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Muang Rae Geothermal System: Drilling and Borehole Geophysics, 1000-m Core Hole Into Granitic Rock, Amphoe Pai, Mae Hong Son Province, Northern Thailand

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Keywords

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ABSTRACT

In 2015, a 1-km core hole was drilled into granitic rock at the Muang Rae geothermal area. Previous drilling in 1993 to 200 m was unsuccessful in obtaining flows, but one of the "dry" wells began flowing in August, 2013 at 9.75 L/s of 96.9°C water from a fracture zone 80 m deep. In the sandy bed of the Pai River, 150 m south of that well is a 600-m long line of hot seeps, oriented NE, with highest temperature measured at 94.5°C. Geology is foliated Triassic (?) granitic rock cut by a NE-SW-trending normal fault zone (dip 65° NW) with extensive fluorite mineralization. Mineral equilibrium geothermometer analysis predicts a reservoir temperature of 132°C. The core hole was sited NW of the seep zone to drill into the fault zone at 600 m. MT indicated a low-resistivity anomaly 150-500 m deep at the site. The well did not flow, but was pumped at 6.4 L/s of 86°C water with 2.5 m of drawdown. Temperature logs indicate the well intersects a fracture with flowing hot water of 91.5°C at 600 m. The log shows a temperature inversion related to the transient effect of conductive heating of the surrounding rock by hot-water flow in the fracture. The bottom 150 m of the well shows a 23°C/km temperature gradient, which reflects the regional crustal conductive gradient.

Introduction

In Northern Thailand, 16 hot springs systems with temperatures greater than 80°C were investigated for potential power generation using binary plant technology. The study was narrowed to 5 systems to obtain more detailed geology, hydrology, MT survey, water-chemistry geothermometry, and land availability (Ensol Co., Ltd, 2015). This report provides information on the 1005-m core hole in granitic rocks that was completed in 2015, funded by the Thailand Department of Groundwater Resources.

In 1995 the Electrical Generating Authority of Thailand (EGAT) drilled 3 wells to ~200 m into the Muang Rae system, but none of those wells flowed and the project was abandoned. Remarkably, 18 years later, August, 2013, the village people reported that one of the wells began to flow, and we measured the flow of 9.75 L/s of 96.9°C in May, 2014. Geochemistry of the water indicated subsurface temperature of 132-146°C. After gathering data and a MT survey, the Muang Rae hot springs area was selected for a 1-km test hole.

In this report, we review the geothermal systems in this northwestern-most part of Thailand (Fig. 1). Previous reports from recent northern Thai geothermal studies to the east are in Singharajwarapan, et al. (2012), Singharajwarapan, et al. (2015), Wood and Singharajwarapan (2014), Chaiyat, et al. (2014); Amatyakul et al. (2015), Amatyakul et al. (in review, 2016). We present here the results of the 2015 core hole into granitic rocks of the fault zone and fracture system associated with the Muang Rae hot springs.

Regional Geology

Northwestern Thailand, west of Chiang Mai and Chiang Rai, is underlain by a group of crystalline rocks and folded Paleozoic rocks called the Inthanon Zone (Barber, et al., 2011). Some of the gneissic rocks are considered to be the crystalline basement of the Sibumasu continental block that was thrust eastward and under its cover of Paleozoic marginal sediments during the Mid-Late Triassic Indosinian Orogeny, as the Sibumasu collided with the Indochina block (Gardiner, et al., 2015). In post-collision time these rocks were invaded by large plutons of undeformed biotite granite (S-type) mostly with late Triassic ages. In the Muang Rae area both deformed granite (augen gneiss, and gneissic granite) and undeformed biotite granite occur. The foliated rocks are not simply explained by prevailing tectonic studies, but they are regarded as Triassic in age, and not Carboniferous as had been earlier suggested by Hess and Koch (1979). South of this area the gneissic rocks have been more thoroughly studied and dated and are interpreted as core complexes (MacDonald et al., 1993; Morley et al., 2011). Gardner et al. (2015) believe these core-complex gneisses are mid-crustal gneisses metamorphosed during the Indosinian Orogeny and uplifted in Cenozoic time. We show both the foliated crystalline rocks and the undeformed granites in Fig. 1 as mapped by Hess and Koch (1979), recognizing that boundaries are not precise, and that there may be enclaves of one granite type within the other.

Geothermal waters in the region are mostly associated with Cenozoic faults, but in this region of rugged mountains of granitic rock, deep weathering and heavy vegetation cover, fault mapping is incomplete, and physiographic features such as aligned valleys and steep linear mountain fronts are at times the only indication of faulting. Relief in the area rises to 1100 m elevation above the Pai River valley which is situated at about 500 m elevation.

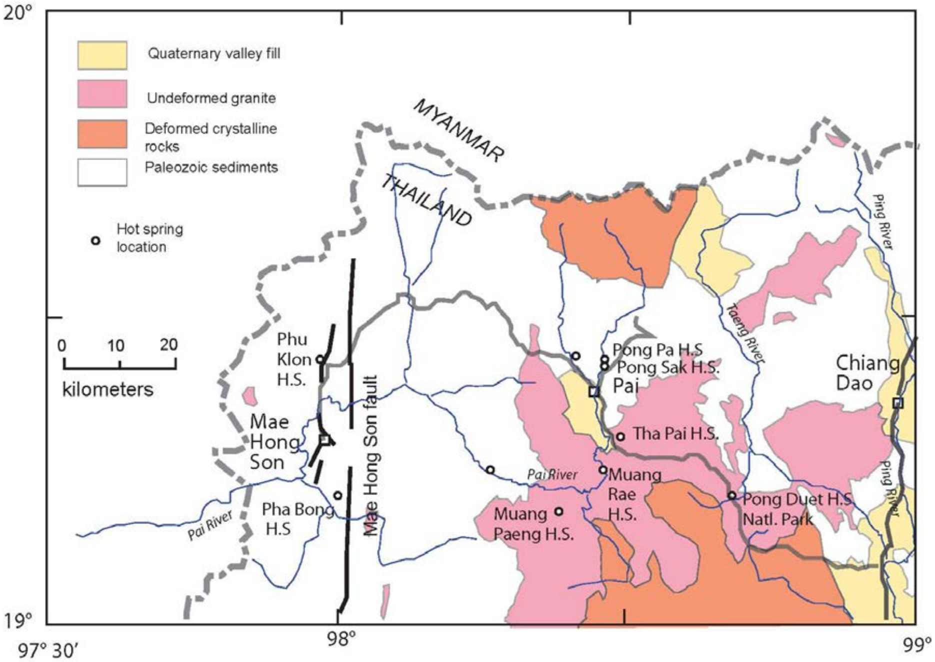

Figure 1. Map of northwestern Thailand showing location of Muang Rae Hot Springs and other hot springs in the area. Map shows distribution of both the foliated (deformed) granite, and the undeformed granite as mapped by Hess and Koch (1979) in Thailand.

Hot Springs in the Region

We provide here new information on other hot springs we visited in the region of Fig. 1. A more complete list of other springs is in Ramingwong et al., 1978.

By far largest springs in the area are designated the Pong Duet National Park, and cannot be developed under present regulations (Fig. 1). Surface water temperature is 97.8°C. Water in the largest pools geyser to about 1 m height, and pools are lined with white travertine. The natural flow rate was estimated in 1976 to be 17.5 L/s, but has not been measured recently. Geothermometry indicates subsurface temperatures in excess of 155°C (Singharajwarapan et al., 2012). The springs emanate from biotite gneiss over an area of about 1 hectare. The hot pools align with 130° azimuth (Ramingwong et al., 1978). No fault has been mapped here, but a N-NW-trending linear valley followed by the highway, extends for 20 km to the south of the springs.

The main Tha Pai hot springs emanate from porphyritic biotite granite over an area of about 0.3 hectare, 10 km SW of the town of Pai. Maximum temperature is 78°C and the estimated flow is 1.4 L/s, although Chaturongkwanich et al.(1985) report a flow of 64 L/s which we believe is a misprint. Seepage points in pools align 037°, but no fault is mapped here by Chuaviroj et al. (1985) and Chaturongkwanich et al.(1985). Geothermometry of waters is relatively low 87-116°C (Singharajwarapan et al., 2012). A second small seepage point of 73°C lies 380 m to the west near the park entrance.

The Muang Paeng hot springs are from a single bubbling vent in a mound of travertine, about 15 m wide. The spring area is coarse crystalline biotite granite. Temperature is 95.8°C. We measured a total flow of 10 L/s from a temporary wier in the outlet stream in 2014. Earlier flow reports of 40 L/s on a V-notch weir by (Prasatkhetwittaya, 1995) and 86 L/s (Chaturongkwanich et al. (1985) were not obtained by us. Geologic mapping of the area by Asnachinda et al. (1994) show that the spring emanates from the 160° striking Huai Mai Paeng Fault, a fault that is aligned along the creek channel and traceable for distance of 3 km to the N-NE of the spring. The fault appears to cause a left-lateral offset a large (200 m wide) quartz vein about 1 km. They also show a fault system with smaller offset of the vein, oriented 050° that crosses the Huai Mai Paeng fault at the hot springs vent. Reconsideration of the water chemistry geothermometry indicates a maximum reservoir temperature of 114°C (Owens, 2014), although earlier estimates (Singharajwarapan, 2012; Prasatkhetwittaya, 1995) range up to 150°C.

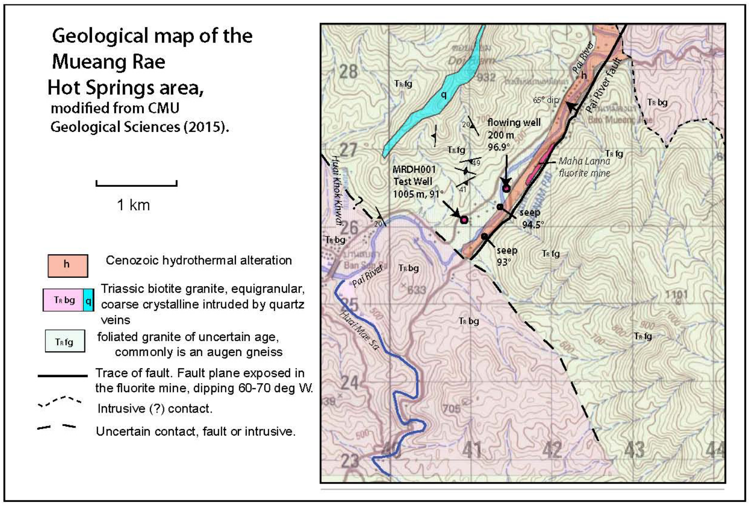

Figure 2. Geological map of the Muang Rae Hot Springs area modified from mapping by Sarawute Chantraprasert and colleagues at Chiang Mai University reported in Ensol Co., Ltd. (2015).

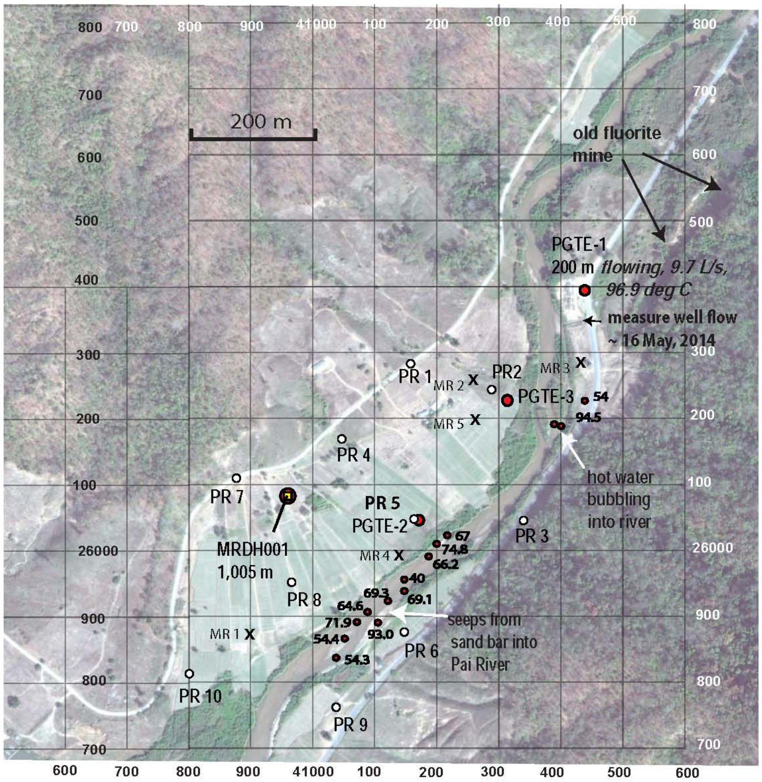

Figure 3. Map of Muang Rae Hot Springs showing natural seeps of hot water (small red dots), locations of wells (circles) and Schlumberger soundings (denoted by X), WGS-84 UTM grid.

Resistivity profiling, vertical electric soundings, and head-on resistivity surveys were carried out by EGAT in 1993-94, and the Muang Paeng prospect was drilled with 11 temperature holes. Temperature logs are contained in the report by Prasatkhetwittaya (1995). Four explorations wells 250 m deep, 5 ¾ inch diameter were drilled near the spring. MPE-1, MPE-3, and MPE-4 were drilled within 100 m of the spring. The wells flowed 0.5-0 L/s, 13-11 L/s, and 18-15 L/s respectively. MPE-1 ceased to flow while MPE-3 and MPE-4 flowed with a combined long-term(>17 hrs) flow of about 25 L/s of 94°C water, and a pressure (shut-in ?) of 0.2 bars. Fracture zones in MPE-3 were at 53, 94, 123, and 148 m depth. At MPE-4 fracture zones were at 54, 71, and 88 m depth. MPE-2 was drilled 200 m SW of the spring on an area of resistivity profiling anomaly of 40-60 ohm m, but did not flow. The MPE-2 well was in granite with clay 1-3%, chlorite 3-5%, and pyrite <1% to 1%, with lithology similar to the other 3 wells, but showed a clay alteration zone 21-23 m (Prasatkhetwittaya, 1997). We did not locate these wells in 2014, nor were temperature logs for the 4 deep wells reported.

Pong Pa hot springs are small seeps that collectively flow 1.5 L/s from Paleozoic sedimentary rocks on the west bank of the Pai River. Maximum surface temperature is 95.6°C.

Pong Sak hot springs are seeps over a distance of 50 m from gravel bars of the Pai River with maximum measured temperature of 79.8. Flow appears small but flow and temperature cannot be measured accurately where covered by shallow river water.

Geology of the Muang Rae Geothermal Area

The Muang Rae geothermal area was originally known from hot seepages within the sand bars along the Pai River (Figs. 2 and 3). Geological mapping of the area has identified at least three distinct hydrothermal events (and mineral populations) that have occurred at this site: Mesozoic/Cenozoic ? mesothermal quartz veins, Cenozoic epithermal fluorite-bearing veins and

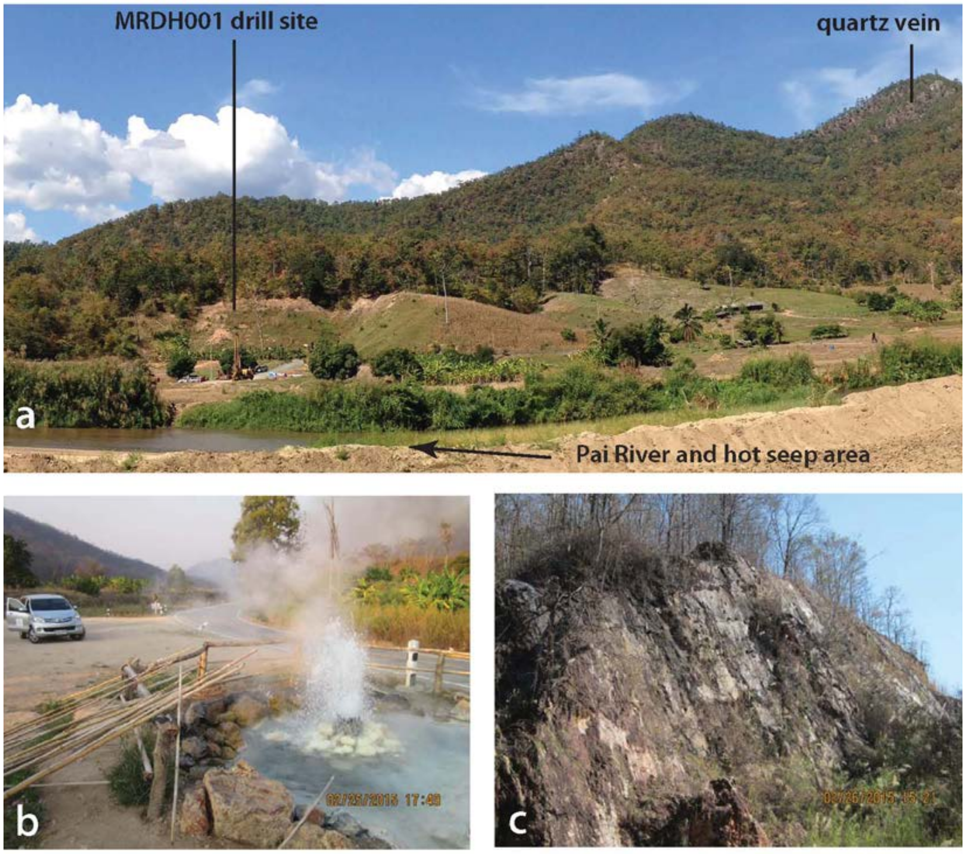

Figure 4. (a) Photograph looking west from Hwy. 1265 across the hot springs seep area and the Pai River to the MRDH001 drill. Hill are composed of gneissic granite intruded by a 100-m thick quartz vein at the top of the hill, and small quartz vein on the hillside. (b) Photograph of the PGTE-1 well which began flowing in August, 2013, 9.75 L/s, 96.9°water. (c) Photograph of fault exposed in the Maha Lanna fluorite mine. The fault strikes 030°, and dips 65° NW, locality shown on Fig. 2. Grooves and slickensides run vertically down the fault plane. These three photographs show three separate and unrelated hydrothermal events that have occurred at this local; the fossil quartz veins identified in photograph a; the fluorite-bearing hydrothermal mineralized fault plane in photograph c; and the current flowing hot water in photographs a and b.

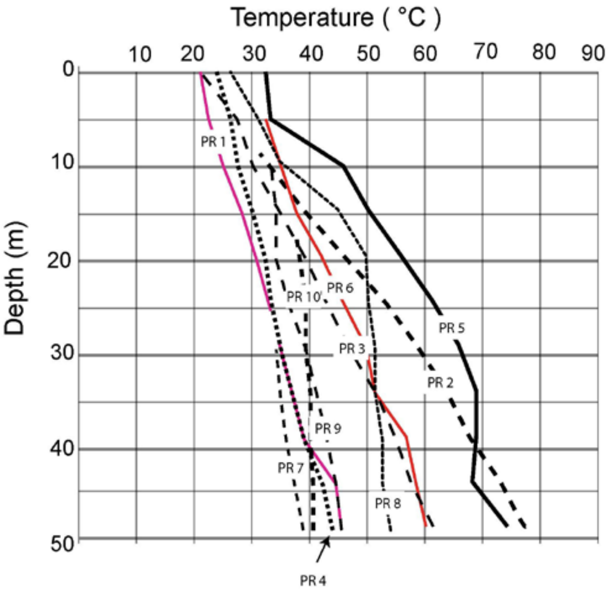

Figure 5. Temperature logs of the 50-m test holes drilled in 1994 (from Prasatkhetwittaya, 1995). Locations of wells are shown in Fig. 3.

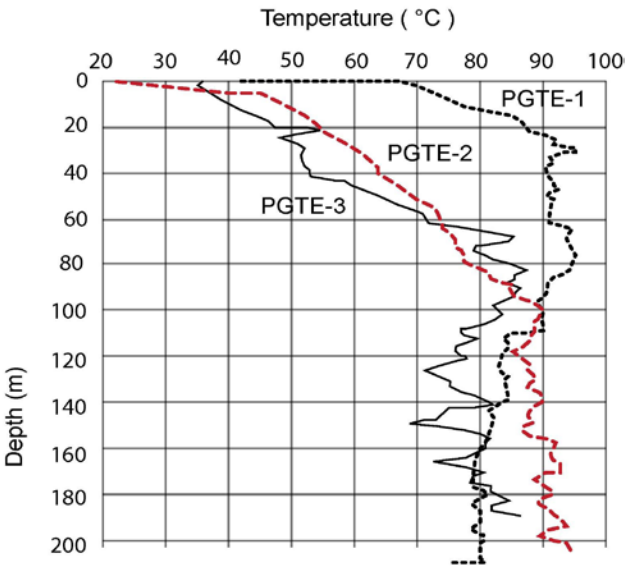

Figure 6. Temperature logs of 200-m exploratory holes drilled in 1995. Locations of wells shown in Fig. 3 (from Prasatkhetwittaya, 1995).

the current geothermal system (see Figure 4). The scope of this work does not include analyses of the chemical/mineral characteristics of the fossil hydrothermal systems. The surface exposure of the fluorite-bearing fault vein was examined at the abandoned Maha Lanna fluorite mine immediately north of the PGTE-1 flowing well. The west wall of the mine is a fault plane striking 034° and dipping 60°W with prominent vertical slickensides and grooves (Fig. 4). The fault was named the Pai River fault by Prasatkhetwittaya (1995). The fluorite ore zone is a 40 m thick zone, parallel to the fault, made up of silicified and brecciated cryptocrystalline quartz with veins of banded fluorite. The mine and the hot springs area are within foliated gneissic granite, but coarse grained undeformed biotite granite occurs in the area, and at places is associated with the foliated granite. The quartz vein, mostly of massive milky quartz with a 030° strike, 51° NW dip, ~ 15-m thick crops out at the top of Doi Riam, 1.5 km NW of the springs (Figs. 2 and 4). Thinner cryptocrystalline quartz veins of similar strike are common on the hill.

Interestingly, the alignment of hot seeps in the riverbed aligns with the NE strike of the exposed fault in the mine (Fig 3.). The temperatures of seeps in the sandbars range up to 94.5°C, at the northeasternmost seep. A considerable natural flow of hot water is from the submerged bed of the river, and cannot be measured. The mine fault appears to terminate at its southwest end, at the contact of foliated granite with the biotite granite. This contact line is also the base of a 500-m physiographic escarpment that we suspect is a NW-trending fault and is also the cause of the abrupt NW turn in the course of the Pai River SW of the hot spring. The mappable NE-SW Pai River fault is only 4 km long and its north end is not well defined (Fig. 2)

The Muang Rae area was explored by EGAT in 1993-1994 using resistivity profiling, vertical electric soundings, and head-on resistivity. Geology and geothermometry of waters were evaluated. Ten 50-m temperature holes were drilled in April, 1994 (Figs. 3 and 5). In February-March, 1995 three exploration wells were drilled to ~200 m close to the fracture location indicated by the resistivity surveys (Fig. 3). None of the wells flowed. Temperature logs recorded >90°C in two of the wells. Lack of flow and low temperature caused EGAT to abandon the project as a potential electrical generation site (Prasatkhetwittaya, 1995).

Eighteen years later, in April 2013, the PGTE-1 well began to flow 9.75 L/s of 96.9°C water, without any known triggering event. This prompted the Department of Groundwater Resources to sponsor renewed examination of this geothermal area.

Results from the 1993-1995 Exploration of Muang Rae

Schlumberger soundings at 6 points (Fig. 3) show a shallow low resistivity zone underlain by high resistivity (>600 ohm m). Low resistivity (12-50 ohm m) occurs down to 90 m on MR 4, MR 5, and MR 6, below which the resistivity is > 600 ohm m. The low resistivity zone (12 ohm m) occurs from 9-63 m on MR 3. The low resistivity (20-90 ohm m) zone is 3-172 m on MR 2, and 9-215 m on MR 1 (Prasatkhetwittaya, 1995).

Temperature holes drilled in 1994 to 50 m show an upper 10-20 m of boulder alluvium of sand silt and clay, except for PR 5 which shows 33 m. Wells drilled altered granite, with feldspars mostly altered to clay, and minor amounts of chlorite, clay and pyrite noted in some holes. Bottom-hole temperatures > 70°C on at PR 2 and PR 6 (Figs. 3 and 5). The other 8 holes had bottom-hole temperatures < 61°C. These temperature holes and the results of the head-on resistivity surveys were the basis for locating the sites of 3 exploration holes to 200 m (Prasatkhetwittaya, 1995).

The PGTE-1 well is logged as "weathered granite" to a depth of 96 m where circulation was lost. Temperature logs were run 20 days after circulation stopped. The temperature log on PGTE-1 shows 96°C temperature water at 35 m that persists down to 85 m, below which the water in the hole cools to 90°C to 110 m, and then sharply cools to 85°C at 110 m and then gradually cools to 80°C at the bottom of the log at 209 m depth (Fig. 6). At the time of drilling the well did not flow. Water levels were not recorded in data available to us.

The PGTE-2 well lost circulation at 144 m. The temperature log (Fig. 6) shows a gradually increasing temperature to 90°C at 100 m, then irregularly dropping to 87°C down to 155 m, where it increases 90-93°C to the bottom of the log at ~ 200 m. The log shows cooler temperatures 85-158 m, and then an inflow of hotter water ~92°C from 158 m that persists to the bottom of the hole at 209 m. (Prasatkhetwittaya, 1995). Temperatures of PGTE-2 increase gradually with depth to 90°C at 100 m, then fluctuate slightly around that temperature to the bottom of the log at 205 m.

The PGTE-3 well lost circulation at 62 m. The temperature of PGTE-3 (Fig. 6) increases gradually to 62 m, and then abruptly rises from 72°C to 86°C at 65 m. At 128 m the temperature drops to 71°C. Below 128 m the temperature fluctuates from 70-80°C, and rises to 86°C at the bottom of the log at 190 m.

We are uncertain on the causes of small temperature fluctuations in the logs shown in Fig. 6 and we have no information on the logging instrumentation. Logs were run at least 20 days after drilling. Small fluctuations and the ~ isothermal sections may be caused by small flows entering the well and exiting in lost circulation zones. The "temperature inversions" where lower temperatures occur deeper in the PGTE-1 and PGTE-3 appear to be the transient effect of the heated formation that results from the flow hot water in a nearby or adjacent fracture in the upper part of the hole. Bodvardsson (1973) and Ziagos and Blackwell (1986) show examples and model this temperature-depth effect over the time of a high temperature fracture flow superposed on the background geothermal gradient.

3-D Magnetotelluric (MT) Survey

In 2014-15, 19 MT stations were deployed by the Physics Department of Mahidol University to cover the area surrounding the Muang Rae hot springs. Stations are in the valley of the Pai River, and not in the steep forested surrounding mountains. Results of this survey are reported in Ensol Co., Ltd (2015), and an interpretation is in preparation (W. Siripunvaraporn, written communication, 2016).

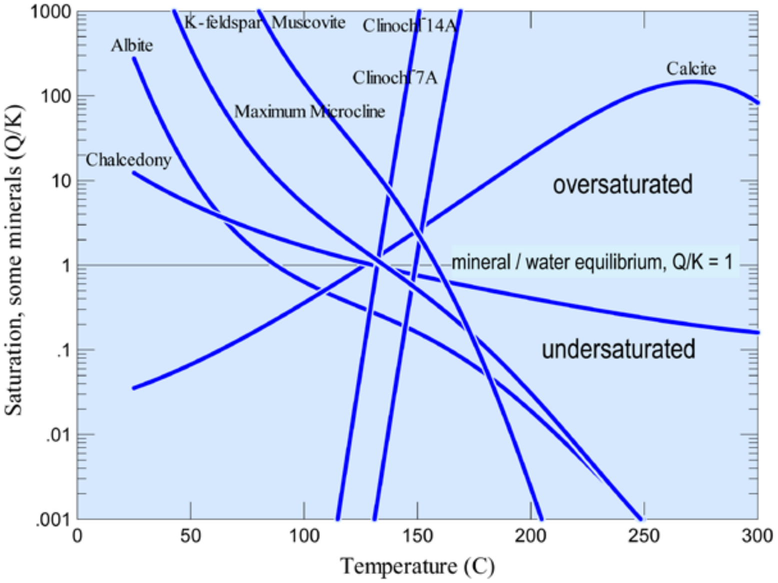

Figure 7. Mineral equilibria model for 96.9°C water from flowing well PGTE-1: sample MH-05-06. The model suggests the deeper reservoir is about 132°C. (from Owens, 2014).

Geochemistry of the Geothermal Water

The seeps in the river sand bars, the hot flowing well, and the adjacent Pai River waters were sampled in May, 2015 and analyzed for chemistry (Table 1). We also include in the table analysis made by the Department of Mineral Resources (DMR) in 1986 and reported in (Prasatkhetwittaya, 1995). These older analysis generally agree with the new analyses except for the lower values of Cl and SiO_2.

This presumed primary end member (MH-05-6) was examined using geothermal equilibria models [WATCH (Arnórsson et al, 1982; Iceland Water Chemistry Group, 2010)] and saturation indices calculations in WATCH and Geochemist's Workbench (Fig. 7). The estimated reservoir conditions for MH-05-6 were estimated at 132°C, based on mineral equilibria shown in Fig. 7 (Owens, 2014).

We show also the analysis of water pumped from the 2015 MRD001 well (Table 1). Water was sampled 3 times after the pumped water showed a stable EC of 998-1008μSiemans/cm and temperature of 86°C. There are uncertainties in the Cl, and SiO_2 analysis, as they are quite different from analysis of water from the PGTE-1 well. The silica is ~230 mg/L in the new pumped well, compared to 129 mg/L in the flowing well. The high silica of the pumped well is not easily explained. The chloride is much less (3.5-8.3 mg/L) in the pumped well, compared to 12.2 mg/L in the flowing well. Fluoride is similar, but slightly less in the pumped well (6.8-7.5 mg/L) compared to 12.5 mg/L in the flowing well. We have no explanation for these variations, except that some fractures are in direct contact with fluorite veins, and some may be diluted by cold waters entering the well.

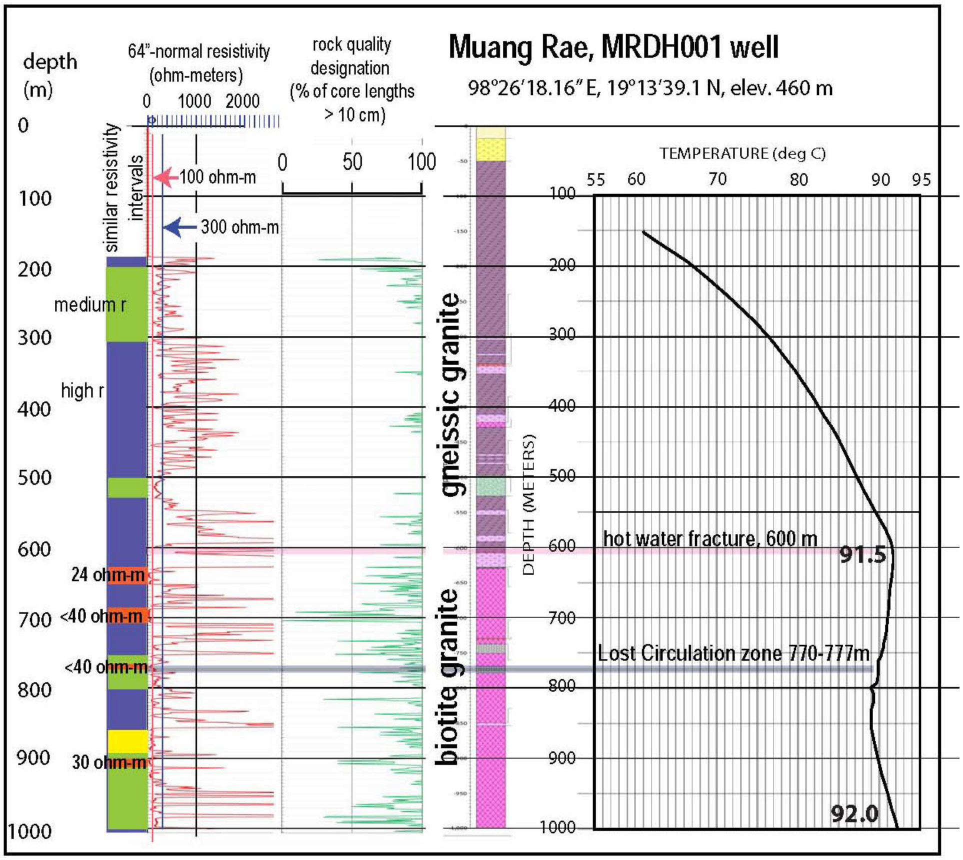

Figure 8. Long-normal resistivity log, core rock-quality designation (RQD) and temperature logs from the MRDH001 core hole drilled in 2015. Hole is cased to 185 m. The resistivity log below 600 m shows the low resistivity fracture zones within the higher resistivity granite, associated with higher degree of fracturing (RQD). The 91.5°C peak in temperature at 600 m is interpreted as the flow of hot water in a fracture that has been in existence long enough to conductively heat the rock above and below the fracture (cf; Ziagos and Blackwell, 1986). Bottom of the hole (850-1000 m) shows a positive geothermal gradient (23°C/km) and temperature increasing to 92°C.

Table 1. Chemistry of waters sampled at the Muang Rae Hot Springs

	CODE	pH	Temp °C	Cond µS/cm	TDS mg/l	CO3 mg/l	HCO3 mg/l	Cl (mg/l)	SO4 (mg/l)	F mg/l	H2S mg/l	SiO2 (mg/l)	Na (mg/l)	K (mg/l)	Li (mg/l)	Ca (mg/l)	Mg (mg/l)	Fe (mg/l)	Mn (mg/l)	Zn (mg/l)	Al (µg/L)	As µg/L	%error (Cat/An balance)
seeps, DMR 1986		8.5	79		550		450	4.6	19	6		48	170.0	18.8		5	0.8	0.9					
seeps, DMR 1986		8.5	75		600		444	4.5	72	6		95	169.0	18.8		6	0.12	2.5					
Pai River water 5/14/15	MH-05-10	7.86	32.7	246	167	0.0	30.5	0.5	0.2	0.2	<0.2	23	10.6	2.8	0.010256	0.22	0.039	<0.005	<0.005	<0.005	16.9	5.1	-1.7
Pai River water 5/17/14	MH-05-1	7.88	36.0	252	173	0.0	40.5	3.5	0.5	0.2	<0.2	22	15.7	2.9	0.013	0.27	0.049	<0.005	<0.005	<0.005	23.9	6.7	0.5
seep-l. sandbar 5/14/15	MH-05-2	8.83	87.1	900	624	0.0	435.8	20.8	30.9	6.2	<0.2	124	162.9	19.1	0.551	11.68	2.120	<0.005	<0.005	<0.005	40.0	20.6	1.7
seep-l. sandbar 5/14/15	MH-05-3	7.55	93.6	916	635	0.0	418.5	21.8	32.6	5.5	0.3	123	169.9	19.0	0.031	0.65	0.118	<0.005	<0.005	<0.005	69.8	23.7	3.2
seep-l. sandbar 5/14/15	MH-05-4	8.72	78.2	1116	776	22.5	475.8	23.5	33.3	7.2	0.2	166	182.4	25.7	0.623	13.20	2.396	<0.005	<0.005	<0.005	232.6	22.4	3.8
seep-NW bank 5/17/15	MH-05-5	6.82	83.6	665	458	0.0	308.5	19.7	23.6	3.8	0.3	89	118.4	13.7	0.367	7.77	1.410	<0.005	<0.005	<0.005	22.3	21.1	2.0
seep-u. sandbar 5/17/15	MH-05-6	7.52	94.6	892	621	0.0	455.5	19.4	22.8	6.5	<0.2	135	157.5	18.9	0.577	12.23	2.218	<0.005	<0.005	<0.005	259.6	9.9	3.6
seep-u. sandbar 5/17/15	MH-05-7	7.23	92.5	915	641	0.0	480.5	20.2	20.2	4.5	<0.2	123	167.4	18.4	0.569	12.06	2.189	<0.005	<0.005	<0.005	32.4	7.9	2.7
seep-u. sandbar 5/17/15	MH-05-8	7.25	91.4	863	601	0.0	440.5	19.4	25.5	9.8	<0.2	120	156.9	18.0	0.553824	11.74	2.129	<0.005	<0.005	<0.005	223.5	< 5.0	4.1
FTGE-1 well 5/17/15	MH-05-9	8.20	96.9	901	627	0.0	420.5	12.2	45.8	12.5	<0.2	129	158.9	18.6	0.571772	12.12	2.198	<0.005	<0.005	<0.005	16.6	< 5.0	3.5
MRDH001 pumped#1, 12/11/15	1	6.86	86	1008	628	0	510	8.2	46.3	6.8	0.3	238	187.7	20.5	0.49	14.50	1.022	0.011	0.056	0.086	30.5	<2.0	1.7
MRDH001 pumped#2, 12/11/15	2	6.76	86	998	590	0	435	3.8	72.4	7.3	0.7	233	179.8	19.0	0.469	12.00	0.911	0.005	0.014	<0.005	44.2	<2.0	0.4
MRDH001 pumped#3, 12/12/15	3	6.75	86	998	598	0	425	3.5	80.8	7.5	0.7	231	177.2	18.5	0.469	11.57	0.901	0.005	0.014	<0.005	45.8	<2.0	1.3

1005 m Core Hole

Based on projection of fault structure of the NW dipping Pai River fault, and the SE dipping, antithetic structure imaged by the 3-D MT survey, it was believed that these fault structures should be drilled from the well location 230 m northwest of the seepage alignment in the river, drilling to 600-1000 m. Drilling of the MRDH001 well by PSI Drilling Thailand, Inc. commenced in August, 2015, using mud rotary to 46 m, setting and cementing 8 inch casing. The 6 ¾ inch hole was air-percussion drilled to 186 m obtaining cuttings and then 5 ½ inch casing placed and cemented. The rest of the hole was core drilled with PQ3 (4.8 inch) to 450.1 m, and then NQ3 (3.7 inch) to 1005.0 m. The core hole was completed on October 1, 2015, and circulation stopped on that date. The drillers encountered a lost circulation zone 770-777 m which was plugged to drill ahead.

Geologists noted the downward change from the upper "stressed granite" to an equigranular biotite granit that occurred within the interval 583-635 m. Below 630 m RQD (Rock quality designation) is generally 50-90% to the bottom of the hole at 1005 m. RQD, is the percent of core pieces longer than 10 cm, in an individual core run: highly fractured rock will have a low value RQD. A very fractured zone occurs 690-705 m with RQD from 0-70%. The first certain fluorite vein occurs at 576 m. Veining and hydrothermal alteration is prevalent from 630 m down to the bottom (Manapanya and Songgul, 2015).

Open-hole logs runs were run on November 1, 2015 by Flow Active Co., Ltd using the Shianghai Geological Instruments logging system, from 50-184 meters: gamma, long and short normal resistivity, SP, single-point resistance and temperature. On October 29, 2015 the completed hole was logged with temperature and flowmeter logs, by Scientific Drilling Co., 185-1005 m. The well was pumped for 72 hours starting November 3, 2015 at a rate of ~ 6 L/s.Flow Active ran logs December 9, 2015 from 0-1005 m, well cased 0-185 m, and open-hole from 185-1005: gamma, long and short normal resistivity, SP, single-point resistance (Figs. 9 and 10). Starting December 10, 2015, the well was pumped again for 50 hours at 6.4 L/s of 86°C water. (Fig. 11). Flow Active, Ltd. ran a second temperature log on December 12, 2015, 0-1005 m, in the well open-hole from 185-1005. Wireline logging had difficulty logging through 700 m because of a constriction or fragments blocking the hole. Hammering through the zone opened the hole to get the complete log. This temperature log was identical to the October 29 log. It is our belief that after the well was pumped on November 3, and December 10, the fluid in the hole was formation water of electrical conductivity (EC) of ~ 950µSiemans/cm (25°C) which converts to 10.5 ohm-m at 25°C, 4.5 ohm-m at 80°C and to 4.1 ohm-m at 90°C using Arp's equation of Sen and Goode (1992).

Interpretation of Geophysical Logs of the MRDH001 Well

Temperature Logs

The first open-hole log 50-184 m (not shown) had a maximum temperature of 62°C at bottom. From 128-184 meters the hole is isothermal at 60-61°C, indicating a downward flow of water of that temperature from a 128-m-deep fracture. This flow zone is cased and cemented off and does not affect the completed well.

The temperature log was run open-hole, 184-1005 m, 28 days after hole completion and last circulation, by Scientific Drilling (Fig. 10), and then again 73 days after hole completion by Flow Active Co., The logs are identical showing a maximum bottom-hole temperature of 92°C., a zone in which lost-circulation was experienced during drilling. The upper zone 184-600 m shows a remarkably smooth gradient suggesting the upper zone has been heated by conductive heating by the 600-m fracture for a long time. The area below the 600m (600-850m) also shows the same conductive heating of the formation by warm fluid flow in the fracture zone. Below 850m the regional background conductive crustal gradient is encountered. A regional temperature gradient for this region of 23.3°C/km can be inferred from the work of Searle and Morley (2011) and Noisagool et al. (2014) where they indicate the crust is ≈ 40 km thick, T at base ≈ 900+°C.

Short and Long Normal Resistivity Logs: The two open-hole logging runs (01/09/2015 and 12/09/2015) by Flow Active Co. using Shianghai Geological Instruments logging systems are spliced in Fig. 9. Resistivity log from 185-1005 was run after pumping the hole for 50 hours.

The resistivity logs are of a hole that is mostly granite, with two mineralized (fluorite/pyrite) silicified breccia veins (9-13 m thick) at 738 and 770 m (Manapanya and Songgul, 2015). Resistivity of the granite varies from several thousand ohm-m for the solid intact granite to 25 ohm-m interpreted as a fluid filled fracture or fault zone at 636-642 m depth, or clay from hydrothermal alteration. One anomalous zone shows 1.6 ohm m 703-704 m, probably caused by pyrite.

Zones of anomalously low resistivity are as follows:

From Base of Casing 54 -128 m: An interval of low resistivity (33 to 64 ohm m). We only have cuttings from this zone, but geologists noted feldspar altered to clay, which may explain the low resistivity values. Note also that the open-hole temperature log shows that at 128 m, 61°C water enters the hole and flows downward.

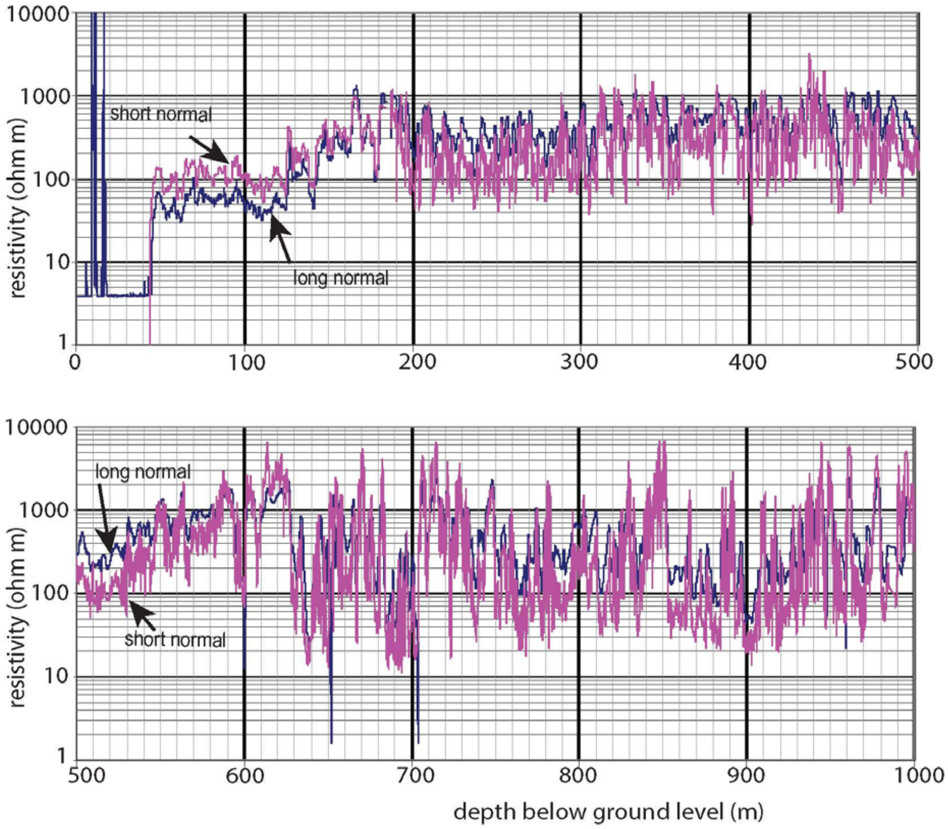

Figure 9. Resistivity logs of MRDH001 geothermal exploration well at Muang Rae. Short (16-inch) normal resistivity is in red, and long (64-inch) resistivity is in blue. The Long normal is a better measure of the rock saturated with formation fluid, because the short normal may be affected by drilling fluid, hole conditions, thin beds and fracture openings. The 50-185 m log was in an air percussion drilled 6 ¾ inch hole. Fluid in the borehole was probably 50-60°C water of 6 ohm m resistivity. The 185-1000 m log was filled with water of variable temperature shown by the temperature log of Figure 9.

From 204 to 310 m: About 8 thin (1-3 ft) zones of low (106-200 ohm m), and overall low resistivity (<500 ohm m) indicates a fractured zone, also indicated by several intervals of RQD <80%. This zone is also indicated to have feldspars altered to clay which may contribute to low resistivity.

From 401 to 601 m: Three zones: 401-402 m, 65 ohm m; 452-455 m, 82 ohm m; 598-601 m, 12 ohm m.

From 684-704 m: Low resistivity of 1.6 to 42 ohm m. This 20-m zone shows the lowest resistivity on the log. 1.6 ohm m at 703 m is lower than the geothermal water (4.1 ohm m). Therefore some other effect, probably vein or disseminated pyrite (10^{-4} – 10^{-5} ohm-m) causes low resistivity. Manapanya and Songgul (2015) visually estimated pyrite contents up to 5 % in some core sections, but did not specifically identify this zone.

From 899-959 m: Two zones: 899-903 m, 46-60 ohm m, 959 m, 22 ohm m.

Comments on Resistivity: There is no perfect correlation of electrical resistivity on the logs with fracture zones filled with hot water; however, 90°C water is 2.3 times more conductive than water at 25°C (Sen and Goode, 1992, Arp's Equation). Electrical conduction paths in granite are through ion movement in the pore water and water in fractures, paths through conductive clay minerals (called "surface conduction") (Revil et al., 1998, 2002; Kennedy, 2015, p. 249, Fig 8.21; Mavko et al., 2009), or through pyrite (Rider, 2002, p. 61, Fig. 6.29; Kennedy (2015, p. 241). Using the model of Pirson (1977) for fractured rock, low resistivity of ~ 25 ohm meters would require ~ 16 cm of total open fracture width per meter width of rock, if all conduction was through the 4 ohm-m water in the fracture. This might be possible in zones with low RQD, less than 70 %, but more detailed examination of the cores is needed to confirm this association. Alternatively, very low resistivity in some zones is likely due to conductive minerals (clays and pyrite) (cf: Ussher et al., 2000). Clay alteration was noted in the core within zones (Manapanya and Songgul, 2015) identified by MT as low electrical resistivity, but those zones do not correlate with increased temperature. In both explanations, closer examination of the cores in zones of low resistivity will be useful, particularly, because MT resistivity had been chosen to be the major method of subsurface exploration in granitic rocks in Northern Thailand.

Spontaneous Potential Log: The SP log (not shown) is without inflections, except for the zone 620-650 m where there is a – 50 mv deflection starting above a very resistive section of the granite. Most SP deflections occur when there is a strong contrast between drilling fluid and the formation water resistivity, at permeable beds, or where there is a strong flow into or out of the borehole. This is exactly the zone where 91°C water enters the borehole, and that flow must be producing the deflection.

Natural Gamma Ray Log: The natural gamma log responds to the combined gamma radioactivity of potassium, uranium, and thorium in the rock. The Flow-Active probe has not been calibrated to API gamma ray units, so no quantitative estimate of rock radioactivity (c.f., Keys and MacCary, 1981, p. 64) is made here. Nevertheless, the granitic rock from 920-960 m has anomalously high radioactivity (50-150 cps), compared to most of the log (~ 35 cps) (Fig. 10). No unusual rock associated with radioactivity was noted by the well-site geologists examining the core. No gamma log character

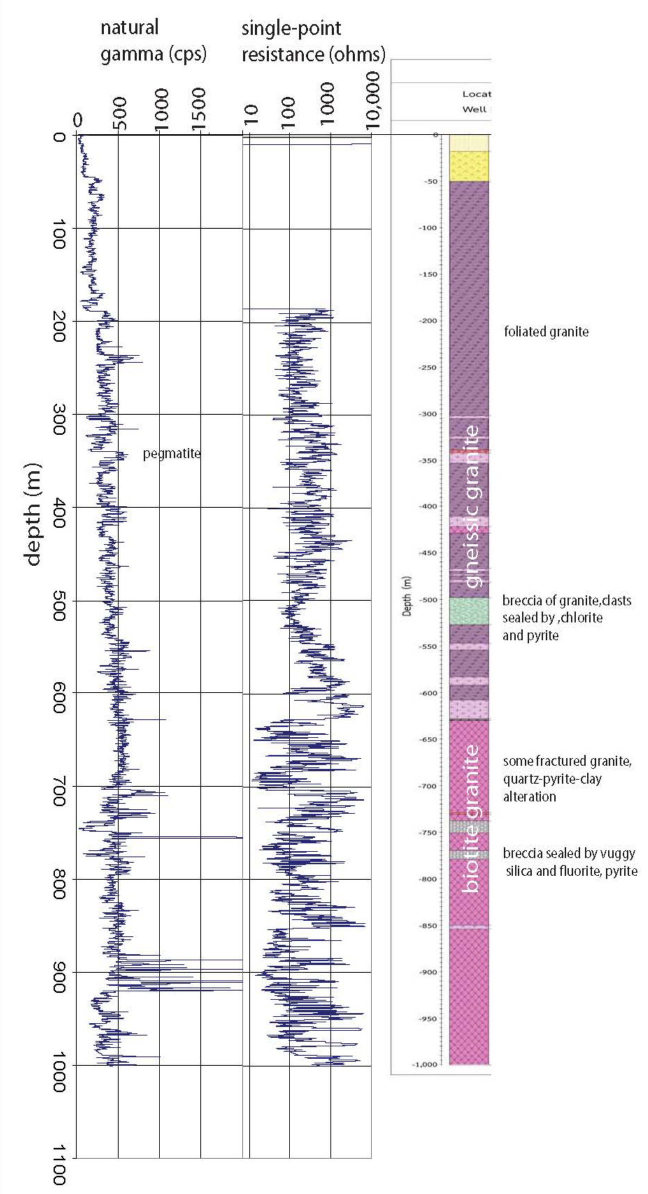

Figure 10. Natural gamma and single-point resistance logs from MRDH001 well. Low resistance is likely due to enlarged hole in the fractured zones, where the tool responds more to the fluid in the well (4 ohm m), because that is the favored current conduction path in highly resistive crystalline rock (cf. Keys and MacCary, 1971).

relates directly to water-producing fractures. The breaks at 50 m and at 184 m are the reduced radioactivity caused by metal casing partially shielding the rock radioactivity.

Spinner Flowmeter Log: No flow was detected by a spinner flowmeter (184-1005 m) (not shown). Resolution of the flow log is about ±2-3 m/minute, or a volumetric flow in the hole of 0.24 – 0.37 l/s. Because log indicates +45 m/minute, the sonde was probably towed upward at that speed, but we do not have specifications from Scientific Drilling on the meaning of left and right excursions for sense of upflow or downflow. Stall speed of spinner flow meters is typically 3-4 m/minute, and typical logging speed used by contractors is 8 m/minute.

Pump Test of MRDH001 Well

The well was first step-tested for 72 hours on November 3. Static water level was 6.99 m below ground level, water first rose to 4.8 m and then maximum drawdown was to 8.1 m at 5.2 L/s, and remarkably when pumping stopped water level rose to 2.46 m and then after 7 hours slowly declined to 6.90 m.

The static level December 10, 2015 was 8.36 m. A submersible pump was placed at 50 m and the well pumped for 50 hours at 6.4 L/s of ~ 86°C water (Fig. 11). The peculiar response of water level is explained by the cap of cooler water that enters below casing and fills the upper well bore as it sits over time (see temperature log of Fig. 8). The weight (pressure) of that cold water is such that hot water from the fracture at 600 m cannot flow upward until the cold-water cap is removed by pumping. At that point (~ 6 hours) the water level rises to ~ 11 m and remains at that

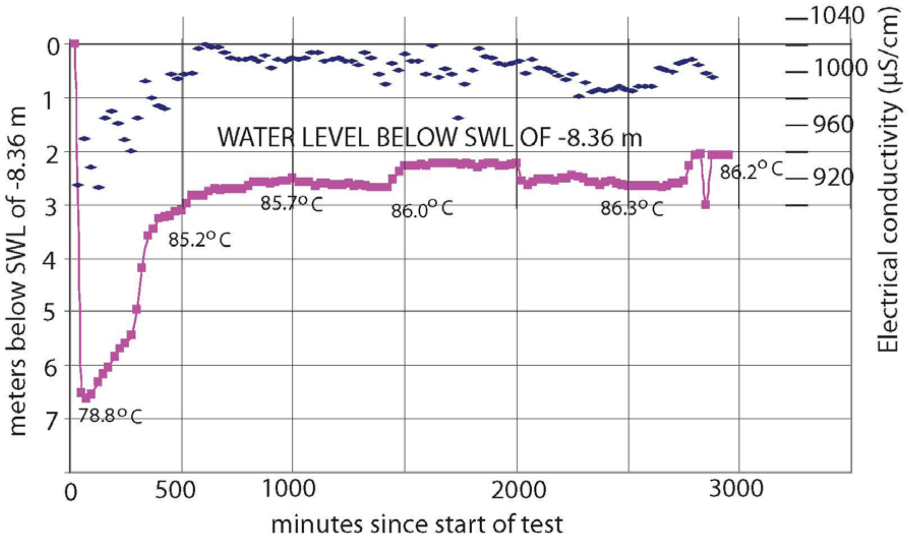

Figure 11. Pump test of the MRDH001 well showing water-level response to pumping, EC and temperature of pumped water at a steady rate of 6.4 L/s for 50 hours. Pump set at 50 m. Static water level is 8.36 m below ground level. Rapid water-level decline of 6.7 m in the early part of the test is the result of pumping the cold water at the top of the well. The rise in water level is the result of removing the weight of the cold water, as the well column filled with 86°C water. Steady state drawdown is 2.6 m, indicating a specific capacity of 2.5 L/s per meter of drawdown. Well was not heavily pumped so extrapolation of the specific capacity to much higher pumpage is uncertain.

level for the 50 hour test because the entire water column is hot. Electrical conductivity (EC) of the pumped water and temperature were measured so that the 3 samples (Table 1) could be verified as sampling the deeper geothermal water (EC ~ 1000µSiemans/cm) (Fig. 11).

The small drawdown (2.5 m) for a pumpage of 6.4 L/s shows the well is in a permeable fractured aquifer system with specific capacity of 2.5 L/s per meter drawdown suggesting the well could be pumped at higher rate with small drawdown. After pumping, the well was capped and exists as an open hole to 1005 m with cemented casing to 185 m.

Conclusions

The highest of the temperature measurements of the system is 96.9°C on the flow from PGTE-1 well. That well appears to be fed by a higher pressure fracture, or a higher head owing to temperature of the water column. According to the 1995 temperature log that high temperature occurred at a depth of 30 m. As was experienced in all the wells, the cooler water in the upper well bore is enough weight to prevent the upward flow of the hot water, indicating the hot water pressures near the surface are not great. None of the temperatures in drill holes approach the 132°C temperature predicted by geothermometry. Lower near-surface temperatures would be expected due to conductive heat loss from the geothermal fluid to the host rock. The higher chemical-geothermometer predicted temperatures would not be encountered within the up-flowing fluid above about 1000m depth, as the up-flowing fluid is conductively losing heat to the host rock (which is why the surrounding country rock is hotter near the geothermal fluid flow). Until fluids from a well drilled into the up-flow conduit are sampled and analyzed there will be unresolved data extrapolation issues.Deeper temperatures are predicted by the positive geothermal gradient at the bottom of the MRDH001 well, from 850-1000 m, + 3.5°C/150 m, or 23.3 /km. This is not a high gradient, and is typical of continental interiors (SMU Geothermal Laboratory). This regional crustal gradient extrapolates to temperatures > 115°C at 2 km depth and 200°C at 3.7 km

The present accessible resource at Muang Rae is 97°C water, with flows of at least 10 to perhaps 50 L/s that might be obtained by pumping wells, or drilling fortunate new shallow wells. Fractures tapping this water can be reached by shallow drilling, but the fracture or fractures are a narrow target zone that was missed by most previous wells. The alignment of seeps show a typical surface leakage from a lateral-flowing discharge plume and also suggests a narrow fracture zone. One explanation for the system is shown in Fig. 12. In this explanation, the geothermal up-flow zone is up hydrologic gradient from most of the seeps and wells, possibly located in the vicinity of well PGTE-1. As the thermal water approaches the surface it flows laterally through fractures and near-surface river deposits, progressively integrating into the local groundwater. No wells have explored north of the flowing PGTE-1.

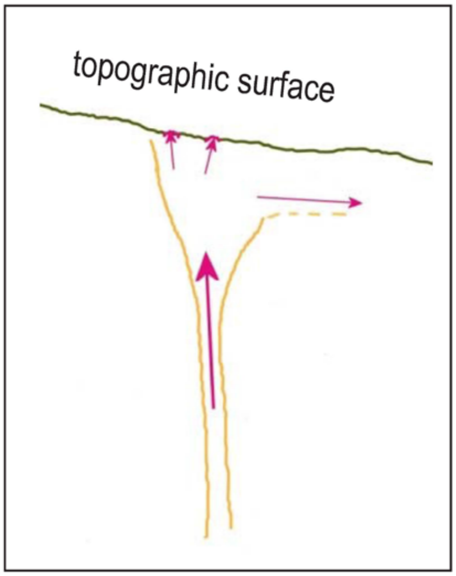

Figure 12. A generic diagram of geothermal fluid flow in a structural dilation conduit (Waibel, 2014) . At Muang Rae, the narrow hot fractures delivering buoyant hot water from depth discharge laterally in a shallow permeable zone, down the topographic gradient of the river valley, on top of and mixing into the local groundwater. This suggests further exploration should be more focused on the up-stream area expanding outward from flowing well PGTE-1, the site of the highest measured temperature.

References

Amatyakul, P., Boonchaisuk,S., Rung-arunwan, T., Vachiratienchai, C., Wood, S.H., Pirarai, K., Fuangswasdi, A., and Siripunvaraporn, W., (in review, 2016); Exploring the shallow geothermal fluid reservoir of Fang geothermal system, Thailand by a 3-D magnetotelluric survey . Submitted to Geothermics, 24 p. manuscript.

Amatyakul, P., Rung-Arunwan, T., Siripunvaraporn, W., 2015. A pilot magnetotelluric survey for geothermal exploration in Mae Chan region, northern Thailand. Geothermics 55, 31–38.

Arnórsson, S., Sigurdsson, S., and Svavarsson, H., 1982. The chemistry of geothermal waters in Iceland. I. Calculation of aqueous speciation from 0°C to 370°C. Geochimica et Cosmochimica Acta, vol. 46, pp. 1513 - 1532.

Asnachinda, P., Uttamo, W., Ramingwong, T., 1994. Geological and hydrogeochemical investigation of Muang Paeng geothermal area, Amphoe Pai, Changwat Mae Hong Son. A final report submitted to the Electrical Generating Authority of Thailand. (unpublished).

Barber, A.J, Ridd, M.F., and Crow, M.J.: The origin, movement and assembly of the pre-Tertiary tectonic units of Thailand. In M.F. Ridd, AJ Barber, and MJ Crow (eds.) The Geology of Thailand. The Geological Society of London. (2011), 507-537.

Bodvarsson, G., 1973. Temperature inversions in geothermal systems. Geoexploration 11, 141-149.

Chaiyat, N., Chaychana, C., and Singharajwarapan, F.S., 2014. Geothermal energy potentials and technologies in Thailand. Journal of Fundamentals of Renewable Energy and Applications, 4(2), 1-9.

Chaturongkawanich, S., Soponpongpipat, P., and Chuaviroj, S., 1985. Geology and geothermal resources of Pai District, Mae Hong Son Province, Northern Thailand. Proceedings 7th New Zealand Geothermal Workshop, 193-196.

Chuaviroj, S., Chaturongkawanich, S., Soponpongpipat, P., Leewongcharoen, S., 1991. Geological Map of Thailand, Sheet 4647-I, Amphoe Pai Quadrangle, 1:50,000. Department of Mineral Resources, Bangkok.

Ensol Co., Ltd. (2015). Geothermal resources survey for promoting geothermal energy production and local industry: Progress Report No. 2. Report to the Thailand Department of Groundwater Resources from P&C Management, Ltd, Ensol Co., Ltd with technical support from the Groundwater Technology Service Center of Chiang Mai University. Bangkok, 8 chapters. (In Thai).

Gardiner, N.J., Searle M.P., Morley C.K.., Whitehouse M.P., Spencer C.J., Robb, L.J., 2015. The closure of Palaeo-Tethys in Eastern Myanmar and Northern Thailand: New insights from zircon U–Pb and Hf isotope data. Gondwana Research, http://dx.doi.org/10.1016/j.gr.2015.03.001.

Hess, A., and Koch, K.E., 1979, Sheet 4 (Chiang Dao), Geological Map of Northern Thailand (1:250,000). Federal (German) Institute for Geosciences and Natural Resources, Stuttgart.

Iceland Water Chemistry Group, 2010. WATCH, v. 2.4 (April, 2010) (aqueous speciation program) [online]. available: http://geothermal.is/software/ software [accessed May 1, 2012].

Kennedy, M., 2015. Practical Petrophysics. Elsevier Developments in Petroleum Science, 62. Elsevier, 402 p.

Keys, W.S., and MacCary, L.M., 1971. Application of borehole geophysics to water-resource investigations. Techniques of Water-Resources Investigations of the United States Geological Survey. 126 p. Internet: http://pubs.usgs.gov/twri/twri2-e2/pdf/TWRI_2-E2.pdf

Manapanya, A., and Songgul, T., 2015. Geology and logging report, Exploration drilling hole MRDH001, Ban Muang Rae, Mae Hong Son Province (October, 2015). Unpublished report to PSI Drilling, Inc., 9 pages and appendices.

MacDonald, A.S., Barr, S.M., Dunning, G.R., Yaowanoiyothin, W., 1993. The Doi Inthanon metamorphic core complex in NW Thailand: age and tectonic significance. Journal of Southeast Asian Earth Sciences 8, 117–125.

Mavko, G., Mukerji, T., and Dvorkin, J., 2009. The Rock Physics Handbook (2nd Ed.): Tools for Seismic Analysis of Porous Media. Cambridge University Press, Cambridge. 511 p.

Morley, C.K., Charusiri, P., and Watkinson, I.M., 2011. Structural geology of Thailand during the Cenozoic. In MF Ridd, AJ Barber, and MJ Crow (eds.) The Geology of Thailand. The Geological Society of London (2011), 273-334.

Noisagool, S., Boonchaisuk, S., Pornsopin, P., Siripunvaraporn, W., 2014. Thailand's crustal properties from tele-seismic receiver function studies. Tectonophysics 632. DOI: 10.1016/j.tecto.2014.06.014.

Owens, L., 2014. Geochemical assessment of northern Thailand geothermal prospects. Report to the Groundwater Technology Service Center, Chiang Mai University (unpublished), 19 p.

Prasatkhetwittaya, W., 1995. Resistivity study of the Muang Paeng geothermal area. Report 95.16, Geothermal Institute, University of Aukland, New Zealand, 87 p.

Prasatkhetwittaya, W., 1997. Pai geothermal exploration. Proceedings, 12th Meeting of ASEAN Power Utilities/Authorities on geothermal power development, Chiang Mai, Thailand. 17 pages.

Ramingwong, T., Ratanasathien, S., Sertsrivanit, S., 1978. Geothermal resources of Northern Thailand: Hydrologic considerations. Proceedings, 3rd Regional Conference on Geology and Mineral Resources of Southeast Asia, Bangkok, November, 1978. 239-251.

Revil, A. Cathles III, L.M., and S . Losh., 1998. Electrical conductivity in shaly sands with geophysical applications, Journal of Geophysical Research, 103(B10), Pages 23,925-23,936,

Revil, A., Hermitte, D., Spangenberg, E., and Cochemé, J.J., 2002. Electrical properties of zeolitized volcaniclastic materials. Journal of Geophysical Research, 107(B8), 2168, 10.1029/2001jb000599, 2002 ECB 3, 1-17.

Rider, M., 2002 The Geological Interpretation of Well Logs (2nd Edition). Rider-French Consulting Ltd., Sutherland. 280 p.

Pirson, S.J., 1977. Geologic Well Log Analysis (2nd Ed.). Gulf Publishing, Houston, 377 p.

Searle, M.P. and Morley, C.K., 2011, Tectonic and thermal evolution of Thailand in the regional context of SE Asia. In MF Ridd, AJ Barber, and MJ Crow (eds.) The Geology of Thailand. The Geological Society of London (2011), 539-571.

Sen, P.N. and Goode, P.A., 1992. Influence of temperature on electrical conductivity of shaly sands. Geophysics, 57(1), 89-96.

Singharajwarapan, F.S., Wood, S. H., Prommakorn, N., and Owens, L., 2012. Northern Thailand Geothermal Resources and Development - A Review and 2012 update. Transactions Geothermal Resources Council, 36, 787-791.

Singharajwarapan, F.S., Wood, S. H., Fuangswasdi, A. , Kriangsak Pirarai, K., 2015. Anomalous Fluoride and warm water wells may indicate blind geothermal systems in Cenozoic basins of Northwestern Thailand. Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015, p. 1-15.

Ussher, G., Harvey, C., Johnstone, R., Anderson, E., 2000. Understanding the resistivities observed in geothermal systems. Proceedings World Geothermal Congress, 2000. Kyushu-Tohoku, Japan. 1915-1918.

Waibel, A.F., 2014, A Consideration of geological settings for and the structural morphology of terrestrial hydrothermal systems. Geothermal Resources Council Transactions 38, 185-193.

Wiwegwin, W. , Hisada, K., Charusiri, P., Kosuwan, S., Pailoplee, S., Saithong, P., Khaowiset, K. and Won-In, K., 2014. Paleoearthquake investigations of the Mae Hong Son Fault, Mae Hong Son region, Northern Thailand. Journal of Earthquake and Tsunami, 8(2), DOI: 10.1142/S1793431114500079

Wood, S.H. and Singharajwarapan, F.S., 2014. Geothermal systems of Northern Thailand and their association with faults active in the Quaternary. Geothermal Resources Council Transactions 38, 607-615.

Ziagos, J.P., and Blackwell, D.D., 1986. A model for the transient termperature effects of horizontal fluid flow in geothermal waters. Journal of Volcanology and Geothermal Research 27, 371-397.