PROCEEDINGS, Thirty-Ninth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 24-26, 2014
SGP-TR-202

Preliminary results of deep geothermal drilling and testing on the Island of Montserrat

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Keywords: Geothermal, Exploration, Montserrat, Caribbean, Soufriere hills, volcano, magnetotelluric geothermal reservoir, drilling, flow test results.

ABSTRACT

Montserrat is an active volcanic island in the Caribbean Lesser Antilles arc. Renewed eruptive activity from the Soufriere Hills volcano since 1995 destroyed the main town of Plymouth and left approximately a third of the island uninhabitable. As a result, such an active volcanic heat source suggests a great potential for geothermal electrical power generation, as is the case with many of the Caribbean islands. In 2009 at the request of the Government of Montserrat, EGS, Inc. completed a resource assessment of the island and developed a conceptual exploration model of the potential geothermal resource. Exploration work included geologic mapping, geophysical and geochemical surveys. Based on structural geology, geochemistry, magnetotelluric and time-domain EM data and microseismic interpretations, high priority areas were defined for exploratory drilling. Preferred sites were identified in a zone protected from potential hazards, mostly pyroclastic flows, within a faulted half-graben between St George’s and Garibaldi Hills where MT interpretations suggested an altered clay cap covered a potential hydrothermal system. Two successful wells were drilled in this faulted half graben in the central-southern part of the island during 2013. MON-1 encountered at least one fractured zone at 2191m and was drilled to a total depth of 2298m where static bottom hole temperatures of +230°C were measured. MON-2 was drilled approximately 500m northeast to a total depth of 2870m. Based on circulation losses, the well crossed several fracture zones and bottom hole temperatures of 260°C were recorded. A preliminary flow test of MON-1 indicates the well is capable of producing 92.5 thousand pounds per hour total mass flow and 32.5 thousand pounds per hour steam at wellhead temperatures of 145.2°C and 7.5 bars. Similar testing of MON-2 indicates the well is capable of producing 83.3 pounds per hour total mass flow and 28.65 thousand pounds per hour steam at 7.1 bars. Additional testing is planned to determine the nature and extent of the resource but the two wells appear each to be capable of supplying the current 2MW peak electrical load of the island

1. INTRODUCTION

Montserrat is an active volcanic island in the Caribbean Lesser Antilles arc and one of several Caribbean volcanic islands that have a potential for geothermal electrical power generation. The arc results from westward subduction of the Atlantic oceanic lithosphere beneath the Caribbean plate. Geothermal exploration programs are in various stages on the islands of Nevis, Saba, St Vincent and St Lucia and a 15MWe power plant has been installed in French island of Guadeloupe.

The Soufrière Hills volcanic complex includes a series of andesitic lava domes primarily associated with block-and-ash flow and surge deposits. The Soufrière Hills volcano became active in 1995 with ash eruptions, lava dome growth and pyroclastic flows forcing evacuation of the southern part of the island and eventually destroying the town of Plymouth, the island’s capitol and principal population center. The southern third of the island remains uninhabitable and exclusion zone restrictions preclude any exploration of the upper the flanks of the volcano and effectively limit access to potential exploration areas.

The Government of Montserrat (a British Overseas Territory) has recognized the potential for geothermal development on the island as a means to reduce the cost of electricity which in turn would lead to development of new island industries and possible re-settlement by those forced off the island by earlier eruptive activity. Funding for the geothermal project has been through the U.K. Department for International Development.

2. VOLCANIC AND STRUCTUTRAL SETTING

Montserrat is part of the northern section of the Lesser Antilles Island Arc in the eastern Caribbean (Figure 1). The arc was initiated in the Early Cretaceous and is considered the oldest active intraoceanic island arc systems in the world. The island of Montserrat measures 10 km east-west by 15 km north-south and is built on the south-central part of a submarine plateau that is ~100 m below sea level. The island was formed by a succession of andesitic eruptive centers ranging in age from the older Silver Hills (2,580 ± 60 ka and 1,160 ± 46 ka) and Centre Hills (954 +/- 12 and 550+/- 23 ka) (Harford et al., 2002) in the north to the currently active Soufrière and South Soufrière Hills in the southern half of the island (Figure 2).

EGS Inc. completed a geothermal exploration program in 2009 for the Government of Montserrat that included geologic mapping, geochemical sampling and magnetotelluric and time-domain EM surveys. The prominent NW striking Basse-Terre and Redonda regional fault systems dominate the tectonic framework of Montserrat (Figure 3) and are reflected in the distribution of microseismic events in the southern part of the island. Early geochemical surveys sampled the vigorous fumarolic fields in the upper elevations of the of Soufriere Hills volcano that were obliterated in the most recent phase of eruptive activity. (Chiodini, 1996) Widely distributed hot springs and fumaroles in the central and southern part of the island were still accessible and EGS and Thermochem Inc. (EGS/TCI) collected geochemical samples to verify earlier analytical results, evaluate any potential changes resulting the most recent eruptive activity and to refine exploration areas within the exclusion zone. Based on analytical results, geothermometry estimates of potential reservoir temperatures range from 241°C (N/K) to 212°C (Si) and 151°C (K_2/Mg) (Poux and Brophy 2012). Geochemical data suggested that the hot springs around the Plymouth area on the island's southwest coast were well-equilibrated surface manifestations of potential geothermal reservoir waters. (Poux and Brophy, 2012; Chiodini et al, 1996). Exploration also included MT/TDEM data acquisition within the limits of the no-occupancy zones on the southern portion of the island. Microseismic data interpretation and MT surveys were completed by IESE from the University of Auckland, New Zealand. Analysis and interpretation identified a broad zone of low resistivity interpreted as a clay cap related to intense alteration from steam condensate and hot water along the NW and NE trending fault zones that deform the southern section of the island. This low resistivity zone extends northward to include Garibaldi Hill and the southeastern part of Centre Hill.

EGS Inc. developed a conceptual model of the potential geothermal system from survey results and earlier studies and selected exploratory drilling sites. Garibaldi Hill and St George's Hill on the peripheral western lowland flank of the volcano (Figure 3) were selected as potential targets because they are within the area of springs and groundwater wells on the southern part of the island that are likely related to outflow from an active geothermal system (Poux and Brophy, 2012; Chiodini et al,1996), within a low-resistivity zone interpreted as the clay cap of a potential system and within an area of faulting related to major fault systems that deform the southern part of the island. In contrast, Harford et al. (2002) and recent exploration work (Poux et al, 2012) suggest that these prominent hills are a sequence of distal volcaniclastic rocks that were subsequently uplifted tectonically rather than erupted locally near their source. The NW strike of interpreted fault planes are consistent with the strike of the major Redonda fault system that deforms the southern part of Montserrat and is a potential permeability zone targeted for exploration drilling.

3. EXPLORATION DRILLING RESULTS

Specific drilling locations were restricted to areas considered lower risk for drilling operations. The Montserrat Volcanic Observatory (MVO) were consulted regarding well site locations since they are the agency primarily responsible for managing safety conditions associated with the on-going eruptive activity of the Soufriere Hills volcano. Fortunately the two well site locations selected were protected from potential block and ash flows by St George's Hill and clearance to occupy the two sites was granted by MVO. (Figure 4)

3.1 Well MON-1

MON-1 well was spudded on March 17th 2013 and drilled through a sequence of young andesite flows and breccias eventually bottoming in silicified sandstone at a total depth of 2298m. The andesite flows and breccias that are most likely related to the young Soufrière Hills volcanic complex extend to a depth of 530m. Breccia units may be partly related to the Garibaldi and St George's Hills particularly in the upper 100m of the wellbore but with cuttings alone, it is impossible to evaluate gross formation characteristics to determine source, sequence and how the units were emplaced. Units logged as breccia are based on interpretations of whatever fine matrix materials survived the mud circulation system. Breccia sections may represent debris avalanche deposits or block-and-ash flows typical of eruptive units exposed in road cuts and beach exposures that built most of the current island above sea level. Logged flow units vary from hornblende to pyroxene andesites and the mixed nature of some cuttings samples suggests emplacement as debris flows rather than uniform flow units.

A sequence of sandstones, mudstones and clays from 530-1210m represent a distinct lithologic change from volcanic flows and breccias to clastic sedimentary rocks in MON-1. Sandstone grains are angular to sub-angular, moderately sorted, and medium-grained and are usually broken crystals or lithic fragments derived from andesite flows implying the units were probably deposited on the flanks or offshore shelf of the island. Notable dolomite units were distinguished in thin sections of cuttings from 610m and 650m with distinct broken fossil fragments of corals and shells. The sedimentary sequence may represent a break between the younger Soufrière Hills volcano and the older Centre Hills and is likely the shore/reef sedimentary sequence that developed as the southern part of the island evolved.

Silicified tuff, breccias and sedimentary rocks from 1210m to total depth are the anticipated reservoir section in MON-1 and are interpreted as older Centre Hills volcanic units and sedimentary units deposited on the volcano's flanks. Thin section evaluations indicate that rocks logged as tuffs are actually sedimentary units of volcaniclastic materials reworked during deposition. Intercalated andesite or basalt lava flows occur occasionally but, based on thin sections, much of the potential geothermal reservoir is hosted within clastic sedimentary rocks composed primarily of reworked tuff and lithic fragments. Petrographic analysis of cuttings was completed by the Energy and Geoscience Institute at the University of Utah.

Circulation losses occurred at depths below 2165m in brittle silicified tuffs or volcaniclastic sandstones although losses were modest with maximum rates < 6 L/sec. Maximum bottom-hole static temperature was 230°C (8 days static after short flow). Relatively depressed shallow temperatures may be related to cold water influx since the well site is within ~ 1km of the coast. Low temperatures at shallow levels were difficult to overcome in attempting to flow the well and ~24,000 m^3 of cold water had been injected into the well at the total depth when the drill string could not be pulled out of the hole for 11 days because of rig problems. After several attempts to flow the well without assistance MON-1 was initiated with air assist from tubing placed at a 200m depth and the well produced intermittently for a total of 35 days.

Flow testing included:

- August 28th – September 9th 2013: Initial test after drilling and continual circulation losses from 2165m to TD. Brine flow rate ~7kg/sec at wellhead temperatures of 153°C.
- September 15th – 21st 2013: Flowing for wellbore clean up.
- September 23rd – October 11th 2013: Continual flow with daily readings of wellhead temperatures, pressures, James-tube lip pressure and weir level by Capuano Engineering.
- September 24th – September 30th 2013: Detailed flow testing by Thermochem Inc. including full data logging of all test parameters and geochemical sampling of steam and brine.

MON-1 was tested with the flowline valve fully open 3 different James-tube sizes (internal diameter):

- 3 inch – wellhead pressure 8 bara, stable flow rate 14 kg/sec
- 4 inch – wellhead pressure 7 bara, stable flow rate 17 kg/sec
- 6-inch – wellhead pressure 4 bara, stable flow rate 22 kg/sec

A brief attempt was made to throttle the well on October 27th but for the majority of the test, flow was controlled by the James-tube. The total fluid enthalpy measured at the surface stabilized to between 1075 and 1140 kJ/kg, equivalent to single-phase reservoir brine at 248 °C to 260 °C ("enthalpy temperature").

3.2 Well MON-2

MON-2 was spud on May 19th 2013 and drilled through a sequence of young andesite flows, breccias and clay-altered ash units eventually bottoming in silicified tuff or tuffaceous sandstone at a total depth of 2870m. Petrographic descriptions of cuttings are yet to be completed.

Circulation losses of 1-2 L/sec began in brittle silicified volcaniclastic units below 2100m and the entire lower portion of the hole was drilled with variable returns below 2348m and loss rates ranging from 1 to 4 L/sec. Maximum bottom-hole temperatures were 265°C (61 days static). Lower gradients in the shallow portion of the hole were similar to MON-1 and ~63,000 m^3 of cold water had been injected into the well at total depth when the drill string could not be pulled out of the hole for 35 days because of rig problems.

Flow from MON-2 was initiated with air assist from tubing placed at a 100m depth and the well produced intermittently for a total of 40 days. Flow testing included:

- November 13th 2013 – November 19th 2013: Initial flow to clean up and allow the wellbore to heat up after circulation losses from 2130m to TD and continual injection during rig repairs. Brine flow rate ~5.5kg/sec at wellhead pressures up to 5 bara.
- November 20th 2013 – December 23rd 2013: Flow with short shut in periods and daily readings of wellhead temperatures, pressures, James-tube lip pressure and weir level by Capuano Engineering.
    - December 6th 2013: Well killed with cold water to remove tubing and run a flowing pressure-temperature survey.
    - December 9th - 10th 2013: Shut in.
    - December 19th – 20th 2013: Shut in.

MON-2 was tested with 2 different James-tube sizes (internal diameter):

- 4 inch – wellhead pressure 5 bara, stabilized flow rate 12 kg/sec.
- 3 inch – wellhead pressure 6.5 - 7 bara, stabilized flow rate 11 kg/sec.

The total fluid enthalpy reached 1290 kJ/kg and enthalpy temperatures of 290°C during testing with the 4 inch James tube. Enthalpies reached 1190 kJ/kg while testing with the smaller diameter 3 inch James tube with an enthalpy temperature of 270°C. Measured surface enthalpy and downhole enthalpy were equivalent before and after killing the well on 12/6/2013 so the well was cooled by the kill operation but shortly attained an enthalpy temperature of 270 °C which is the maximum measured bottom-hole temperature for MON-2. The flowing pressure-temperature survey on 12/10/2013 measured flow zone temperatures 222 °C at an apparent flash depth ~ 1000 m consequently the bottom section of the well is probably not contributing to production.

The MON-1 and MON-2 temperature profiles suggest that both wells encountered outflow from the Soufriere Hills geothermal system. Short-term testing indicates that either of the wells is capable of producing enough fluid to sustain ~2MWe of generation although the initial flow test results are preliminary. More detailed temperature-pressure- spinner surveys have been proposed to determine which zones contribute most of the production in each well. Sustainable long-term geothermal system productivity requires a balance between well production capacity and strategic injection of the produced fluids. Solely considering power plant characteristics essentially ignores the geothermal reservoir that fuels the system therefore a comprehensive plan is required that considers surface production facilities and the geothermal reservoir.

4. PRELIMINARY RESRVOIR CHARACTERISTICS

Geochemical samples of production fluids, summarized in Table1, were collected during flow tests for MON-1 and MON-2 after the wellbore was flushed of drilling fluid and debris. Geochemical data suggest that the fluids produced from MON-1 and -2 may be the parent source for partially-equilibrated geothermal reservoir waters reaching the surface as high chloride hot springs near Plymouth on the western seacoast (Chiodini et al., 1996) The data presented in Table 2 summarizes the enthalpy, reservoir steam fraction, reservoir chloride content, and geothermometer temperatures for each well. It is important to note that MON-1 and MON-2 both produced excess steam, ranging from 3.8 to 5.9 % for MON-1 and 10.2 % for MON-2 however it was most likely generated as a result of production and near-wellbore boiling in the formation, rather than production from an evolved steam cap. Assuming that all fluid from the discharges for both wells originates as single-phase brine, the samples indicate reservoir chloride concentrations near that of seawater (19,350 ppm). The quartz (T-QTZ) and Na/K geothermometer temperatures for flash-corrected reservoir fluid range from 225 to 235°C (T-QTZ) and 222 to 224 °C (Na/K) and appear to reflect production temperatures, however the lower cation (NKCMg and K^2/Mg) temperatures may not be suitable due to fluid-rock interactions that may precipitate or dissolve calcium and magnesium.

The gas chemistry of the Montserrat well fluids is quite different from the volcanic fumaroles surveyed during early exploration (Chiodini, 1996). These compositions are compared in Table 2, with MON-1 and MON-2 discharge representing the well gases, which are quite similar. The fumaroles show a distinctly magmatic chemistry, with moderately high gas concentration, high proportion of H_2S and very low proportion of CH_4. Figure 7 is a CO_2/Ar – H_2/Ar geothermometer plot of the well discharges, with horizontal and vertical arrows showing the geothermometer temperature of liquid reservoir water based upon the H_2/Ar geothermometer and CO_2/Ar geothermometers, respectively. The indicated H_2/Ar geothermometer temperature of MON-1 well waters is around 230°C, close to the quartz and Na/K geothermometer temperatures, mentioned earlier. MON-2 shows a slightly higher H_2/Ar temperature at around 245°C. The CO_2/Ar geothermometer temperature of both wells is around 260°C. Similarly, the well discharges show H_2S geothermometer temperatures close to 220°C. Figure 8 shows a Y-T geothermometer grid of the Fischer-Tropsch reaction (FT) and H_2S geothermometer of Giggenbach (1997). The wells plot close to the Y = 0 grid line, which would be the composition of gas in single-phase liquid reservoir. H_2S geothermometer temperatures for single-phase liquid are indicated by dashed horizontal arrows which indicate a temperature for MON-1 of 210°C and 225°C for MON-2.

5. PRODUCTION WELL SCALING POTENTIAL

The program WATCH was used to evaluate calcite ($CaCO_3$) and anhydrite ($CaSO_4$) mineral saturations, which are common scale-forming minerals in geothermal production wells. Other potential scale-forming minerals, such as silicates and sulfides, were undersaturated, mass-limited by primary constituents in the brine or not kinetically prone to deposit at production conditions, so these were not considered further. Figures 9 and 10 are plots of the mineral saturation (Q/K) for calcite and anhydrite as a function of flash temperature and pressure for MON-1 and MON-2, respectively. A mineral saturation of Q/K = 1 indicates equilibrium (saturation), while any value greater than 1 indicates supersaturation of the mineral and favorable conditions for mineral precipitation and scale formation. If Q/K is less than 1, the mineral will not precipitate.

For the flash conditions modeled, anhydrite is slightly supersaturated for both wells under reservoir conditions (near wellbore), while calcite is undersaturated. At lower flash temperatures anhydrite becomes undersaturated (Q/K is less than 1) because it is more soluble at lower temperatures. The initial supersaturation of anhydrite could be the result of mixing incompatible fluids from different feed zones in the wellbore. Calcite is only slightly supersaturated at flash temperatures below about 120 °C for both wells. Calcite scaling is not expected to be a problem for the Montserrat wells. There could be some localized anhydrite scale forming in the wellbores, if the supersaturation observed is due to mixing of incompatible fluids from different feed zones.

6. CONCLUSIONS

The Montserrat exploration wells appear to have encountered an equilibrated geothermal system with commercially viable enthalpy and relatively benign fluid chemistry. The potential fracturing related to faults between St. George's Hill and Garibaldi Hill and the close correspondence of production at similar depths suggests the potential of a stratigraphically controlled reservoir with permeability related to the older volcanic and sedimentary foundation of the current island of Montserrat. The successful exploration wells provide the basis of future development close to the presently active Soufrière Hills volcano in a relatively safe portion of the island with respect to volcanic hazards. Long-term testing is planned to evaluate reservoir productivity and potential well interference and additional drilling is certainly a possibility to determine the nature and extent of the resource and provide reliable back-up wells for a viable system capable of supplying the current 2MW electrical load of the island.

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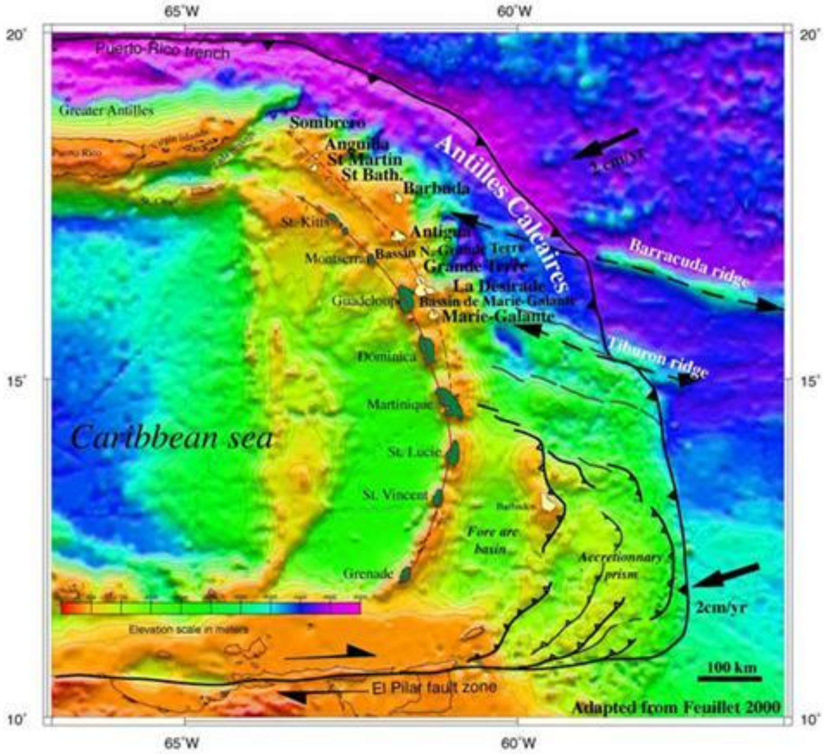

Figure 1: Tectonic Setting of the Caribbean

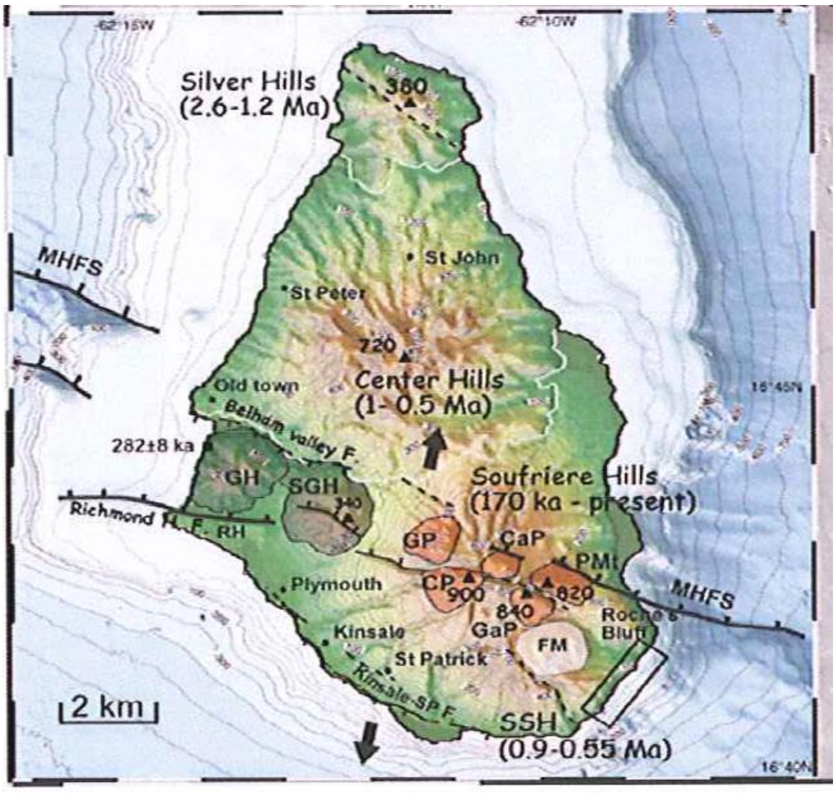

Figure 2: Montserrat Volcanic Setting (Feuillet et al, 2010)

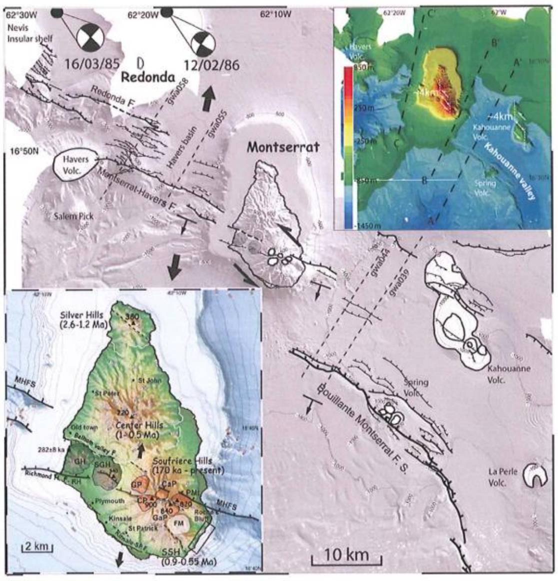

Figure 3: Seismotectonic Map of Montserrat (Feuillet et al, 2010)

Figure 4. MON-1, MON-2, spring and fumarole locations

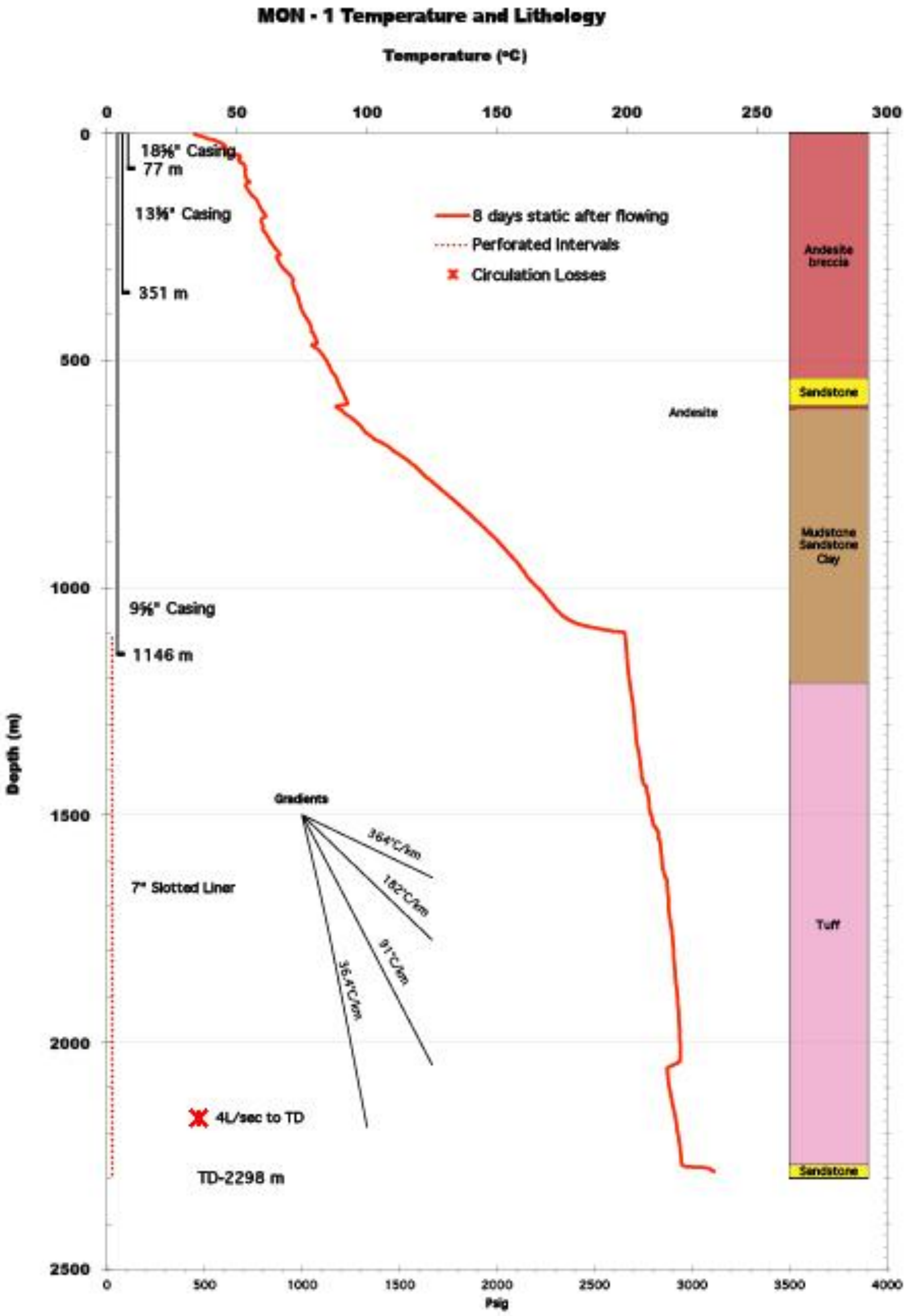

Figure 5. MON-1 Temperature and lithology plotdata compilation

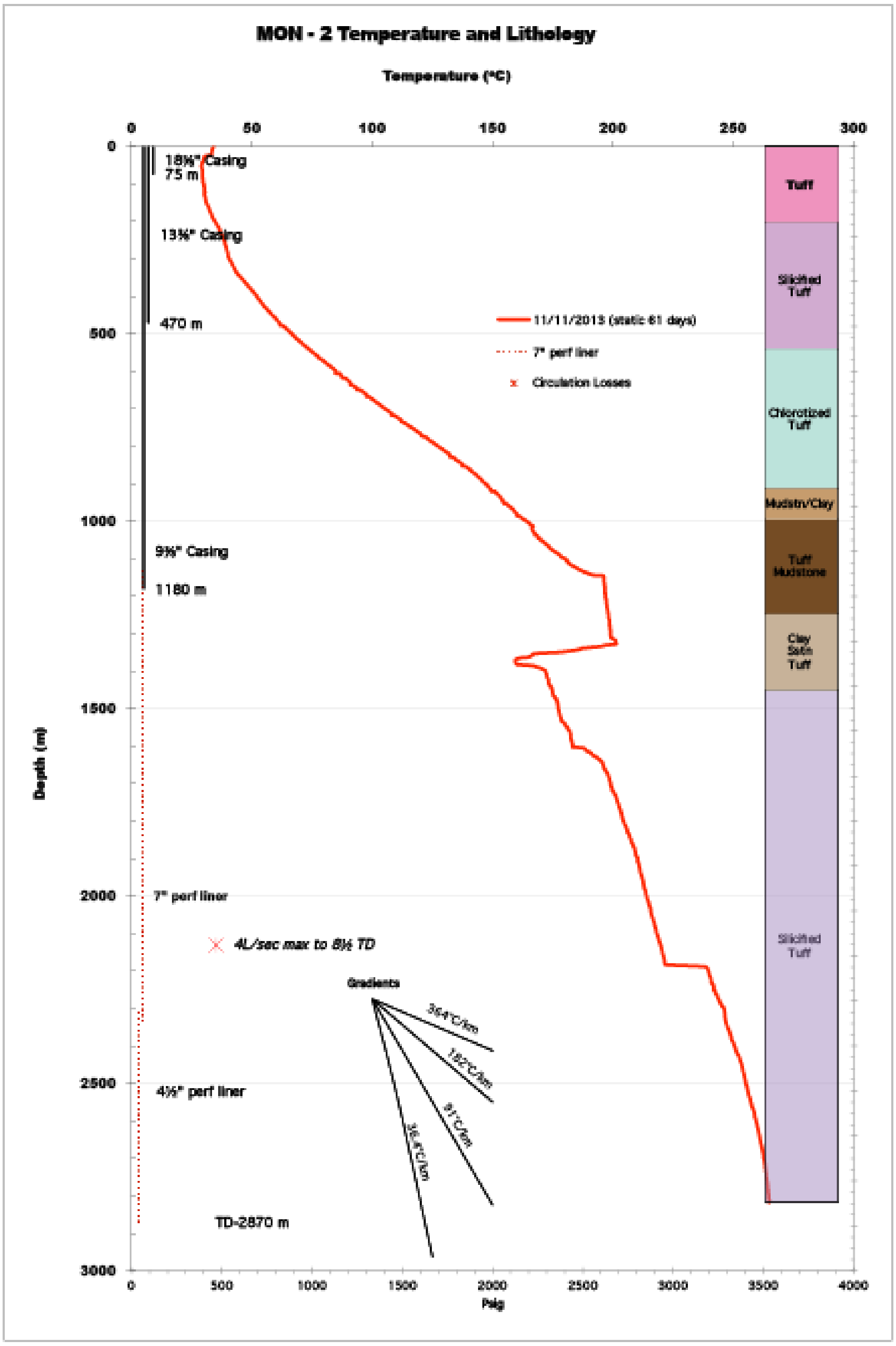

Figure 6. MON-2 Temperature and lithology plot

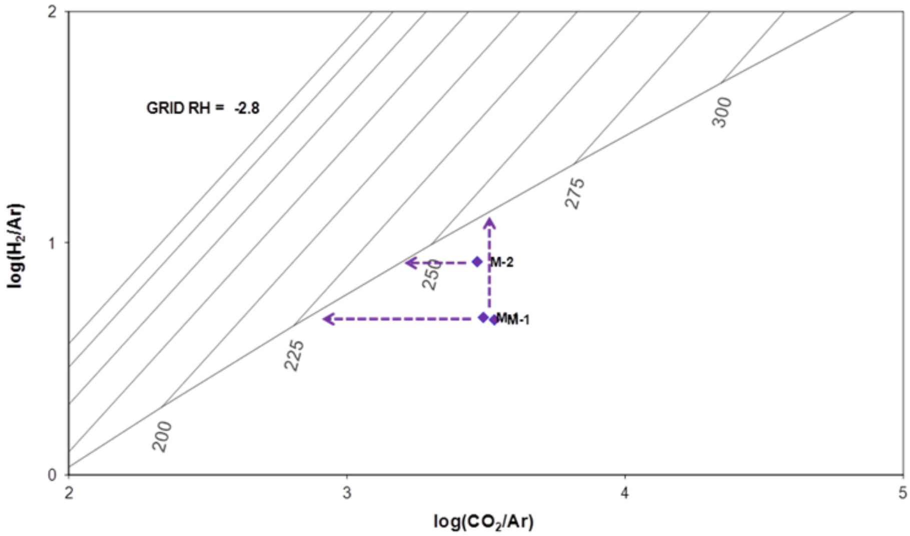

Figure 7. CO_2/Ar-H_2/Ar geothermometer plot of Montserrat well discharges. Horizontal arrows indicate apparent H_2/Ar geothermometer temperature and vertical arrow shows CO_2/Ar temperature.

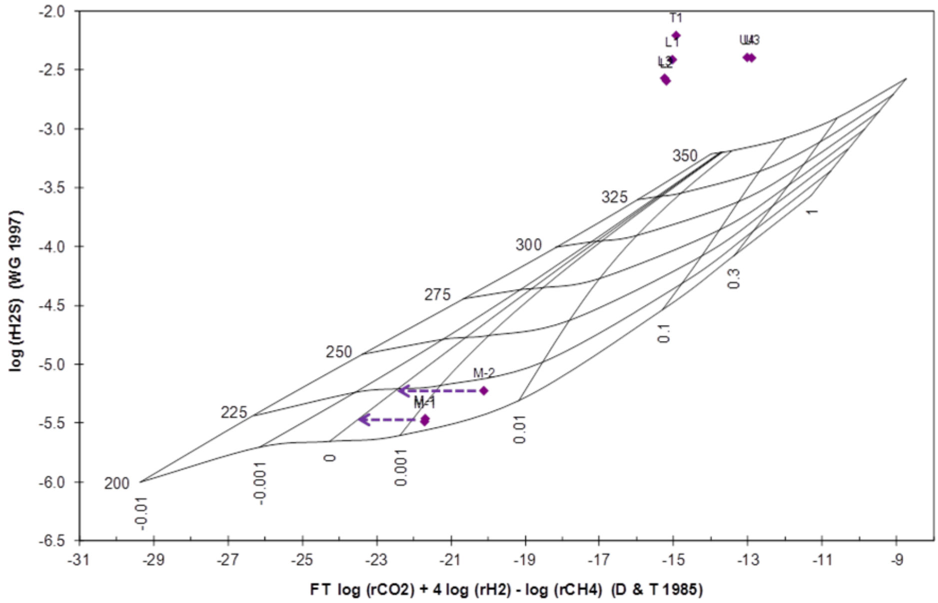

Figure 8. Fischer-Tropsch – H2S Y-T geothermometer grid with Montserrat well discharge gases. The well discharges plot at H_2S temperatures of 210 - 225°C (dashed arrow to Y=0 grid line), close to reservoir temperature indicated by liquid geothermometers and wellbore modeling. A few of the fumarole gases are also plotted on this grid and plot off the grid at very high apparent H_2S temperature.

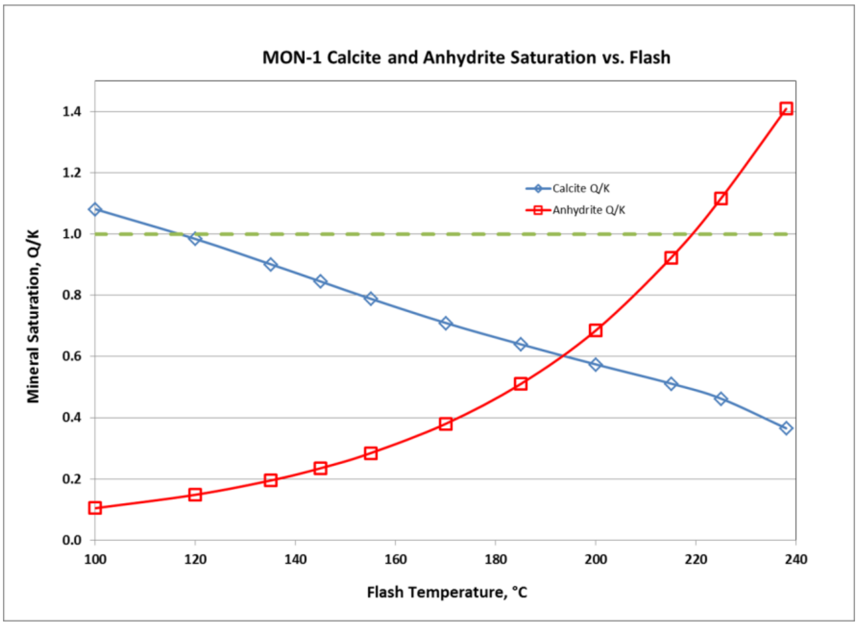

Figure 9. MON-1 Calcite and Anhydrite Saturation

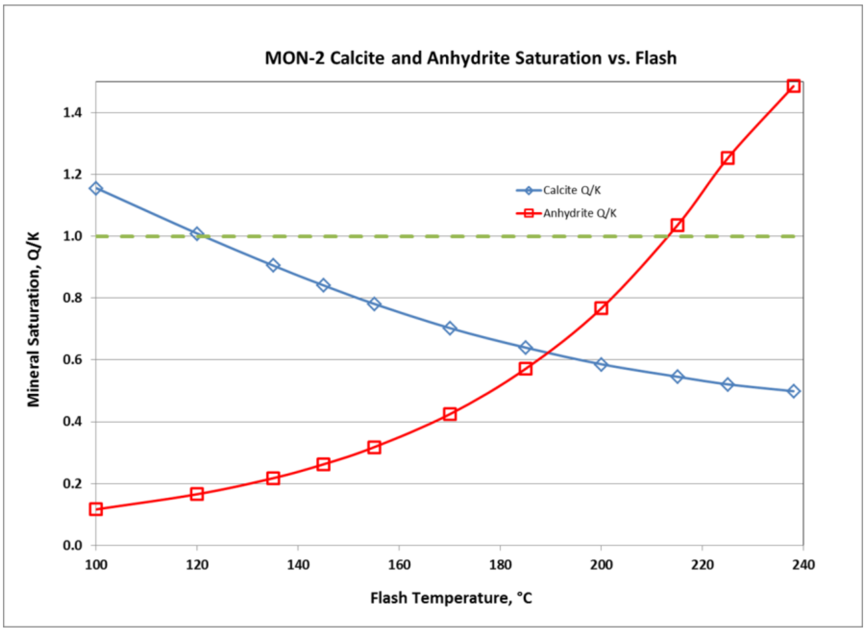

Figure 10. MON-2 Calcite and Anhydrite Saturation

Water	Na ppm	K ppm	Ca ppm	Mg ppm	B ppm	SiO_2 ppm	Cl ppm	SO_4 ppm	Sr ppm	As ppm
MON-1	8660	761	3757	10	16	383	20557	23	47	1.8
MON-2	7950	703	3370	8.1	14	355	19080	18	45	1.6
Seawater	10500	390	410	1350	4.5	6.4	19350	2700	8.0	0.003

Table 1: MON-1 and MON-2 brine chemistry corrected to reservoir conditions compared to seawater.

Well	Date	Enthalpy kJ/kg	Excess Steam Fraction	Res Cl ppm	T-QTZ Fournier & Potter	T-NKCM Fournier & Truesdell	T-K^2/Mg Giggenbach (1986)	Na/K Giggenbach (1988)
MON-1	27/10/13	1096	3.8%	20982	235	199	200	224
MON-1	27/10/13	1096	4.5%	20790	231	198	197	223
MON-1	29/10/13	1125	5.8%	20679	231	198	197	223
MON-1	29/10/13	1125	5.9%	20557	231	198	199	222
MON-2	18/12/13	1192	10.1%	19079	225	198	199	223

Table 2. Selected well test parameters and calculated reservoir geochemistry, with geothermometer temperatures in °C.

Sample	Total Gas wt%	Mole% of dry gas						
		CO_2	H_2S	NH3	Ar	N_2	CH_4	H_2
Fumarole maximum	90	92	56	-	-	1.0	0.62	0.57
Fumarole median	12	77	21	-	-	0.55	0.15	0.11
Fumarole minimum	7.6	42	6.9	-	-	0.41	0.02	0.004
MON-1 (gas in total discharge)	0.33	90	0.24	0.28	0.03	4.2	5.5	0.14
MON-2 (gas in total discharge)	0.43	88	0.32	0.48	0.03	4.5	6.0	0.25

Table 3. . Montserrat fumarole data (Chiodini 1996) MON-1, MON-2 gas geochemistry.