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Geothermal Exploration on the Island of St. Vincent, West Indies- A Country Update

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ABSTRACT

St. Vincent and the Grenadines is a volcanic island located along the Lesser Antilles volcanic island arc. The La Soufrière volcano dominates the northern half of the island and is one of the most active volcanoes in the Caribbean. The need for energy security has prompted the Government of St. Vincent & the Grenadines (GoSVG) to explore its indigenous energy resources. In 2013 Reykjavik Geothermal and Light & Power Holdings consortium (RG/LPH) signed a Letter of Intent with the Government of St. Vincent to conduct a geothermal survey aimed at developing its geothermal resources for electricity production. Geothermal exploration conducted at La Soufrière was completed in 2015 with emphasis on structural geology, volcanology, geochemical interpretation and resistivity surveys. These studies detected areas of geothermal potential on the south-west and south-east flanks of the La Soufrière volcano. A joint interpretation of magnetotelluric (MT) and transient electromagnetic surveys (TEM) revealed a resistivity structure that is consistent with the expected structure of high-enthalpy geothermal systems worldwide, namely low resistivity clay cap zone underlined by higher resistivity reservoir. This interpretation is supported by geochemical surveys which suggest reservoir temperatures in excess of 200 °C. A recent volumetric assessment has indicated with a 90% probability that the potential geothermal system at La Soufrière- St. Vincent is capable of sustaining a power plant with a capacity of up to 160 MW_e for 30 years. The recent success in geothermal exploration has brought the country to the next phase of its Geothermal Developmental Project - exploratory drilling, and subsequently, the construction of a 10-12 MW_e geothermal power plant. The first three production wells are planned in 2019 and an update on the drilling progress will be given.

1. INTRODUCTION

The Caribbean's Small Island Developing States (SIDS) face tremendous challenges associated with the generation and utilization of energy for their various needs. Most islands in fact, depend almost entirely on a constant influx of petroleum derived fuels for their energy needs which leaves these countries vulnerable to the instability of high international oil prices. This results in much of the countries annual Gross Domestic Product (GDP) being allocated to fuel import.

The multi-island nation of St. Vincent and the Grenadines (SVG), located at the southern end of the 750 km long Lesser Antilles volcanic island arc, occupies a total area of only 389 km^2 (Figure 1a). SVG's small population of just under 110,000 inhabitants, coupled with an obvious lack of large industrialised activities have resulted in a small peak demand of 21 MW_e, with economic projections showing an increase in electricity consumption at a rate of 3-4% per annum by 2025 (GoSVG 2010). Regardless of this, in 2014 SVG had among the highest electricity rates in the Caribbean at USD $0.43/kWh- second only to Dominica. St. Vincent and the Grenadines depends on diesel generation for the majority of its electricity supply, with hydro power accounting for approximately 20% of the electricity demand. There is a minor but growing contribution by solar power to the existing electricity grid, along with a prospective geothermal energy source, which aims to contribute an additional 10 MW of electrical power. Given the instability of fluctuating international oil prices, as well as the projected growth of electricity consumption, renewable energy is the most cost-efficient energy source for St. Vincent and the Grenadines. The Government of St. Vincent and the Grenadines (GoSVG) anticipates that with the introduction of a geothermal energy plant in the foreseeable future, almost 80% of the country's electricity would be generated by a mix of renewable energy sources, including geothermal, hydro, and solar energy.

The potential for geothermal development is not new to St. Vincent and the Grenadines, in fact, the GoSVG has been expressing interest in geothermal exploration since the late 1980s. Geothermal exploration conducted on the island of St. Vincent since 1991(Geothermica Italiana, 1991; Huttrer, 1996; Caribbean Power, 1998; GeothermEX, 2001; Björnsson et al, 2013; Eysteinsson, 2015; VSO Consulting, 2016) revealed a possible high temperature geothermal field in the La Soufrière region in excess of 200 °C. This paper therefore presents an update on the recent geothermal exploration conducted on the island of St. Vincent to date.

2. ST. VINCENT GEOTHERMAL DEVELOPMENT PROJECT

2.1 Geological Overview of St. Vincent

The Lesser Antilles of the Caribbean was formed by a subduction zone, as a result of the collision between the North and South American Plate margins with the minor Caribbean plate. This has given rise to a very volcanically active region on the oceanic crust of the Caribbean Plate, with approximately 19 active volcanoes.

The island of St. Vincent is entirely volcanic with lava flows and pyroclastic deposits ranging in composition from basalts to basaltic-andesites to rare andesites. Basalts are commonly found in the southernmost parts of the island, while basaltic-andesites dominate the north (Melekhova, et al. 2015). Figure 1b shows the distribution of geological material throughout the island as well as two extinct volcanic centres – Morne Garu and Grand Bonhomme.

The La Soufrière is a basaltic-andesitic type stratovolcano that dominates the northern half of the island of St. Vincent (Figure 1b) and is one of the most active volcanoes in the Caribbean, with at least five major historic eruptions recorded in 1718, 1812, 1902, 1971 and 1979 (Sigurdsson and Carey 1991). It consists of an older strato-cone of diameter of 2.5 km, forming a steep arcuate ridge to the north and a younger pyroclastic cone within the crater. Minor intrusions occur within the Soufrière volcano summit with three northerly striking dikes observed within the walls of the main crater. These dikes are thought to be abundant throughout the entire volcanic system (Huttrer 1996). Linear fault strikes illustrated in Figure 1b correlate with the locations of hot springs (Figure 2) observed along the Wallibou River on the western slope of the La Soufrière volcano, implying that the potential geothermal reservoir is deep rooted with fracture controlled permeability (Huttrer, 1996). St. Vincent's geological location and highly active volcanism therefore indicates a prospective geothermal resource, with molten volcanic material assumed to be the heat source for geothermal activity (Eysteinsson 2015).

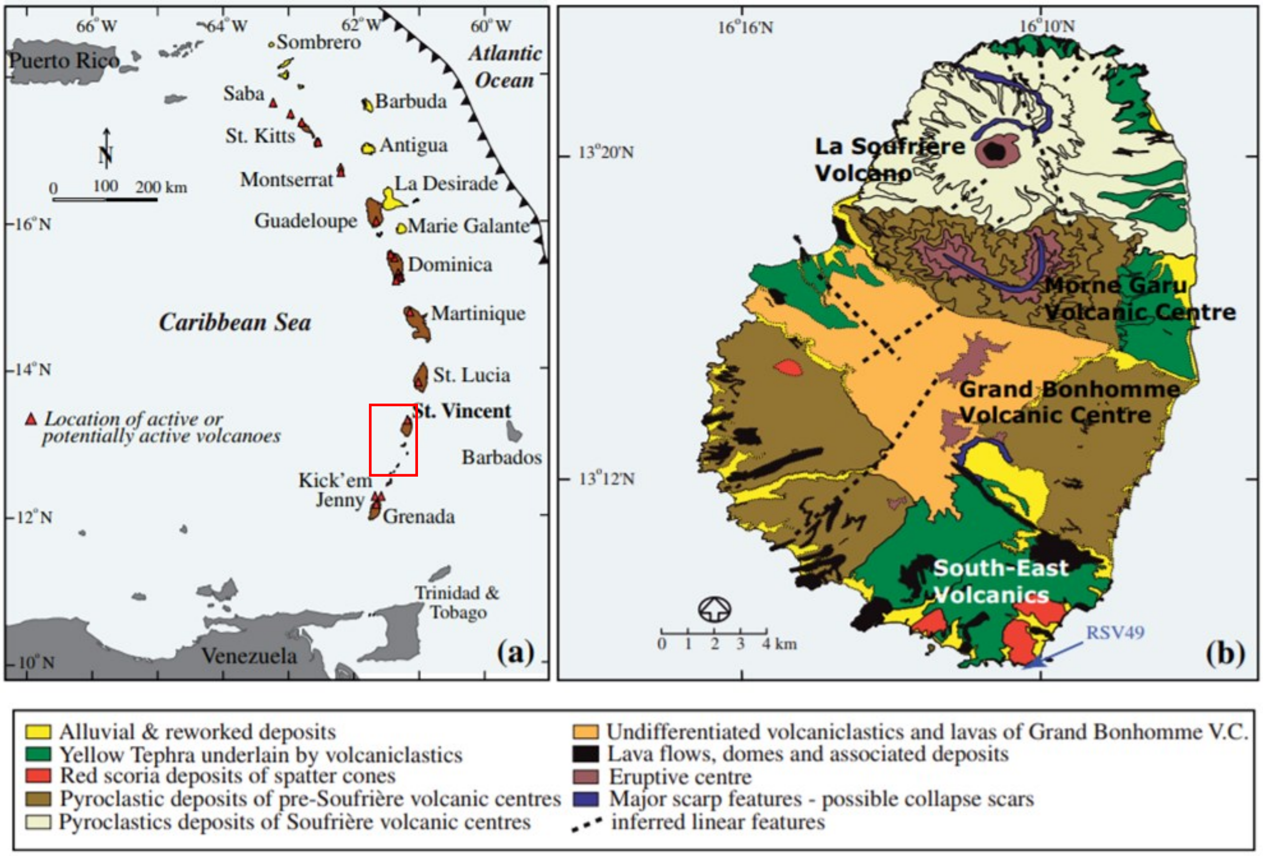

Figure 1: (a) The Lesser island volcanic arc showing the location of St. Vincent and the Grenadines. (b) Geological map of St. Vincent showing the main rock distribution throughout the island, adapted from Rowley (1978) with inferred linear fault zones Geothermica Italiana (1991)

2.2 Geochemical Analysis of Fluid Samples

There are two known areas of geothermal surface manifestation on the island. Warm springs flow along river bed at several sites down the Wallibou river (location shown in Figure 2), yielding temperatures greater than 35 °C while the fumaroles present within the La Soufrière crater have recorded temperatures in excess of 100 °C (Björnsson, et al. 2013). Numerous geochemical analysis were done on samples from the warm discharge springs in the Wallibou River, the waters flowing through the lava bed at La Soufrière; and the fumaroles present in the La Soufrière crater.

The anion classification diagram in Figure 3a, shows the Cl-SO_4-HCO_3 components of 60 water samples taken from the above sources. The ambient shallow groundwater plots close to the bicarbonate corner as expected, with low sulphate content that can be considered peripheral water in geothermal systems. With increasing temperature, the waters are enriched in sulphate (SO_4) and chloride (Cl). This indicates increased water-rock interaction with rising temperature. Although Figure 3a suggests possible on-going alteration, it also reveals the water samples are not in yet equilibrium with the host rock, partly due to a combination of relatively low temperature as well as a short residence time (Björnsson, et al. 2013).

Figure 3b illustrates the components of magnesium, potassium and sodium present in the samples. As expected with non-equilibrated groundwater, all samples plot in the magnesium (Mg) corner of Figure 3b. Figure 3 indicates that warm springs are tapping water from a reservoir that has not reached chemical equilibrium with the host rock. This may however result in non-reliable geothermometery analysis while assessing the reservoir temperature. Regardless of this, the quartz and chalcedony geothermometers were applied. These yielded temperatures in the range 150-240 °C with a mean of 207 ˚C.

The fumarole activity is restricted to the lava dome from the 1979 eruption. Steam samples from there have been interpreted to originate from a high enthalpy reservoir. Björnsson et al (2013) therefore concluded that a conservative estimate of the reservoir temperature may lie in the lower 200 – 300 °C range with the thermal manifestation of St. Vincent geothermal prospect originating from a single high temperature resource fed by the La Soufrière volcano.

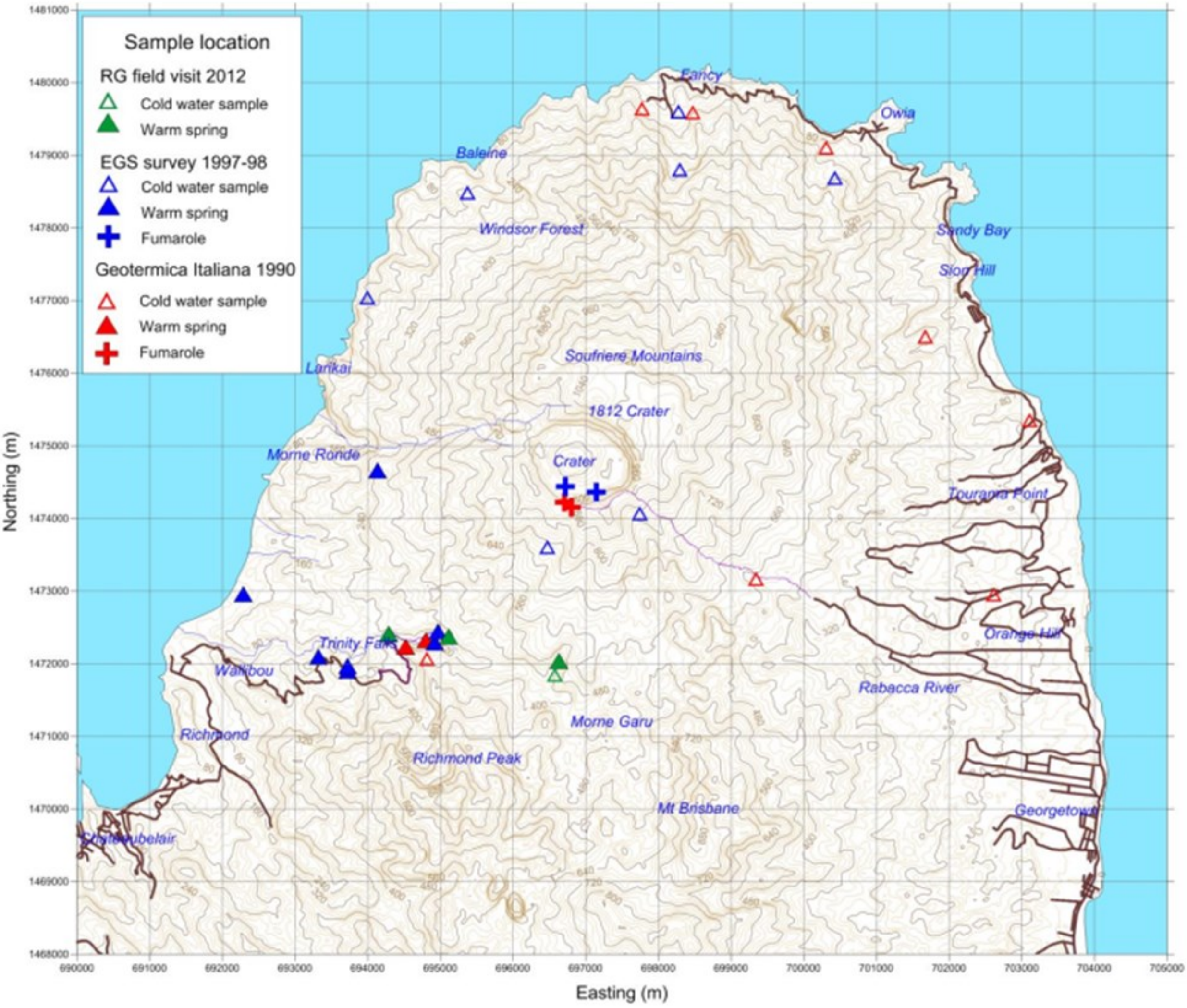

Figure 2: Map of the northern half of St. Vincent showing the locations of hot springs and fluid samples collected along the Wallibou River (Björnsson, et al. 2013)

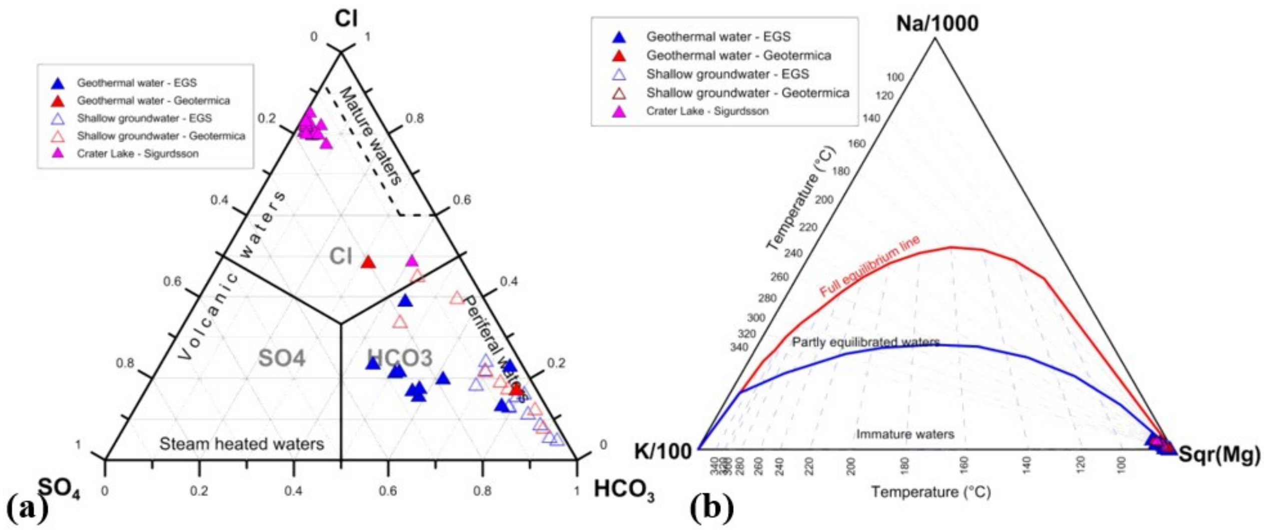

Figure 3: (a) Anion classification and (b) cation (Giggenbach) classification of water and steam samples taken from hot springs in the Wallibou River and from Fumeroles in the La Soufrière crater (Björnsson, et al. 2013).

2.3 Resistivity Structure

A joint Magnetotelluric (MT)/ Transient Electromagnetic (TEM) survey was undertaken between 2013-2014 with a total of 45 MT and 44 TEM soundings (locations shown in Figure 4a) in an effort to obtain a better understanding of the potential geothermal system in the La Soufrière region.

MT results presented in Figure 4b reveal a resistivity structure synonymous with that of a high enthalpy geothermal system. In such systems, the resistivity appears high in colder, unaltered rock material outside of the geothermal reservoir. A low resistivity clay, cap layer is observed on the upper, outer margins of the reservoir which is underlain by a high resistivity core. This structure has reportedly been observed over the entire surveyed area from La Soufrière extending to both the eastern and western coastline (Eysteinsson 2015).

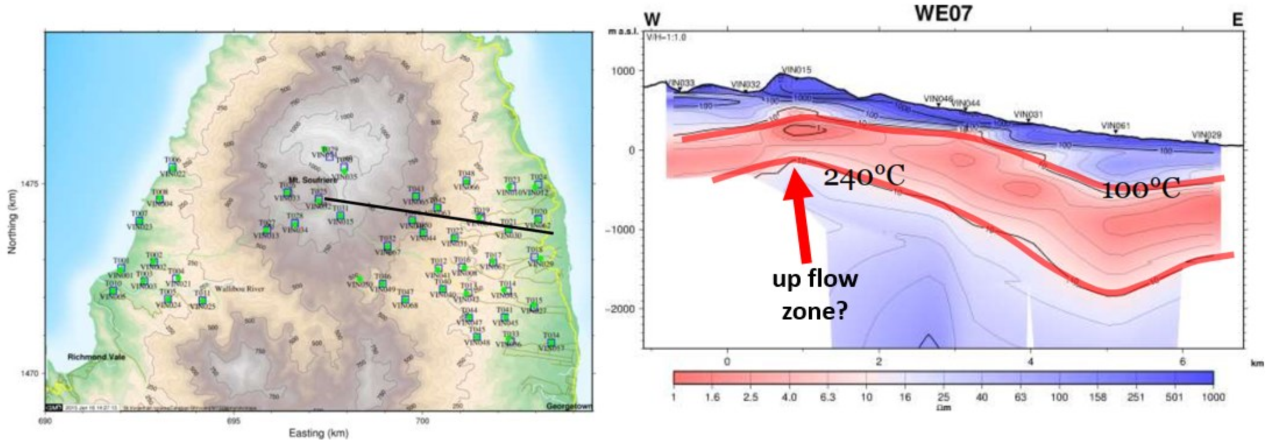

Figure 4: (a) Map of St. Vincent showing the locations of the 2013-2014 MT/TEM surveyed area and (b) Resistivity profile of the La Soufrière prospective geothermal area, modified from Eysteinsson (2015)

Similar trends are observed in high temperature geothermal systems in the volcanic zones of Iceland such as the Svartsengi geothermal system - located along the Reykjanes Peninsula in South West, Iceland. A comparison between the resistivity profile, thermal alteration and formation temperature profiles derived from well data at Svartsengi has revealed that resistivity measurements reflect the alteration in the geothermal field (Franzson, 1983; Björnsson and Steingrímsson 1991; Karlsdóttir 1998; Karlsdottir and Vilhjálmsson 2015). A clay cap is formed due to the temperature dependent alternation of minerals due to a chemical interaction between the rock material and fluid within the rock matrix. In such basaltic systems, the low-resistivity cap coincides with the more conductive, low resistivity smectite-zeolite and mixed layer clay zones, whereas the high resistivity core corresponds to the chlorite-epidote alteration zone. This observation is of utmost importance, since the temperature dependence of the alteration mineralogy makes it possible to interpret the resistivity profile in terms of temperature. The upper boundary of the low resistivity cap layer in corresponds to temperatures within the range of 50 °C and 100 °C, as temperature increases, smectites and zeolites are altered readily into chlorite and epidote corresponding to temperatures of 230 °C and 250 °C respectively. Providing that the thermal alteration is in equilibrium with temperature of the geothermal system, the mapping of the resistivity structure may in fact be the mapping of isotherms (Árnason, et al. 2000).

In Figure 4b, the clay cap rock layer is interpreted to be between the two thick red contours. Assuming that the reservoir temperature is in equilibrium with the formation temperature of the prospective La Soufrière system, the temperature of the top and bottom of the clay cap layer is approximately 100°C and 240°C respectively. The central geothermal reservoir would therefore be located below this lower boundary, with the main up flow zone close to the centre of the mountain. This correlates well with the geothermometry results which approximated reservoir temperatures between 150-243 °C.

2.3 Resource Estimation

Geothermal resource assessment is a broad-based estimation of the amount of geothermal energy that might become available for use, given reasonable technological and economical assumptions, governmental policy, and environmental constraints (Muffler 1978). The volumetric method is used to be the main static modelling method used in the past to assess geothermal resource capacity and is most practically done in the initial assessment. It is based on estimating the total thermal energy stored in a volume of rock. The main drawback of the volumetric method however is that the dynamic response of a reservoir is not considered. It does not account for natural recharge or increased recharge to the reservoir due to drawdown, nor does it consider the role of permeability. This may result in an overestimated model, although however, there have been some reported cases of underestimation (Grant and Bixley 2011). In order to address these uncertainties, the Monte Carlo approach is often applied. This statistical method enables the incorporation of overall uncertainty in the results and assigns a probability distribution to each parameter in the volumetric calculation. The Monte Carlo simulation then calculates and produces a probability distribution for the final estimate of electrical (or heat) energy. This approach determines the 10% value, which is often referred to as proven, i.e. the 90% probability that the stored heat estimate would exceed this value.

Results from geoscientific exploration indicate that the island of St. Vincent possess a high enthalpy geothermal system. Using the values and probability distribution listed in Table 1: Estimated reservoir parameters used in the Volumetric AssessmentTable 1, a volumetric assessment (VSO Consulting 2016) was done for the prospective La Soufrière project. The results for both a 30 year and

50 year plant lifespan is given in Figure 5. Figures 5a and 5b illustrate with 90% confidence that the power production capacity is between 300 and 160 MW_e for a production period of 30 years- the normal economic lifetime of a geothermal power plant. Similarly, Figures 5c and 5d demonstrate that for a production period of 50 years, based on the estimates used in Table 1, there is a 90% probability that there is an estimated power capacity of between 80 MW_e and 240 MW_e. The Volumetric method therefore estimates an extensive heat source that, once managed sustainably may be able to sustain a 10-20 MW geothermal power plant for a production period of over 50 years. This however can only be confirmed by exploratory drilling.

Table 1: Estimated reservoir parameters used in the Volumetric Assessment (VSO Consulting 2016)

Input Variables	Units	Most Likely	Min	Max	Probability Distribution
Area	km^2	15	10	35	Triangular
Thickness	m	1400	1000	1800	Triangular
Temperature	ºC	230	200	300	Triangular
Recovery Factor		0.1	0.05	0.2	Triangular
Load Factor		0.95	0.90	0.98	Triangular
Rejection Temperature	ºC	46			Single Value

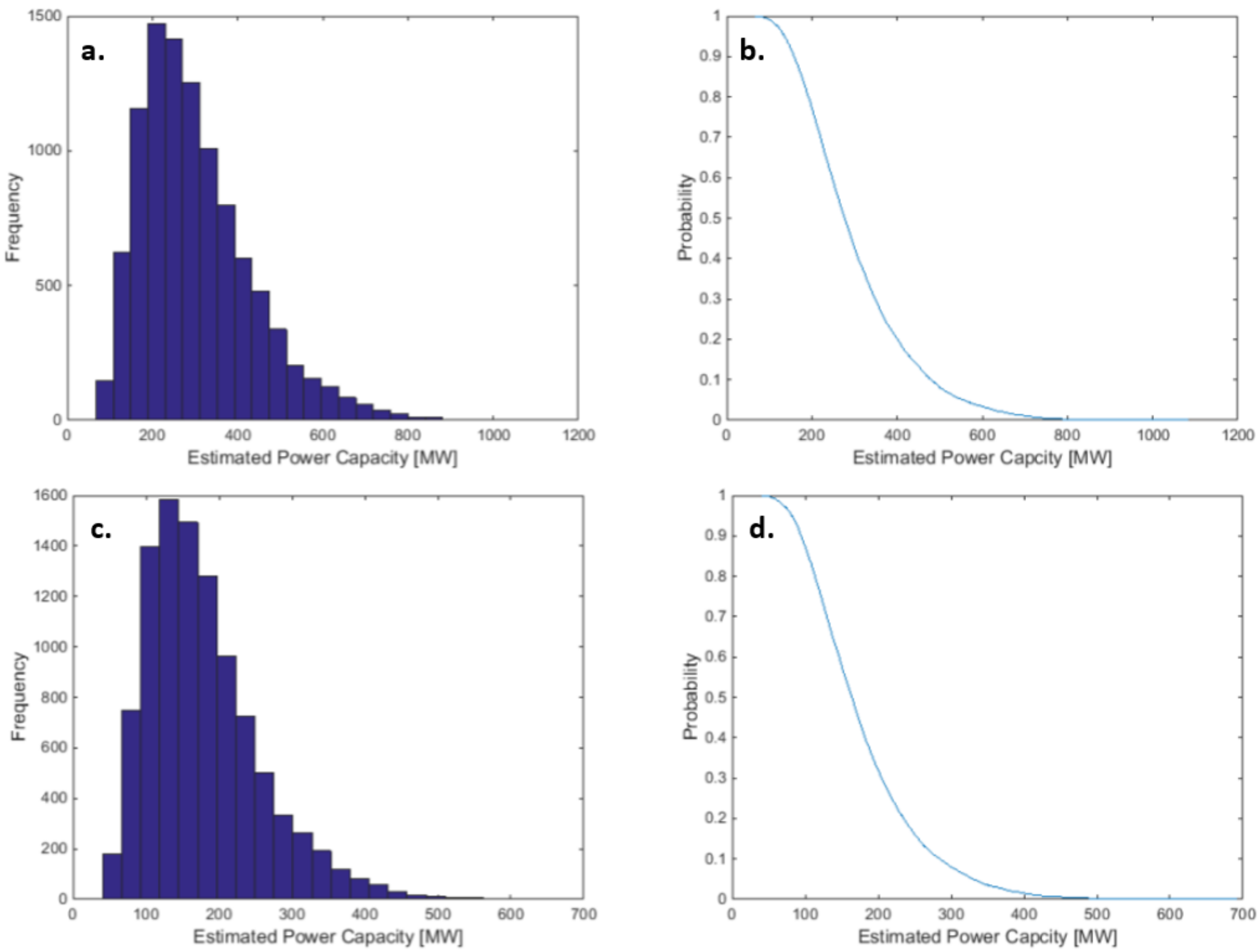

Figure 5: (a) Monte Carlo volumetric discrete probability distribution and (b) volumetric cumulative probability distribution for electrical power production for a period of 30 years, with (c) Monte Carlo volumetric discrete probability distribution and (d) volumetric cumulative probability distribution for electrical power production for a period of 50 years

4. EXPLORATORY DRILLING

The St. Vincent Geothermal Company Ltd. has proposed the drilling of three production sized exploration wells and one reinjection well at the La Soufrière geothermal project site with locations shown in Figure 6. The first well SVG-01 was spudded in on April 30, 2019 at 1310 hours. Though initially anticipated to drill to a target depth of 2500 m, SVG-01 attained a final depth of 2700 m MD on July 17, 2019.

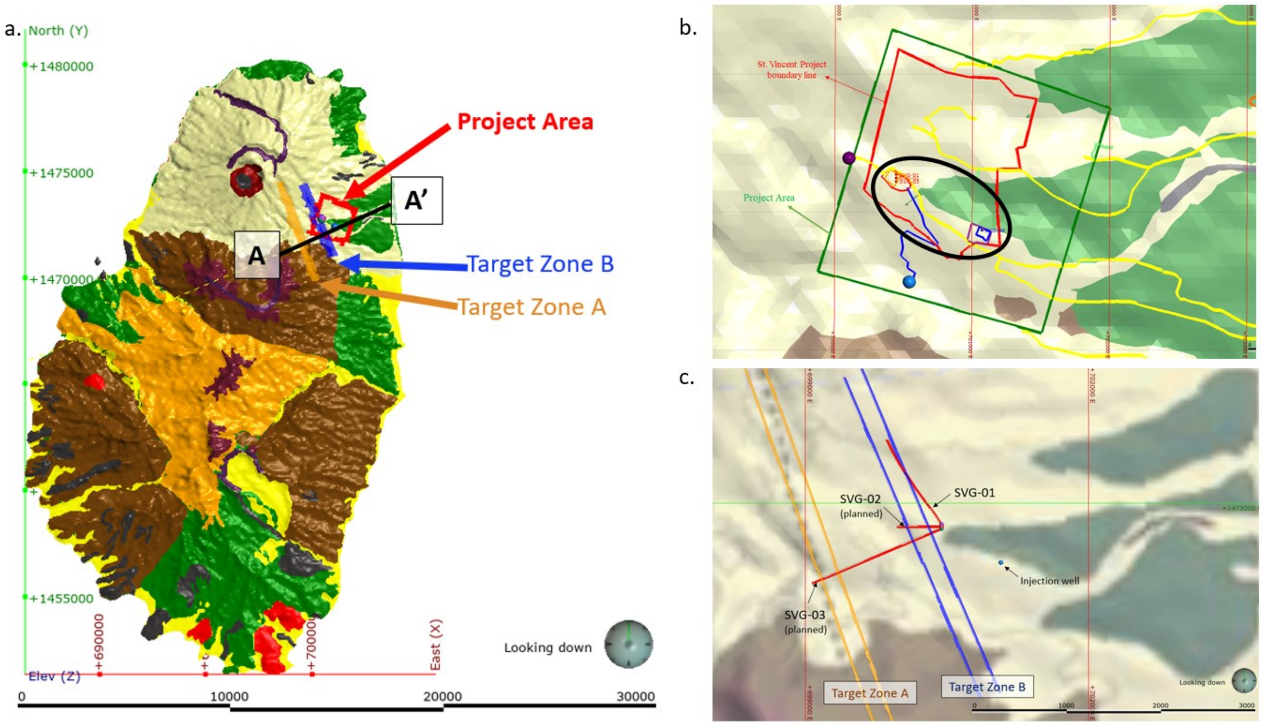

Figure 6: (a) Map of St. Vincent showing the location of (b) geothermal project site, modified from Geothermica Italiana (1991), (c) with a closer look at the locations of the production and reinjection well pads

The lithology currently in SVG-01 down to 2390 mD is presented in Figure 7. Initial analysis have confirmed that the main rock materials present in SVG-01 are andesite, basaltic- andesite and tuff with smectite-chlorite-epidote alteration identified. The most significant finding thus far is an intrusive formation, possibly diorite or granodiorite, first identified at about 2318 m MD, extending beyond 2600 m MD. This intrusive is assumed to be a near vertical dike, dipping at approximately 1° to the west, representing the target fault Zone B, earlier identified by Geothermica Italiana (1991) and confirmed through LiDAR surveying in Gíslasson and Jónsson (2015). Further analysis, logging and testing of SVG-01 will be carried out over the next year.

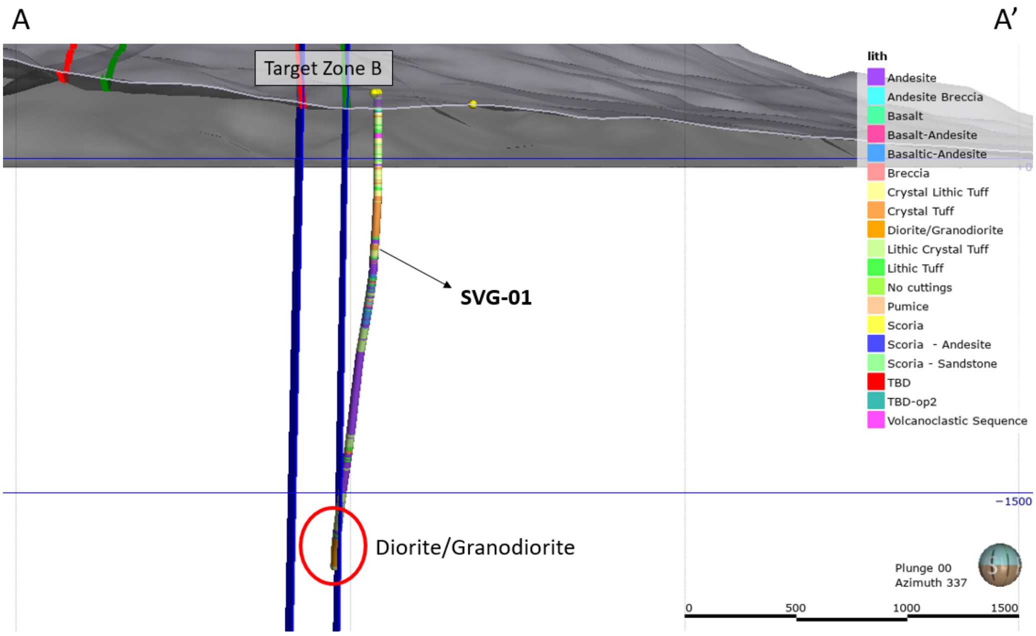

Figure 7: Summary of the lithology in well SVG-01 down to 2300 m MD

Epidote and other high temperature alteration mineralogy was observed approximately 300 m deeper in well SVG-01 than estimated by earlier resistivity surveys (Eysteinsson 2015). Based on these observations and a slightly deeper than anticipated heat source, the final well design for well SVG-03 was modified to reflect this. It is anticipated that SVG-03 will be drilled through the diorite intrusion (Target Zone B) observed in SVG-01, and hit the Target Zone A at 2800 m MD (Figure 8). The drilling of well SVG-03 is expected to be completed by October 2019.

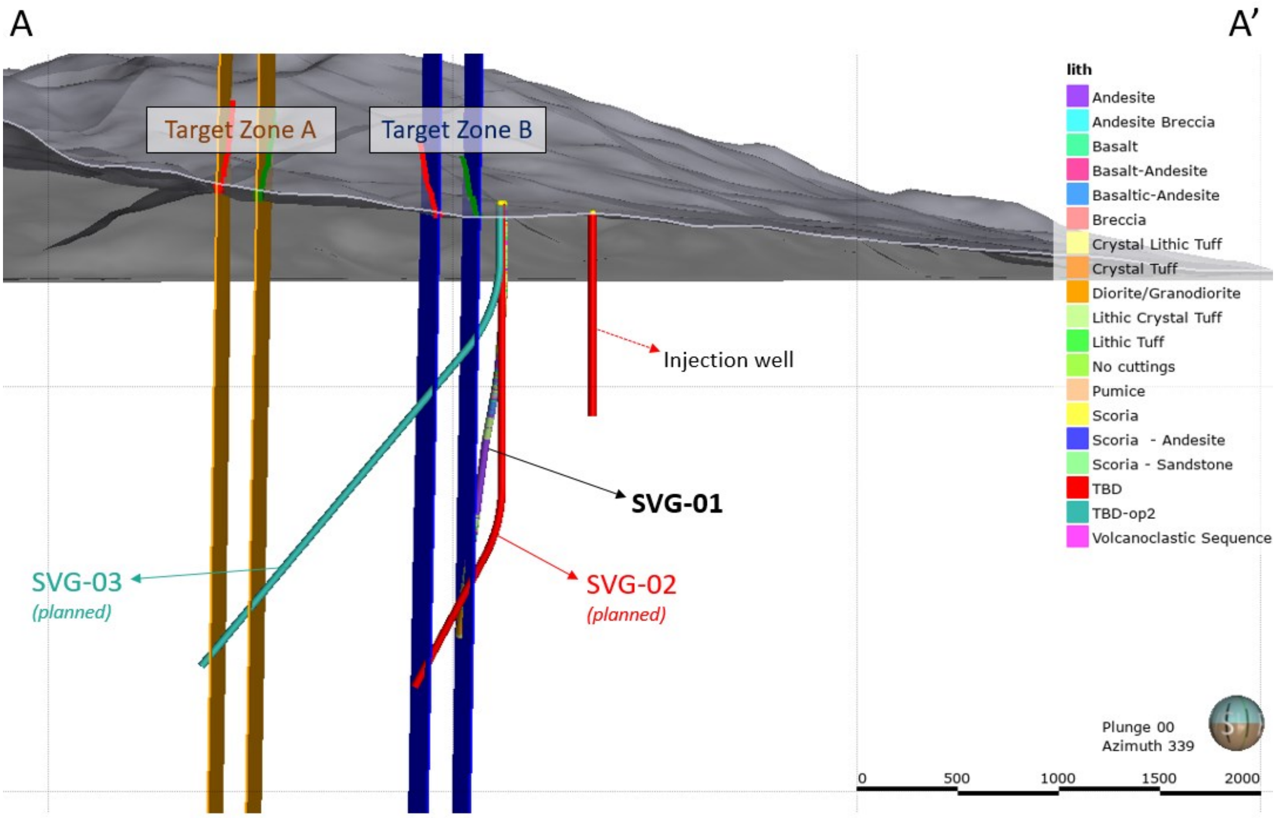

Figure 8: Location of well SVG-01 and planned wells SVG-02, SVG-03

5. CONCLUSION

Geothermal exploration conducted at La Soufrière – St. Vincent and the Grenadines in 2015 has revealed a potential deep-rooted high temperature geothermal system. A volumetric assessment conducted based on the results from exploration surveys has suggested with a 90% probability that the potential geothermal system at La Soufrière- St. Vincent is capable of sustaining a power plant with a capacity of up to 160 MW_e for 30 years. The recent success in geothermal exploration has led the country to the next phase of its Geothermal Developmental Project - exploratory drilling, in which well SVG-01 has been drilled down to a 2700 m MD, intersecting a near vertical fault zone at 2318 m MD. Moderate to strongly altered Epidote, which points to temperatures in excess of 240 °C was observed approximately 300 m deeper than originally anticipated, indicating a deeper rooted geothermal reservoir.

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REFERENCES

Árnason, Knútur, Ragna Karlsdóttir, Hjálmar Eysteinsson, Ólafur G. Flóvenz, and Steinar Þór Guðlaugsson. 2000. "The resistivity structure of high-temperature geothermal systems in Iceland." *World Geothermal Congress proceedings.* Tohoku, Japan. 923-928.

Björnsson, Grimur, and Benedikt Steingrímsson. 1991. *Hiti og þrýstingur í jarðhitakerfinu í Svartsengi- Upphafsástand og breytingar vegna vinnslu.* Prepared for Hitaveitu Suðurnesja OS-91016/JHD-04, Reykjavík: Orkustofnun.

Björnsson, Grímur, Hjálmar Eysteinsson, Gestur Gíslason, and Haraldur Sigurðsson. 2013. *A geothermal desktop study for Mt. Soufriere, St. Vincent.* Report No. 13002-01, Reykjavík Geothermal.

Caribbean Power. 1998. *Preliminary resource assessment of the St.VIncent geothermal prospect - Island of St. Vincent, Lesser Antilles, Eastern Caribbean Region.* Closed Report, Caribbean Power, St. Vincent Ltd.

Eysteinsson, Hjalmar. 2015. *Resistivity study of Mt. Soufriere, Saint Vincent and the Grenadines.* Report No. 13002-03, Reykjavík Geothermal.

Franzson, Hjalti. 1983. "The Svartsengi high-temperature field subsurface geology and alteration." *Trans. Geothermal Resources Council* 141-145.

Geotermica Italiana. 1991. "Exploration for geothermal resources in the Eastern Caribbean. Island Report: St. Vincent." Report prepared for United Nations - DTCD and CARICOM Secretariat, Pisa, Italy, 166 pp.

GeothermEX. 2011. *Evaluation of geothermal potential and exploration plan for the Soufriere resource area- St. Vincent, West Indies.* Prepared for Bluewater Renewables, California, USA: GeothermEX Ltd.

Gíslasson, Gestur, and Sigurbjörn Jónsson. 2015. *Remote Sensing Report.* Closed Report No.: 13002:4, Reykjavík: Reykjavík Geothermal.

GoSVG. 2010. *Energy Action Plan for St. Vincent & the Grenadines.* Open Report, Kingstown: Government of St. Vincent and the Grenadines.

Grant, Malcom, and Paul Bixley. 2011. *Geothermal Reservoir Engineering.* 2nd Edition. New York: Academic Press.

Huttrer, Gerald. 1996. "Final report regarding prefeasibility studies of the potential of geothermal development in St. VIncent, West Indies." Report for Lockheed Martin Idaho Tech Co. & US/ECRE.

Karlsdóttir, Ragna. 1998. *TEM-viðnámsmælingar í Svartsengi 1997.* Closed Report, Reykjavík: Iceland Geosurvey (ÍSOR).

Karlsdóttir, Ragna, and Arnar Már Viljálmsson. 2015. *Svartsengi-Eldvörp-Sandvík 3D inversion of MT data.* Closed Report ÍSOR-2015/001, Reykjavík: Iceland Geosurvey (ÍSOR).

Melekhova, Elena, Jon Blundy, Richard Robertson, and Madeleine C.S. Humphreys. 2015. "Experimental evidence for polybaric differentiation of primative arc basalt beaneath St. Vincent, Lesser Antilles." *Journal of Petrology* 56 (1): 161-192.

Muffler, L.J. Patrick. 1978. *USGS Geothermal resource assessment.* USA: US Geological Survey.

Rowley, Keith. 1978. "Late Pleistocene pyroclastic deposits of Soufrière volcano, St. Vincent, West Indies." *Geological Society of America Bulletin* 89 (6).

Sigurdsson, H., and S. Carey. 1991. "Caribbean volcanoes, a field guide." (Geological Association of Canada) 101 pp.

VSO Consulting. 2016. "Technical due diligence - Corbetti and St. Vincent project." Closed Report.