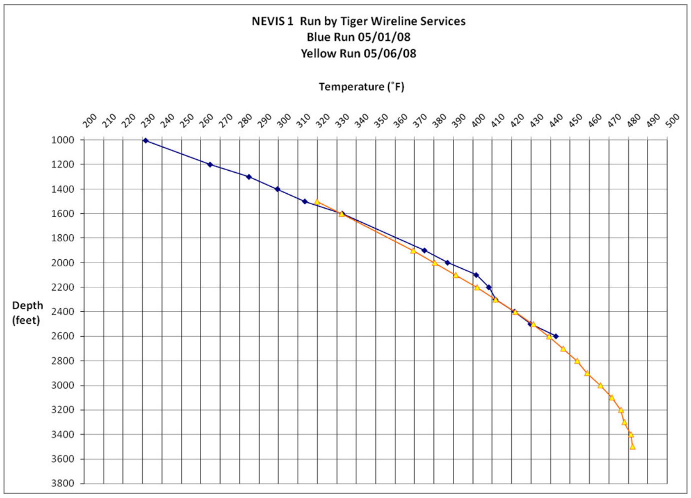

Figure 11. Graph of temperature versus depth for Nevis-1.

Within a day after flowing, the bottom hole temperature stabilized at 464ºF (240°C), which we consider to be the formation temperature at that depth. Because the formation temperature is 20ºF (11°C) less than the flowing temperature, we know that the true upflow zone is at a distance from the bottom of the hole. We suspect that the flow in N-1 is coming from the Spring Hill Fault Zone, a short distance south of the drill site (Figure 5). This fault zone will be our bottom-hole target for an initial production test well (Figure 12).

Figure 12. Planned trajectory of initial production test well.

Results of the Nevis 2 Slim-Hole

The N-2 slim-hole was drilled to a total depth of 2,567 feet (-1,840 feet bsl.). At this depth, increasing drilling difficulties exacerbated by a predominance of sticky clays became quite problematic. The bottom-hole temperature was measured three separate times at approximately 500ºF (260°C). Drilling progress had slowed to the point that, in the interest of cost-effectiveness, it was decided to quit the hole at that depth. It was decided that the high temperatures measured this shallowly indicated that the hydrothermal system is still alive and well beneath the clay cap that was creating the drilling problems. We do not think this high temperature would occur at this relatively shallow depth from purely conductive heat transfer, especially since the last igneous eruption event was 100,000 years ago. Although no fluid entries were reported in the N-2 slim-hole, our conclusion that the shallow high temperature evidences the hydrothermal system is strongly supported by the fact that thermal domestic water wells and offshore hydrothermal vents occur just down hydrologic gradient from the N-2 drill site.

Results of the Nevis 3 Slim-Hole

The N-3 slim-hole well was drilled to a total depth of 2,950 feet (-2,410 bsl). At this depth the drilling was shut down and the site secured due to a hurricane warning. Two days later when the well was reopened to resume drilling, it began to flow vigorously.

Application of the "James Tube" testing methodology using an assumed enthalpy of 476 BTU/lb (equivalent to 254°C (489°F), based upon the geothermometry of fluid samples) provided estimates of 76,000 to 86,000 lb/hr total mass flow. In light of the fact that the open-hole diameter is only 3 inches, this is a very impressive flow rate from a slim-hole. The stabilized shut-in pressure is approximately 700 psi.

Results of Fluid Sampling

Collection and analyses of fluid samples from the N-1 and N-3 wells was performed by Paul Hirtz of Thermochem Inc. of Santa Rosa, CA. This testing shows that the reservoir is predominantly hydrothermally altered seawater slightly diluted with meteoric water. The total dissolved solids (TDS) for the flashed fluid at N-1 was 31,608 mg/kg and the TDS calculated for the total fluid was 25,108 mg/kg. The flashed fluid at N-3 was 37,164 mg/kg and the calculated TDS for the total fluid was 32,082 mg/kg.

Field pH measurements of the flashed fluids from N-1 and N-3 made by Thermochem gave values of 6.13 and 5.54 pH units respectively. Laboratory pH determinations were 6.57 and 5.90 pH units for N-1 and N-3 respectively.

Geothermometry of the Nevis Samples

Thermochem Inc. reported quartz adiabatic temperature calculations of 517ºF (269°C) for the Nevis 1 sample and 534ºF (279°C) for the N-3 sample. Quartz enthalpy calculation for N-1 and N-3 were 509 Btu/lb and 529 Btu/lb respectively. The standard cation geothermometry calculations were considered invalid for the Nevis reservoir samples because of unusually high calcium content inferring the presence of carbonates within the reservoir lithologies.

Noncondensible Gasses

As usually seen in high-temperature hydrothermal systems, the noncondensible gas (NCG) content of the Nevis reservoir is predominantly CO_2, constituting about 93-96% by volume. The NCG content of the N-1 steam sample is fairly low, approximately 774 ppm by weight. In the total flow, the H_2S content of the N-1 sample was 34 ppm by weight.

In the N-3 sample, the NCG content of the total flow was 3,378 ppm by weight and H_2S content of the total flow was 55 ppm by weight, which is typical of high-temperature geothermal wells.

Conclusions

The drilling results and the surface manifestations evidence an extensive hydrothermal system that is at least 3.5 miles in the north-south direction along the west and northwest flank of Mount Nevis. The system extends at least from the Spring Hill Fault Zone on the north to the Bath Fault Zone on the south (Figure 5). The width of the system is unknown.

As a result of these investigations, accurate predictions of the size of the potential resource are not possible until additional larger diameter drilling has been completed. However, based on the data acquired to date, we believe that the hydrothermal system identified on Nevis has the potential to support geothermal power generation adequate to supply the total 45 megawatt electrical power demand of Nevis and the adjacent island of St. Kitts. The country of St. Kitts - Nevis has the potential to become the first totally geothermal-powered country in the world.

Not only has the CSAMT surveying successfully identified faults and their orientations, but also it has mapped an almost continuous highly conductive zone (1 to 5 ohm/meters) that extends from the surface to a depth of two or three hundred meters and is most likely a hydrothermally altered zone that forms a cap on the geothermal system. The fault zones that have offset the clay cap have been seismically active since the highly conductive zone was formed. Consequently, these faults may represent active conduits that may be transmitting hot geothermal fluids from depth to the surface.

The results of the MT surveying have demonstrated the effectiveness of using the magnetotelluric method to model the geothermal system to great depths. However, in order to image fault zones to determine the dips of the structures, measurements have to be made much closer together, i.e. 100 meters between soundings versus 500 meters, as was the case during this reconnaissance style investigation. Since the productivity of geothermal wells is dependant on drilling into highly permeable zones and these permeable zones are possibly very narrow and probably steeply dipping, it is critical to drill precisely into these zones.

The slim-hole drilling conducted by West Indies Power on Nevis has demonstrated the presence of a commercially viable hydrothermal system that appears to be continuous for at least 3.5 miles in a north-south direction along the western flank of the Nevis Peak Volcano. The top of the reservoir was encountered at depths generally between 3,000 to 3,500 feet. The reservoir consists of hydrothermally altered seawater with a minor component of meteoric water. The measured bottom-hole temperatures were approximately 500ºF (260°C) and the silica geothermometry is about 520-535ºF (271°C-279°C). The measured pH of the reservoir fluid is approximately 6 pH units. It is anticipated that these parameters may vary considerably in deeper parts of the reservoir, as is often the case in high-temperature, volcanic-related hydrothermal systems.

References

GeothermEx, Inc. (2005). Geological and Geochemical Studies in Nevis, West Indies, Organization of American States, Washington, D.C.

Hutton, C.O. and S.R. Nockolds, (1978). The petrology of Nevis, Leeward Islands, West Indies. Overseas Geology & Mineral Resources, v. 52. London: HMSO.