FANG HOT SPRINGS GEOTHERMAL AREA, CHIANG MAI PROVINCE, NORTHERN THAILAND – GEOLOGICAL AND GEOPHYSICAL EXPLORATION IN 2014-2015

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ABSTRACT

Fang Hot Springs binary power plant generates 115-250 kW_e that varies with season. Four wells (92-500 m deep) collectively flow ~ 20 liters/second of 110-115°C water. None of the wells are pumped, nor is the spent water re-injected. Some wells show maximum temperature of 130°C, slightly more than the 124°C temperature predicted by mineral-equilibria modeling of the water geochemistry. Hot wells and seeps are distributed over an 8 hectare area. Producing wells FX-2 and FX-4, 500 m deep are 250 m apart, and lie 200 m distant from the 3 original producing shallow (<92 m) wells FTGE-7, FTGE-14, and FTGE-15. Hot seeps align along a 350° azimuth for a distance of 170 m, and another 150-m alignment of 270° azimuth. Springs and wells are in Triassic (?) gneiss and foliated granite.

Electrical resistivity surveys and a magnetotelluric surveys detect low-resistivity (< 60 ohm m) only within the upper 50-100 m of the hot springs area. No deep low resistivity anomaly is detected in the crystalline rocks beneath the seeps or the producing wells.

The MT survey clearly shows the structure of the shallow-dipping Doi Kia detachment fault that lies to either side of the hot springs area, and also the steeply dipping, NE-SW-striking Mae Chan active strike-slip fault that lies 1 km south of the hot springs area. However, neither of these faults simply relate to the locations and alignments of seeps or locations of producing wells. We have no drill data on fracture orientation. The fracture system is believed to be developed at an intersection of the strike-slip Mae Chan fault with the N-S striking normal fault system near the west side of the Fang basin. Fractures are likely steeply-dipping thin fracture zones with hydrothermal alteration. Future surveys should be designed with precision to study the fractures of the known geothermal area in order to define drilling targets.

Future development for increased electrical power generation should focus on drilling shallow wells (≤ 500 m), with diameters large enough to install submersible pumps to increase flows. Development should include a designed re-injection well system to sustain pump levels.

1. INTRODUCTION

Important to the further development of the Fang Hot Springs geothermal area is an understanding of the fault system geometry that conducts hot water to the surface. Ideally we would like to know the location of the main fault conduits for hot water, the strike and dip of the fault planes and width of the permeable fault zone. In this paper we describe the geology of the hot springs, document the wells and seeps and incorporate results from an earlier resistivity survey and a recent MT survey and make recommendations for further development.

The geothermal system was initially investigated by EGAT (Electricity Generating Authority of Thailand), Chiang Mai University Geological Sciences, and several foreign research groups in the1970's and 1980's. Successful wells that were drilled in the 1980's and

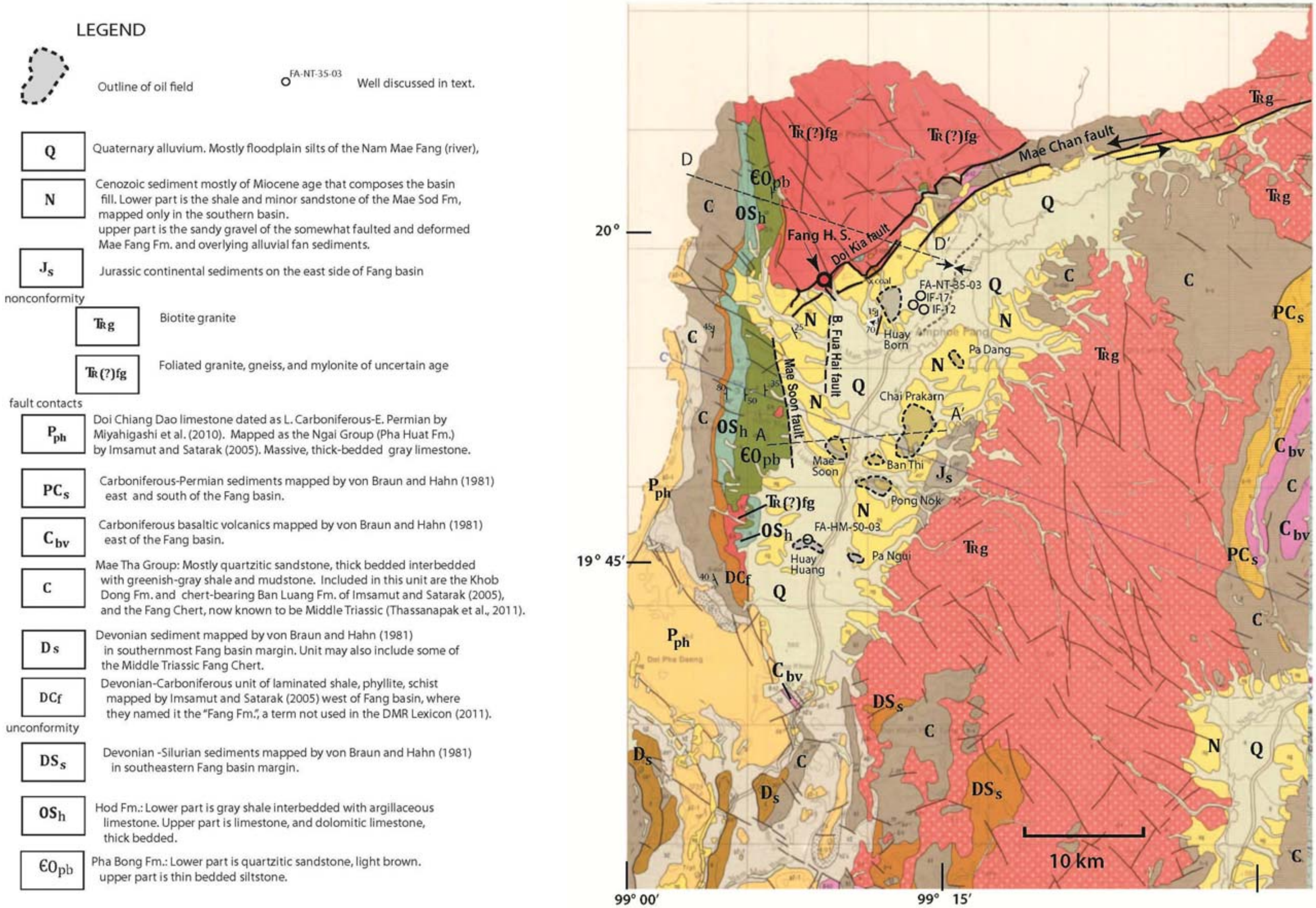

Fig. 2. Geologic map of the Fang Basin area from von Braun and Haun (1981). We label the map with formation names from Imsamut and Satarak (2005) and the Thailand Department of Mineral Resources (2013), recognizing that recent detailed mapping has changed the outcrop areas and re-assigned ages from the 1981 map.

1990's collectively produced 22 l/s of 125°C water. A 300 kW_e binary power plant was installed in 1989. A new round of exploration of northern Thailand geothermal resources was initiated in 2010 funded by the Thailand Department of Alternative Energy Development and Efficiency (Singharjwarapan et al., 2012). ORMAT Corporation examined the geothermal systems for potential siting of power plants (Owens, 2012). The Thailand Department of Groundwater Resources funded investigations by Chiang Mai University, Mahidol University, and Panya Consultants, Ltd. in 2013 (Ensol and P&C Companies, Ltd., 2015). Focus of these studies was to evaluate sites throughout Thailand for drilling new wells for electrical power generation.

2. GEOLOGY AT THE GEOTHERMAL AREA

Fang Hot Springs and producing geothermal wells flow from Triassic (?) crystalline rocks at the NW boundary of the Cenozoic Fang basin. The geothermal area is 140 km north of Chiang Mai City and 9 km NW of Fang (Figs 1, 2, 3 and 4).

The NE-SW trending Mae Chan active left-lateral fault (Kosuwan et al., 1999a, 1999b; Wood and Singharajwarapan, 2014; Weldon, 2015) trends about 1 km south hot springs, and is the obvious large structure with physiographic expression. The fault forms a steeply dipping contact (based on MT data) of the Paleozoic sediments with late Cenozoic deposits: alluvial-fan sediments, the underlying coarse-clastic sediments of the Mae Fang Formation, and the shaly Mae Sot Formation. Contact of the Paleozoic sediment with the Triassic (?) "stressed granite" and mylonite also trends NE-SW similar to the Mae Chan fault, however, the "v-shape" outcrop pattern shows a shallow SE dip indicating the contact is a low-angle normal fault, or a detachment fault (Fig. 2 and 3). Interestingly, the Mae Chan fault trace has right-stepping segments, and the connecting short NW-trending fault appears related to the hot springs, and the orientation of the major hot seeps and wells.

Previous mapping outlines the distribution of rock types, but does not clearly indicate fault contacts. On Fig. 2, linear topographic features believed to be the western part of the Mae Chan fault are shown by a dashed line. Google earth images clearly show these features as edges of hilly topography and as aligned saddles along ridges in the hills. The fault contact is exposed in the bed of the Nam Mae Chai (river) at GPS location (516800E, 2206470N, WGS 84).

Lithology found in the early geothermal drilling was mostly granitic and cataclastic rocks; however FTGE-2, BH-3 and BH-5 drilled into quartzite (Ratanasthien et al., 1985, p. 19). We We have been unable to obtain records of lithology for wells drilled since 1982 (wells since FTGE-5). The cataclastic nature of the foliated granite and gneiss is confirmed by geologists from Chiang Mai University who describe the rock as mylonitic gneiss and schist (Ensol and P&C Companies., Ltd, 2015).

3. LOCATION, NATURAL FLOW AND TEMPERATURE OF SEEPS

An estimate of the collective hot springs seeps of 30 liters/s was made by Nathan (1976) prior to development wells. Ramingwong et al (1980) accurately monitored the natural thermal water discharge 1974-1979, and determined an average discharge of 20 l/s and fluctuations of about 5 liters/s. The highest discharge of about 28 liters/s occurred in the latter part of the rainy season. In February, 2015, seeps were located with hand-held GPS units, temperatures measured, and individual seep flows estimated. The highest temperature seeps are distributed along 200 m of N-NW zone trending azimuth 340-350° (Figs. 4 and 5). The zone is located 50 m west of the producing wells, FTGE-15, -7, sand -14. Seep temperatures in this zone range from 95.7 to 98.6°C. The boiling point of water at this elevation of 600 m is 99.3°C. Another broader zone of 77-89°C seeps trends 120 m to the east of this hot zone. Five small seeps 55.7-71.2°C are scattered in a broad group 450 m to the NE of the hottest zone. A warm springs of unknown temperature previously flowed from the N 40°W fault of the Huai San Fluorspar Mine, ~1.1 km SE of the main seep area (Shawe, 1984). Our estimates of the largest individual seep flows ranged 0.1 to 0.3 liters/s, at 8 locations. Collectively the warm water outflow of the hot-springs stream at 16150E, 07550N is estimated at 10 liters/s in February, 2015.

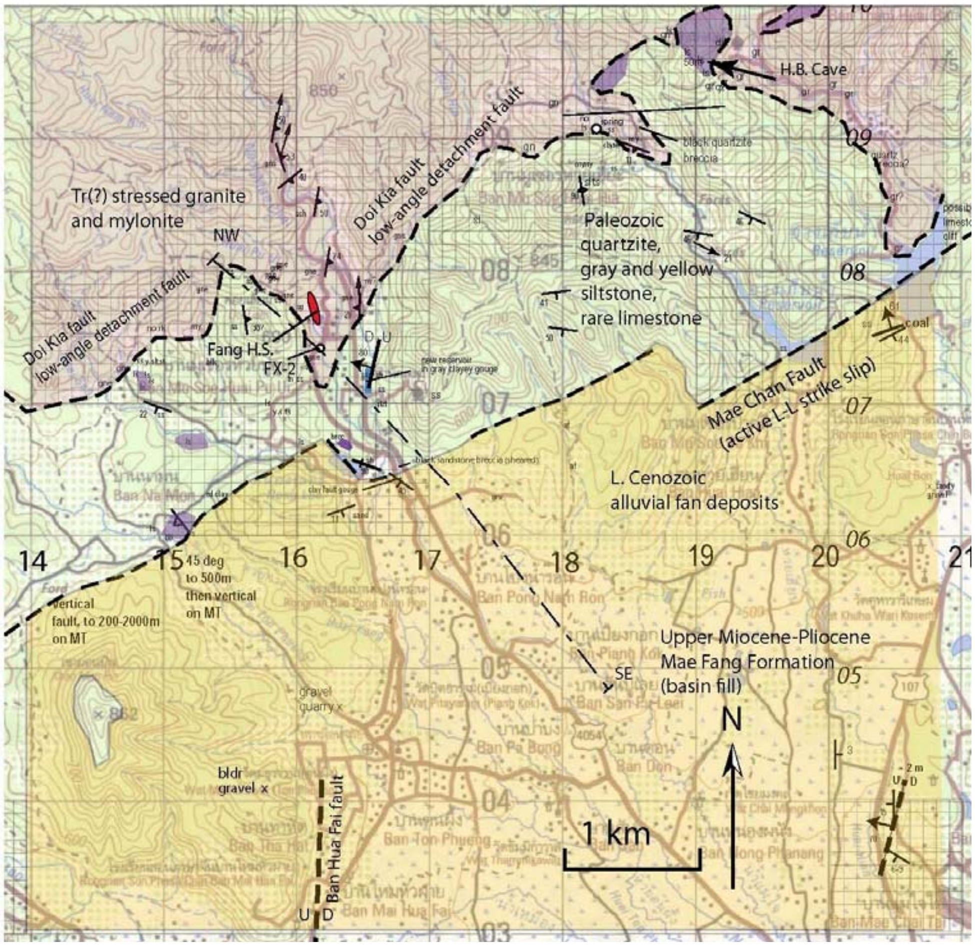

Fig. 2. Geologic map of the Fang geothermal area based on mapping by Dr. Burapha Phajuy and colleagues at Chiang Mai University published in Ensol Co., Ltd. (2015) and by the authors (2015-16). The irregular contact of Paleozoic sedimentary rock with Triassic (?) crystalline rocks is interpreted as a low-angle normal detachment fault, called the Doi Kia fault, originally named by Chaturongkawanich et al. (1980).

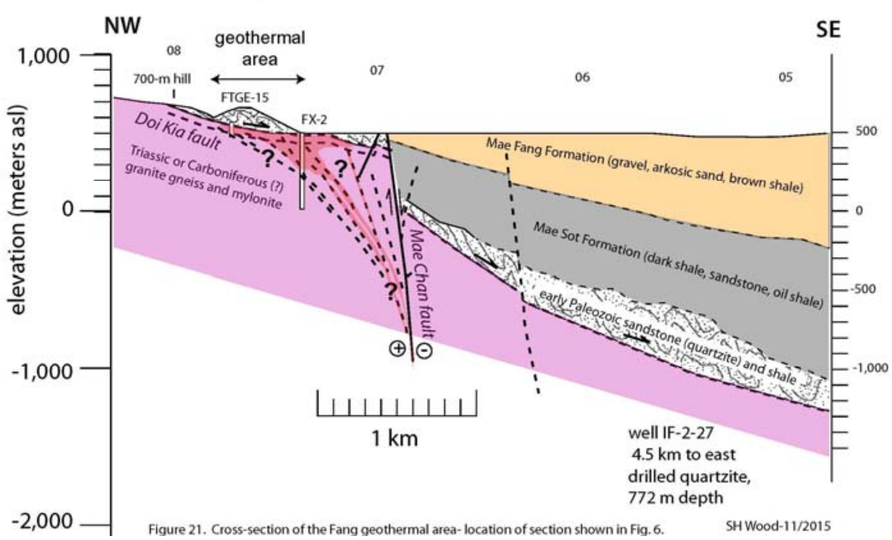

Fig. 3. Geologic cross-section of the Fang geothermal area. Red shaded area is a conceptual depiction of the flow of hot water. Location of section shown in Fig. 2. .

Fig. 4. Photograph looking west at the hot springs area and steam plume from the FTGE-7 well. Hot springs area is studded with core stones of foliated granite.

4. LOCATIONS OF WELLS, DRILLING HISTORY, AND POWER PLANT OPERATION.

In February, 2015 we obtained UTM coordinates of most of the early wells with the help of EGAT staff: Khun Pitak and Khun Inton (Fig. 5 and Table 1). Available maps showing locations of early wells are in publications by Wanaksem and Takabut (1986), Coothungkul and Chinapongsanond (1985). Locations on those maps differ slightly (some are ± ~ 70 m) from the UTM Coordinates we establish. A number of wells could not be located: FGTE-2, FTGE-6, FTGE-10, BH-8, BH-11, FX-1, and FX-3. We hope to eventually obtain locations and well information from EGAT, as past drilling information is important to any further exploration.

Drilling of the geothermal system was begun about 1982 in a cooperative agreement between the Electricity Generation Authority of Thailand (EGAT) and the Bureau de Recherches Geologiques et Minieres (BGRM) and Geowatt of France (Wanakasem and Takabut, 1986). Twelve shallow wells with target depths of 100 m were drilled in the area of relatively low electrical resistivity (FTGE 1 through 12, Table 1). Eight slim holes were drilled by EGAT in 1984 to confirm the productive area of the shallow fractured reservoir. Productive flows were obtained from BH-3, BH-4, and BH-8 (Table 1). In late 1985 to early 1986, FTGE-14 and FTGE-15 were drilled to 73 m and 60 m respectively, and obtained a combined flow of 22 liters/s at 125°C (Table 1). Production testing confirmed a reliable flow, and in December, 1989 the 300 kW_e ORMAT power plant was put into operation (Kordejee, 2000).

Further geological, electrical geophysics, and geochemistry studies were done in 1990 in cooperation with the French Environment and Energy Management Agency (ADEME) (Korjedee, 2000), but we have not located those reports. These studies led to drilling of 4 wells: FX-1 through FX-4 wells with targets 500 m deep, currently the deepest wells in the system. FX-1 and FX-3 were non productive and had bottom hole temperatures of 108°C and 113°C respectively. Locations of these two wells are not known at time of writing. The FX-2 well was completed into a fracture at 270 m depth, and produced 7.0 liters/s of 125°C water. The FX-4 well drilled to 500 m and completed into fractures at depths 268, 337, and 417 m and a bottom hole temperature of 130°C (Korjedee, 2000). The well produced 10 liters/s (Ramingwong et al., 2000). FX-4 and FX-2 were connected to the power plant supply in 1996, and now produce 120°C water (Khun Inton, personal communication, 2015). We have

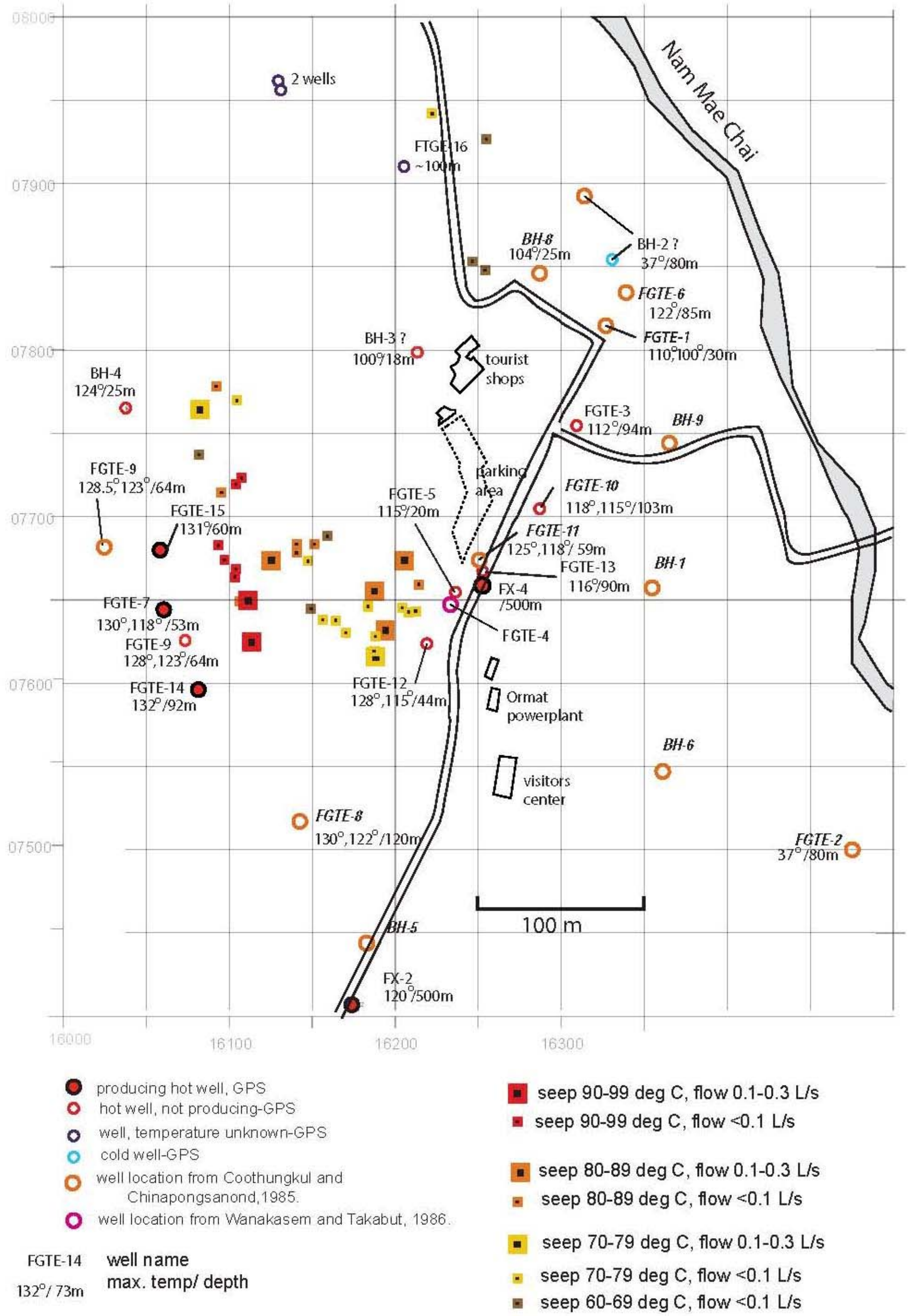

Figure 5. Map showing hot-spring seeps and locations of wells surveyed in 2015. Maximum temperatures of wells shown in this figure are from Chuaviroj (1987) and listed in Table 1. Well temperatures reported by Wanakasem and Takabut (1986) on some wells are 10°C lower for unknown reasons.

been unable to obtain logs, temperature profiles, or production tests from the wells. Table 1 is compiled from all information available at this time.

The FTGE-7 well (53 m deep) is engineered to produce a 15 m high "geyser" as a tourist attraction. The natural well flow is shut in every 30 minutes and the opened for 3 minutes to produce the spout that declines in height until shut in.

As of 2015, the generating system produces from 4 wells, FTGE-14, FTGE-15, FX-2 and FX-4 (original test flows and temperatures shown in Table 1). On a two-week cycle, three wells flow to the power plant at any one time, while one well is reamed and its flow, while reaming, is spilled to a stream to clean scaling. The collective flow from three wells is ~20 l/s of 110-115°C water, somewhat less than earlier tests (Table 1) on account aging wells, perhaps cold-water leakage and transmission losses. Each well has a steam separator, and the steam released to the atmosphere without using the steam energy. The flow goes to the ORMAT binary plant rated at 300 kW_e, and the spent water at 75-80°C is sprayed to a cooling pond, where it cools to ~ 27°C, and then flows to the Nam Mae Chai (river), a stream that has a typical base flow of ~ 1.5 m^3/s. The geothermal water is not re-injected. Cool water (15-30°C) is drawn from the river at a rate up to 97 L/s to cool the working fluid in the cooling condenser. The cooling tower originally installed has not operated for many years. The power plant generates 115-250 kW_e that varies with season.

5. GEOCHEMISTRY OF THE GEOTHERMAL WATER

Ion chemistry of water sampled from the flowing wells and seeps are dominated Na and HCO_3 (~120 ppm, ~100 ppm, respectively). pH values are high, ~ 9.1. Total dissolved solid values are relatively low 440 mg/l (EC is 550 µS/cm). Silica and fluoride concentrations are high at 170 ppm, and 20 ppm, respectively. Mineral equilibria modeling suggests equilibrium concentrations at 122-124° (Fig. 6). Using the Giggenbach et al. (1994) plots of (log(Na/K) vs. log(SiO_2) and log(K^2/Mg) vs. log(SiO_2), Appollaro et al. (2015) obtain apparent equilibrium temperatures of 150±5°C, considerably higher than those obtained by us. They further evaluate the volume of the geothermal reservoir at Fang using $_3$H-based residence time and the natural flow rate.

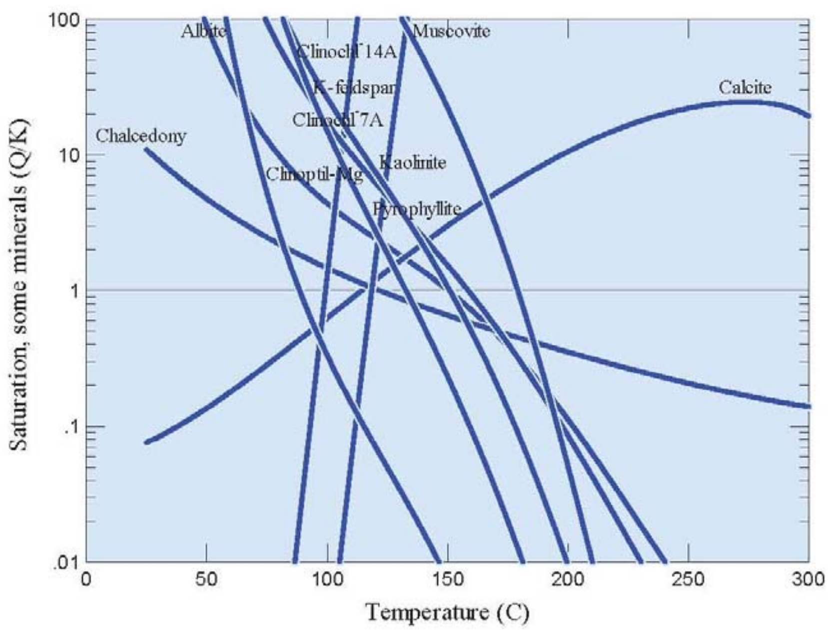

Figure 6. Mineral equilibria model for water from the flowing 97.5°C seep, 40 m east of FTGE-15: sample CM-03-6. Model suggests deeper reservoir is 124°C (from Owens, 2014).

TABLE 1. Wells drilled in the Fang geothermal area

Well name	depth (m)	Flow Temp °C	Maximum Temp°C	flow(l/s)	open hole depth (m)	open hole diameter (cm)	surface csg. diam. (cm)/ depth (m)	type csg. OD/ID (cm)	lower csg. Diam. (cm)/ depth (m)	type csg. OD/ID (cm)	well head press. (bars)	source	remarks	WGS84 easting	WGS84 northing	date drilled
FTGE-1	29(BR), 30(C)		100(C), 110(BR)		30	32.4						c, wt, br	110 deg at 25 m, intermittant shooting flow 30-m high, well collapsed (br)	516.325*	2207.813*	5/1982
FTGE-2	80		37			13.75, 17.1 to 80 m	none					c, wt, br		516.425*	2207.500*	6/1982
FTGE-3	94	98	111.8	1.0-- 2.0	80	17.145	20.32/ 13.75	21.91/ 20.247				c, wt, br	111.8 deg at bottom, flow includes small amount of steam (br)	516.309	2207.754	8/1982
FTGE-4												c, wt, br	eruption of water occurred before casing set, we collapsed (br)	516.235*	2207.645*	1982 (?)
FTGE-5	19.6	105	115	2.0- 4.0	13.1	32.4 to 13.75, 17.1 to 80 m	20.32/ 14	21.91/ 20.247				c, wt, br	max temp after closing well 20 min (BR), presently marked by 1.5m brick outline(ki)	516.236	2207.654	before 1986
FTGE-6	85.4		122.3(c), 93.7(wt)	none	56	14.287	20.32/ 6	21.91/ 21.156	15.24/ 29.4	16.61/ 15.64		c, wt	"dry hole"(wt). location unknown	516.340*	2207.835*	before 1986
FTGE-7	52.7	105	130.2(br) 118(wt)	3.80	35	14.287	20.32/ 6	21.91/ 21.156	15.24/ 29.4	16.61/ 15.64		c, wt	not used for power. Shut in for 30 min. intervals, and then geysers 35 m high (ki)	516.061	2207.643	before 1986
FTGE-8	120	105	130(c) 122(wt)	0.20	96	14.287	20.32/ 6	21.91/ 21.156	15.24/ 29.4	16.61/ 15.64		c, wt		516.142*	2207.515*	before 1986
FTGE-9	64	105	128.5(c) 123(wt)	0.60	34	14.287	20.32/ 11.5	21.91/ 21.156	15.24/ 30	16.83/ 15.48		c, wt		516.073	2207.625	before 1986
FTGE-10	103.3		118.4 (c) 115(wt)	none	79.3	14.287	20.32/ 2	21.91/ 21.156	15.24/ 24	16.83/ 15.49		c, wt	said to be up on hill north of large tree above FTGE-15 (ki)	?	?	before 1986
FTGE-11	58.8	105	125(c) 118(wt)	0.60	40.8	14.287	20.32/ 7	21.91/ 21.157	15.24/ 18	16.83/ 15.50		c, wt	intermediate flow	516.286	2207.704	before 1986

TABLE 1 (Continued). Wells drilled in the Fang geothermal area

FTGE-12	43.7	105	128.1 (c) 115(wt)	4.01	37.7	14.287	20.32/ 6.5	21.91/ 21.158	15.24/ 6?	16.83/ 15.51		c, wt	steady flow	516.218	2207.624	before 1986
FTGE-13	90	105	115.8	1.00	72	14.287	20.32/ 6	21.91/ 21.159	15.24/ 18	16.83/ 15.52		c,	intermediate flow	516.253	2207.667	before 1986
*FTGE-14	73.2 (c) 92(ki)	110	131.6	7.94	64.2	14.287	20.32/6	21.91/ 21.160	15.24/ 9	16.83/ 15.53	1.5	c,	steady flow (c) , said to be 92 m deep with hot water inflow at 18m/38m/66m (ki). Also called the "Khun Theptorn well"	516.081	2207.595	1985-86
*FTGE-15	60.5 (c), 160 (ki)	121	130.6	13.97	52.5	14.287	20.32/6	21.91/ 21.161	15.24/ 8	16.83/ 15.54	1.5	c,	said to be 160 m deep with hot water inflow at 60 m (ki). Also named "Khun Wichian well"	516.058	2207.678	1985-86
FTGE-16	(ki)												no information	516.205	2207.910	1986
FX-1	500		108	none								tk	location unknown	?	?	1995(?)
*FX-2	500	125				6.94					1.5	tk	fracture zone at 270 produces 6.94 l/s of 125°C	516.177	2207.404	1995(?)
FX-3	500		113	none								tk	location unknown	?	?	1995(?)
*FX-4	500		130			10 ?						tk	fracture zones at 268, 337, and 417 m. (tk) indicates a total flow of 10 l/s, but inclear if this is a total of FTX-2 and FTX-4	516.251	2207.658	1995(?)
BH-3	18	100	110	1.00	14	7.302	7.62/4	10.16/ 9.012				c, wt, br	steady flow (wt)	516.213*	2207.798*	6/1984
BH-4	34.7	100	124	0.50	27.7	7.302	10.16/7	11.43/ 10.22			0.85	c, wt, br	steady flow (wt)	516.038*	2207.765*	6/1984
BH-8	25	104	110	1.50	12.2	7.302	8.89/12 .8	10.16/ 9.012				c, wt, br	steady flow (wt)	516.285*	2207.846*	6/1984
BH-11				1.00								wt	steady flow (wt), location unknowr	?	?	6/1984
2 wells												ki	2 wells, 5 m apart near sign (Ing-Doi camp)	516.130	2207.956	?
Bo Luang Camp												ki	this might be BH-3 or BH-8	516.213	2207.798	?

(br) Ratanasthien et al., 1985, (c) Chuaviroj, 1987. (wt)Wanakasem and Takabut, 1986. (tk) Korjedee, 2002. (ki) Khun Inton (EGAT at Fang, 2015) personal communication.

note that Chuaviroj (1987) reports higher maximum temperature than does Wanakasem and Takabut(1986)

* on UTM location indicates it has been scaled from scans of maps by Coothungkul and Chinapongsanond (1986) and Wanakasem and Takabut (1986)

6. INTERPRETATION OF THE RESISTIVITY SURVEYS

In 2014-2015 Mahidol University completed a 3-D magnetotelluric (MT) survey of the area. Results of that project image electrical-resistivity structure to 2 km depth (Amatyakul et al., 2016). MT measurements were made at 25 points spaced 250 to 1000 m apart over a ~ 20 km^2 area south of the hot springs (Fig. 7). The MT (profile b) very robustly shows the high resistivity (>300 ohm m, colored blue) crystalline rock overlain by low resistivity (<30 ohm m, colored yellow and orange) material to a depth of ~ 80 m at the hot springs area (Fig. 7). That upper layer of low resistivity material is believed to be hydrothermally altered crystalline rock as observed by Ratanasthien et al (1985; p. 94-96) in the upper 23 m of well FTGE-7.

Measured electrical conductance of water from the wells is 550µS/cm at 25°C, which converts to a geothermal fluid resistivity (R_w) of 6 ohm m at 120°C using Arp's equation (Sen and Goode, 1992) to correct for temperature. Using Pirson's (1977) model for the resistivity of fractured non-conductive rock, a 30-ohm-m rock would require an unreasonably high fracture porosity of 20 percent, filled with 6 ohm m water. For this reason these broad areas of low resistivity may not be caused solely by hot water in fractures. More likely these low resistivity anomalies in crystalline rocks are caused by conductive clay minerals in hydrothermal alteration zones (cf: Ussher et al., 2000) and possibly some contribution from pyrite. We are uncertain if the hot water in fractures contributes significantly to the low resistivity anomalies at Fang.

The profiles (Figs. 7 (a) and (b)) show the top of the crystalline rock dipping south at about 22° beneath low resistivity material, from station 800 to 1400 m, and this is interpreted to be the contact between crystalline rock and overlying Paleozoic sediment. At station 1900 the crystalline rock interface steepens, with a high-angle to vertical contact. This is the position of the mapped trace of the Mae Chan fault (Fig. 2), indicating the fault has a steep dip and considerable vertical offset (> 2 km on profile (a). The low resistivity material to the SE of the Mae Chan fault is the Cenozoic basin fill sediment of which the sediment from 300 to 800 m depth has resistivity less than 10 ohm m, owing to the clay sediment. Horizontal slices (map views) of the 3D MT survey published by Amatyakul et al. (2016) clearly show the NE-SW striking boundary of the crystalline rock at depth.

The hot springs area underlain by crystalline rocks, shows only moderately low resistivity at the 25 m level (< 40 ohm m) over an 150,000 m^2 area, and <20 ohm m over a 40,000 m^2 area. This anomaly, labeled "C1" on Fig. 7 disappears at 50 m depth, and the deeper levels generally have high resistivity (100-300 ohm m).

Three hundred meters southeast of FX-2 well is a 15-m deep reservoir excavation (in February, 2016) into gray clay with scattered sheared quartzite fragments. We interpret this as gouge between the crystalline rocks and the overlying detachment of Paleozoic quartzite. This gouge may contribute to low resistivity in the hills to either side of the hot springs area, but it has been eroded from the hot springs area.

On both profiles (a) and (b) of Fig. 7, between stations 2000 and 2700 m is a low resistivity anomaly labeled "C2" by Amatyakul et al. (2016). The "C2" anomaly is broadest at depth 200 m (Fig. 8). This anomaly occurs in a complex structural area where the trace of the Mae Chan fault takes a step to the right. It is also the area of the fluorspar mine with a warm springs seep described by Shawe (1984). The mine pit originally 700 m long is now filled with water, but at its south end is an exposure of black carbonaceous shale disseminated pyrite suggesting that the "C2" anomaly may be partly caused by conductive minerals and not necessarily hot water in fractures.

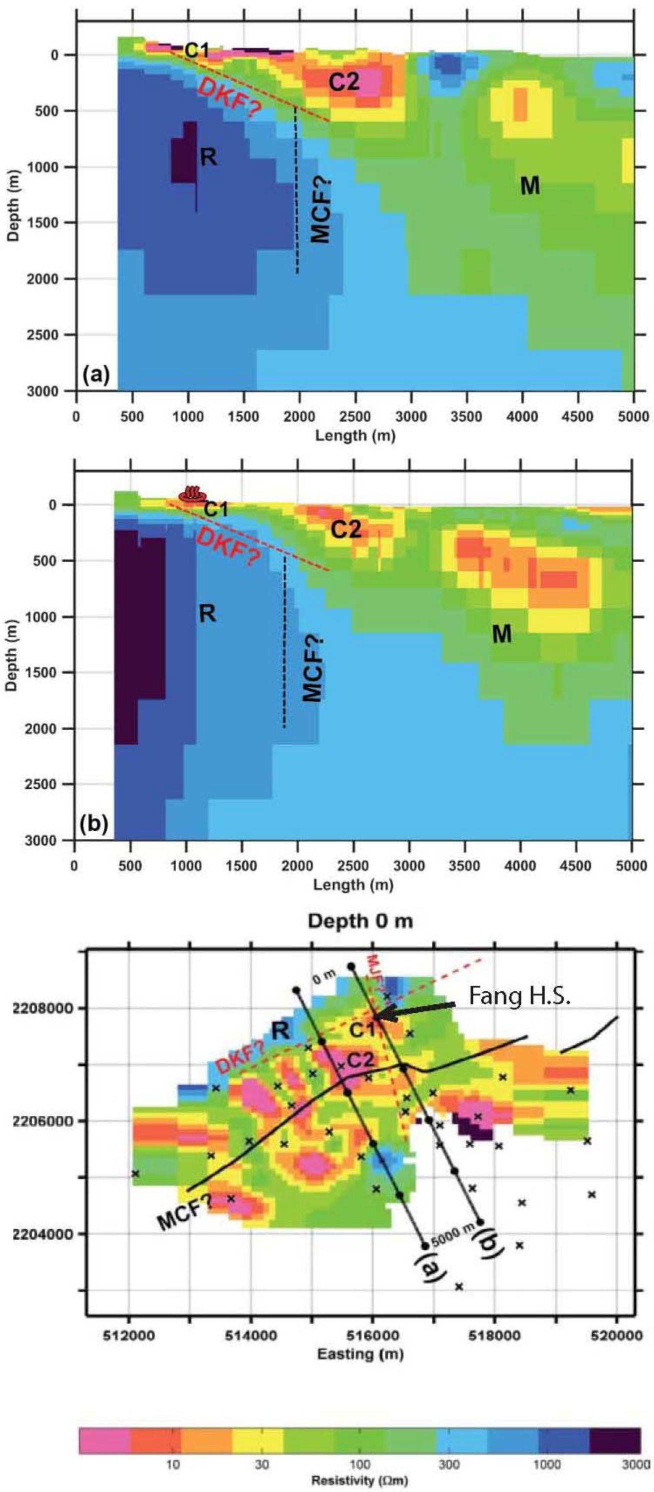

Figure 7. MT profiles and map of near surface anomaly (0 depth) from Amatyakul et al. (2016).

The map slices of the MT data (Amatyakul et al., 2016) show that 3 areas underlain by very low (<12 ohm m) resistivity lie adjacent and south of the Mae Chan fault trace (Fig. 8). These anomalies extend vertically from 100 m to 400 m depth, and are broadest at 200 m depth. We show the outline of the anomaly of the 200 m level on Fig. 8. Because these "C2" anomalies occur in the Cenozoic sediments southeast of the fault we interpret them as shale bodies. We know from resistivity logs of oil wells that shale in the Mae Sot Formation typically has a resistivity of 5-10 ohm m, and is 400 or more meters thick in the southern Fang basin (Giao et al., 2011).

At a location 400 m southwest of well FX-2 and 300 m due south of the topographic-map "hill 690" is a N-S oriented anomaly (< 12 ohm m) at the 25-100 m depth, that extends south 900 m to the south and is 200 m wide at the 50-m level (Fig.8). We label this on Fig. 8 at the "C3" anomaly. The central part shows a resistivity < 5 ohm m. This anomaly occurs in the area underlain by Paleozoic sediment, just north of the Mae Chan fault, but appears to extend south of the fault to the 200 m level at "C2" where it is much broader. Although we believe that low resistivity south of the fault is primarily due to shaly Cenozoic sediment, the N-S linear nature of this shallow anomaly "C3" north of the fault may have significance, perhaps as the manifestation of a conduit for hot water and hydrothermal alteration in a zone leading north toward FX-2. Such a zone may be associated with a permeable fractured damage zone of the Mae Chan fault.

In the hot springs and wells area, similar results to the "C1" anomaly were obtained by

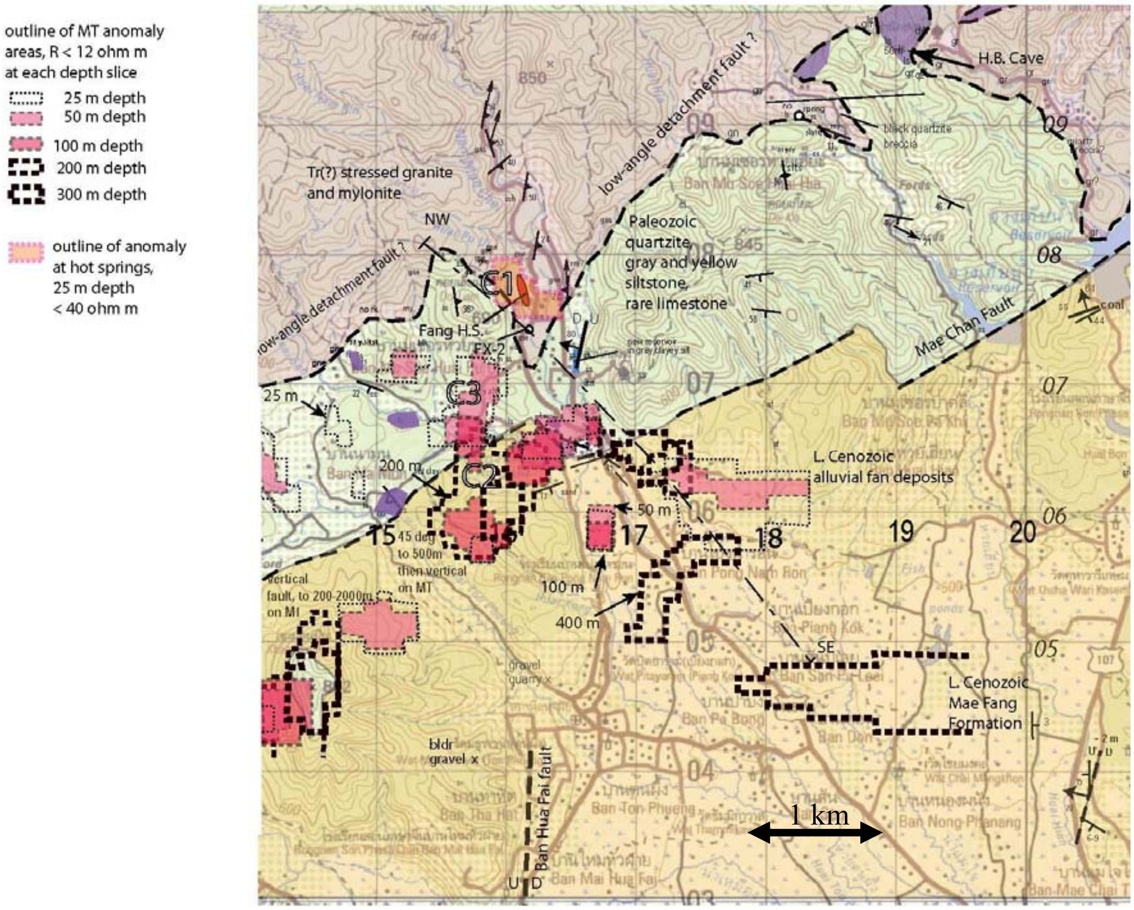

Figure 8. Zones of low resistivity determined by the 3D Magnetotelluric (MT) survey by Amatyakul et al. (2016) superposed on the geologic map. In their paper they show map slices at 0, 50, 200, 400, 600, and 1000 m depths and we have outlined areas of low resistivity from those maps slices for this illustration. The 25-m depth outline of <40 ohm m at the hot springs is from an earlier report on the survey by Weerachai Siripunvaraporn published in Ensol and P&C Companies, Ltd. (2015). C2 and C3 anomalies are labeled.

Coothungkul and Chinapongsanond (1985), where they show low resistivity only at shallow depth. They mapped a NE-SW trending low resistivity anomaly of 60 ohm m at the AB/2 = 100 m under a 25,000 m^2 area (Fig. 9). The anomaly was 30 ohm m, and narrower at the AB/2 = 50 m. Therefore, it appears that crystalline rocks in the hot springs area have anomalous, but moderately low resistivities, and the anomalous zones are quite narrow, < 200 m wide, linear, and shallow. This suggests that the thermal waters are in narrow fracture zones, and future geophysical methods need to be designed for greater precision and coverage than has hitherto been done. The Schlumberger soundings of Coothungkul and Chinapongsanond (1985) (700m to 2 km spacing) show low resistivity (< 25 ohm m) over the hot spring area to a depth of ~ 50 m, below which the resistivity is greater than 100 ohm m.

Whilst much of this discussion attributes low resistivity to shale and conductive minerals, the temperature of the pore water must also contribute. The distinction between the effect of conductive minerals and the effect of temperature cannot be made with existing information.

7. RECOMMENDATIONS

Good spatial resolution of the low-resistivity hot springs area is needed to explore (50-400 for hydrothermal alteration zones as indicators of the main fractures. The 500-m FX-2 well

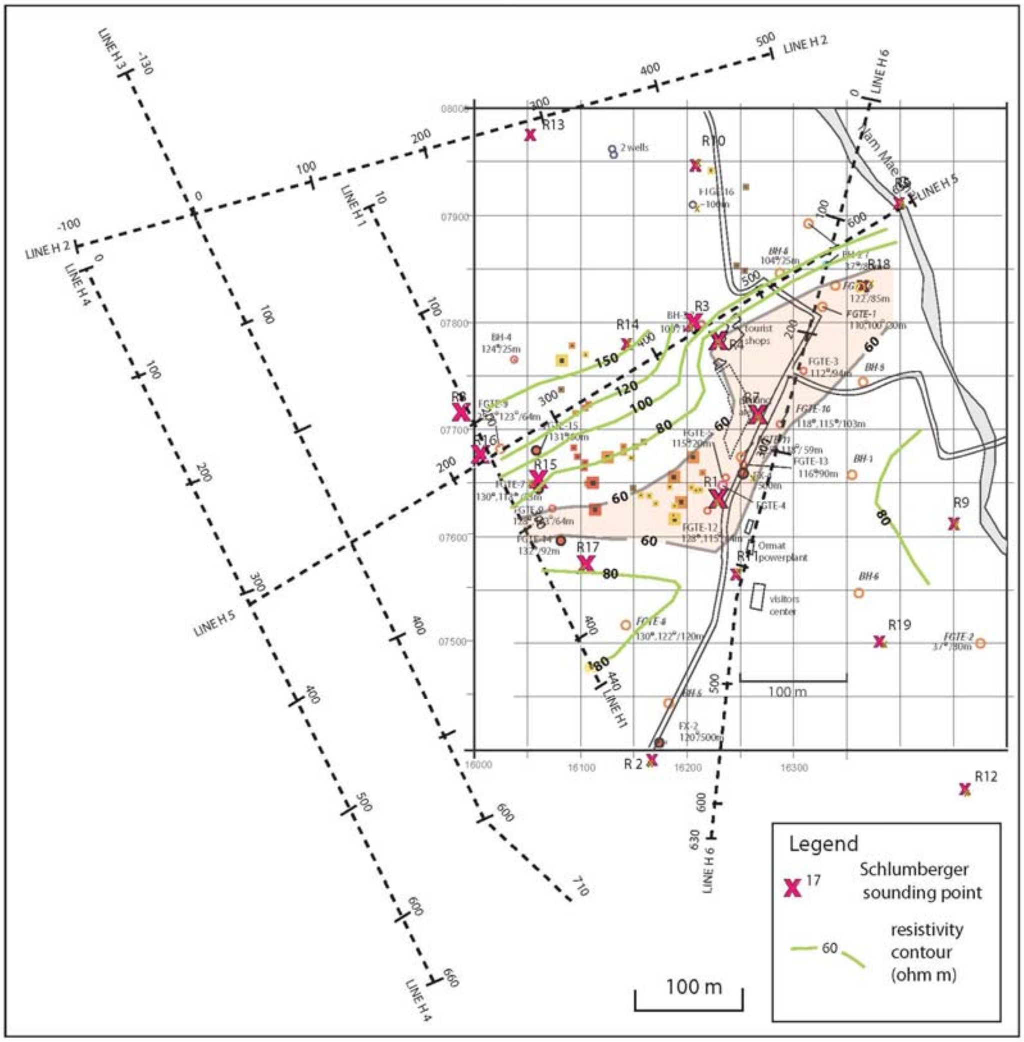

Figure 9. Resistivity map for AB/2 = 100 m from Coothungkul and Chinapongsanond (1985). Their report shows maps for AB/2 = 5, 25, 50, 80 and 100 m, with similar configuration for of anomalously low resistivity, shown by the red shaded area < 60 ohm m. Dipole-dipole line data nor Schlumberger sounding data not shown in this report. See Figure 5 for better resolution of well names within the gridded area.

was drilled 200 m south of the known seepage area. We do not know the strategy of that 1995 location, but the well is at the south edge of the 1984 survey coverage, where low apparent resistivity (30-50 ohm m) is at the south ends of lines H-1 and H-6 (data not shown in the present paper). A Schlumberger sounding near FX-2 well showed resistivity from ~30 ohm m below 30 m depth to a depth of about 100 m. It should be relatively inexpensive to obtain detailed 2D profiling, or 3D coverage to a depth of 100 m, and interpret this survey with respect to seepage areas and previous drilling. The survey should include the known geothermal area and continued south to examine more closely the “C2” and “C3” anomalies detected by the MT survey.

The wells currently produce by natural flow. Greater flow could be obtained by pumping the wells, but these wells have never been pump tested. The existing wells are old (> 20 years), have accumulated scale, and the casings have presumably partly deteriorated. Many successful exploratory wells in the past (temperatures > 110°C), are shallow (<150 m), so the cost of new wells is not great. The problem has been to drill into a fracture system that will produce > 5 L/s. The area underlain by fracture systems bearing hot water appears to be overlain by low-resistivity altered granite to a depth of 25 to 50 m, as shown by past geophysical surveys and the recent MT survey of Amatyakul et al. (2016). Reports from past wells are not detailed, but fractures from 18 m to 417 m are reported from wells FTGE-14, FTGE-15, FX-2, FX-4 (Table 1). A simple strategy is to drill new wells into the low-resistivity areas to depths less than 300 m, and obtain good information from cuttings, and temperature and caliper logs to locate the fracture systems Well design should case and cement off cold water inflows. A budget for multiple wells is necessary because these wells are exploring for steeply-dipping open fractures capable of producing water, and some may not encounter a producing fracture. The wells are to some extent exploratory, but they should be drilled so that they can be completed as production or re-injection wells. Diameter of wells should be large enough to set a >6 L/s submersible pump (in principle, 6 L/s of 115°C water should contribute about 0.075 MW_e to a generating plant). Exploratory drilling and production wells should also be designed to allow for a re-injection well system.

8. CONCLUSIONS

The Fang geothermal area has not been explored by drilling since 1995. Current generation from the ORMAT power plant is much less than the rated 300 kW_e, largely because of lower flows and temperatures from old wells and the aging plant and cooling system. MT and resistivity surveys, at the hot seep and well area, show low resistivity to a depth of ~60 m, below which are highly resistive crystalline rocks. The system appears to be fed by steeply dipping fractures in crystalline rock that are not imaged with widely spaced recording points or electrodes of resistivity surveys. Detailed electrical surveys using closely space recording points might be successful in imaging fractures known to feed the FX-2 and FX-4 wells at 270-417 m depth, and if successful used to design a larger 2-D or 3-D survey for drilling targets. Relatively shallow wells (<500 m) have been successful obtaining in useful flows.

Future development with new wells and an upgraded power plant should more than exceed 1 MW_e of electrical power. Spent geothermal waters should be re-injected in an engineered system in order to maintain flow, pressure and temperature of producing wells.

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