

GEOOTHERMOMETRY AND SHALLOW CIRCULATION OF A LOW ENTHALPY SYSTEM: THE BATH GEOTHERMAL RESERVOIR, JAMAICA

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ABSTRACT

Geothermometry was applied to the thermal fluid discharges from fractures at the Bath hot springs to estimate the temperature of the geothermal reservoir expected to be encountered by drilling. Bath is situated in Jamaica's most seismically-active region. Na-K geothermometers estimate reservoir temperatures at 83°C-102°C compared to geotemperatures of 80°C-83°C estimated from silica geothermometers. The $\delta^2\text{H}$ - $\delta^{18}\text{O}$ relationship of surface discharge temperatures indicate shallow mixing and the influence of saline geothermal source. The depth to circulation is estimated to be between 1 – 1.8 km. SiO_2/Cl and B/Cl relationships suggest the existence of a low enthalpy geothermal system. A comparative interpretation of the results of thermal discharges from springs of central Jamaica shows Bath has the greatest geothermal potential and warrants hydrogeophysical exploration to target the region for shallow well drilling and geothermal energy generation. The total stored heat (E) is 1.54×10^{15} J with a determined reservoir thickness of 0.4 km, an area of 3 km², and 25 years of production. The total reserve in the Bath geothermal system is 33.83 MW_e with a power capacity per km² of 13.54 MW. A hydrogeological conceptual model for the geothermal reservoir is proposed based on hydrogeochemical, geological, structural, and isotopic data.

INTRODUCTION

Chemical geothermometry is an invaluable tool used for the evaluation of geothermal potential and geothermal exploration. Geothermometers are based on the several assumptions: 1) specific temperature-dependent mineral-solution equilibria are attained in the geothermal reservoir between water and host rocks as water is saturated by the mineral phases governing the geothermometer; 2) the waters neither re-equilibrate nor mix with shallow circulating fluids during their ascent towards the surface; 3) the amount of conductive heat loss of ascending geothermal waters is proportional to the distance travelled and inversely proportional to the flow rate; and

geothermometers relate to specific mineral-solute reactions as the hot equilibrium temperature is stored in the fluid and reflects the chemical signature of solute concentration (solute ratios). Fluid composition in many geothermal fields worldwide appear to closely approach chemical equilibrium with secondary minerals for all major aqueous components except chloride and boron which are conservative elements (Giggenbach, 1980; Giggenbach, 1981, Arnórsson et al. 1983). The objectives of this hydrogeochemical investigation are to estimate the geotemperatures and the depth to the Bath geothermal reservoir.

GEOLOGY

Regional Tectonic Setting

The Caribbean island of Jamaica is situated within a geologically young and seismically-active fault zone which evolved at the boundary separating the North American Plate and the Caribbean Plate during the Miocene Epoch 23 million years ago (Figure 1a). Geochemical and paleomagnetic evidence suggests the Caribbean Plate is the remnant of two separate Cretaceous oceanic plateaus (terranes) that migrated northeastward on the Farallon Plate along major strike-slip faults into Caribbean basin between North and South America (Kerr and Tarney, 2005). The largest zone of Cretaceous rocks are in Blue Mountain Inlier (BMI) of eastern Jamaica, a region of rugged topography and ongoing neotectonic uplift (Figure 1b). The Blue Mountain Inlier lies on the Blue Mountain Block which is the smaller of two terranes. The other terrane contains the Clarendon and Hanover Blocks shown in Figure 1b-c (Lewis et al. 1990). Evidence of the uplift of oceanic lithosphere are the ultramafic rocks (part of a dismembered Late Cretaceous ophiolite suite) that span an area of approximately 2 km² and adjoin other strata in the Blue Mountain Inlier (Wadge et al. 1982, Hastie et al. 2008). These ultramafic rocks are primarily dunite with unaltered olivine, orthopyroxene, clinopyroxene and chromite. The tectonic and geologic settings of the Blue Mountain Inlier are extremely complex.

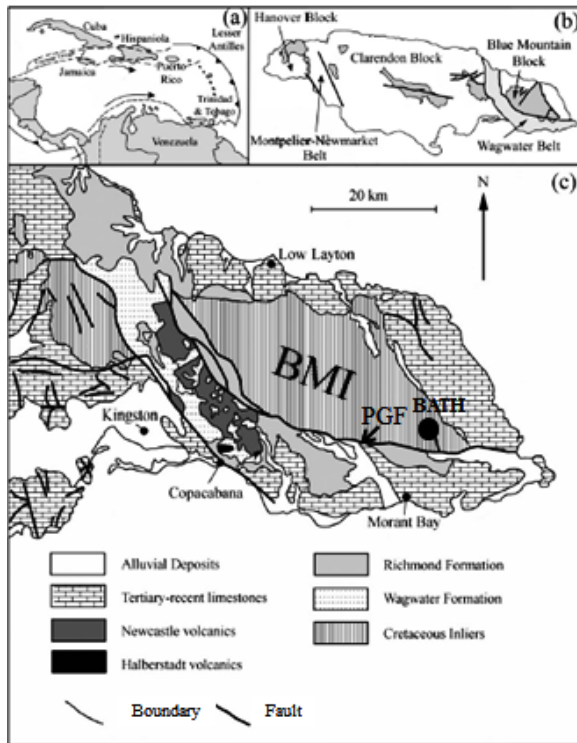


Figure 1:(a) Map of the Caribbean region, (b) Map of volcano-sedimentary Cretaceous inliers and the two terranes of Jamaica, and (c) Geologic map of eastern Jamaica showing the Plantain Garden fault (PGF) that borders the Blue Mountain Inlier (BMI) and the location of the Bath springs (modified from Hastie et al. 2011).

Geologic Setting of Study Region

The Bath hot springs emerge from the Bath Dunrobin Formation, a Late Cretaceous suite of massive tholeiitic basalts intercalated with tuffs and overlain by a sedimentary succession of thick deep marine shales (Hastie et al. 2008; Hastie et al. 2010). The lavas extruded between two fault-bounded blocks within a 2–3 km-wide fault zone on the southern side of the Blue Mountain Inlier and to the north of the left lateral strike slip Plantain Garden Fault (PGF)-a prominent structural feature (Figure 1c). The fault-bounded blocks occupy an area of ~11 km² around Bath (Wadge et al. 1982). The Plantain Garden fault borders the Plantain Garden River and extends across the Caribbean Sea to the Enriquillo–Plantain Garden Fault Zone (EPGFZ) that transects Haiti and the Dominican Republic (Hispaniola).

Springs

Several hot springs and cold springs emerge from fissures and fractures in the rugged terrain of the Blue Mountain Inlier that extends across the parishes of St. Thomas (Bath Springs) and Portland (Guava River

springs). Guava River is a tributary of the Plantain Garden River with hot springs at 52–53°C ascending from numerous fissures in quartz porphyry and tonalite rocks along its valley. The more easily accessible hot springs located at Bath and are used for Balnesian therapy and serve as a tourist attraction. Bath springs are situated 3 km north of the town of Bath and 200 m from the Bath Fountain Hotel and Spa (BFHS). Geothermal activity at Bath is manifested as hot boiling and sulfurous springs that ascend from fissures within tens of meters of each other at a height of 9m above the east side of the Sulfur River gorge (Hylton, 1987). These hot springs are assumed to be in contact with a single, shallow geothermal source. The fissure or outlet with the highest temperature is considered the most representative sample with the least amount of mixing and shallow ground water (Allen et al. 2006). The largest cold spring surfaces flows from permeable rocks at 200 m south of the hot springs and 18 m above the gorge. For the purposes of this hydrogeochemical study, the chemical signatures of the Bath springs (BTHS, BTHN, and BTHC) are compared with two other thermals springs: Milk River spring (MKR) and Windsor spring (WS) in south central and north central Jamaica. Faults appear to exert structural control and localize the shallow upwelling of thermal fluids in the case of all the springs mentioned in this study.

Hydrothermal Alteration

Zones of hydrothermal alteration resulting from fluid-rock interaction lie in close proximity to prospective geothermal sources. The stability of secondary minerals formed from hydrothermal alteration is dependent on temperature, pressure, lithology, and fluid composition (Harvey and Browne, 1991). At Bath, the Cretaceous tholeiitic volcanic-arc series dominated by intermediate acid lavas and a calc-alkaline series dominated by basic lavas (Hastie et al. 2008) have undergone variations in hydrothermal alteration from tropical weathering. Element mobility (e.g. potassium and barium) was accelerated by both hydrothermal and metamorphic processes (Hastie et al. 2008). Readily mobilized elements include Ca, Mg, Na, K, Rb, Ba, Sr, Pb (Hastie et al. 2008).

METHODOLOGY

Water Sampling and Analyses

All physiochemical parameters (temperature, pH, conductivity (EC), total dissolved solids (TDS), oxidation reduction potential (Eh), dissolved oxygen and DO) were measured *in situ* using electrical

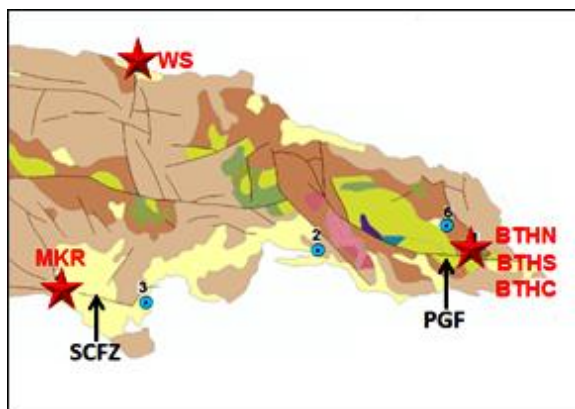


Figure 2: Map of sampling sites (BTHN, BTHS, BTHC, MKR and WS) and major faults PGF and the South Coast Fault Zone SCFZ).

meters at field sites. Thermal and cold water samples for hydrogeochemical analysis were collected in 250 ml high density polyethylene (HDPE) bottles with 1:1 nitric acid (HNO_3) preservative enclosed to prevent bioalteration. Pre-cleaned HDPE bottles of un-acidified water samples were collected for anion determination and stable isotope ($\delta^2\text{H}$, $\delta^3\text{H}$ and $\delta^{18}\text{O}$) analysis. A total of 35 chemical parameters were determined including major ions (Ca, Mg, Na, K, HCO_3^- , SO_4 , Cl^-), trace metals (Li, Al, Ag, As, B, Cd, Cs, Cu, Fe, Mn, Pb, Si, Sr, Rb, Zn, Br^- , F^- , HS^- , CO_3 , NO_2 , NO_3 , SiO_2 , PO_4 , and isotopes (Ra^{226} , O^{16} , O^{18} , deuterium ($\delta^2\text{H}$), and tritium (^3H)). The samples were filtered using a 0.45 μm cellulose membrane filter. Chemical analyses for cations and anions were carried out by Summit Environmental Technologies (USA) and the Mines and Geology Division (MGD) Analytical Laboratory of Jamaica. Cation analyses were performed using inductively coupled plasma-mass spectroscopy (ICP-MS), the trace-ICP method and flame absorption spectroscopy (FAAS). Isotopic analyses of hydrogen ($\delta^2\text{H}$), (^3H), and oxygen ($\delta^{18}\text{O}$) values were analyzed by stable isotope mass spectrometry at ISOTECH Laboratories in Illinois.

RESULTS AND DISCUSSION

The temperatures of thermal water discharges ranged 36.4°C-51.3°C; TDS = 588-35000 mg/L; EC = 840 – 50000 $\mu\text{S}/\text{cm}$; pH = 7.13-8.82; and Eh = -75 to 99 mV. The parameters of the only cold water sample were T = 29.1°C; TDS = 385 mg/l; EC = 550 $\mu\text{S}/\text{cm}$; pH = 8.27; and Eh = 137. The thermal waters all have low dissolved oxygen concentrations.

Hydrogeochemical Modeling

The Schoeller diagram in Figure 3 shows the most important constituents of the samples BTHN, BTHS,

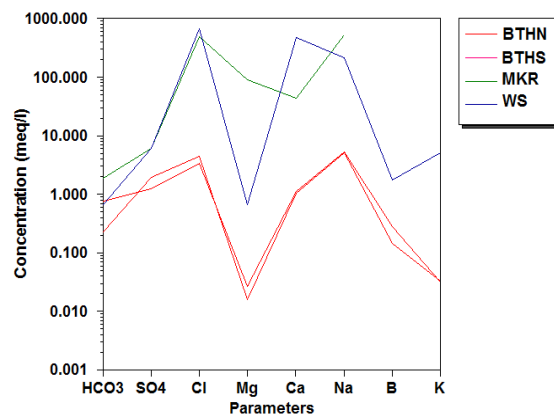


Figure 3: Schoeller diagram for the most important constituents in the thermal waters of BTHN, BTHS, MKR and WS.

MKR, WS and BTHC as the slopes of the lines between the constituents represent the concentration ratios. Three thermal water types were classified for the thermal waters: Na-Cl- SO_4 type (BTHN and BTHS) with alkaline pH (8.76-8.82); Na-Cl type (MKR), and Ca-Na-Cl type (WS) each with closer to neutral pH. BTHS, BTHN and WS have negative ORP values (Eh = -99 to -75 mV). These values were probably lowered by loss of oxygen during the convection of fluids and are representative of reducing conditions at depth. Negative Eh values are associated with H_2S dissolved in spring waters from the bacterial reduction of H_2S . They may also have formed at depth by the oxidation of sulfide (in H_2S) present in alkali chloride waters that form bisulfate (HSO_4) due to the buffer action and neutralization of the wall rocks (Ellis and Mahon, 1977). The cold water sample BTHC is Ca-Mg-Na- HCO_3 type.

The relative contents of Cl, SO_4 , and HCO_3 in the BTHN and BTHS waters plot in the “volcanic waters” field whereas MKR and WS are classified as “mature waters” (Figure 4). MKR and WS are enriched in Na and Cl and have extremely high EC values (15,540 – 35,000 $\mu\text{S}/\text{cm}$) indicative of influence by seawater intermixing with thermal fluids. The enrichment of Cl and SO_4 in groundwater is generally due to mixing of seawater or dissolution of evaporite minerals deposited in a marine environment. Boron, chloride and lithium are tracers for fluids from geothermal sources. Boron may be leached from the wall rocks and lithium indicates a the migration of thermal fluids from deeper geothermal sources. BTHN, BTHS, MKR and WS all plot in the low B/Cl region of the Cl-Li-B ternary plot and suggest these thermal waters emerge from aging hydrothermal systems (Figure 5).

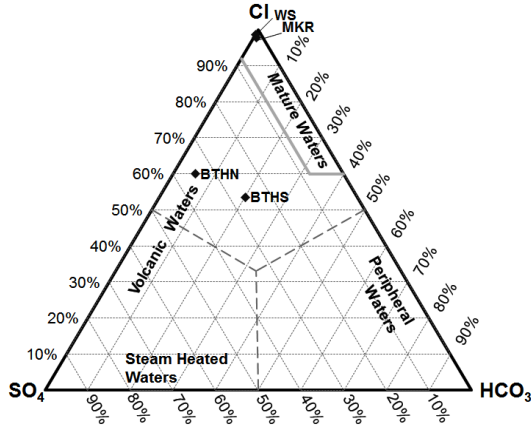


Figure 4: Cl-SO₄-HCO₃ ternary plot of thermal waters (Giggenbach and Goguel, 1989).

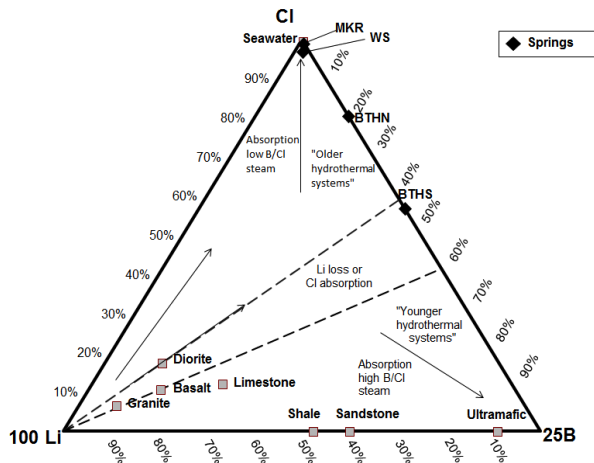


Figure 5: Cl-Li-B ternary plot of thermal waters. (Giggenbach, 1991a)

Isotopic Analysis

The hydrogeochemical and isotopic characteristics of the thermal fluids may be impacted by interaction between fluids and wall rocks along the flow path and during ascent through fissures; dissolution, oxidation-reduction, sulfate reduction, and high temperatures and pH. The equilibration between a migrating fluid and the mineral assemblages in a rock is also temperature-dependent. Isotopic data of the waters were compared with the Global Meteoritic Water Line (GMWL) developed by (Craig, 1961) and expressed by the equation:

$$\delta^2H = 8 \delta^{18}O + 10\text{‰} \quad (1)$$

Figure 6 shows the results of the $\delta^{18}O$ vs. δ^2H analysis. BTHN and BTHS plot fairly close and above the GWML. This slight deviation or shift in $\delta^{18}O$ values may be the result of the impact of

meteoritic recharge. The general decrease in the $^{18}O/^{16}O$ ratio of BTHS is probably due to the CO₂

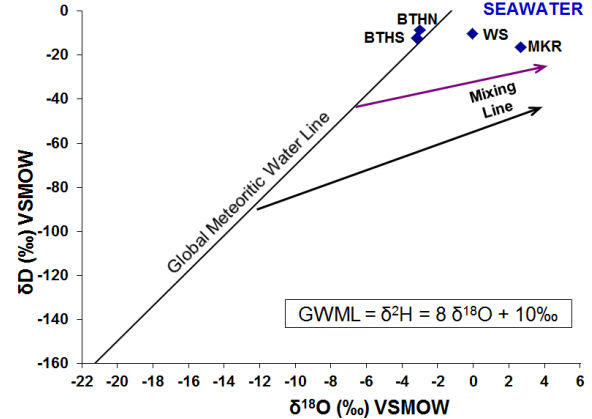


Figure 6: Plot of $\delta^{18}O$ versus δ^2H for thermal waters.

loss during the ascent of circulating waters towards the surface. The tritium (3H) concentrations of BTHS and BTHN are <1.0 tritium unit (TU) and are indicative of deep and long residence time (slow circulation). The seasonal variation and short half-life ($t^{0.5}$) of the tritium (H^3) = 12.46 years) makes it very suitable for the identification of recent water discharges. Age estimation of groundwater using tritium (H^3) provides only semi-quantitative values as tritium concentrations in groundwater reflect atmospheric tritium levels when water was last in contact with the atmosphere. The thermal character of the BTHN and BTHS samples are indicative of minimal mixing of some meteoritic recharge or shallow waters deep circulating waters ≥ 50 years. The MKR and WS samples plot extremely in the seawater region of the diagram ($\delta^{18}O$ enrichment). These samples have high TDS, Cl, Mg, and SO₄ suggesting intense mixing resulting in the circulation of deep, briny fluids. The d-excess values of isotopic analyses are used to determine the source area for waters. The deuterium-excess (*d*-excess) values in Table 1 were compared with the global range of *d*-excess values. The global average for *d*-excess is 10‰. Vengosh et al. (2000) has suggested that low *d*-excess values $\sim 10\text{‰}$ indicates older recharge whereas *d*-excess values $>20\text{‰}$ indicate modern recharge. The isotopic composition BTHS has a *d*-excesses in the range of 10.5‰ confirming the contribution of meteoritic recharge and mixing with saline water.

Table 1: Isotopic data for thermal springs.

Spring	$\delta^{18}O$ ‰	δ^2H ‰	δ^3H (TU)	Ra ²²⁶ (pci/L)	<i>d</i> - Excess
BTHS	-3.15	-12.1	<1.0	1.09	10.5
MKR	0.6	2.7	-	-	4.98
WS	-0.03	-10.3	-	2.63	-2.18

Saturation Indices

The calculation of saturation indices are based on minerals presumed to dissolve or precipitate with respect to wall rock-water interaction. The saturation indices of the water samples were calculated for minerals assumed to be relevant like calcite, dolomite, gypsum, anhydrite, fluorite, hematite, goethite, talc, amorphous silica, chalcedony, quartz, albite-low for all water samples using the United States Geological Survey's PHREEQC package (Parkhurst and Appelo, 1999) interfaced with the AquaChem model. The saturation indices or equilibrium between the fluid saturation and the hydrothermal minerals in the reservoir may be determined from the saturation index (SI) defined by the Equation (2) below,

$$SI = \text{Log} \frac{IAP}{K_T} \quad (2)$$

where, SI is the saturation index, IAP is the product of the ionic activity of the ions, and K_T is the equilibrium constant of the mineral at the discharge temperature of the sample.

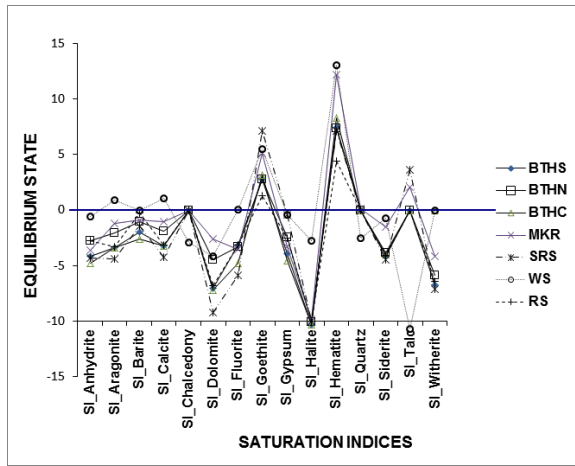


Figure 7: Saturation indices for minerals in the study area.

The BTHN and BTHS samples are generally oversaturated with respect to hematite, goethite and talc and may precipitate; but are undersaturated with respect to calcite, dolomite, anhydrite, and gypsum and suggest the continued dissolution of these minerals. The precipitation of hematite and goethite results from the hydrothermal alteration of the basalts.

Geothermometry

The estimated reservoir temperatures predicted from various solute and silica geothermometers are shown

in Table 1. Na-K and Na-K-Ca solute geothermometers assume the attainment of chemical equilibrium between fluid-rock reactions in geothermal systems. Fluid-rock reactions, mixing, and degassing during ascent due to lack of equilibrium between the solution may yield a variation of estimated reservoir temperatures when different geothermometers are applied to the same fluid.

The highest Na-K geotemperatures were predicted by the geothermometer developed by Giggenbach (1988) and Can (2002) (Table 2). Na-K geothermometers estimated temperatures ranges of 87-114°C. A fairly good agreement exists for temperatures predicted by both Na-K and silica geothermometers for BTHN and BTHS given $\pm 20^\circ\text{C}$. The silica geothermometers appeared to underestimate the temperatures of MKR and WS. This was probably because the silica geothermometers indicate the supply water temperature for the reservoir whereas the Na-K geothermometers excluding Truesdell (1977) indicate deeper and hotter systems.

The geotemperatures estimated by the K-Mg geothermometer were too low to be plausible.

Table 2: Temperatures estimated from solute and silica geothermometers

Geothermometer	BTHN	BTHS	MKR	WS
Discharge T°C	49.7	51.3	36.4	34.7
Na-K ^a	93	97	189	149
Na-K ^b	89	107	195	157
Na-K ^c	114	118	206	168
Na-K ^d	87	104	193	155
Na-K ^e	102	112	179	146
Na-K ^f	48	44	153	106
K-Mg ^c	71	71	123	157
Na-K-Ca ^g	43	48	206	167
Quartz ^h	81	80	35	61
Quartz ^h	84	83	45	67

a (Fournier, 1979); b (Anorsson et al. 1983); c (Giggenbach, 1988); d (Verma & Santoya, 1997); e (Can 2002); f (Truesdell, 1977); g (Fournier & Truesdell), and h (Fournier, 1977).

The Na-K-Mg ternary diagram (Giggenbach, 1988) in Figure 8 is based on the temperature dependence of the full equilibrium assemblage of K and Na minerals before the fluid reaches the surface. BTHS and BTHS are partially equilibrated whereas MKR and WS are closer to full equilibrium as mature waters. Partially equilibrated means there is dilution rather than dissolution. If excessive dilution existed the sample would plot in the immature field making the results of Na-K geothermometers uncertain. Low

Cl-SO₄ concentrations (Giggenbach, 1983) in the BTHS and BTHN samples further confirm a partially-equilibrated geothermal water system in the Bath-Dunrobin volcanics.

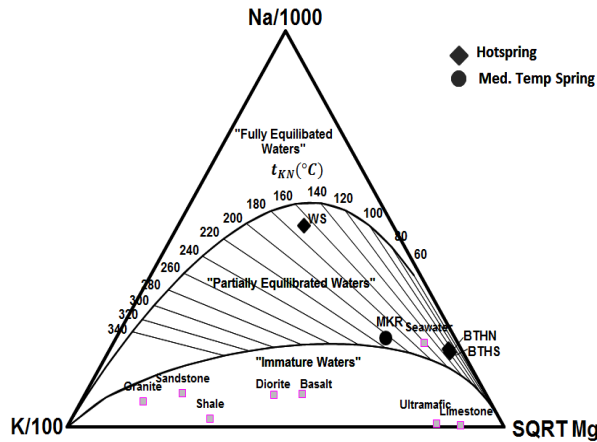


Figure 8: Graphical evaluation of water-rock equilibrium temperatures for thermal springs using Na-K-Mg concentrations in mg/kg (Giggenbach, 1988).

Boron-Chloride and Quartz Enthalpy

For the purposes of this paper, the division between low and high enthalpy is set at 180°C. Low enthalpy fluids are harnessed for direct use of heat at <120 °C and binary cycles at 107-180°C. The Cl-B relationship between enthalpy of fluids in separate geothermal systems is shown in Figure 9. The quartz-enthalpy for all in Figure 10 demonstrates the Bath geothermal system is also a low enthalpy system. These results are based on emergence temperature in the case of BTHN and BTHS are lower due to dilution and conduction during ascent to the surface. The estimated temperatures and the results above indicate that these are low enthalpy systems.

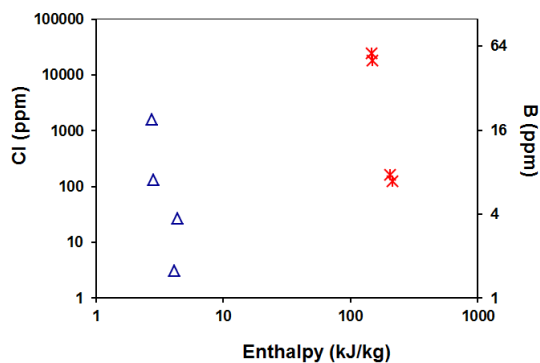


Figure 9: Chloride and boron-chloride as functions of enthalpy for thermal waters.

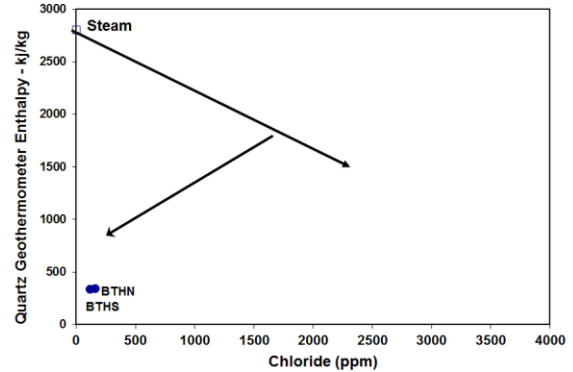


Figure 10: Quartz Geothermometer enthalpy vs. chloride in thermal waters (Truesdell and Fournier, 1977)

Estimation of Depth to Geothermal Reservoir

The measured discharge temperatures of the water samples were assumed to relate to the temperature of the subsurface. The equilibrium temperature for each spring and the regional geothermal gradient are the two parameters required to estimate the depth to which the thermal spring waters circulate. Complex geothermal gradients may develop in response to deep circulation systems as based on models by Lopez and Smith (1995; 1996), depth integrated gradients vary purely from conductive heat flow by up to approximately 20%. However, borehole data are not yet available for the field sites. The approach taken was to use equilibrated geotemperatures with average geothermal gradient of the Caribbean region at 25°C/km - 30°C/km (Haraksingh and Koon Koon, 2011) and make the assumption that it is representative of the eastern region of the island.

There are also a variety of geothermometers which result in a range of temperatures for each spring. Caution was exercised to apply geothermometers which tend to minimize depth estimates. It is presumed regional conductive geothermal gradient representative within a 20% error and the reservoir depths may be estimated with these limitations borne in mind. The estimated depths of circulation for the thermal samples are: BTHS/BTHN = 1-1.8 km at 80°C - 102 °C; MKR= 4-6 km at 158°C - 206°C and 3.3-4.8 km for WWS at 128°C - 156°C. Of a particular note, these results are minimal estimates and do not preclude the possibility of deeper circulation systems. An important limitation of applying this assumption is the mantle is at a higher elevation in eastern Jamaica compared the thick limestone sediments that overlie the volcanic basement of central Jamaica. A positive Bouguer anomaly can (1) represent very dense oceanic lithosphere or (2) hot rising mantle. If a magmatic intrusion lies shallow within the crust under the Bath

region this may explain ascent of lower density heated water (BTHS and BTHN) at a lower elevation than the surrounding cold groundwater (BTHC) along permeable fractures associated with an existing along the ENE-SW trending fault. Calculated temperatures may be lowered as re-equilibration occurs along the flow path and dilution occurs due to near surface mixing possibly resulting in a minimum estimate of the highest temperature reached in the system (Grasby and Hutcheon, 2001).

Evaluation of the Bath Geothermal System

The volumetric assessment of “stored heat” contained in the subsurface rocks and fluids of a geothermal reservoir may be calculated given the assumption that hydrothermal reservoir is homogenous and closed (no recharge is occurring) (Hochstein, 1975). A rough estimate of the thermal energy in the subsurface is calculated using Equation (3) as follows:

$$E = E_t + E_w = VC_r\rho_r(1 - \phi)(T_i - T_0) + VC_w\rho_w(1 - \phi)(T_i - T_0) \quad (3)$$

where,

- E = Total energy (stored heat in the system), rock and fluid (kJ);
- V = Reservoir volume (m³)
- T_i = Temperature of the aquifer (°C)
- T_o = Reference temperature (°C)
- C_r = Rock specific heat capacity (kJ/ kg°C)
- C_w = Specific heat of water (kJ/ kg°C)
- p_{r, f} = Density of rock and fluid (kg/m³)
- p_w = Steam and water density (kg/m³)
- Ø = Rock porosity
- hf_w = Steam and water enthalpy (kJ/kg).

The following assumptions were made for to determine a rough estimate of potential thermal energy of the Bath, St. Thomas hydrothermal system:

A = 1 km²; V = 5 x 10⁵ m³; T_i = 80°C; T_o = 15°C (discharge temperature at ground surface); p_r = 2,641 kg/km³; p_{w51.3°C} = 971.2 kg/m³; hf_{80°C} = 334.96 (kJ/kg); hf_{51.3°C} = 214.76 (kJ/kg) (Zarrouk and Watson), 2001; Ø = 0.06; C_r = 0.804 kJ/kg°C; C_w = 4.184 kJ/kg°C (at 80°C all the water is liquid); ΔT/ΔZ = 30°C/km; thickness = 400 m; therefore the assumed temperature gradient is 30°C x (300/1000) = 12°C. The temperature difference ΔT = (80 - 51.3). The estimated hydrothermal reserve potential of heat energy of the fractured hydrothermal reservoir calculated using Equation 10 is 1.54 x 10¹⁵ J. From Equation 3, the total stored heat (E) is 6.68 x 10¹⁶ J with a reservoir area of 3 km², the reservoir thickness is determined to be 0.4 km and assuming a

recovery factor of 25 % of the stored heat and 25 years of production for the total reserve (MW_e) in Equation 4, this results in:

$$\begin{aligned} & \text{Reserve (MW}_e\text{)} \\ &= \frac{\text{Stored heat X Recovery Factor}}{\text{Life Time}} \quad (4) \\ &= 21.16 \text{ MW}_e \end{aligned}$$

The above estimate equals a 13.54 MW power capacity per km².

Conceptual Model of the Bath Geothermal System

A conceptual model of circulation in the Bath geothermal system was developed on the basis of the results of this study and is shown in Figure 11. Na-Cl-SO₄ waters flow upward below the Bath area through fissures and fractures along a southwest-northeast trending fault (Sulfur River gorge) that is associated with the Plantain Garden fault (PGF). It is possible that remnant seawater or water with a long residence time starts boiling at depth. H₂S and CO₂ gases are released as steam heated waters undergo conduction and shallow mixing with meteoritic recharge. The Bath system may be the result of the Plantain Garden producing local areas of stress transfer that lead to fracturing and permeable networks; these networks allows temperature hydrothermal circulation. The geothermal resources on the island of Jamaica though unrelated to volcanoes appears to contribute to the mixing of deep circulation of meteoritic and remnant waters of submarine origin in high porosity rocks under hydrostatic pressure.

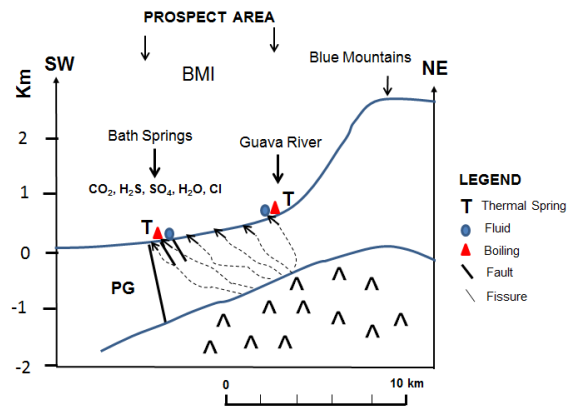


Figure 11: Conceptual model of the Bath, St. Thomas, Jamaica WI geothermal system.

CONCLUSION

The Bath geothermal system is classified as having partially equilibrated fluids with some dilution occurring whereas MKR and WS are closer to full equilibrium. Analyses of isotopic and chemical data show that BTHS, BTHN, WS and MKR all have deep circulating systems influenced by mixing with seawater. Bearing in mind the uncertainties in the application of chemical geothermometers, calculations using Na-K geothermometers, the estimated to the Bath geothermal reservoir or circulation is 1 – 1.8 km compared to estimated depths of 3.3-4.6km for WS and 4-6km for MKR. All thermal sites BTHS, BTHN, MKR, and WS may be regarded as important geothermal sources, but the Bath Site appears to be a shallow, more accessible geothermal system that warrants immediate geophysical investigations for well exploratory drilling and geothermal development. Heat flow in the Bath system has been estimated to provide at minimum of 21mW/m² based on the average geothermal gradient for the Caribbean region (28°C/km - 30°C/km). Based on estimated reservoirs temperatures of <180°C and B-Cl and quartz enthalpies, the BTHS-BTHN, MKR and WS are all classified as low enthalpy geothermal systems. A schematic conceptual model of the Bath site is proposed as constrained by hydrogeological characteristics. The fluid emerging through fractures and fissures at the sites are from separate and older hydrothermal systems.

In conclusion, the use of hydrogeochemical modeling, pattern recognition, and geothermometry greatly improves the ability to estimate depths of geothermal reservoirs. Future work will involve geophysical methods, thermal near-infrared and thermal infrared imagery remote sensing methods in a GIS to analyze their effectiveness in a predictive mode for drilling and site placement of new power plants.

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