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GEOTHERMAL RESOURCE ASSESSMENT OF THE WOTTEN WAVEN GEOTHERMAL FIELD – DOMINICA, WEST INDIES

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ABSTRACT

Geothermal resource assessment involves the estimation of the geothermal energy that can be extracted from a reservoir and utilized economically for a specified time period. It is based on the evaluation of surface discharge, well logs and other geoscientific information obtained via geological, geophysical and geochemical measurements. This report is aimed at conducting a geothermal resource assessment of the Wotten Waven geothermal field in Dominica, based on available surface exploration data and data obtained from three exploratory wells: WW-01, WW-02 and WW-03, by establishing a simple natural-state numerical model of the Wotten Waven field and through the determination of the field's resource potential. The success of recent exploratory work resulted in the proposed installation of a 10-15 MW_e plant for domestic consumption with plans to extend the capacity to 120 MW_e by 2020. Available downhole temperatures indicate the presence of a 234-250°C high-temperature reservoir of 600-2000 m thickness at depths greater than 100 m b.s.l. A conservative volumetric analysis confirms with a 90% probability that the current Wotten Waven field should be able to sustain a capacity of 10-15 MWe for up to 100 years. A natural-state numerical model modelled over an area of 5 km^2 requires 80 kg/s of fluid with an enthalpy of approximately 3300 kJ/kg to be injected into three pre-determined heat sources giving a thermal input of approximately 260 MW_t. A more detailed numerical model is needed to cater for a greater reservoir surface area to accurately model the reservoir conditions of the Wotten Waven field, including data from the newly drilled production and injection wells. Once the wells are put into production, a production model should be set up to simulate the response of the reservoir (pressure, enthalpy, etc.) to utilization and to assist in optimizing the power production during future utilization.

1. INTRODUCTION

The Caribbean islands face extraordinary challenges associated with the generation and utilization of energy for their various needs. Most island nations depend almost entirely on a constant influx of petroleum for their energy needs which leaves these countries vulnerable to the instability of international oil prices, resulting in much of a country's Gross Domestic Product (GDP) being allocated to fuel import.

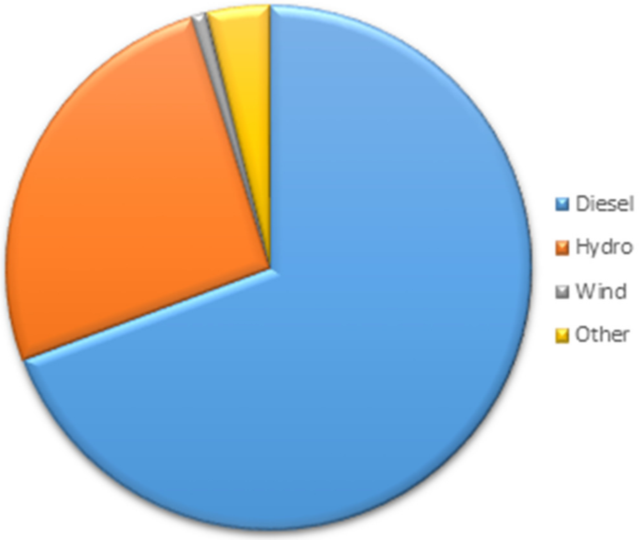

FIGURE 1: Energy matrix of Dominica (based on 2008 estimates in NREL, 2012)

The Commonwealth of Dominica occupies an area of approximately 750 km^2 and has a relatively small population of just about 72,800 inhabitants. The island's small population has resulted in a low demand for energy, with a peak demand of 14.7 MW$_e$. Economic projections show an expected annual growth of 2.7% to 25 MW$_e$ by 2028. Regardless of this, in 2008 Dominica had the highest electricity rates in the Caribbean (NREL, 2012) at USD \$0.4567 per kilowatt-hour (kWh). Figure 1 shows the energy matrix of the island of Dominica, based on 2008 statistics.

Renewable energy may, therefore, be the most cost efficient energy source for Dominica, given current costs and available technology. The Caribbean region facilitates an abundant supply of renewable energy resources. Many volcanic islands of the Eastern Caribbean have large geothermal prospects and are currently exploring this possibility. The possibility for geothermal energy was being explored in Dominica as early as 1977. Although there has been some extremely optimistic studies that suggest that the island's geothermal potential is as high as 1390 MW$_e$, more realistic exploratory work suggests that it may range from 100-300 MW$_e$ (NREL, 2012). The Wotten Waven site is the current priority of Dominica's aim for geothermal development and, with the recent success of exploratory drilling, the Government aims to construct a small 10-15 MW$_e$ plant for the local market to meet the current peak demand, with plans to do further exploration and to upgrade to a 60 MW$_e$ plant by the end of 2018 and an additional 60 MW$_e$ by the end of 2020 (Maynard-Date and George, 2013).

This report seeks to conduct a geothermal resource assessment of the Wotten Waven geothermal field, based on data obtained from three exploratory wells: WW-01, WW-02 and WW-03. Basically, a geothermal resource assessment involves the estimation of geothermal energy that may be extracted from a reservoir and utilized economically for a specified time period of usually less than 100 years (Sarmiento and Steingrímsson, 2011). It consists of evaluating surface discharge and downhole data through the integration of data obtained by geological, geochemical and geophysical measurements. A volumetric assessment of the Wotten Waven field was conducted to determine its resource potential while an initial numerical model was set up to model the natural conditions of the Wotten Waven field. A volumetric assessment is usually done during the early stages of development when data are often quite limited. Although proven to be fairly accurate, the volumetric model does not account for the amount of vertical or lateral recharge to a geothermal system, and reserves may be underestimated. These reservoir conditions, though not considered in volumetric calculations, are sensitized through numerical modelling. Sarmiento and Björnsson (2007) describe numerical modelling as the best approach in conducting reserve evaluation.

2. BACKGROUND

The Caribbean is home to thousands of islands extending from The Bahamas in the north to Trinidad and Tobago in the south. Dominica, the Nature Island of the Caribbean, lies at the centre of the Lesser Antilles island arc (Figure 2). The islands of the Lesser Antilles are located between the Anegada

Passage and the South American continental plate margin. It 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 led to the formation of several volcanically active islands on the oceanic crust of the Caribbean Plate (Smith et al., 2013). Dominica is the most rugged of the Lesser Antilles and occupies a total land area of 750 km^2. It has one of the highest concentrations of live volcanoes in the world (Lindsay et al., 2005). Unlike its Caribbean neighbours, Dominica has nine potentially active volcanoes. Frequent earthquakes and confirmed geothermal activity throughout the island indicate that it may be underlain by an active magma reservoir.

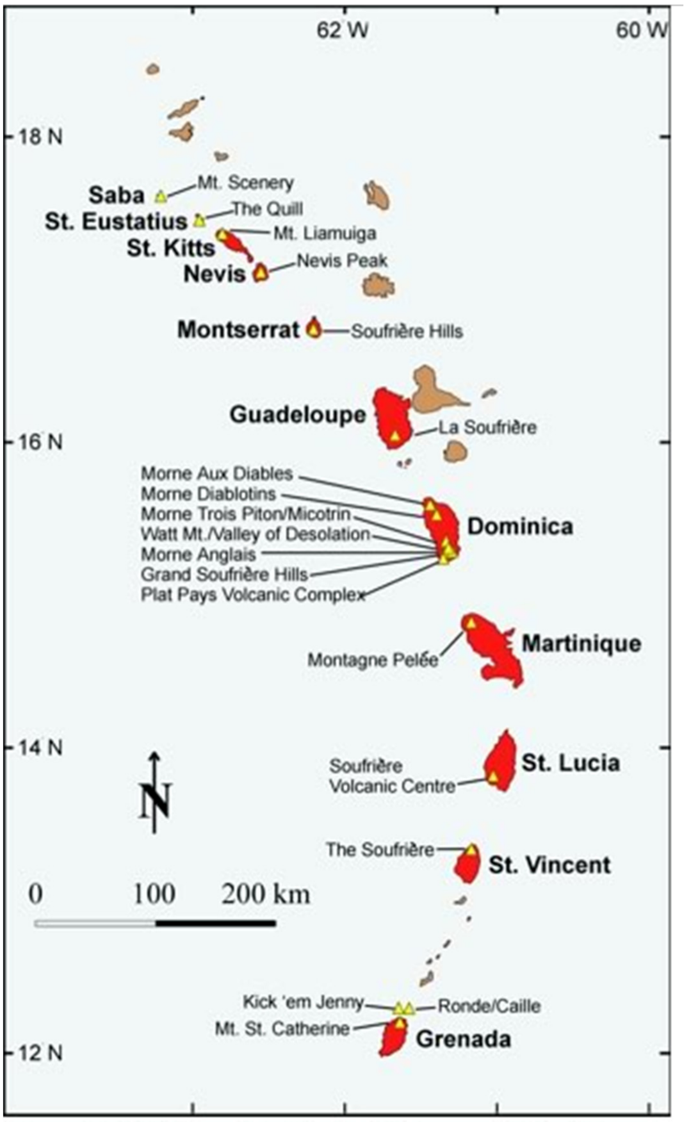

FIGURE 2: Lesser Antilles volcanic island arc (Lindsay et al., 2005)

2.1 Geology of Dominica

Dominica is primarily composed of volcanic rocks and their weathered by-products (see geological map in Appendix I). The volcanic stratigraphy of the island is subdivided according to Miocene, Pliocene, Older Pleistocene and Younger Pleistocene units. The Wotten Waven geothermal field is located in the south-central part of the island, 8 km east-northeast of the capital, Roseau, in and around the communities of Laudat, Wotten Waven and Trafalgar (Figure 3). South-central Dominica is dominated by the central graben - a 12 km long, 7 km wide depression that is marked by a chain of low hills (Smith et al., 2013). The graben's eastern and southern borders are buried under pyroclastic deposits that erupted from two calderas located within the graben's structure. The Wotten Waven caldera was first described as a large “volcano-tectonic depression (Lindsay et al., 2005). It is approximately 7 km in length and 4.5 km in width and is parallel to the Pelean volcanic chain that borders the margin of the Central Graben, thought to be partly fault controlled (Lindsay et al., 2005).

Historically referred to as “Grande Soufrière”, this region that includes the Valley of Desolation, the Boiling Lake, Plat Pays Volcanic Complex, Wotten Waven/Micotrin and Mourne aux Diables, is the most thermally active in Dominica, characterized by numerous hot springs and fumaroles with temperatures in the range 40-96 and 91-99°C, respectively (Lindsay et al., 2005).

2.2 Geochemistry of the Wotten Waven geothermal field

The European Union, along with the Governments of Dominica and France initiated a programme called Géothermie Caraïbes in 2008. This programme consisted of a geological and geochemical survey of the

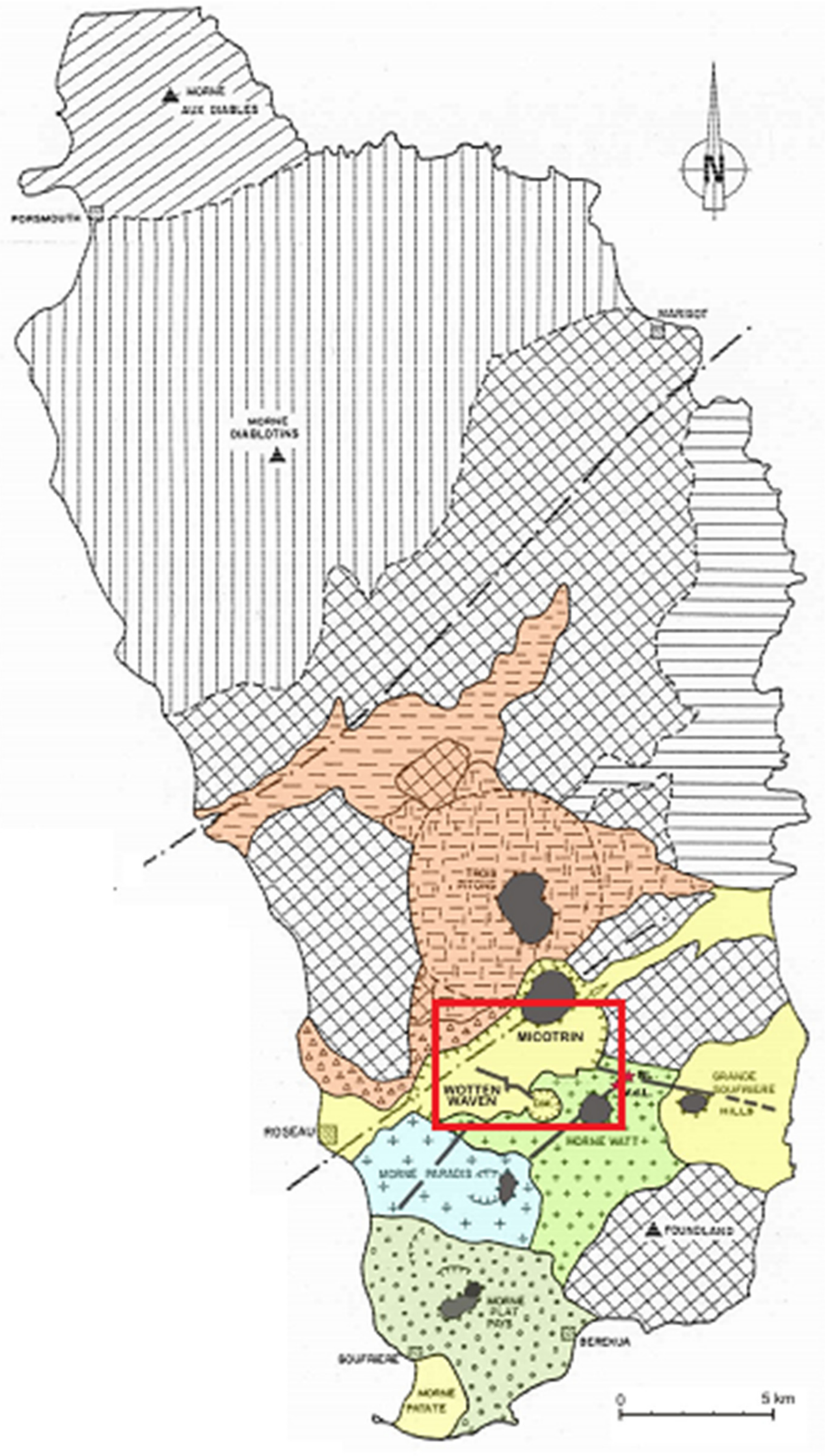

FIGURE 3: Location of the Wotten Waven Field in Dominica

Wotten Waven geothermal field. Geochemical results revealed that the fluid chemistry of the field is consistent with waters that classically occur in hydrothermal areas. Primary waters consisting of Na-Cl and secondary waters (acid sulphate type, Ca-Na-HCO_3 type and Na-HCO_3-SO_4 type) have been identified in the Wotten Waven area and near the Boiling Lake / Valley of Desolation. Ca-Na-Cl mineralised water discharged from the Valley of Desolation containing no sea water was interpreted as one piece of evidence that the fluid had a distinct origin. Further analysis confirms a relationship between the fluids of Wotten Waven and The Valley of Desolation, suggesting that they might be derived from a common source (Traineau and Lasne, 2008).

Chemical and isotopic data were obtained for springs located in the River Blanc and Roseau River valley. Surface manifestations present in the vicinity of the River Blanc were thought to be a part of a lateral fluid outflow from a deep high-temperature Na-Cl reservoir (Traineau and Lasne, 2008). An updated conceptual model of the area (Figure 4) provides the likely location of the deep Na-Cl reservoir, extending deep below the Micotrin dome. Geothermometry data suggests that reservoir temperatures may be in the range of 250-300°C.

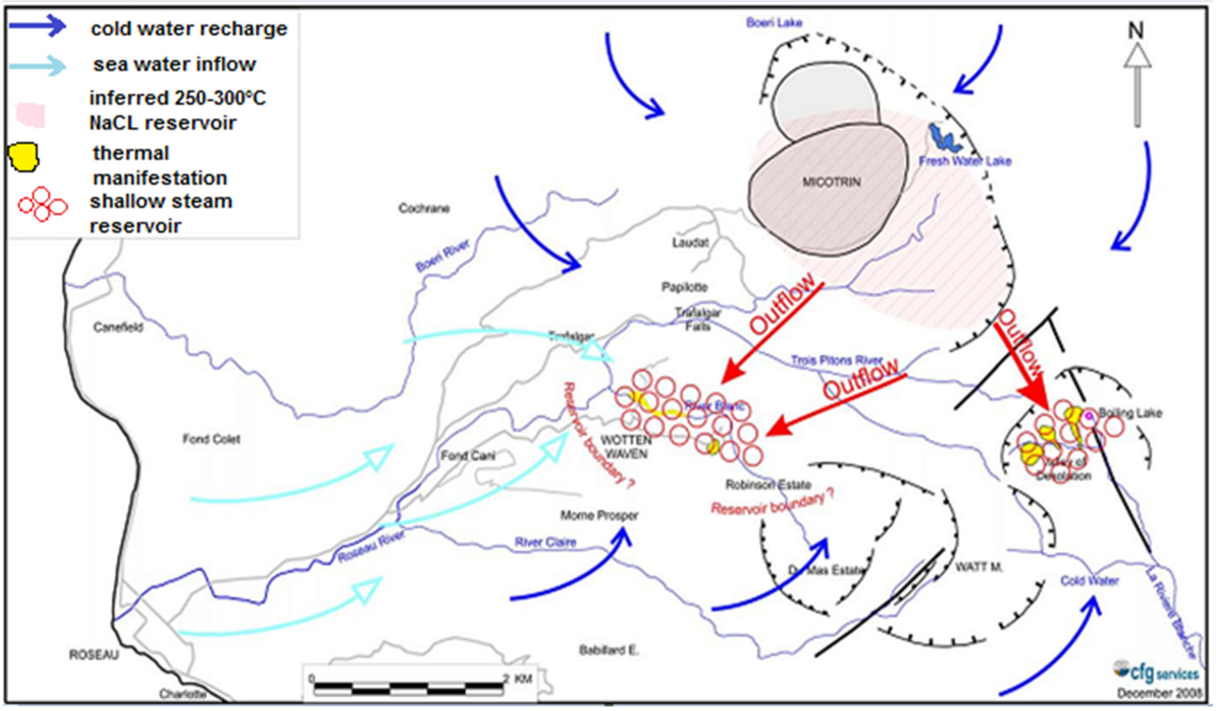

FIGURE 4: Conceptual model of the Wotten Waven geothermal field
(Traineau and Lasne, 2008)

2.3 Geophysics of the Wotten Waven geothermal field

2.3.1 Magnetotelluric (MT) / Transient Electromagnetic (TEM) survey

A joint MT/TEM survey was undertaken in 2008 to obtain a better understanding of the potential geothermal system in the Wotten Waven / Laudat / Trafalgar region. Thirty-two MT soundings were measured across a region of 25 km^2. A low natural MT signal activity resulted in a low signal to noise ratio in the low frequency range. As a result, most soundings revealed unusable data below 1 Hz, and the penetration depth was thus limited to 100-400 m depth (Baltassat et al., 2008).

MT data, shown in Figure 5, revealed the presence of a highly conductive layer (>2 Ωm), with the top of this layer located 200-500 m above sea level, with a thickness ranging from 250-300 m (Baltassat et al., 2008). This conductive layer was identified as the cap rock of the potential geothermal system. It over-lays a more resistive layer which was interpreted as the possible reservoir. Baltassat et al. (2008) assumed that a possible reservoir, therefore, exists below the conductive layer, extending from Wotten Waven eastwards to the Boiling Lake-Valley of Desolation area.

2.3.2 Gravimetric investigation

A total of 106 gravity stations were measured, covering a total area of 30 km^2. The results of gravity surveys have been virtually unchanged throughout the years (Baltassat et al., 2008). Gravity modelling revealed an anomaly – the possible heat source of the geothermal system - a low density intrusion related to recent volcanic activity, seen in Figure 6. The geophysical information presented in Figure 6 has led to estimations of the reservoir thickness which is later presented in sections on Volumetric and Numerical Models in later chapters. With an estimated thickness of 250-300 m, the caprock extends to elevations ranging from 200 m – 500 m a.s.l. It is, therefore, possible that the base of the caprock may extend to 100-200 m b.s.l. According to Figure 6, the dense magmatic intrusion of non-uniformed Thickness may be located at 1000 m b.s.l. It is, therefore, safe to approximate the reservoir thickness as ranging between 600 and 2000 m.

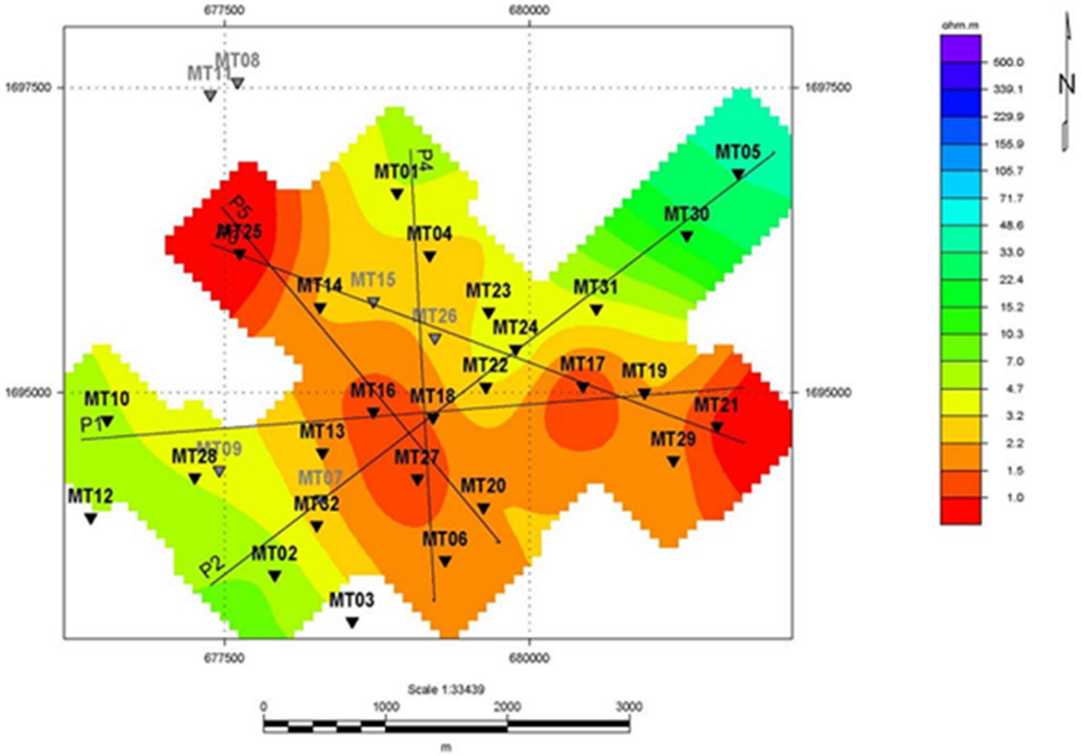

FIGURE 5: Resistivity map at a depth of 300 m extending from Wotten Waven to the Boiling Lake (Baltassat et al., 2008)

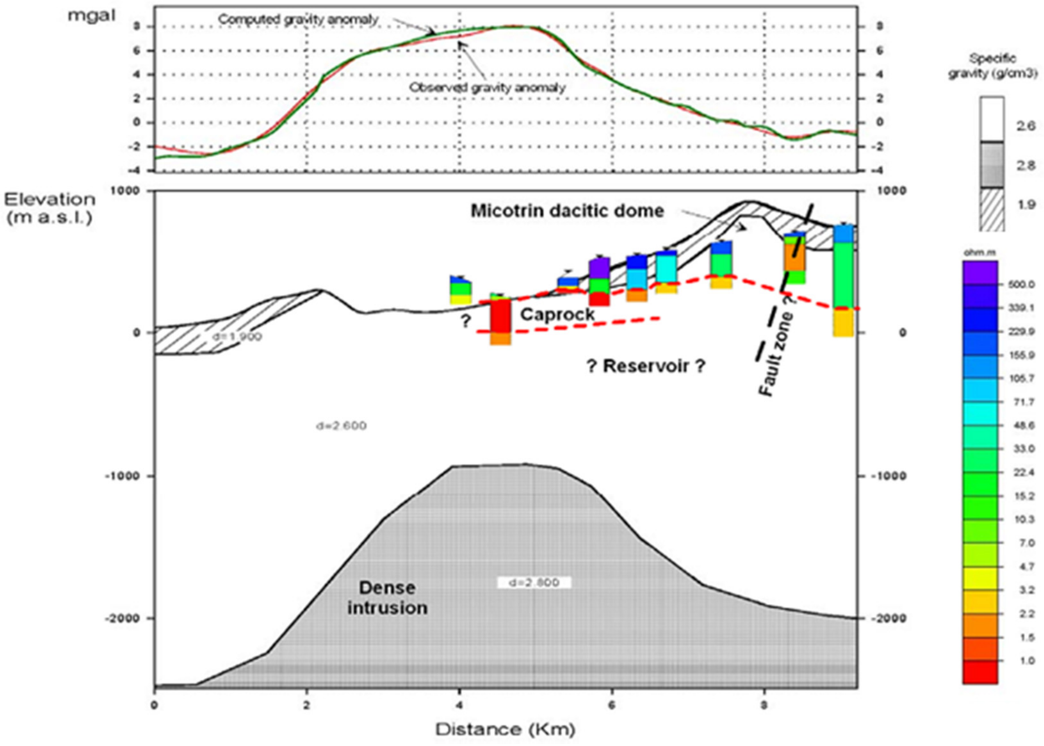

FIGURE 6: Proposed E-W cross-section showing the potential geothermal reservoir based on observed and modelled gravity data (Baltassat et al., 2008)

3. TEMPERATURE AND PRESSURE LOGS FROM EXPLORATORY WELLS

Temperature and pressure profiles are the most important tools in geothermal exploration and development. Although aimed primarily at determining formation temperatures and reservoir pressures, temperature and pressure logs can provide information on feed-zones and aquifers, fluid and heat flow and the overall physical state of the geothermal system. It is also, therefore, a very useful tool in field management. They can be measured at different periods during a well's lifetime, whether it be during drilling, immediately after drilling, during the well's warm up period, during injection and production testing, and anytime thereafter for general maintenance and monitoring. Circulation and fluid flow in wells during drilling and flow testing will cool the well and thus screen the conditions in the formation. The determination of the formation temperature would, therefore, be difficult or even impossible (Steingrímsson, 2014; Grant and Bixley, 2011). After drilling, the well is usually shut off; then well temperatures will eventually recover and gain equilibrium with the formation.

Dominica's three exploratory wells, WW-01, WW-02 and WW-03 were drilled between December 16, 2011 and April 27, 2012, obtaining depths of 1200, 1468 and 1613 m, respectively. Figure 7 shows the location of the three wells. WW-01 is located along the Trafalgar-Wotten Waven link road, while both WW-02 and WW-03 are located in the Laudat area. The target location of these wells was determined from the 2008 geochemical and geophysical surveys.

The temperature and pressure profiles available for WW-01, WW-02 and WW-03 were plotted against measured depths. They are measured during injections and production tests and for each well there exists 1-2 static profiles which represent warm up data.

3.1 Well WW-01

Well WW-01 was drilled from March 29, 2012 till April 27, 2012, with the well pad located at 270 m a.s.l., shown in Figure 7. Drilling reports (Thorbjörnsson, 2012), as well as injection test logs, revealed the presence of three major feed zones located at 31, 720 and 895 m depths. Production testing was done on June 27, 2012 with static temperature and pressure profiles, measured the previous day. A maximum temperature of approximately 239°C was recorded at a measured depth of 700 m. This corresponded with the geothermometry of fluids collected during the flow test, yielding temperatures of 236-237°C (Thorbjörnsson, 2012). Production testing also confirmed the presence of feed zones, revealed during the injection test, seen as minor temperature changes at these zones in Figure 8.

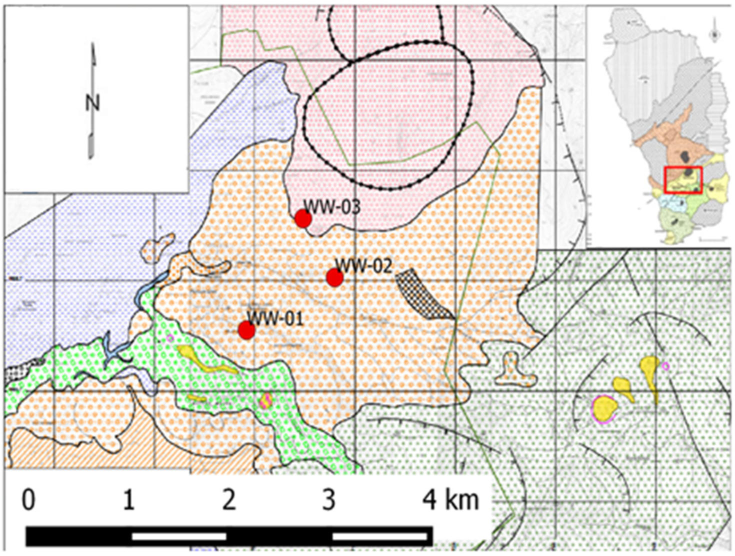

FIGURE 7: Location of exploratory wells in Wotten Waven field

The static logs provide information on the natural, undisturbed state of the well. Figure 9 shows that the well has a wellhead pressure of approximately 11 bar. A wellhead pressure develops when there is an internal flow in the well, so that the fluid boils, steam accumulates in the upper part of the well and, as

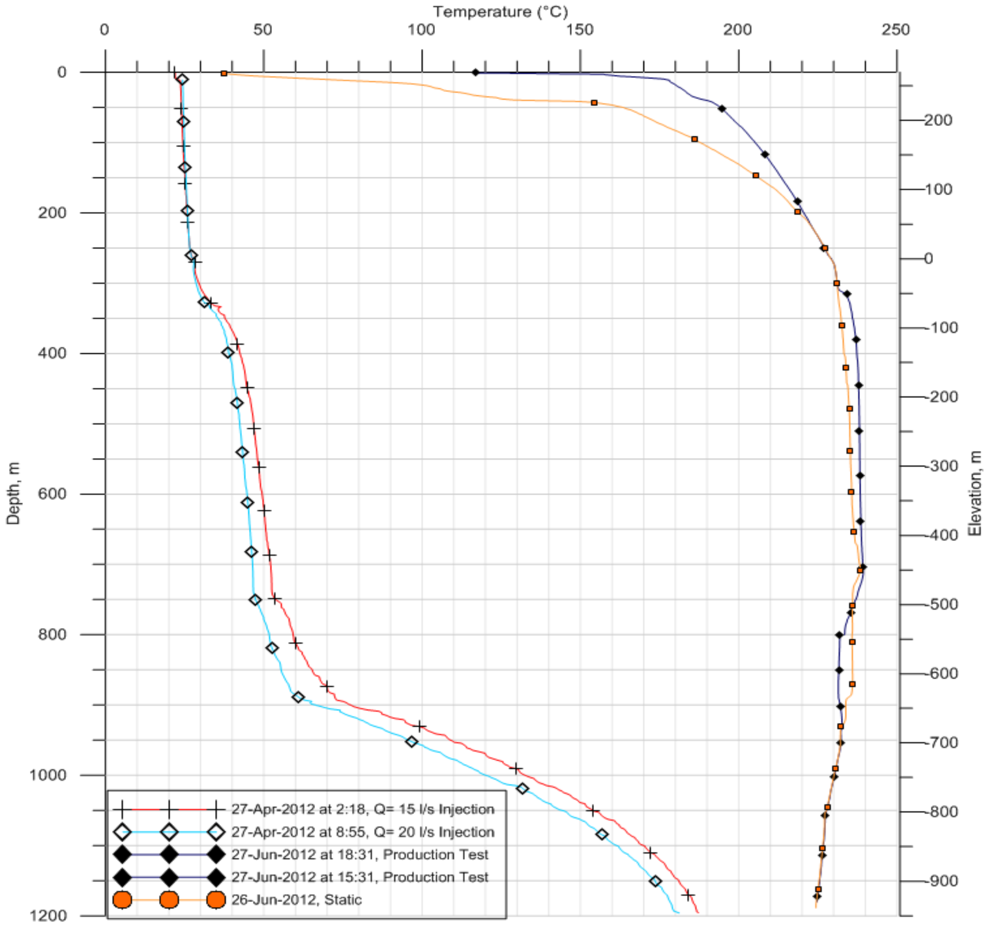

FIGURE 8: Temperature log for well WW-01 in
Wotten Waven field, Dominica

a result, pressure is built up at the wellhead (Grant and Bixley, 2011). This may also be due to a build-up of gas released from the geothermal fluid. Due to this pressure, the water table is located at a measured depth of 37.5 m. Static temperature profiles reveal much about the type of heat present in the well. In impermeable rock, heat is transported via conduction. This produces a characteristic linear profile with changes in thermal conductivity altering the temperature gradient (Steingrímsson, 2014; Grant and Bixley, 2011). Figure 8 reveals a linear profile at a measured depth of approximately 0-300 m with varying temperature gradients, suggesting that perhaps the upper 300 m is an impermeable layer of rock heated via conduction. This corresponds to the magnetotelluric data which suggested that the impermeable caprock is approximately 250-300 m thick. In Figure 8, below 300 m depth, the temperature profile is relatively isothermal. Isothermal profiles may either reflect a circulation of fluid or convective heating. In temperature logs, convective profiles may be represented by isothermal sections, inversions, and boiling sections (Grant and Bixley, 2011).

3.2 Well WW-02

Well WW-02 is located in Laudat at approximately 590 m a.s.l., as shown in Figure 7. The well was drilled between December 17, 2011 and January 28, 2012. Temperature and pressure profiles from injection testing, production testing and logging during warm up were plotted against measured depth (Figures 10 and 11).

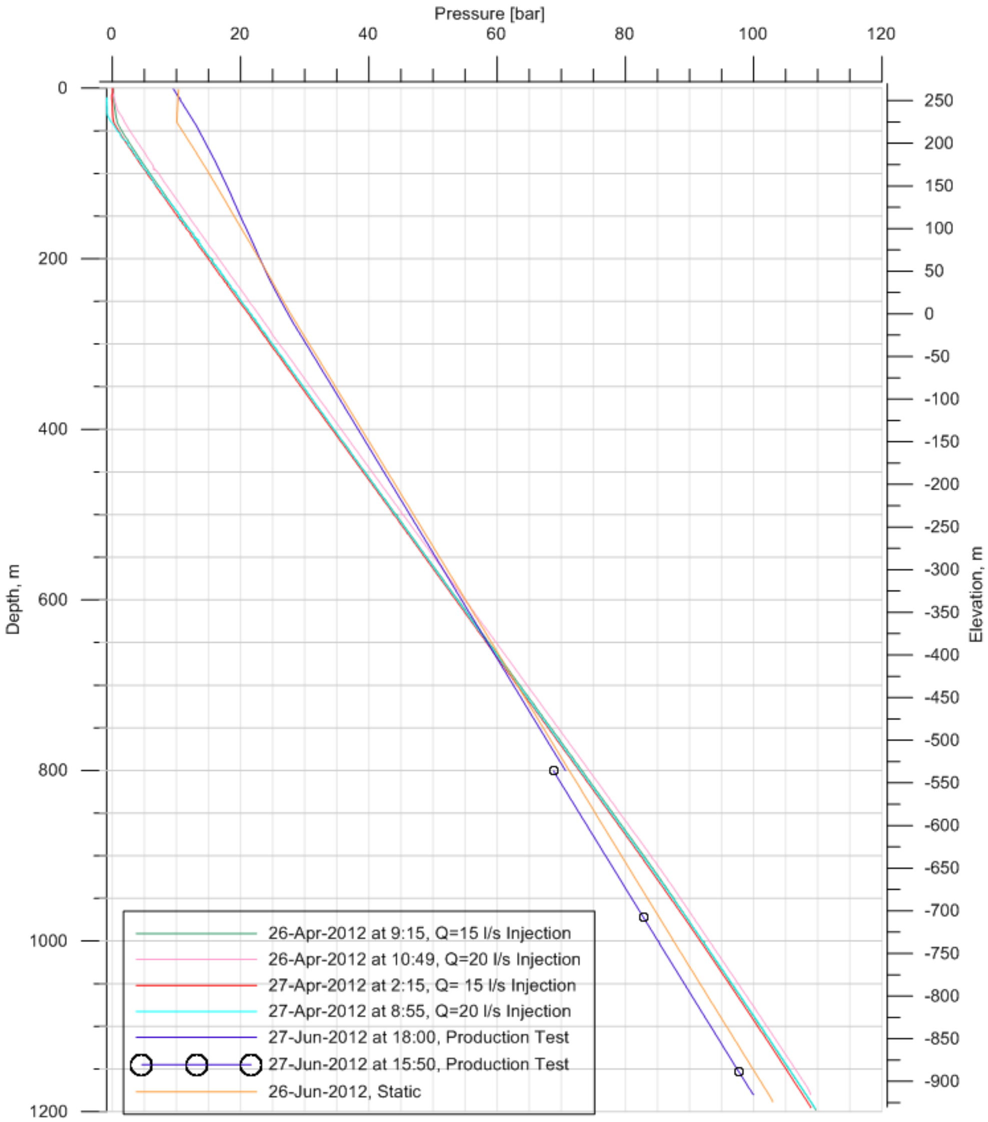

FIGURE 9: Pressure log for well WW-01 in Wotten Waven field, Dominica

WW-02 was closed immediately after drilling, thereby allowing it to heat up for 38 days before the temperature and pressure profiling was run on March 6. A maximum temperature of 236°C was observed at a measured depth of approximately 1140 m. Figure 11 reveals a wellhead pressure (WHP) of approximately 32 bar; the static pressure profile reveals that the boiling level is at a measured depth of 740 m. However, upon extrapolation, the March 6 profile shows that the static water table is at 300 m depth.

Permeable zones were located by identifying circulation losses as well as fluid inflows encountered during drilling and by injectivity and production tests. Temperature profiles suggest a very permeable formation, since many minor inflows and losses can be seen in Figure 10. At a measured depth of 430 m, circulation losses were observed. However, as this was the depth of the casing, Egilson and Thorbjörnsson (2012) concluded that the casing was not deep enough to reach into the geothermal reservoir and, therefore, future production casings in the area should be set at greater depths. Other major permeable zones could be identified in Figure 10 at 860 m and 900 m depths.

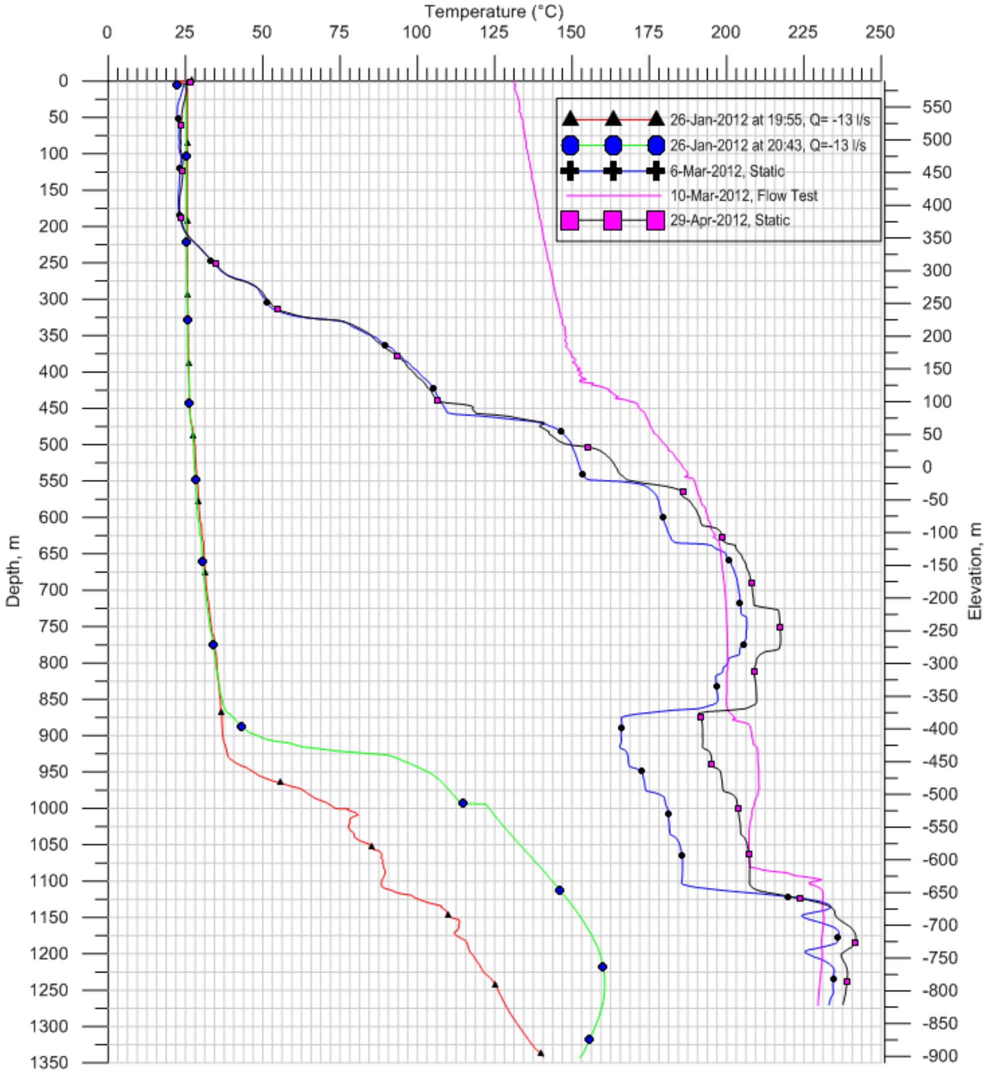

FIGURE 10: Temperature log for well WW-02 in
Wotten Waven field, Dominica

The static profile run on March 6 indicated that at the measured depth interval 860-1110 m, cooling was still occurring after drilling, therefore suggesting that this particular region is the best connected part of the well (Egilson and Thorbjörnsson, 2012). A static profile, repeated on April 29, 2012, yielded temperatures greater than 240°C.

3.3 Well WW-03

Well WW-03 is located in Laudat at approximately 560 m a.s.l. The well was drilled between February 15 and March 14, 2012. Three temperature and pressure profiles measured during injection and static conditions were plotted against measured depths (Figures 12 and 13).

Three feed zones were identified at measured depths of approximately 965, 1095 and 1181 m, seen in Figure 12. From the static temperature profile in Figure 12, a maximum temperature of 245°C was recorded at a depth of approximately 950 m. This is in agreement with the geothermometry of sampled fluids which suggest an estimated temperature of 247°C (Egilson and Óskarsson, 2012).

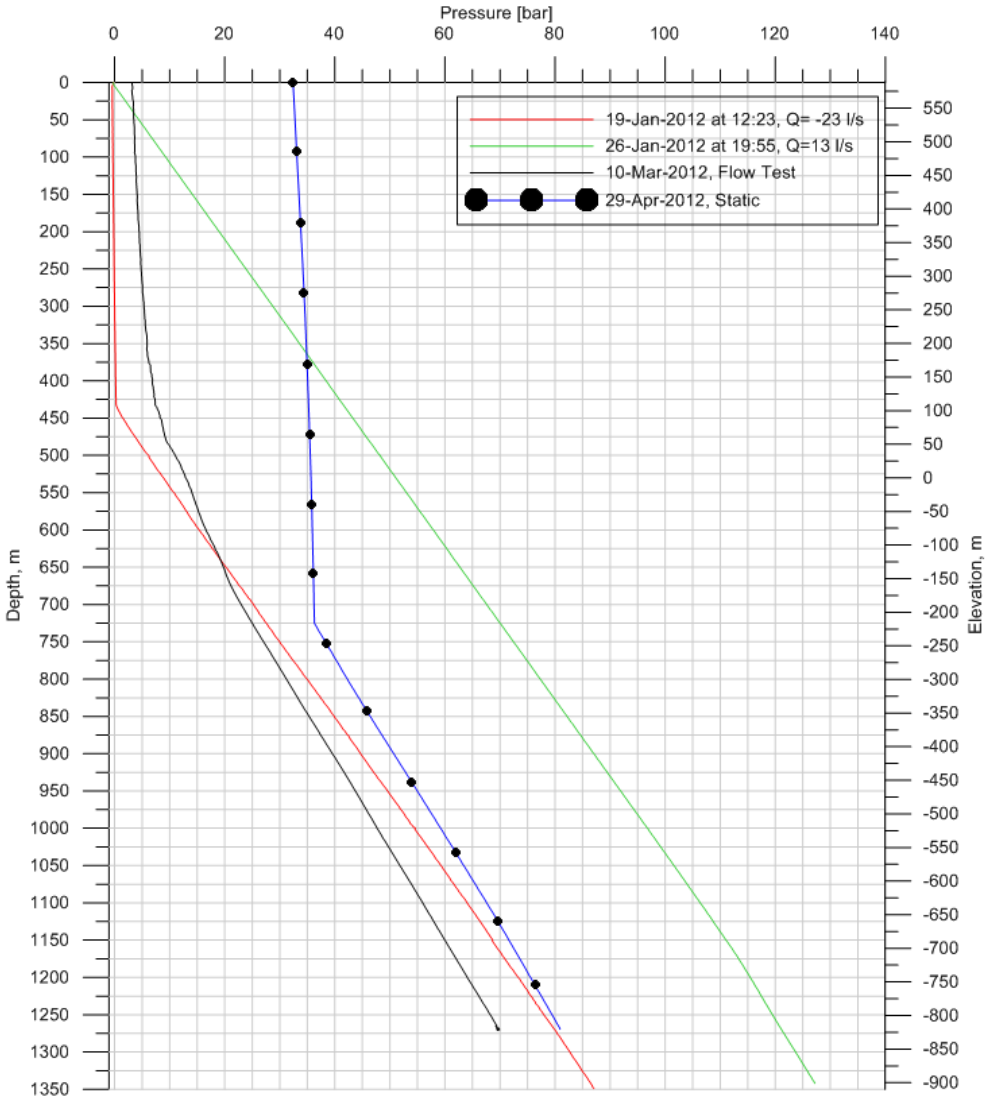

FIGURE 11: Pressure log for well WW-02 in Wotten Waven field, Dominica

In the static pressure profile, a WHP of 39 bar can be observed, resulting in the boiling level being located at a measured depth of 730 m. Extrapolation of this profile reveals a static water table at 55 m.

At the top of the water column, the temperature is just over 210°C, therefore suggesting that the well would flow easily once the gas cap was removed. On April 17, the well was opened for flow testing, however no flowing logs could be recorded because of a casing collapse (Egilson and Óskarsson, 2012).

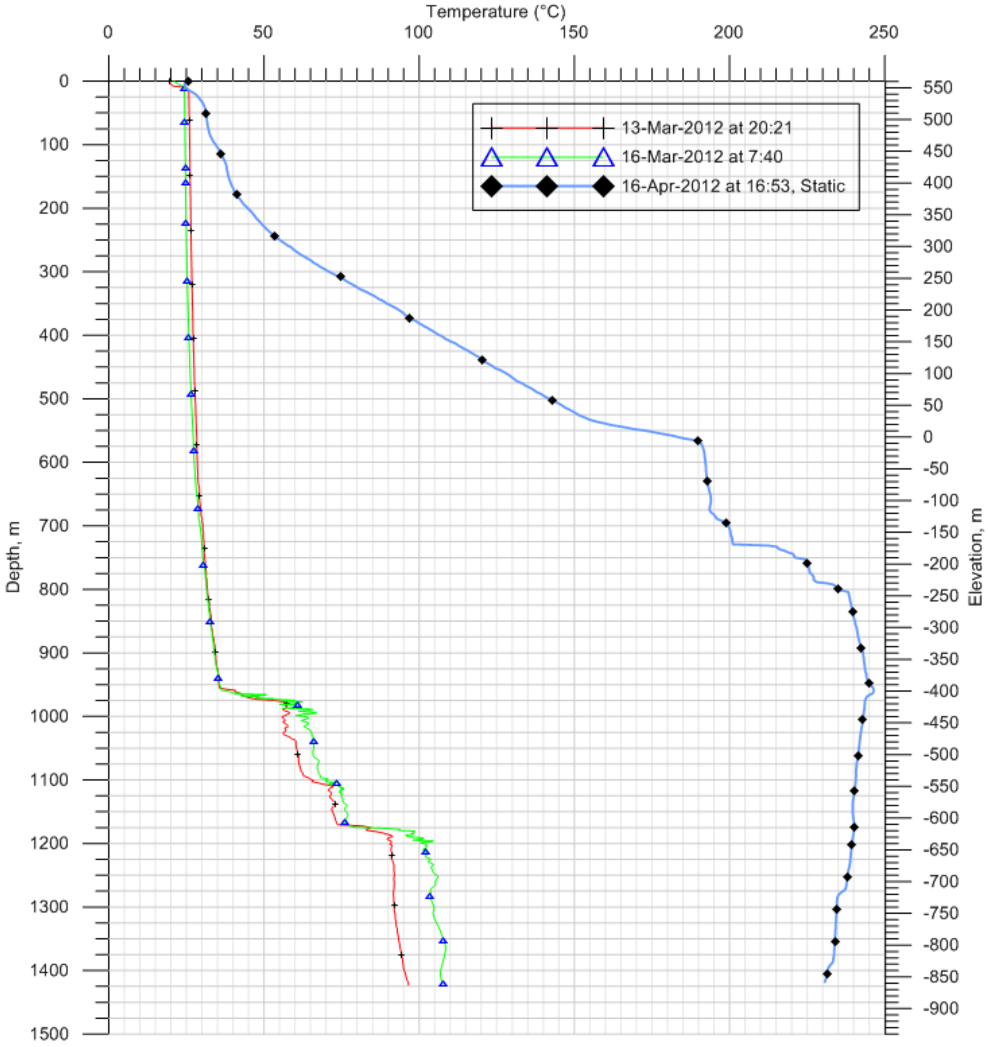

FIGURE 12: Temperature log for Well WW-03 in Wotten Waven field, Dominica

4. CONCEPTUAL MODEL

A conceptual model is the basis for all other types of geothermal models. It is a qualitative model of a geothermal system incorporating the essential physical features of the system discovered by the analysis of available exploratory, drilling and well data (Axelsson, 2014).

The 2008 conceptual model proposed by Traineau and Lasne (2008), shown in Figure 14, is based on geochemical sampling done in the vicinity of Wotten Waven, Trafalgar, Micotrin and the Valley of Desolation. It outlines the proposed fluid flow pattern at depth. The geochecmical analysis of fluids in the Wotten Waven and the Boiling Lake areas has confirmed a relationship between these areas and the potential Na-Cl reservoir located beneath the Micotrin lava dome. This may be explained by a lateral outflow from Micotrin towards both Wotten Waven and the Boiling Lake/Valley of Desolation. A marked absence of mineralised salt water in fluids sampled at the Boiling Lake, in comparison to those sampled at Wotten Waven, has suggested that there is an inflow of sea water (light blue arrows) from the west towards Wotten Waven, with no effects at the Valley of Desolation. Cold water inflows represented in the conceptual model (dark blue arrows) may be interpreted as sites of natural recharge.

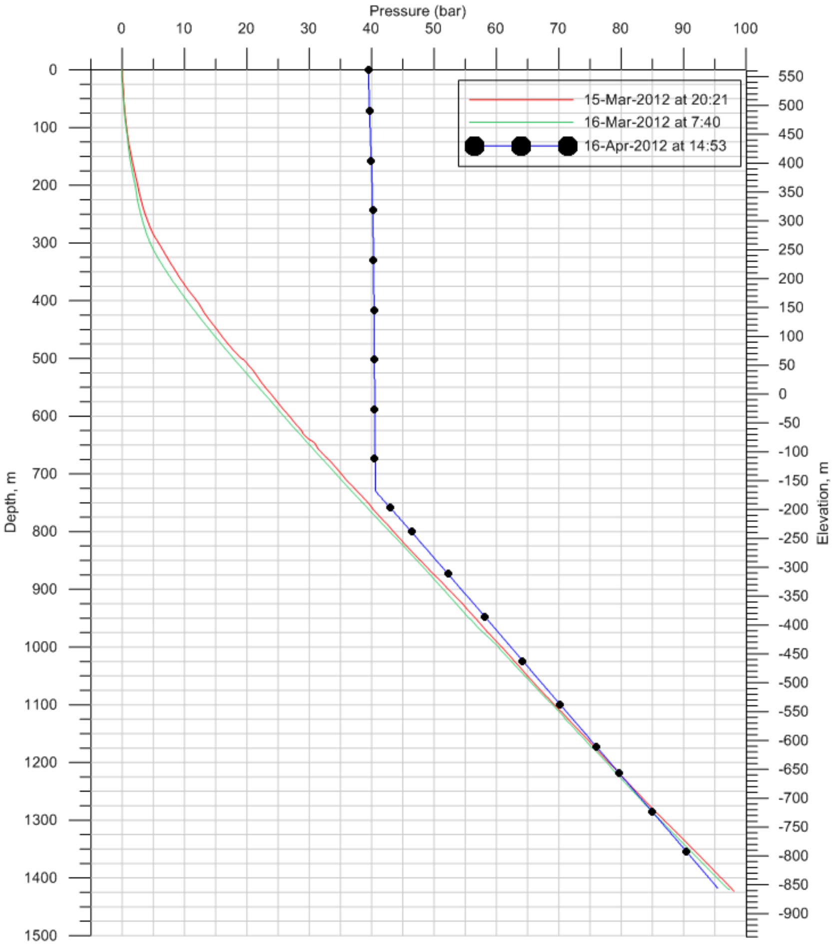

FIGURE 13: Pressure log for Well WW-03 in Wotten Waven field, Dominica

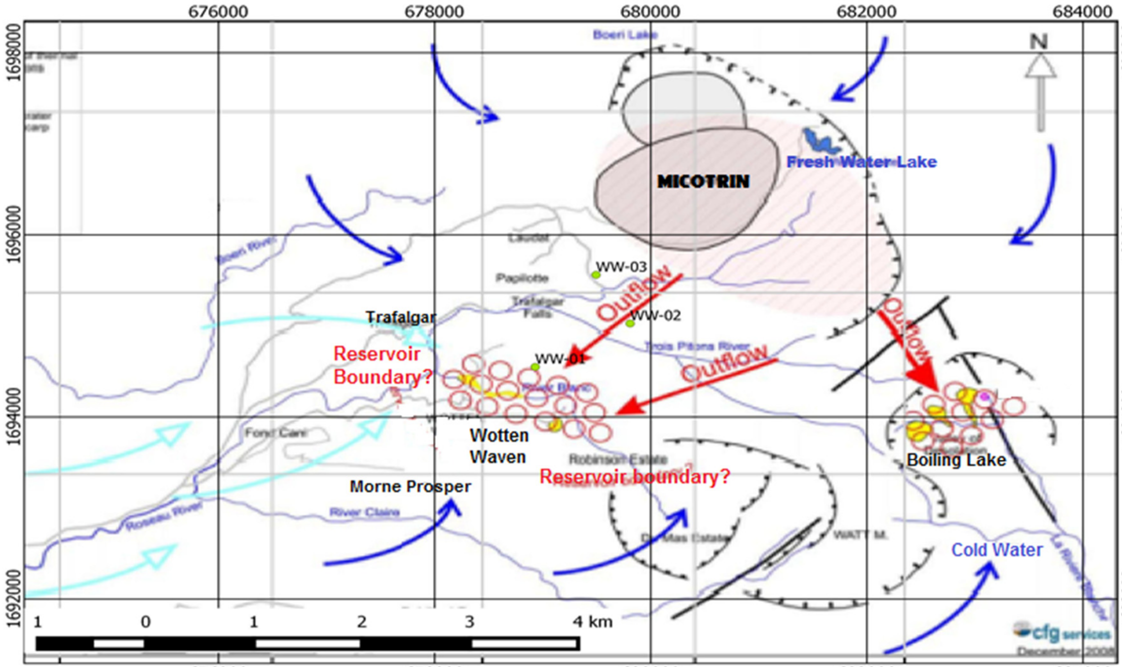

FIGURE 14: Conceptual model of the Wotten Waven field, with locations of the exploratory wells (modified from Traineau and Lasne, 2008)

This conceptual model was used to locate sites for drilling. The three exploratory wells are, therefore, ideally located laterally between Micotrin and the sites of natural thermal discharge in Wotten Waven, away from the effects of salt and cold water inflows. The temperature logs of wells WW-01, WW-02 and WW-03 further confirm this early conceptual model since they indicate that they were drilled in the proposed outflow from Microtrin which is feeding the Wotten Waven field. The logs do not confirm a reservoir boundary, which indicates that the reservoir boundary is set far from the exploratory wells.

5. MODELLING METHODS - LITERATURE REVIEW

5.1 Volumetric modelling

The volumetric method is the main static modelling method used in geothermal resource assessment. During the early stages of geothermal development, in initial-stage assessment, it is considered the most practical approach. Simple volumetric calculations done to determine the generating capacity of potential power plants in the Philippines have proven that this method can reliably predict the minimum commitment for geothermal fields, with as little as two or three exploratory wells (Sarmiento and Björnsson, 2007).

The volumetric method is based on approximate estimates of the total heat energy stored in a volume of rock, including both the thermal energy contained in the rock matrix and water (or steam) in its pores. The total heat in a liquid-dominated geothermal system may be estimated as follows (Halldórsdóttir, 2014):

$$Q = Q_R + Q_W \tag{1}$$

And

$$Q_R = A \cdot h\,[\rho_r c_r (1-\emptyset) \cdot (T_r - T_c)] \tag{2}$$

$$Q_w = A \cdot h . \rho_w c_w \emptyset \cdot (T_r - T_c) \tag{3}$$

where Q_R = Thermal energy of rock (J);
Q_W = Heat of the water (J);
A = Surface area of the reservoir (m^2);
h = Thickness of the reservoir (m);
ρ_r = Rock density ($kg.m^{-3}$);
c_r = Specific heat capacity of rock ($Jkg^{-1}K^{-1}$);
$\emptyset$ = Rock Porosity (-);
T_r = Temperature of reservoir (°C);
T_c = Cut-off/base temperature (°C);
ρ_w = Density of water ($kg.m^{-3}$);
c_w = Specific heat capacity of water ($J.kg^{-1}K^{-1}$).

The recoverable heat, Q_R, defined as the energy that is technically recovered by the system, is controlled by the recovery factor, R.

$$Q_R = R \cdot Q \tag{4}$$

The recovery factor is dependent on the nature of the geothermal system, incorporating factors such as permeability, porosity, significance of fractures and recharge as well as to what extent reinjection is applied. It is often approximated to be in the range of 0.05-0.25.

For electrical generation, only a small portion of the recoverable heat can be utilized. This is dependent on a factor known as the conversion efficiency, η. The correlation between the thermal conversion efficiency and reservoir temperatures can be seen in Figure 15.

$$Q_E = \eta \cdot Q_R \tag{5}$$

The electrical power potential, P, relative to a time period, t, is given as:

$$P= \frac{Q_E}{t} \tag{6}$$

One of the main drawbacks of volumetric modelling is that it does not account for natural recharge to the reservoir, or increased recharge due to drawdown, or for the important role of permeability. In such cases, volumetric modelling may lead to overestimates, although 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 assigns a probability distribution to each parameter in the volumetric calculation. The Monte Carlo simulation 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.

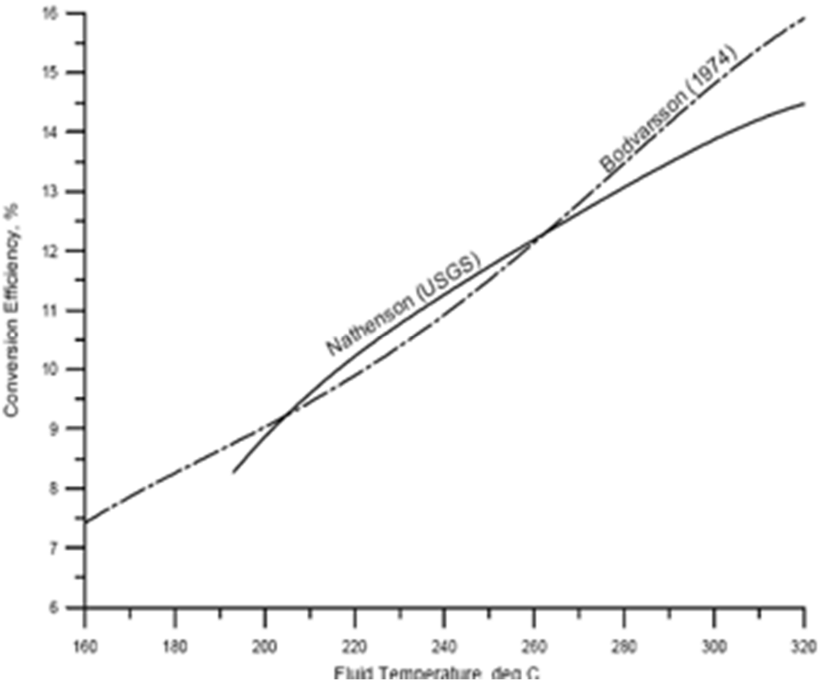

FIGURE 15: Relationship between conversion efficiency and reservoir temperature (Sarmiento and Steingrímsson, 2011)

5.2 Numerical modelling

TOUGH2 is a numerical simulator for multi-dimensional, non-isothermal heat flows of fluid in porous and fractured media. Through the application of Darcy's Law, TOUGH2 solves mass and energy balance equations that describe fluid and heat flow in such systems (Pruess et al., 1999). The TOUGH2 model consists of a number of interconnected elements. For each element, equations defining the accumulated heat and mass as well as the heat and mass flux and points of generation (i.e. heat sources and sinks) are set up (Gylfadóttir, 2014). The basic mass and energy equation describing this kind of flow is expressed as:

$$\frac{d}{dt}\int_{V_n} M^k \, dV_n = \int_{\Gamma_n} F^k \cdot n \, d\Gamma_n + \int_{V_n} q^k \, dV_n \tag{7}$$

Equation 7 expresses the equivalence of the rate of change of fluid mass in sub-volume V_n to the sum of the net inflow across the surface and the net gain from fluid sources and sinks. The $\frac{d}{dt}\int_{V_n} M^k \, dV_n$ term represents the total mass and heat accumulation in sub-volume V_n. The $\int_{\Gamma_n} F^k \cdot n \, d\Gamma_n$ term represents the mass and heat fluxes through the subsurface Γ_n while the $\int_{V_n} q^k \, dV_n$ term represents the sources and sinks of mass and heat.

For numerical simulation, the continuous space and time must be discretized by introducing volume and area averages (Pruess et al., 1999; Gylfadóttir, 2014).

The mass/heat accumulation term in Equation 7 becomes:

$$\frac{\mathrm{d}}{\mathrm{dt}}\int_{\mathrm{V_n}} \mathrm{M^k\, dV_n} = \frac{\mathrm{d}}{\mathrm{dt}}\mathrm{V_n M_n} \tag{8}$$

The source and sink term becomes:

$$\int_{\mathrm{V_n}} \mathrm{q^k\, dV_n} = V_n q_n \tag{9}$$

The mass/heat flow term becomes:

$$\int_{\Gamma_n} \mathrm{F^k \cdot n\, d\Gamma_n} = \sum_m A_{nm} F_{nm} \tag{10}$$

where M_n is the average value of mass/heat in V_n
A_{nm} is the area between V_n and V_m
q_n is the average flow rate of source/sink in V_n
F_{nm} is the average value of normal flow over A_{nm}

Substituting Equations 8, 9, 10 into 7 gives:

$$\frac{dM_n}{dt} = \frac{1}{V_n}\sum_m A_{nm} F_{nm} + q_n \tag{11}$$

The governing TOUGH2 equations are discretized as first order finite difference equations and solved between consecutive time-steps by the Newton-Raphson iteration scheme.

6. ANALYSIS

6.1 Volumetric model

The accuracy of the volumetric method is dependent on both the development and maturity of a given geothermal field. While stated that this method can be done with as little as two to three exploratory wells, accuracy increases as more well data become available. The Monte Carlo method is a probabilistic method that accounts for the great uncertainties in the selected parameters.

In order to obtain a model with a higher chance of accuracy, the following parameters must be approximated using geological, geochemical, geophysical and logging data:

- Surface area of the geothermal reservoir;
- Reservoir thickness;
- Rock porosity;
- Specific heat and densities of rock and water;
- Reservoir and base temperature;
- Recovery factor;
- Plant conversion efficiency.

The surface area of the Wotten Waven geothermal field was estimated by finding the area of the confirmed geothermal resource, i.e. the area surrounding the three exploratory wells, as well as extending just beyond the areas of natural thermal discharge in Wotten Waven, as shown in Figure 14. A triangular distribution was assigned and the confirmed area of 5 km^2 was set as the minimum, while the maximum area was extended to 20 km^2 to include areas of thermal manifestations in Boiling Lake. The most likely area was estimated to be 10 km^2.

Reservoir thickness was also assigned a triangular distribution. It was estimated from the results of the gravity survey, discussed in Section 2, which proposed a total reservoir thickness ranging from 600 to 2000 m. The minimum thickness, however, was selected as 500 m, the maximum 2000 m and the most likely thickness was selected as 1000 m. These values also correspond with values suggested by Muffler and Cataldi (1978), in the event that geophysical data failed to reveal the reservoir thickness.

Geological data as well as lithological logs have revealed that andesite is the primary rock type of the Wotten Waven geothermal field. This corresponds to a porosity of 10% and rock density of 2600 kg/m^3. Porosity and rock density are given a fixed value.

Muffler (1979) suggested that in estimating the total accessible resource, one must assume that the geothermal reservoir has a single characteristic temperature. Geothermometry suggests a value for reservoir temperatures ranging between 250 and 300°C. Reservoir temperature is normally assigned a triangular distribution. The value for the minimum temperature was selected to be 150°C. This temperature is close to the minimum required useable temperature for a conventional binary plant. The maximum temperature was, consequently, assigned the value of 300°C, corresponding to the geothermometry results. There is an almost zero probability that the reservoir temperature is greater than this value. The most likely temperature was selected to be 230°C since the highest downhole temperatures for the three exploratory wells ranged from 234 to 245°C. This value, according to Muffler (1979), may therefore be considered as the characteristic reservoir temperature. The values for the specific heat and densities of the rocks and water were determined based on the reservoir temperature values.

The recovery factor is defined as the ratio of extracted thermal energy (measured at the well-head) to the total geothermal energy contained in given volumes of rock and water (Muffler, 1979). In typical cases of permeability and porosity, the recovery factor may be as high as 25% in convective systems, however, it may approach zero in unfractured, impermeable rock. The recovery factor can though be estimated based on the type of geothermal system, i.e. whether it is convective or conductive, the porosity of the rock, the type of fluid present in rock pores, reservoir temperature, permeability, effects of natural recharge, and the type of technology used to extract this thermal energy. Most Recover Factor estimations are based on approximations for idealised permeable, convective systems, with little attention paid to less permeable, non-ideal cases. This has resulted in exaggerated geothermal assessments. Muffler (1979) approximated a linear relationship between porosity and Recovery Factor which gives a value of 25% corresponding to the 10% value for the porosity of Andesitic rock. This value is considered to be unrealistically and the recovery factor variable is assigned a triangular distribution ranging from 10 to 25% to account for non-ideal reservoirs.

The plant utilization factor / conversion efficiency is dependent on the efficiency of the geothermal plant. It incorporates both the conversion of thermal energy into mechanical energy and consequently mechanical energy into electrical energy. An estimate for conversion efficiency assumed a uniformed distribution ranging from 5-11%, partially based on the correlation between reservoir temperature and conversion efficiency presented in Figure 15.

The volumetric assessment was carried out using the Monte Carlo method. The input data presented in Table 1 was used in the calculations for generation periods of 30, 50 and 100 years. Results for a typical generation period of 30 years are presented as a discrete probability distribution in Figure 16, and as a cumulative probability distribution in Figure 17, while results for 50 years are presented in Appendix II and those for 100 years in Appendix III.

TABLE 1: Input parameters for the volumetric assessment

Input variables	**Units**	**Minimum**	**Most likely**	**Maximum**	**Distribution**
Surface area	km^2	5	10	20	Triangle
Thickness	m	500	1000	2000	Triangle
Rock density	kg/m^3		2600		Fixed
Porosity	%		10		Fixed
Rock specific heat	J/kg°C		900		Fixed
Temperature	°C	150	230	300	Triangle
Fluid density	kg/m^3	712	827	917	Triangle
Fluid specific heat	J/kg°C		4700		Fixed
Recovery factor	%	10.0	15.0	25.0	Triangle
Conversion efficiency	%	5.0		11.0	Uniform
Plant life	years		30, 50, 100		Fixed
Rejection temperature	°C		35		Fixed

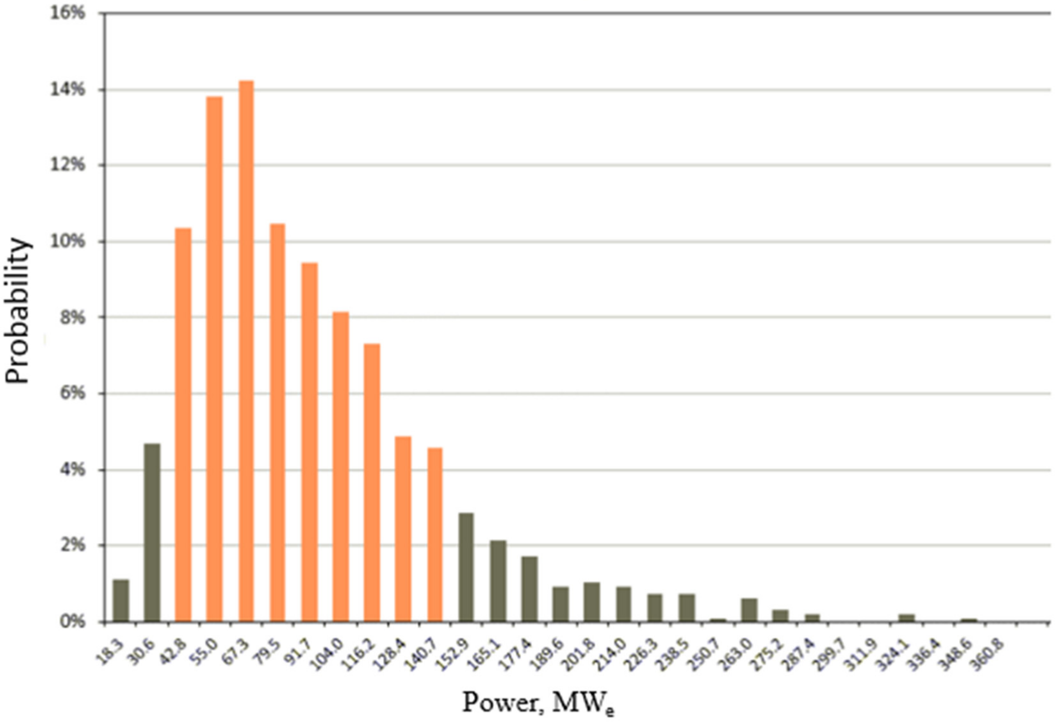

FIGURE 16: Monte Carlo volumetric discrete probability distribution for electrical power production for a period of 30 years

A discrete probability distribution deals with the probabilistic properties of observable pre-defined values. It is characterised by a limited number of possible observations. In Figure 16, the most probable value for electrical power production is 67 MWe with a probability of approximately 14%. This corresponds to a total heat content of over 4860 TJ and, according to Equation 4, a total recoverable energy of 730 TJ. The histogram illustrates with 90% confidence that power production capacity is between 42 and 140 MWe for a production period of 30 years, which is the normal economic lifetime for geothermal power plants.

The cumulative frequency distribution in Figure 17 is comparable to a probability distribution function, plotted by the frequency of each number. The vertical axis represents the cumulative frequency distribution, while the horizontal axis is equal to the corresponding random values for electrical power production. The cumulative frequency equivalent to the maximum value for production is always 1,

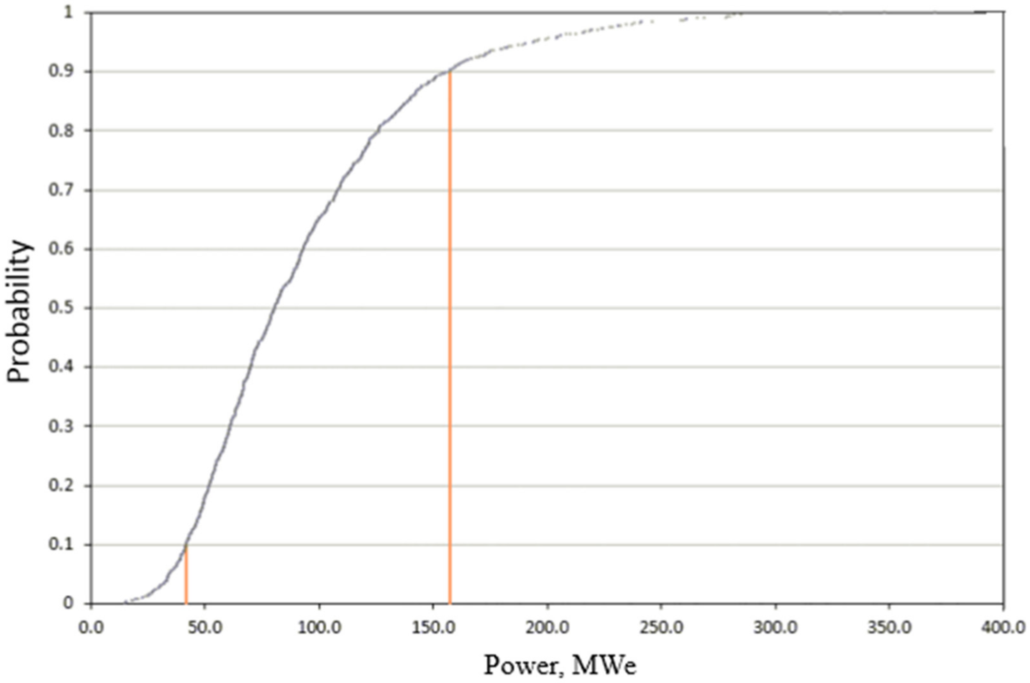

FIGURE 17: Monte Carlo volumetric cumulative probability distribution for electrical power production for a period of 30 years

while that corresponding to the minimum possible value is 0. In Figure 17, the probability that power production capacity is greater than 42 MW_e is 90% for a production period of 30 years. This value, supported by the outcome of the exploration wells, may be considered to represent an estimate of the proven reserves for the Wotten Waven geothermal field, i.e. the capacity that can be estimated with increased certainty based on geoscientific data (Sarmiento and Steingrímsson, 2011).

A similar approach was taken for the generation periods of 50 and 100 years (see Appendices II and III). The results of all the estimates are summarized in Table 2.

TABLE 2: Monte Carlo volumetric generation capacity estimates for generation periods of 30, 50 and 100 years

Statistical sizes	**Power (MWe)**		
	30 years	**50 years**	**100 years**
Most probable value	67	48	19
90% confidence interval	42-140	26-92	15-45
Mean	93	60	30
Median	81	54	28
Standard deviation	51	28	12
90% limit	42	28	14

After the successful completion of exploratory wells WW-01, WW-02 and WW-03, the Government of the Commonwealth of Dominica has proposed the development of a small 10-15 MW_e power plant in Wotten Waven (Maynard-Date and George, 2013). Based on the assessment results for the 30 year generation time period, the reservoir should be able to sustain a minimum of 42 MW_e. If the generating period were extended to 50 years, the 90% limit indicates that the reservoir should be able to sustain a minimum of 28 MW_e. If the time period were extended to 100 years, the 90% limit shows that the reservoir should be able to sustain a minimum of 14 MW_e. The current Wotten Waven geothermal field should be able to sustain a power plant with a maximum capacity of 10-15 MW_e for 100 years. These values, however, may not reflect the true potential of the Wotten Waven field, since the Volumetric Method does not account for either natural recharge of the system or the effects of reinjection.

6.2 Numerical modelling

A simple natural-state numerical model for the Wotten Waven geothermal field was developed for this project. A TOUGH2 grid file was created using the RockEditor software package which uses the Amesh program (Haukwa, 1999) that generates discrete grids for numerical modelling of flow and transport problems, formulated on the integral finite difference method (Mwarania, 2014). The model covers an area of 5 km^2, with a thickness of 2 km and is subdivided into 1428 grid elements. It was specifically designed to focus on the finer model blocks centred on the location of the three exploratory wells, as seen in Figure 18. The larger, coarser blocks were placed around the edges of the model where less accuracy was required.

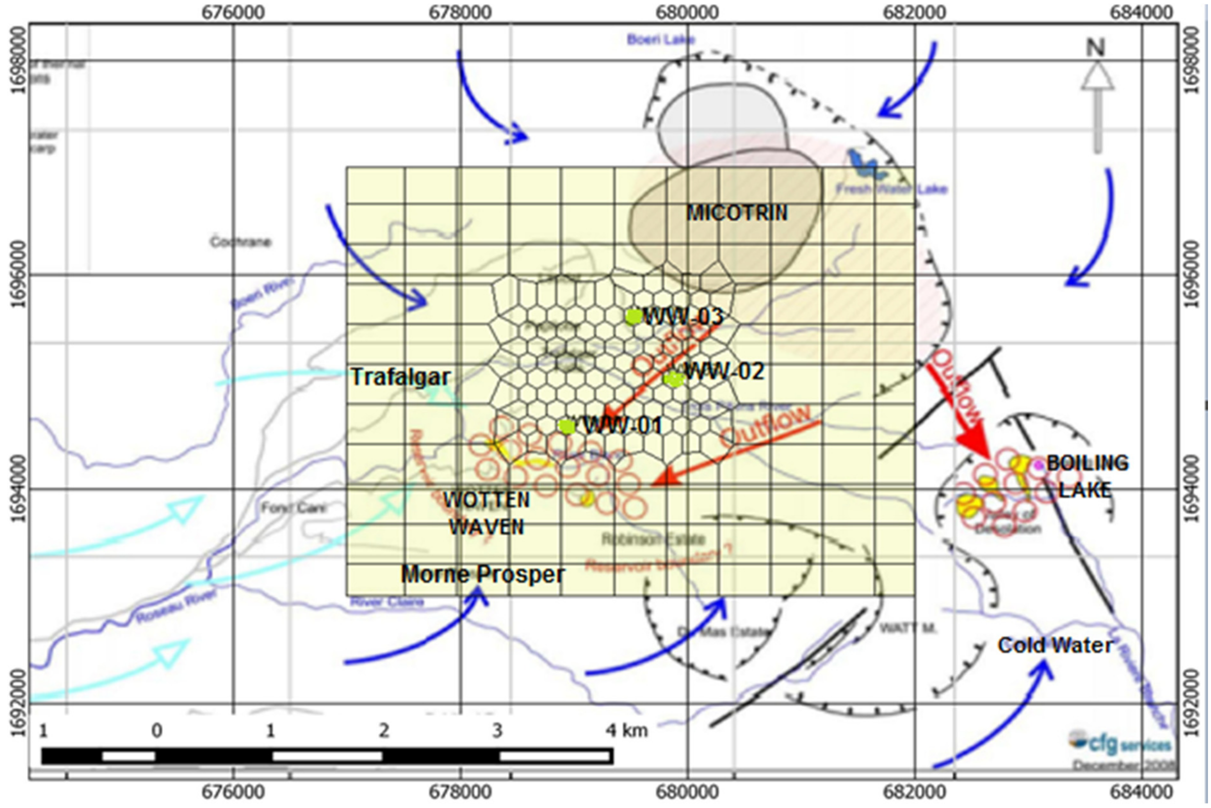

FIGURE 18: Horizontal mesh of the numerical model with an underlying conceptual model from Traineau and Lasne (2008)

The mesh boundary is set far from the exploratory wells, delimited by the Boiling Lake in the east, Trafalgar in the west and Micotrin and Morne Prosper in the north and south, respectively, as shown in Figure 18. The model is composed of six layers (Figure 19) and has a vertical depth of 2000 m, ranging between 100 m a.s.l and 1800 m b.s.l. The top and bottom layers, representing the caprock and bedrock, respectively, are set as inactive and relatively impermeable as compared with the inner layers. A constant temperature and pressure of 32.5°C and 14.67 bars is maintained in the caprock, with the outer mesh of the bedrock set at a lower temperature than the finer mesh elements, thereby limiting fluid flow to layers B-E. The average surface temperature, obtained from well logs, was assumed to be 25°C and a geothermal gradient of 50°C/km was set up at the boundaries. For simplicity, the geological conditions were assumed to be constant. For each layer of the model, the horizontal mesh remains the same as shown in Figure 18.

Four different rock types were assigned to different regions within the model. It was assumed that all elements had the same porosity, thermal conductivity and specific heat, however, permeability and, to some extent, density varied in each rock type. In real cases, permeability differs in the x, y and z dimensions, however for the purpose of this project, permeability was assumed to be equal in all directions (Table 3).

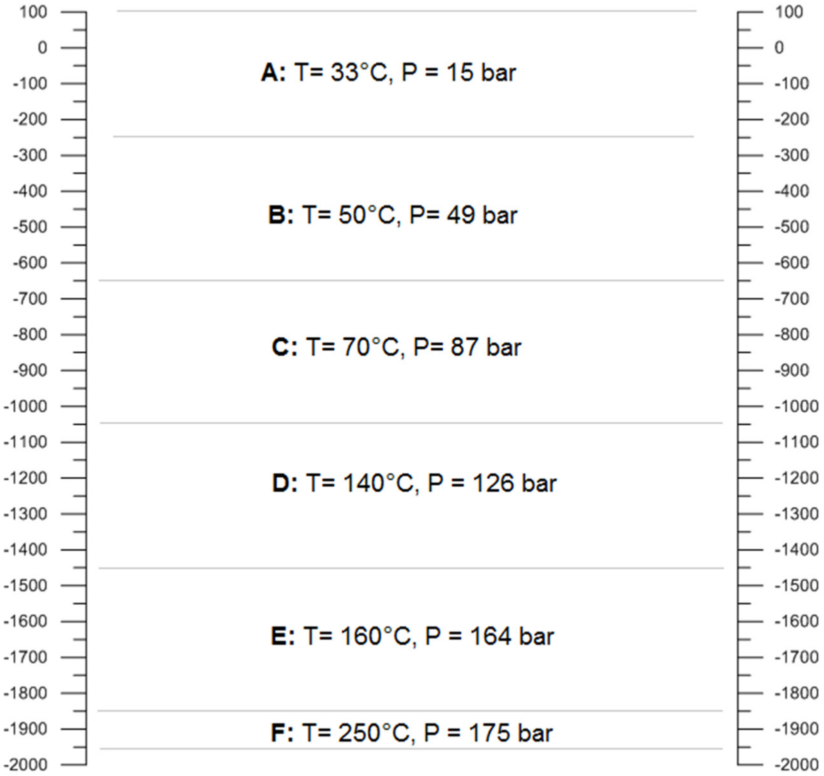

FIGURE 19: The vertical grid of the numerical model

TABLE 3: Table showing varying rock properties of rock types used in model

Rock	Density (kg/m^3)	Porosity	Thermal conductivity (W/m°C)	Specific heat (kJ/kg·K)
CPRCK	2650	10%	2.1	850
BDRCK	2650	10%	2.1	850
PERMR	2640	10%	2.1	850
PERMM	2650	10%	2.1	850

The formation temperatures of wells WW-01, WW-02 and WW-03 were estimated using the static temperature profiles. Heat sources were implemented in layer E of the model, to simulate upflows, while a sink was implemented in layer A to simulate natural discharge from the system. An important assumption made in the TOUGH2 model was that the geothermal fluid is that of pure water. Inflow to the Watten Waven field, or outflow from Microtin, as speculated in the conceptual model, was modelled as upflow by implementing sources. The location, flow rate and enthalpy of the pre-defined sources and sinks can be seen in Table 4.

TABLE 4: Flow rates and enthalpy of various pre-determined sources/sinks in the numerical model

Source/ Sink	Flow rate (kg/s)	Enthalpy (kJ/kg)
EA413SOU01	25.0	1117
EA332SOU02	35.0	1095
EA349SOU03	20.0	1055
AA147SIN01	2.e-09	2.e+02

A natural-state model simulates the geothermal field's physical state prior to production. It is designed to verify the validity of previous conceptual and volumetric models. As described by Mwarania (2014), a natural-state model is simulated for a long period of time until steady state is achieved. Natural state was achieved by manually adjusting the permeability distribution as well as the enthalpy and flow rates of pre-determined heat sources and sinks, seen in Figure 20. In achieving steady state, as seen in Table 4, a total of 80 kg/s of fluid with an enthalpy of approximately 3300 kJ/kg was injected into three elements giving a thermal input of approximately 260 MW_t, which corresponds to 7 MW_e. Although small in comparison to the volumetric assessment, this value corresponds well with the combined estimated capacity of the three exploratory wells, 7.3 MW_e (GDU, 2013). This value reflects the small production area in the model. Further modelling for the Wotten Waven field includes extending the production area, while placing more heat sources in the model that will result in a higher flow rate and enthalpy.

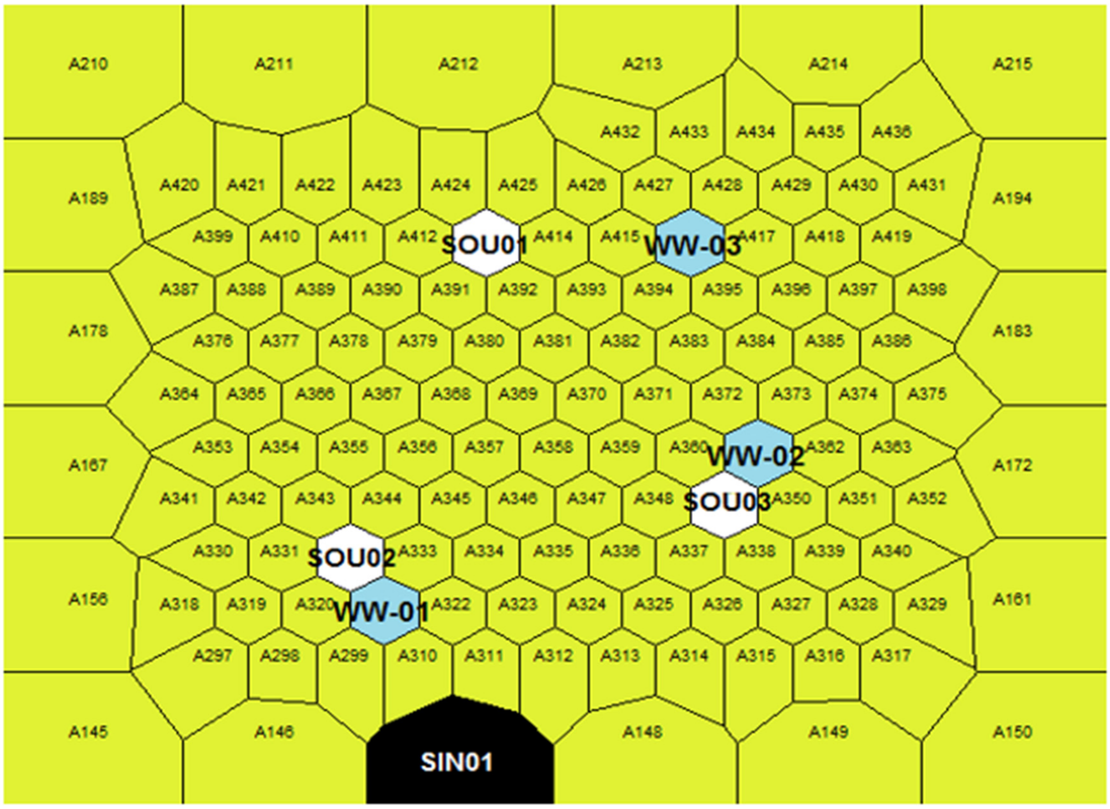

FIGURE 20: Location of exploratory wells, sources and sinks in the numerical model

The modelled results are presented in Figures 21-23, where the results of the natural-state model are compared to the estimated formation temperatures for the three exploratory wells. The modelled and measured data presented show fairly good corrolations. The modelled plot illustrates the characteristic linear plot as seen in the temperature logs of wells WW-01, WW-02 and WW-03 from 100 m a.s.l to -200 m b.s.l – the cap rock of the geothermal system. The isothermal profile was modelled by increasing the permeability of rocks in Layers B-E. This model suggests that the geothermal reservoir may in fact be located at depths as shallow as 100 m b.s.l. This is in agreement with the geophysical model in Figure 6 and is further confirmed by the temperature logs of the three exploratory wells. Inversion was modelled at elevations greater than 1200 m b.s.l. This was achieved by increasing the permeability of the rocks around wells WW-02 and WW-03. The numerous feed zones present in WW-02 (Figure 9) support this hypothesis, that a more permeable formation may in fact be present in the vicinity.

A major discrepancy in Figures 21-23 is the downwards shift of the modelled data. Figure 19 shows the vertical numerical grid generated, with its associated temperatures and pressures. In the numerical model, a vertical depth of approximately 2 km was considered and subdivided into six layers, with the thickness of each layer ranging from 100 to 400 m. In order to correct the shift observed in Figures 21-23, a more sensitive model would have to be developed, with thinner layers to account for more detailed changes in temperature and rock permeability.

Many assumptions made while developing the model should be revised when the model is developed further. Theoretically, a uniform geological section was considered, ignoring the effects of fractures, faults and folds. A single rock type with varying permeability was assumed, thereby disregarding many practical considerations.

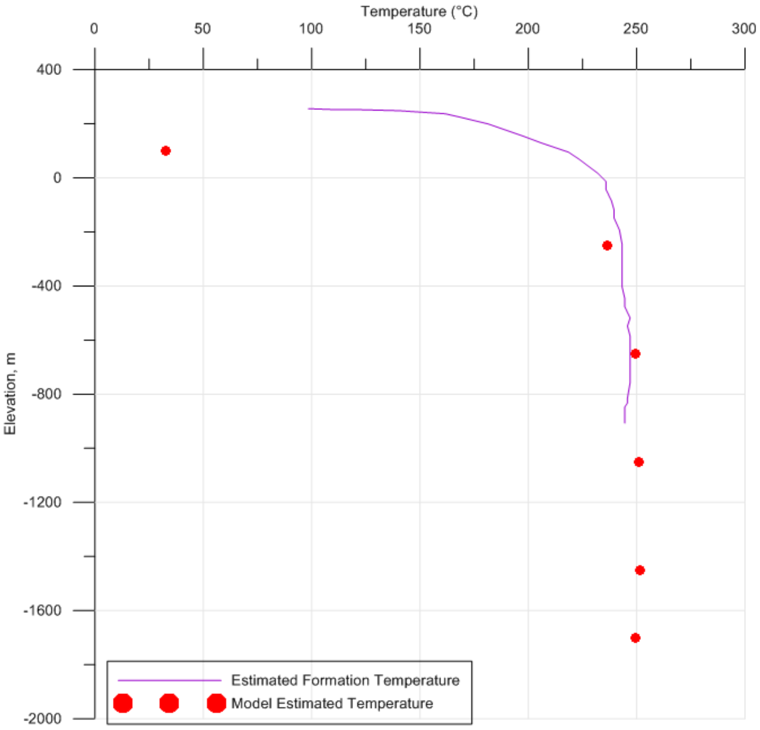

FIGURE 21: Modelled versus measured temperature profiles for Well WW-01

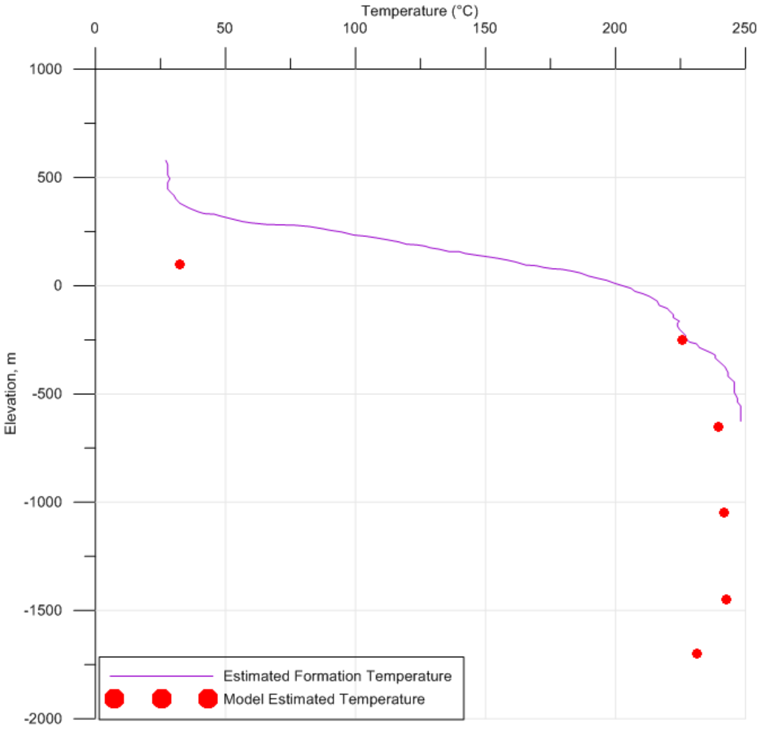

FIGURE 22: Modelled versus measured temperature profiles for Well WW-02

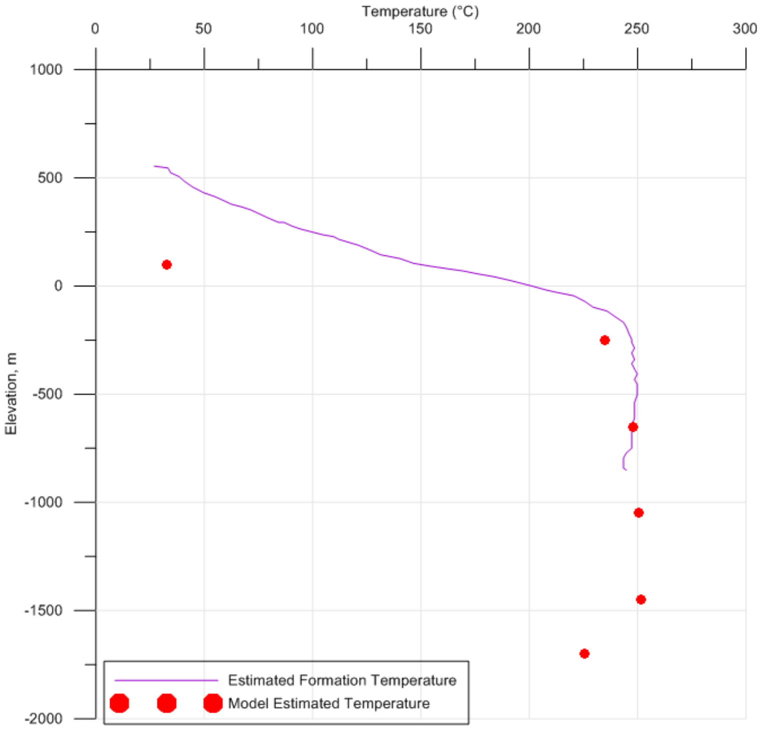

FIGURE 23: Modelled versus measured temperature profiles for Well WW-03

7. CONCLUSIONS

This project was conducted to jointly estimate the resource potential and set up a natural-state numerical model of the Wotten Waven geothermal field. A volumetric model set up for a reservoir area of 5-20 km^2, and a resource temperature of 150-300°C, revealed that the current Wotten Waven geothermal field should be able to sustain a power plant of the capacity 10-15 MW$_e$ for a maximum time period of 100 years. More exploratory drilling needs to be done, however, if the government plans on expanding the capacity to 120 MW$_e$ by 2020.

Temperature logs from exploratory wells WW-01, WW-02 and WW-03, drilled between 2011 and 2012, confirm the earlier conceptual model from 2008. The logs indicate that the wells were drilled in the proposed outflow from Microtrin volcano feeding the Wotten Waven field. The logs show no indications of boundaries, suggesting that the reservoir boundary is far from the exploratory wells.

The numerical natural-state model of the Wotten Waven field was set up for a total area of 5 km^2. Natural state was simulated by manually adjusting the permeability distribution as well as the enthalpy and flow rates of pre-determined heat sources and sinks. In achieving steady state, a total of 80 kg/s of fluid, with an enthalpy of approximately 3300 kJ/kg, was injected into three elements, giving a thermal input of approximately 260 MW$_t$. The numerical model confirmed the presence of a very permeable geothermal reservoir at depths greater than 100 m b.s.l., with an even more permeable formation located around wells WW-01 and WW-02.

A more detailed numerical model should be developed for a greater reservoir surface area to accurately model the reservoir conditions of the Wotten Waven field, including data from the newly drilled production and injection wells. Once the wells are put into production, a production model should be set up to simulate the response of the reservoir (pressure, enthalpy, etc.) to utilization and to assist in optimizing the power production during future utilization.

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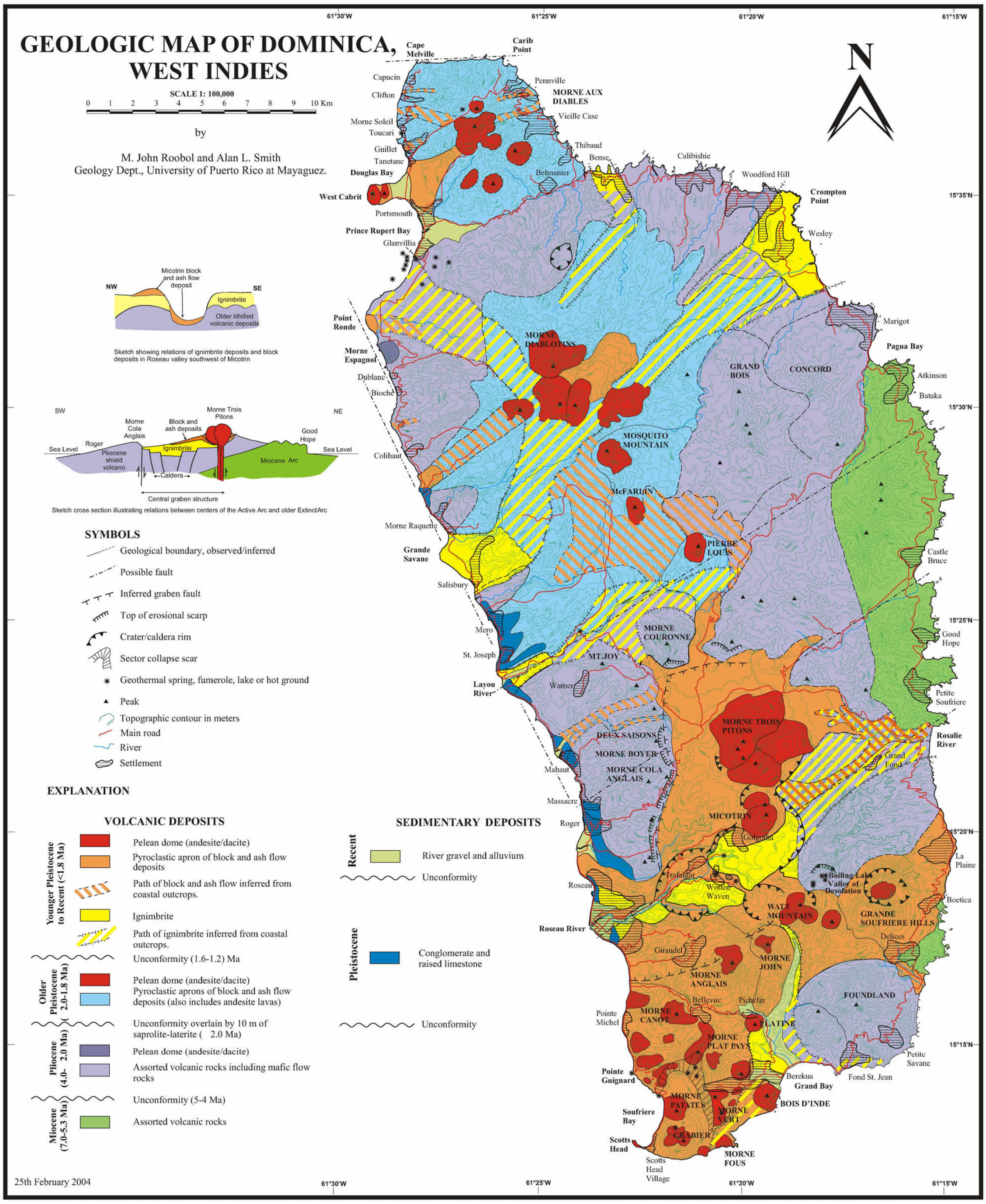
APPENDIX I: Geological map of the island of Dominica



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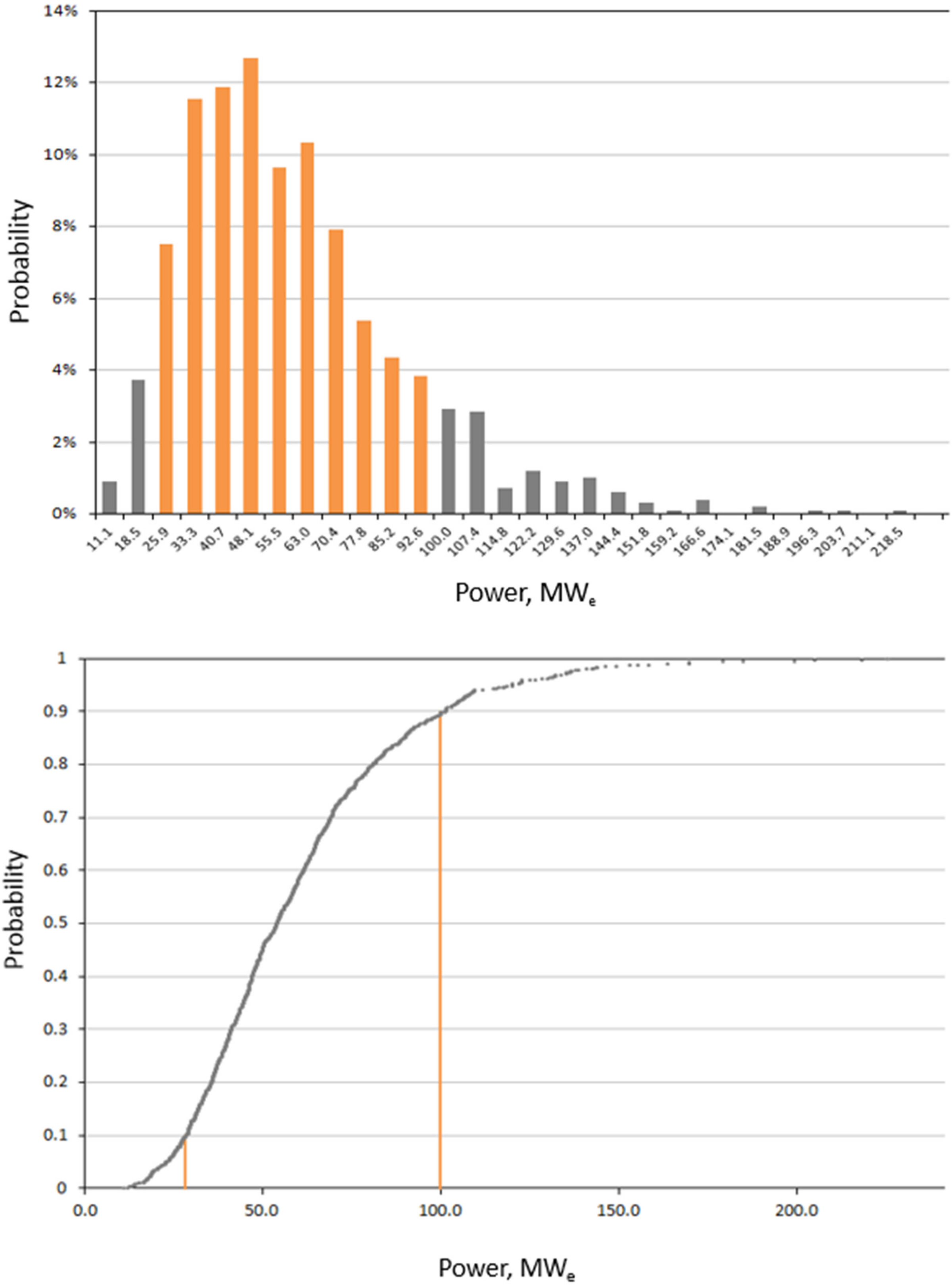
Fieldwork supported by NSF grants EAR 7717064, EAR 9527273, OEDG 01119934 and NASA NCC W-0088.
Note: To print this map at the correct scale of 1:100,000, the 10 kilometer bar scale has to be 10 cm long.

APPENDIX II: Distributive (above) and cumulative (below) probability distribution for a generating period of 50 years



APPENDIX III: Distributive (above) and cumulative (below) probability distribution for a generating period of 100 years