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The Geothermal Resource in the Roseau Valley in Dominica, West-Indies. Drilling of three Exploration wells; Lithology, Alteration, Thermal Conditions and Chemistry

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ABSTRACT

An exploration project aimed at studying the geothermal activity in the Caribbean region was funded by the Organization of American states (OAS) in 2005. It provided a preliminary conceptual model of parts of the reservoir in the Roseau valley, Dominica. The "Géothermie Caraïbes" project, initiated by the EU, Commonwealth of Dominica and France, further focused on the Wotten Waven area and a report was published in 2008 with proposals and site-selection for the drilling of three exploratory wells. The drilling project was funded by the EU development fund, the French development fund and the Commonwealth of Dominica. Resistivity surveys had indicated the presence of a geothermal reservoir, up to 15 km^2 in size and chemical geothermometers estimated the formation temperatures to be in the range of 210-230°C. Drilling of the first well started in November 2011, and the third well was completed in May 2012. The formations drilled though were mostly ignimbrites/welded tuffs and other pyroclastic materials, intercalated with dacitic lava domes and intermediate/basaltic intrusions. Alteration is quite high in the production section and gives indications of a high formation temperature with the appearance of epidote at 900-1000 m. Clay-minerals also show progressive increase in alteration from smectite-zeolite zone near surface succeeded by a chlorite-epidote zone below 900-1000 m. Subsequent flow-testing was successful, and all three wells did flow without aid. Highest temperature values recorded during flow-test after short heat-up period were ~246°C. Total flow of each well was from 6 to 25 kg/s with discharge enthalpy of around 1000 kJ/kg. Environmental monitoring was initiated prior to the drilling operation, during the drilling and three months after the testing of the last well. Results do not show that the drilling operation has affected the ground- and surface water in the area.

1. INTRODUCTION

Dominica is a volcanic island in the Lesser Antilles region, one of many volcanic islands, separating the Atlantic Ocean in the east and the Caribbean Sea in the west. The archipelago stemming from Bahamas in the North to Trinidad and Tobago in the South is commonly referred to as the Eastern Caribbean Islands coinciding with the plate margins of a subduction zone where the Atlantic plate sinks under the Caribbean plate. Dominica is roughly in the centre of the archipelago, south-southeast of Guadeloupe and north-northwest of Martinique (figure 1). The size of the island is 751 km^2. Peaks of volcanic domes extend to an altitude of 1447 m a.s.l. (metres above sea level).

In terms of age of the Caribbean island arc, Dominica is considered to among the youngest islands, with abundant occurrences of recent volcanic activity (less than 50,000 years BP) and small phreato-volcanic events reported as late as 1997, in the vicinity of the Valley of Desolation on the south-west part of the island (Smith et al. 2013). Dominica has been constructed mainly from sub-aerial lava flows and pyroclastic deposits and their reworked equivalent. The sub-aerial pyroclastic deposits of the island reflect different styles of activity, including Peléan, Plinian, phreatic and/or phreatomagmatic ejecta (Smith et al. 2013). Surface manifestations of geothermal activity can be found in many locations in Dominica, but the most notable areas are in the Valley of Desolation, around Wotten Waven, in the Roseau Valley and in the Soufrière area on the southern tip of the island. The morphology of the island shows a N-S trending axial ridge formed by several distinct volcanic complexes and covered by dense tropical forests.

The population of the Commonwealth of Dominica is about 73,000. The republic was founded in 1978 when the nation got independence from the UK and is among the smaller independent nations in the world. The economy of the island is very dependent on agriculture and tourism, but cultivable land is a limiting factor in agricultural growth, due to elevated and mountainous terrain. The island is provided with electricity produced with diesel powered generators but about a one third of the available electricity is from small hydro stations. If the geothermal resource can be harnessed to produce electricity it would save significantly on fossil-fuel purchase and considerably reduce greenhouse-gas emission.

1.1 Location.

The areas of interest are the Wotten Waven area and Laudat, both in the Roseau valley on the south-west side of the island, south of the Micotrin lava dome. Surface geothermal manifestations are abundant in the Wotten Waven area, but small and inferior occurrences are however noted in the Laudat region. Site selection of several exploration wells was proposed by Traineau et al. (2008) and subsequently, sites #3, #6 and #8 proposed, were selected.

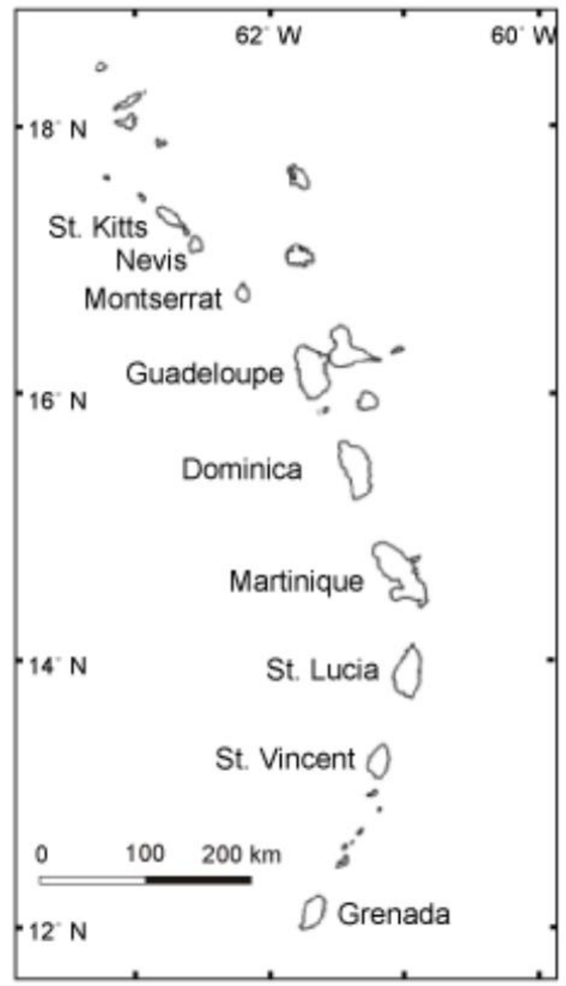

Figure 1. Map of the Eastern Caribbean island arc, extending south towards Venezuela and north to Puerto Rico.

2. PREVIOUS RESEARCH WORK

2.1 Geological settings

Initial summary of the geology of Dominica, together with the first published geological map of the island is given by Lindsay et al. (2005a, 2005b) and represents a compilation of previous studies on the island.

The Roseau Valley's volcanic history is dominated by large eruptions from the Morne Trois Pitons and Micotrin eruptive centres which produced large volumes of welded tuffs and ignimbrites. The most recent large depositional unit is the Roseau Valley ignimbrite where up to 400 m thick outcrops have been mapped (Sigurdsson, 1972). Explosive type of eruptions are generally associated or related to the collapse of a magma chamber and therefore representing geological settings of an evolved central volcano with a cooling magma body as a heat-source at relatively shallow level in the crust.

2.2 Mapping of geothermal manifestations

A detailed study of the geothermal occurrences in the exploration area was conducted by the French geothermal company CFG. In association with the before mentioned framework of the "Géothermie Caraïbes", Lasne and Traineau (2005) and Traineau et al. (2008) published a field report on the geothermal exploration and geological and chemical surveys of the Wotten Waven geothermal field. Their reports and subsequent publications propose a conceptual model which best fits in with the geological, geochemical and geophysical data as being a deep Na-Cl reservoir extending below the Micotrin recent lava dome. The temperature was estimated to be in the range of 200-300°C with lateral fluid outflows developing to the southeast. The size of the geothermal reservoir is now estimated to be around 18 km^2 (Traineau, 2015).

2.3 Resistivity survey

Geophysical survey was first done by the French geological survey BRGM in the 1980's and in 2008 BRGM conducted new resistivity and gravity surveys. Results were published by Baltassat et al. (2008). The aim of the survey was to obtain a resistivity map of the Wotten Waven geothermal field in order to image the size and depth of the geothermal reservoir. The MT (magnetotelluric) survey revealed a highly conductive layer (<20 ohmm) in the surveyed area which was interpreted as a reservoir cap-rock with an assumed thickness of 250-300 m. Underneath a layer with less conductivity occurred (5-80 ohmm) which could be interpreted as a possible water-dominated reservoir or a steam cap.

2.4 Selection of drill sites

The areas selected for the drilling of the three wells in Dominica were selected and the plausible well-locations laid out by Traineau et al. (2008). Locations and site-selection for the three exploratory wells were largely based on the results of the resistivity surveys with geographical considerations. In the Laudat region two of the selected sites were developed and drill-pads constructed. Site #6 (WW-03) close to the parking area near the Aerial-Tram in Laudat and #8 (WW-02) in proximity to water-balancing tank in Laudat. In Wotten Waven, site #3 (WW-01) was also further developed and a drill-pad constructed and access improved. Both wells in Laudat are approximately 560-580 m a.s.l. and the well in Wotten Waven geothermal area is at about 260 m elevation.

3. DRILLING OF EXPLORATION WELLS

3.1 Well design and earlier proposals

Two main options were considered feasible for the exploratory drilling, consisting of slim-holes either fully or partially cored. Drilling cost was considered to be unnecessarily high with either full or partial coring, so a well-design was proposed by Iceland GeoSurvey, using slim-design and conventional tricone bit drilling. The three wells were designed with conductor casing down to about 10-15 metres depth, surface casing down to about to about 60-80 m, anchor casing down to about 150-200 m and production casing to about 300-400 m. The first well drilled, WW-02 was drilled in accordance with the proposed design but in light of the findings, assumed thermal conditions based on alteration mineralogy and progress of the drilling, the design of next well (WW-03) was modified and altered. Conditions encountered during drilling of WW-01 in Wotten Waven again changed the proposed design of the well. Construction ("as built") of the wells is summarized in table 1.

Table 1. Exploration wells in Dominica, as built, listed in drilling order (depths from rig-floor, 5.8 m above surface).

Well n°.	Surface casing 339.7 mm (13 3/8")	Anchor casing 244.8 mm (9 5/8")	Production casing 177.8 mm (7")	Perforated liner 114.3 mm (4 ½")
WW-02	24.5 m	79.2 m	427.5 m	281.2-1337 m
WW-03	30.5 m	155.6 m	590.6 m	569.6-1612 m
WW-01	51.5 m	160 m	301 m	269-1200 m

3.3 Drilling progress

Rigging-up and modifications of the drill-pad took 30 days before the actual drilling of the first well (WW-02) in Laudat was initiated on the 16th of December 2011, after challenging transportation of the rig to the drill-pad in Laudat, at about 580 m elevation. Drilling of well WW-02 continued until the 19th of January 2012, followed by nine days of liner-run, temperature/pressure-logging and injection test. Total number of workdays was thus 65 on WW-02. The drilling, running casings, cementing and logging was completed in 35 working days and the rig was then moved on to the next well (WW-03). When rigging-up was completed, drilling of WW-03 started on the 15th of February 2012 and was completed on the 14th of March 2012, followed by liner-run, logging and injection test. Actual drilling took 19 days and the completion of the well took 43 days in total including moving from WW-02. The third well drilled was considerable distance away, at lower elevation (~260 m) in Wotten Waven and as before the transportation of the rig was laborious and challenging. WW-01 was completed in 40 days, whereof actual drilling took 15 days. The well was shut-in on the 27th of April 2012. Summary of the drilling progress is shown on figure 2.

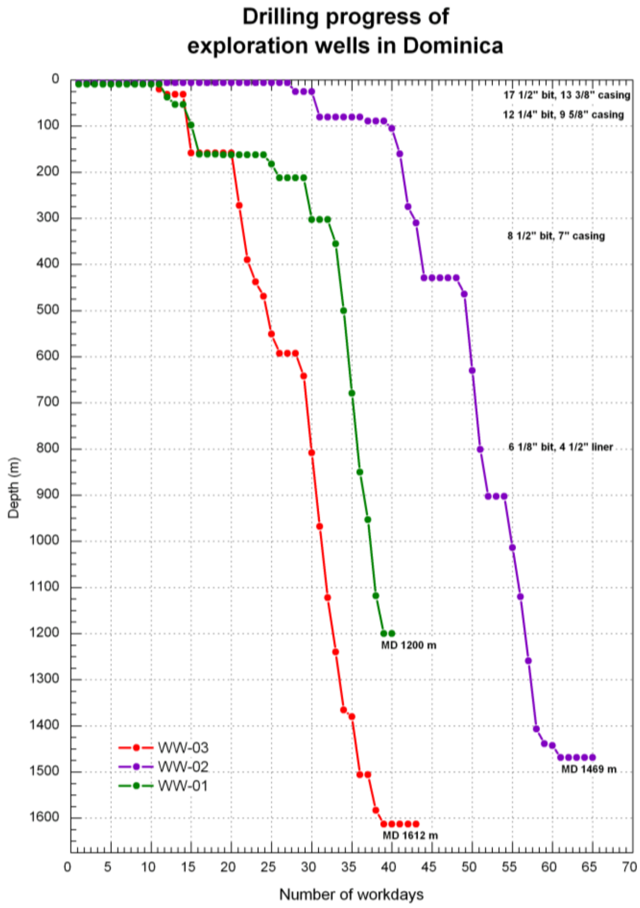

Figure 2. Drilling progress of exploration wells in Laudat and Wotten Waven, Dominica.

4. GEOLOGY

4.1 Lithology

Summary of the lithology, alteration and design of the exploratory wells are shown on figures 3 to 5 with the legend shown in figure 6. Identification and interpretation of alteration minerals and the rock-types intersected during drilling were done on-site with the aid of a binocular microscope. As expected, pyroclastic formations; pumice, breccias and tuffs, are abundant, with conspicuous phenocryst fragments and variable amount of lithic fragments, as a function of the origin and mechanics of the flow. Some units are uniquely identified as block and ash-flow deposits while others are sorted ash flow deposits with less lithic fragments. As due to the proximity of the Micotrin Peléan dome, igneous formations are also rather common. Those encountered are lightly coloured and fine- to medium-grained porphyritic formations of dacitic/andesitic composition. In all three exploratory wells, the sampling of drill-cuttings was continuous from surface to a depth where total loss of circulation was encountered. In well WW-02, set of samples is available from surface to 900 m, in WW-03 from surface to 1174 m and in well WW-01 from surface 736 m and from 806 m to 882 m.

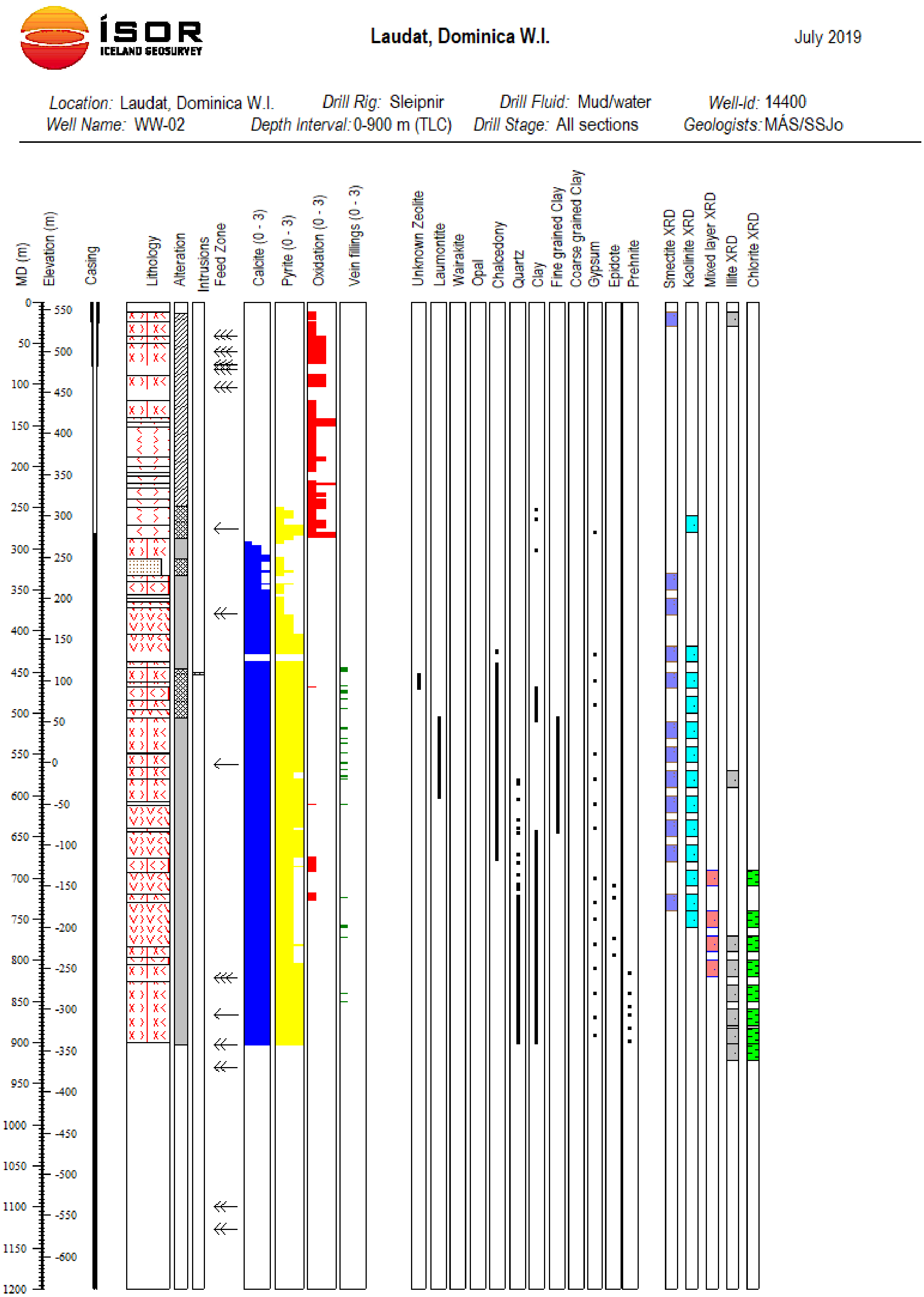

Figure 3. Lithology and alteration in WW-02 in Laudat (revised from Sigurgeirsson et al. 2012a)

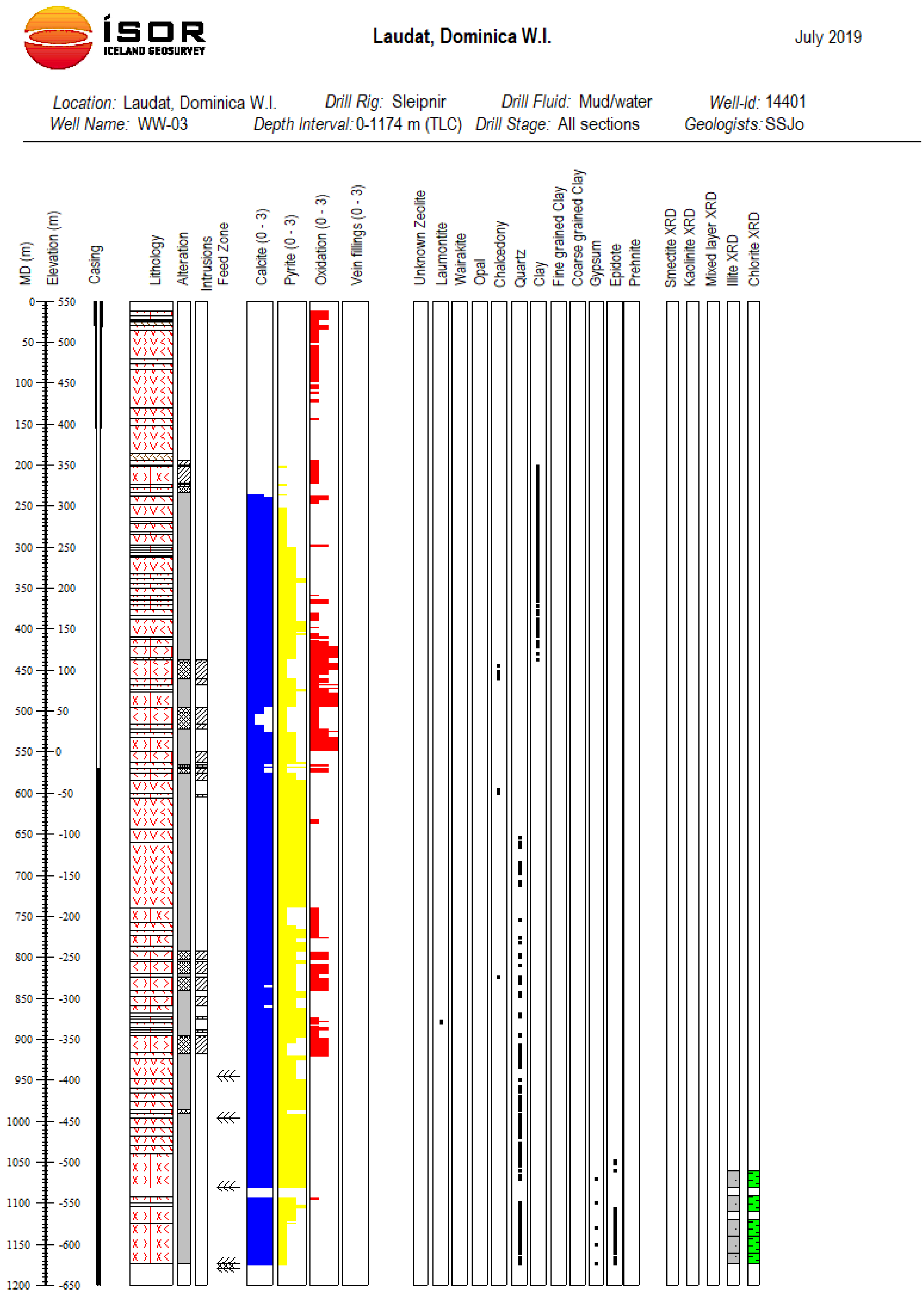

Figure 4. Lithology and alteration in WW-03 in Laudat (revised from Jonsson et al. 2012).

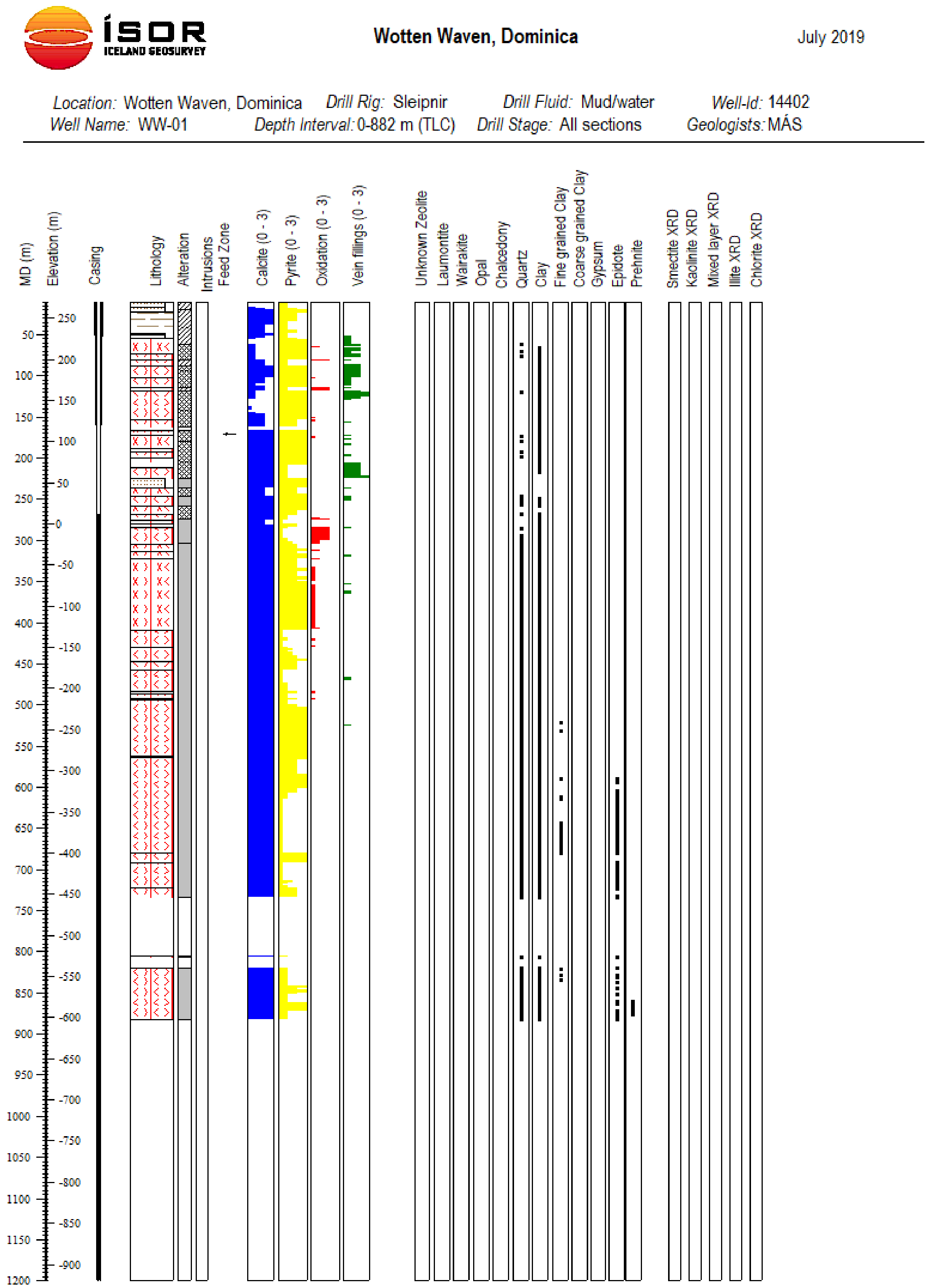

Figure 5. Lithology and alteration in WW-01 in Wotten Waven (revised from Sigurgeirsson et al. 2012b).

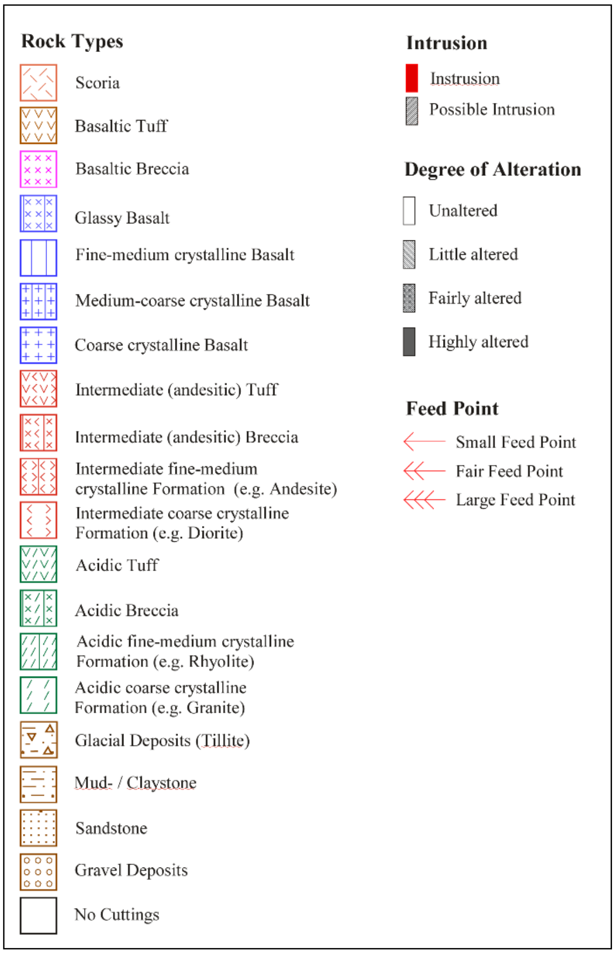

Figure 6. Lithology and alteration. Legend for symbols and patterns.

4.2 Alteration

The interpretation of the alteration stage in the exploratory wells is solely based on on-site examination of the drill-cuttings, except the clay minerals were identified using X-ray diffraction. In the Laudat wells (WW-02, WW-03) the grade of alteration is low in the uppermost 250 metres. Some oxidation is seen at intervals and minor amounts of greenish crust of clay is present below 170 m depth. First signs of hydrothermal alteration are noted at around 250 m depth, with the appearance of pyrite and calcite and the increase of clay (kaolinite/smectite) in the lithified volcanic deposits. Alteration progresses further on with depth and secondary quartz is first noted from 582-654 m (see table 2) in the Laudat wells. Well-formed crystals of epidote are found in WW-03 at 1048 m but identification of epidote in well WW-02 was not confirmed, only vague indications. In WW-01 in Wotten Waven, hydrothermal alteration (pyrite, calcite) is noted from surface, with the exception, that the topmost 60 m have rather low-grade alteration. At 70 m depth the first appearance of quartz as a secondary mineral (vein filling) is noted and below 170 m, quartz is very abundant. Epidote is noted at 590 m depth in WW-01.

The mineral assemblage studies of the drill cuttings suggest that the formation temperatures, if in equilibrium, are less than 180°C above the first occurrence of quartz in the wells and above 230-240°C below the first occurrence of epidote ((Kristmannsdottir 1979, Franzson 1998).

Table 2. Depth to the first observed occurrence of selected minerals. Depth in in parenthesis indicate uncertain identification.

	Quartz	**Epidote**	**Prehnite**
WW-02	582 m	(710 m)	(816 m)
WW-03	654 m	1048 m	--
WW-01	62 m	590 m	860 m

4.2.1 Clay minerals

Samples of drill-cutting from wells WW-02 and WW-03 were collected and prepared for analysis of clay minerals. Around 4 g of drill cuttings were placed in a glass test-tube, mixed with distilled water and shaken in mechanical shaker for about four hours. The slurry was left to settle for 10-15 minutes and then transferred onto glass-slides and left to dry overnight. The air-dried samples were the measured using Bruker D8 Focus diffractometer with Cu kα radiation. The samples were measured again after being kept in a desiccator with ethylene glycol for 24 hours and after heating in 550°C for 1 hour. The set containing the three measurements are superimposed and changes in the crystallography and distance between the crystallographic planes utilized in interpreting the types of clay present in the samples. An example of a sample from 1174 m depth in well WW-03, containing chlorite (7 Å, 14 Å), and illite (10 Å) is depicted on figure 7. Peak at 7.7 Å is due to gypsum.

Clear boundaries are manifested in the clay rich-cap-rock of WW-02 where smectite/montmorillonite is notable in the upper parts of the well, associated with kaolinite. When the hydrothermal alteration has become profound in WW-02, at around 700 m, the character of the clay changes to mixed-layer type clay, where strong bonds in chlorite are noted but with weaker expanding bonds in smectite layers. Where epidote is present in the drill cuttings, chlorite is established in the geothermal system and below 700 m depth, chlorite is the predominant clay mineral, generally associated with illite.

On figure 8, results of clay analysis on samples from well WW-02 in Laudat are added on to a profile showing the pattern of resistivity along MT soundings, presented by Traineau et al. (2015). The well is approximately situated along the elevation profile at around 600 m altitude. The MT profile runs from the Wotten Waven area, about 4 km east towards the Valley of Desolation. The upper limit of the appearance of chlorite is marked on figure 8 at 700 m depth, which or slightly deeper than the upper limit of the underlying resistive layer, as defined by MT soundings. Correlation is however good, and it can be deduced that findings of chlorite below 700 m depth is in good agreement with the results of the MT soundings and location of the resistive underlying reservoir.

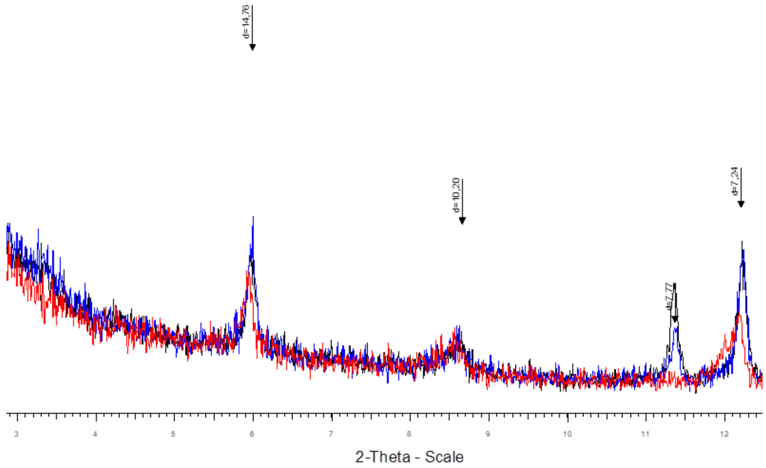

Figure 7. Results of clay analysis of sample from 1174 m depth in WW-03. Black line is air-dried sample, blue line is ethylene glycol saturated sample and red line if heated sample (550°C, 1 hour). Chlorite is manifested by peaks at d=14 and 7Å, illite by peak at d=10Å and gypsum by peak at d=7.7 Å.

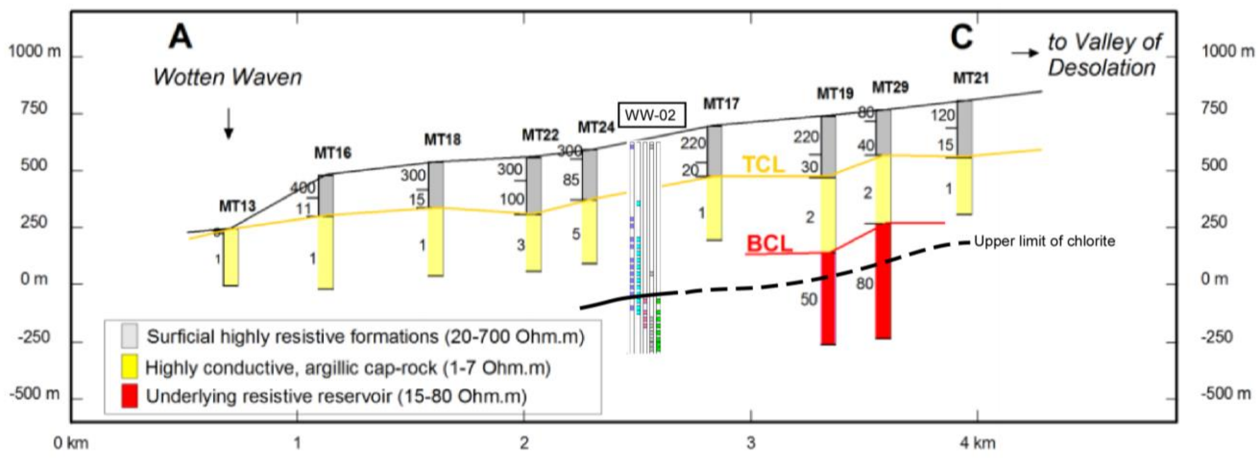

Figure 8. Profile of MT soundings from Wotten Waven to the Valley of Desolation (from Traineau, 2015) with results of clay analysis in WW-02 in Laudat and interpretation of chlorite boundary.

5. CHEMICAL COMPOSITION OF WATER AND STEAM

5.1. Chemistry of liquid and steam

The reservoir liquid is relatively dilute, with total amount of dissolved solids of ~ 8000 mg/L in samples boiled to atmospheric pressure. Chloride is by far the dominating anion and sodium is the dominating cation. Silica concentrations corresponds to reservoir temperatures logs during well testing (~250°C), using the quartz geothermometer of Fournier and Potter (1982). The sodium/potassium geothermometer of Arnorsson et al. (1983) is also in good agreement with the measured temperature. Each of the three wells was only tested for few hours at a time to limit possible environmental effects of the testing. The geothermometers mentioned above postulate that the samples collected during the testing of the wells are representative for the reservoir liquid.

Although gas/condensate ratio was 0.07-2 L/kg in two of the three exploration wells, the same ratio reached 40 L/kg in well WW-02 which was the first well to be drilled. The high gas content of discharge from WW-02 is explained with a gas-rich inflow from cold feed point shortly below the casing at 427.5 m depth. Concentrations of several trace elements in the fluid were analysed for environmental purposes.

5.2 Environmental impacts of the project

An environmental monitoring project was carried out along the geothermal project in the Roseau Valley. Samples of surface water were collected twice a month on five sampling sites in order to evaluate possible impact on the aqueous environment in the valley. The first samples were collected prior to the drilling of the first well in December 2011. The last samples were collected in late September 2012, three months after the testing of the last well.

One of the sampling sites was located upstream from all the wells (50350). One sampling point was close to each well (50351, 50352, 50353) and one sampling point was downstream from all the wells (50354).

The monitoring in the Roseau Valley did not reveal any clear signs of impacts of the geothermal project on the composition of the surface water in the valley. The chemical composition of surface water within the Roseau Valley catchment fluctuates naturally to some degree. The fluctuations are in most cases linked to rain dependent runoff. The chemical composition of streams close to wells WW-03 and WW-01 (sites 50352 and 50353 respectively) is somewhat more stable than that of the Trois Piton River (50350) and the Trafalgar River (50354). This is due to the groundwater origin of water in the streams at sites 50352 and 50353. However, the concentration of dissolved solids in the water from site (50353) increases constantly through the monitoring period. The reason is unknown.

Figure 8 shows SO_4/Cl ratios at different sampling points compared to that of coastal and oceanic precipitation from Savenko (1976) and Maybeck (1983) respectively. The samples from sites 50350, 50351 and 50354 have SO_4/Cl ratio similar to that of coastal and oceanic precipitation. The elevated SO_4/Cl ratio in samples from site 50353 indicate a natural geothermal influence in the samples. Geothermal surface manifestations such as fumaroles and boiling mud pools rich in sulphates are found in the vicinity of the stream upstream from the sampling point. However, the sulphate concentration appears to increase during drilling of well WW-01 and in the first sample after the drilling was completed. Similar trend was also observed in August and September which can neither be traced directly to the drilling operation nor the testing of the well. The very low SO_4 concentrations in samples from site 50352 (Laudat Campsite) signposts a groundwater origin of the water.

The samples from the lower Trois Pitons River (site 50350) and from Trafalgar River (site 50354) show similar trend as samples from the upper Trois Pitons River (site 50351) which is upstream from all the well pads (reference site).

Despite the fluctuating nature of chemical composition of water in the Roseau Valley catchment caused by variations in rainfall and runoff through the monitoring period, concentrations of B, As, Ba, Cd, Cr, Cu, F, Hg, Ni and Pb are in all cases within the WHO guideline values for drinking water.

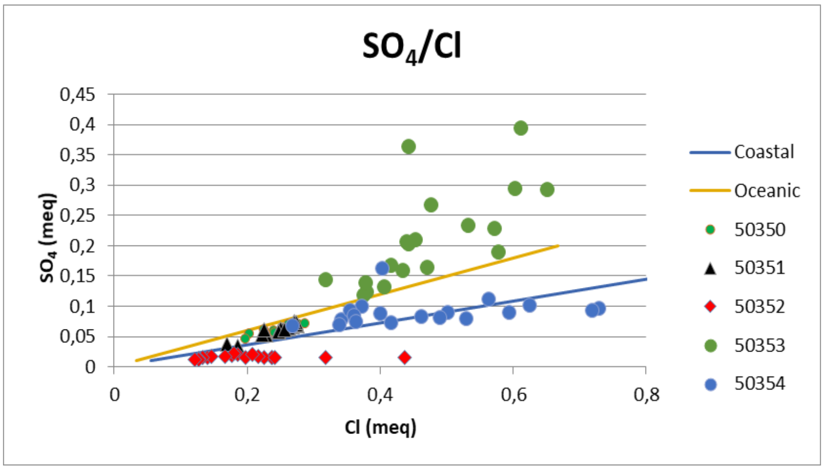

Figure 9. SO_4/Cl ratios of water samples from the sampling points in the Roseau Valley compared to that of coastal and oceanic precipitation. The samples from site 50353 (Trafalgar-Wotten Waven Road) show signs of natural geothermal influence.

6. WELL LOGGING AND TESTING

6.1. Temperature conditions

Several temperature and pressure logs have been measured in the Dominica geothermal wells. In figure 10, logs after some heating periods are shown. In well WW-01, active feed zones dominate the 730-890 m depth interval and after 60 days of heating the measured temperature is close to reservoir temperature, 235°C. In well WW-02, active feed zones are in the 780-1110 m depth interval with the best feed zone close to 1100 m. After 38 days of heating, cooling from the drilling is still significantly affecting the temperature of the feed zone area but the formation temperature is regarded like what is seen in WW-01. In well WW-03 there are definite feed zones at 960 m, 1105 m, 1180 m and 1500 m depth, of which the deepest one is small. The formation temperature of the feed zone area of well WW-03 may be a little higher than for the other wells.

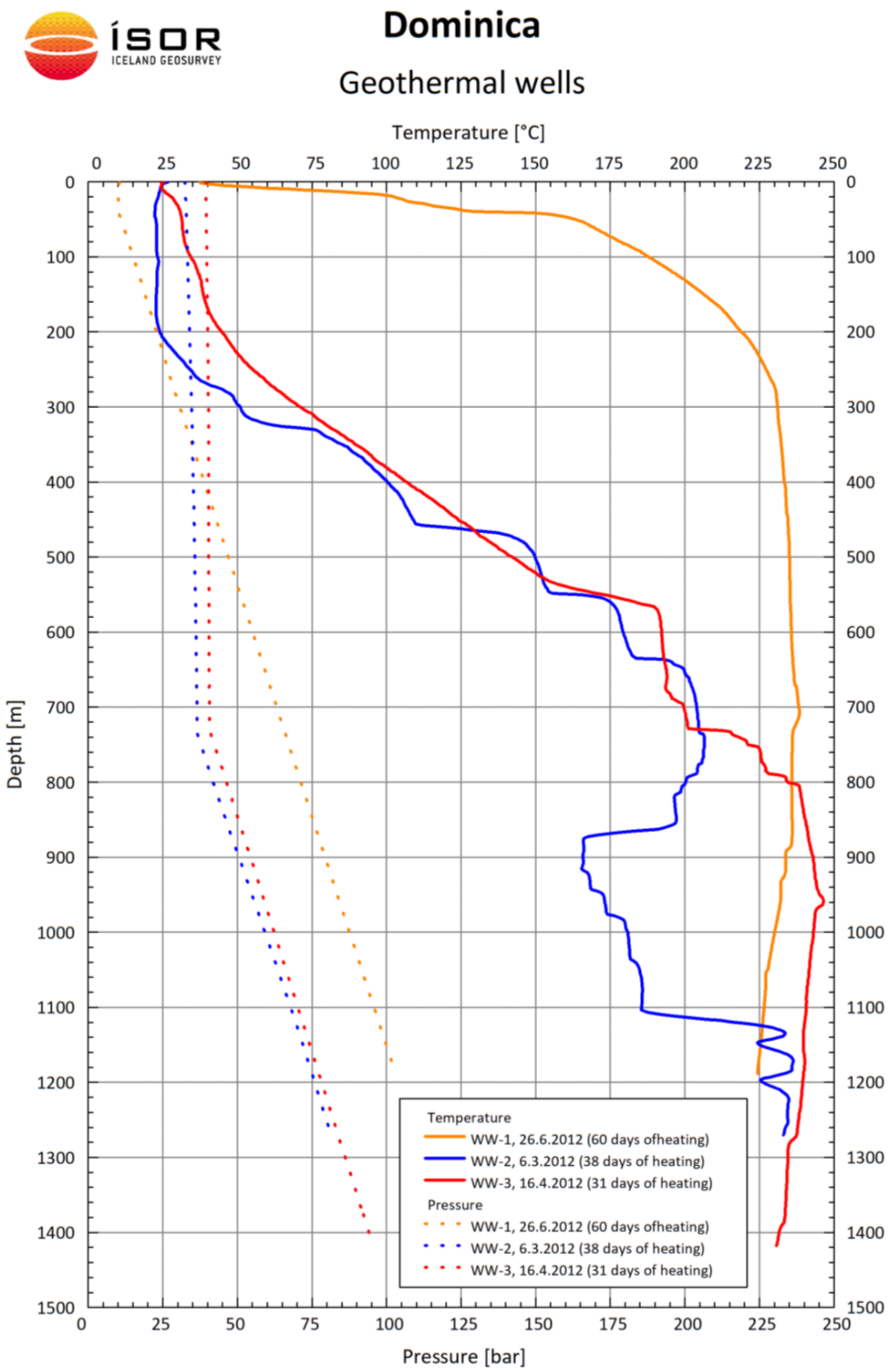

Figure 10. Temperature conditions in the Dominica geothermal wells after some warm-up periods.

6.2. Injectivity tests

All the three wells were tested for permeability with a multi rate injection test. Two of the wells, WW-01 and WW-03, are highly permeable, with injectivity indices, ~13 l/s/bar and >50 l/s/bar respectively. WW-02, however, has a low injectivity index, ~2.5 l/s/bar.

6.3 Discharge tests

All the wells were flow tested with the Russel-James tube setup (Grant and Bixley, 2011) to estimate total fluid flow and enthalpy. The results are presented with figures 11, 12 and 13. Well WW-01 delivers fluid to surface with enthalpy of 1200 kJ/kg corresponds to 275°C single phase liquid which a lot higher temperature than estimated formation temperature. Well WW-02 delivers fluid of about 1000 kJ/kg which corresponds to 235°C in liquid phase water. The 900 kJ/kg total enthalpy fluid delivered by well WW-03 is not up to expectations according to the formation temperature which indicates colder gas rich inflow from upper feed zones.

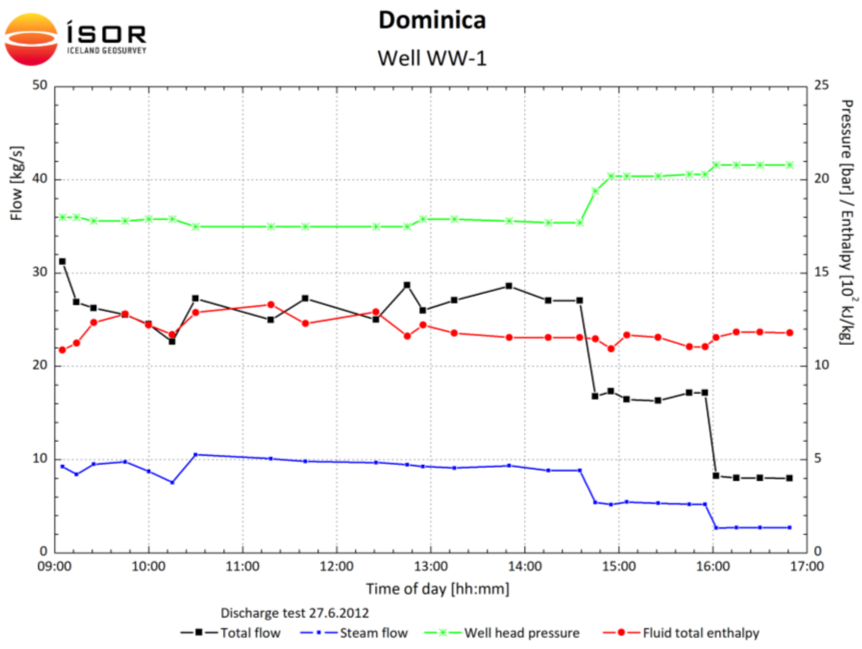

Figure 11. An overview of the results of a discharge test on well WW-01.

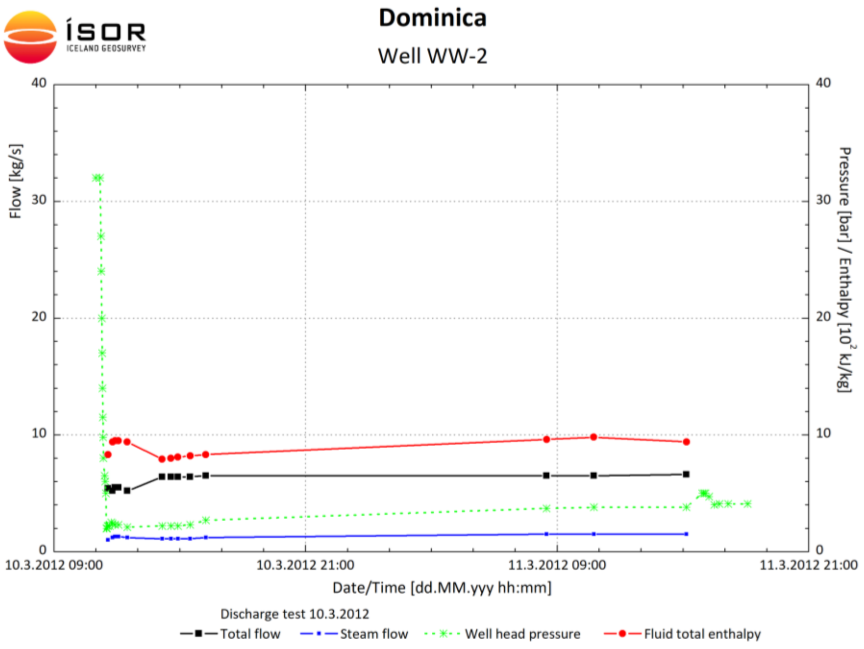

Figure 12. An overview of the results of a discharge test on well WW-02.

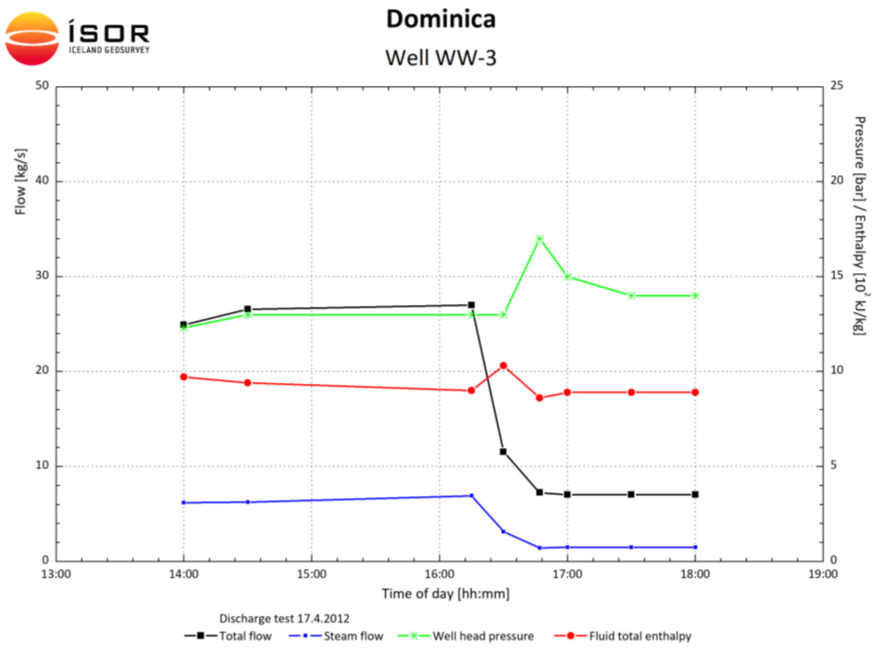

Figure 13. An overview of the results of a discharge test on well WW-03.

CONCLUSIONS

Exploratory drilling of three geothermal wells in the Roseau valley of Dominica turned out to be a successful and incident free venture. The drilling project proved the existence of the proposed geothermal resource in the Roseau valley and provided data on the lithology, chemistry and characteristics of the resource. The formation temperature of the geothermal reservoir in which the wells are drilled is ~235°C-270°C. Clay analysis seem to confirm the boundaries between the highly conductive clay-cap and the high-resistivity reservoir at slightly deeper level than earlier MT soundings had suggested. Alteration minerals like epidote are considered to have formed in thermal equilibrium and to represent the present thermal conditions of the resource. Environmental monitoring during the drilling activities showed that that drilling had no effect on the ground-water system in the Roseau valley.

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