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Delineating Geothermal Systems from Geochemical Characteristics of Hot Spring Water in Southern Thailand

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ABSTRACT

Like in many parts of the world, the electricity demand in Southern Thailand is still steadily increasing due to ongoing industrial development and international tourism, as many people visit the wonderful beaches and mountains every year. On the other site, Southern Thailand hosts more than 30 hot springs, and surface manifestations of active geothermal systems at depth, providing a potential source of regenerative energy with almost zero CO_2 emission. To tap this potential a better understanding of the geothermal systems at depth is required. Besides other methods, e.g. geophysical, geochemical data of hot spring waters can provide information about the subsurface, for example, to estimate the minimum temperature expected at depth, to infer the chemical character and homogeneity of the hot water at depth, and to determine the source of the recharge water. From these boundaries of different geothermal systems at depth can be delineated taken into account available surface geological aspects; this has been attempted in Southern Thailand. The 30 hot spring sites are located in following provinces, Chumphon (CP), Ranong (RN), Surat Thani (SR), Phang Nga (PG), Krabi (KB), Trang (TR), Phatthalung (PL), and Yala (YA), and they are consecutively numbered. Surface temperatures range from 40 to 80 °C, and pH values of all water samples are in a range between 6.7 and 8.4. For total dissolved solids (TDS), content is in general moderate with some quite high exceptions, SR1, SR3, KB2, KB4, and TR2; mostly related to higher Na^+ and Cl^- content and a minor extent of Ca^{2+}, K^+, and SO_4^{2-}. These five hot springs are all more or less influenced by shallower marine water ingression as their locations are relatively close to an estuary or a major river system connecting to the ocean. Most of the hot spring water samples are illustrated that waters are Ca–Na–bicarbonate rich waters and classified into Ca^{2+}–Na^+–K^+–(Mg^{2+})–HCO^{3-} water, but excepted waters from KB and SR systems are indicated a high chloride concentration. Difference between silica and cation geothermometers indicate and separate mixing of the original hot waters with near-surface groundwater. From the synthesis of all available geochemical data hot springs in Southern Thailand can be grouped into four major geothermal systems: (1) RN-PG along two major faults zones, (2) SR-CP, (3) KB-TR, and (4) PL. YL is an isolated hot spring in the south near the Malaysian border. Only the RN-PG group provides hot water with lower TDS content and shows a relatively high potential for electrical energy generation.

1. INTRODUCTION

Hot spring geothermal systems of Thailand are of non-volcanic origin (Charusiri et al., 2000), with heat sources considered to be the decay of granitic rocks, which are widely distributed from the north to the south. More than 112 hot springs can be found in Thailand (Barr et al., 1979; Praserdvigai, 1986; Raksaskulwong, 2008), with surface exit temperatures recorded from 40 to 100 °C. Geochemical investigations were done, for example, by Chaturongkawanich and Leevongchareon (2000), Subtavewung et al., (2005), Ngansom and Durrast (2016), and Ngansom et al. (2017). Hot water is mainly used for spa and tourism purposes; only the Fang geothermal system in Northern Thailand is used for electricity generation (Chuaviroj, 1988; Korjedee, 2002; Raksaskulwong, 2004; Raksaskulwong, 2011). Geothermal exploration in the 1970s of the Fang geothermal system resulted in the first and only geothermal power plant of the country (Wanakasem and Takabut, 1986; Apollaro et al., 2015). Although the 300 kW-Fang geothermal plant is of relatively small scale it was a very important cornerstone, representing the beginning of geothermal energy production in Thailand and neighboring countries (e.g. Praserdvigai, 1986; Chuaviroj, 1988).

In Southern Thailand, at least 30 natural hot spring sites can be found with surface discharge temperatures in the range from 40 to 80 °C. Some of these hot springs are located close to the Gulf of Thailand in the east and the Andaman Sea in the west, which can lead to mixing with ocean water, resulting in higher concentrations of Cl^-, Ca^{2+}, Na^+, K^+, and Mg^{2+}. Geothermal reservoir temperatures therefore estimated by silica geothermometers provide a range from 70 to 200 °C (Subtavewung et al., 2005; Ngansom and Durrast 2016; Ngansom et al., 2017). Preliminary investigations have shown that all hot spring sites in Southern Thailand can be classified as low-enthalpy geothermal systems (Ngansom et al., 2016).

2. GEOLOGICAL SETTINGS OF HOT SPRINGS IN SOUTHERN THAILAND

Southern Thailand comprises of the northern part of the Malay Peninsula, bounded by the Andaman Sea in the west and the Gulf of Thailand in the east, and with a political boundary to Malaysia in the south (Figure 1). The morphological and geological characteristic of Peninsular Thailand is a series of roughly parallel N-S to NNE-SSW trending mountain ranges, which can rise to a height of 1,500 meters, mainly comprising of Paleozoic rocks and granites (e.g., Bunopas, 1982; Ridd and Watkinson, 2013). Larger scale tectonic activities have resulted in complex structures, faults and basins (e.g. Chinoroje, 1993). Major active strike-slip faults zones crossing through the peninsula from west to east are the Ranong Fault (RF) Zone and further south the Khlong Marui Fault (KMF) Zone (e.g. Garson et al. 1975; Watkinson et al., 2008; Ridd, 2012). Both fault zones have been interpreted to be conjugated to the Three Pagodas Fault (TPF) Zone and Mae Ping Fault (MPF) Zone in the central part of Thailand (Polachan et al., 1991; Kanjanapayont, 2014; Shi et al., 2015). All fault zones have been entrenched and subsequently referenced to Cenozoic deformation of SE Asia (Polachan et al., 1991; Kanjanapayont et al., 2012). Granites have been intruded into shale, sandstone, and limestone formations, major lithologies in the area (e.g. Watkinson et al., 2008; Ridd, 2012). Vertical cliffs and rugged terrain were developed on the limestone outcrops found over the whole peninsula (Ridd, 2009); some of them are famous tourist places.

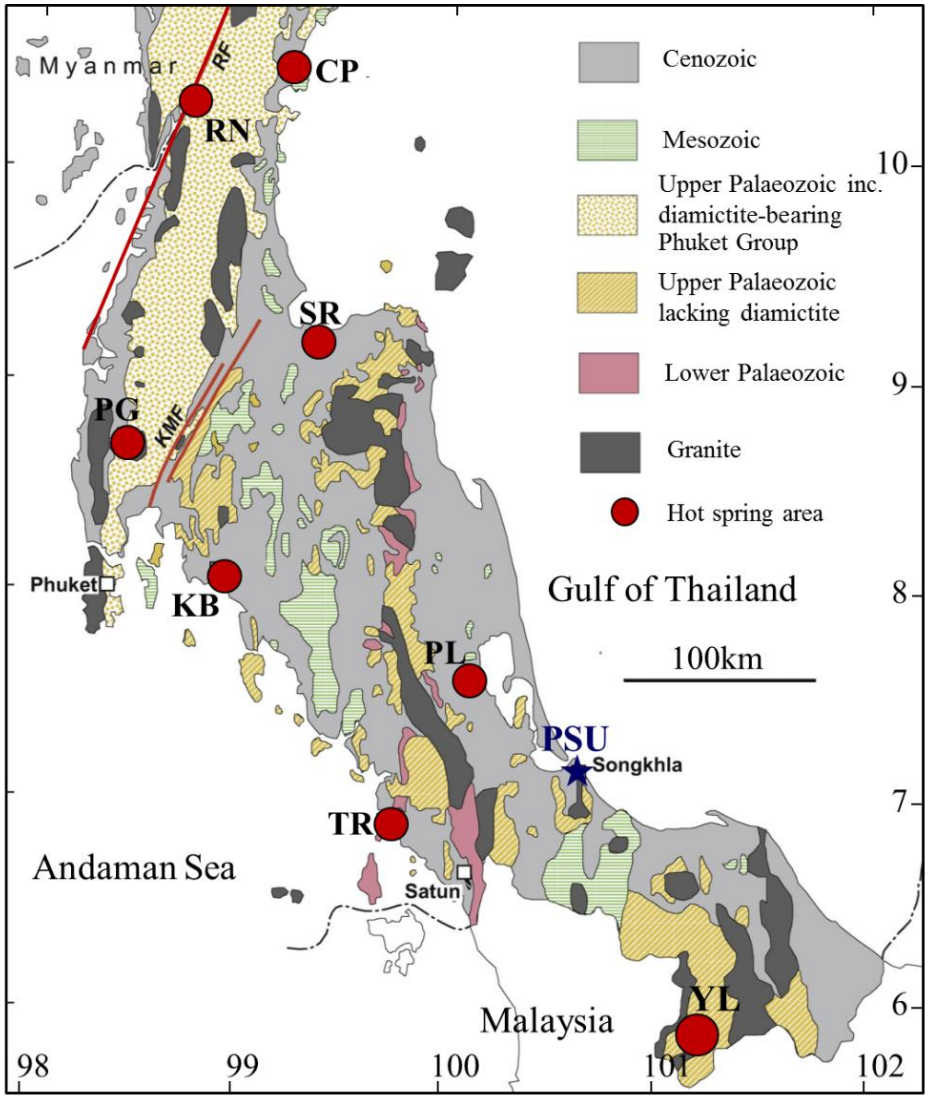

Figure 1: Simplified geological map and location of geothermal hot spring systems part of Southern Thailand (modified from DMR, 1975; Ridd and Watkinson, 2013); CP – Chumphon Geothermal System, RN –Ranong Geothermal System, SR – Surat Thani Geothermal System, PG – Phang Nga Geothermal System, KB – Krabi Geothermal System, TR – Trang Geothermal System, PL – Phatthalung Geothermal System, YL – Yala Geothermal System, RF – Ranong Fault, and KMF – Khlong Marui Fault.

Geothermal hot spring systems in Southern Thailand (Figure 1 and 2, Table 1) in general can be separated into three groups: *Group 1* is characterized by a general granitic setting of geothermal systems, with a lesser extent of sedimentary rocks, and with the surface discharge temperature of more than 60 °C (e.g., Duerrast et al., 2016). *Group 2* is associated with a sedimentary or metamorphic rock setting of geothermal systems, with the surface discharge temperature of about 60 °C or less. *Group 3* is directly or indirectly affected by the fluid flow along and related to the major active fault zones (RF, KMF; Khawtawan et al., 2004). Moreover, for all hot springs in Southern Thailand the real heat sources are not known. It can be either an igneous body where radioactive decay produces heat or a higher heat flow during basin development onshore. One exception is the Ranong hot spring area as geophysical investigations hint a possible igneous (magmatic) body at larger depth as the possible heat source (Khoonphunnarai et al., 2007).

3. SAMPLES AND ANALYTICAL METHODS

At each hot spring, the surface discharge temperature and the salinity were measured on-site using a standard glass thermometer (max. 100 °C) and an Atago Master refractometer, respectively. In all cases, water samples for geochemical analysis were collected in 1,000 ml well cleaned airtight polypropylene bottles (with good chemical resistance), after it was rinsed at least three times with the same water before final collection (Ármannsson and Ólafsson, 2007; Huang et al., 2012). Bottles, labeled accordingly, indicating the date, sample number, purpose of analysis, and location; these samples were cooled down naturally to ambient temperatures (30-35°C) as thermal contraction is reasonably small (around 0.5% and smaller, Arnórsson et al., 2006), and then sent to the laboratory. Parameters were analyzed in a few days after samples were taken.

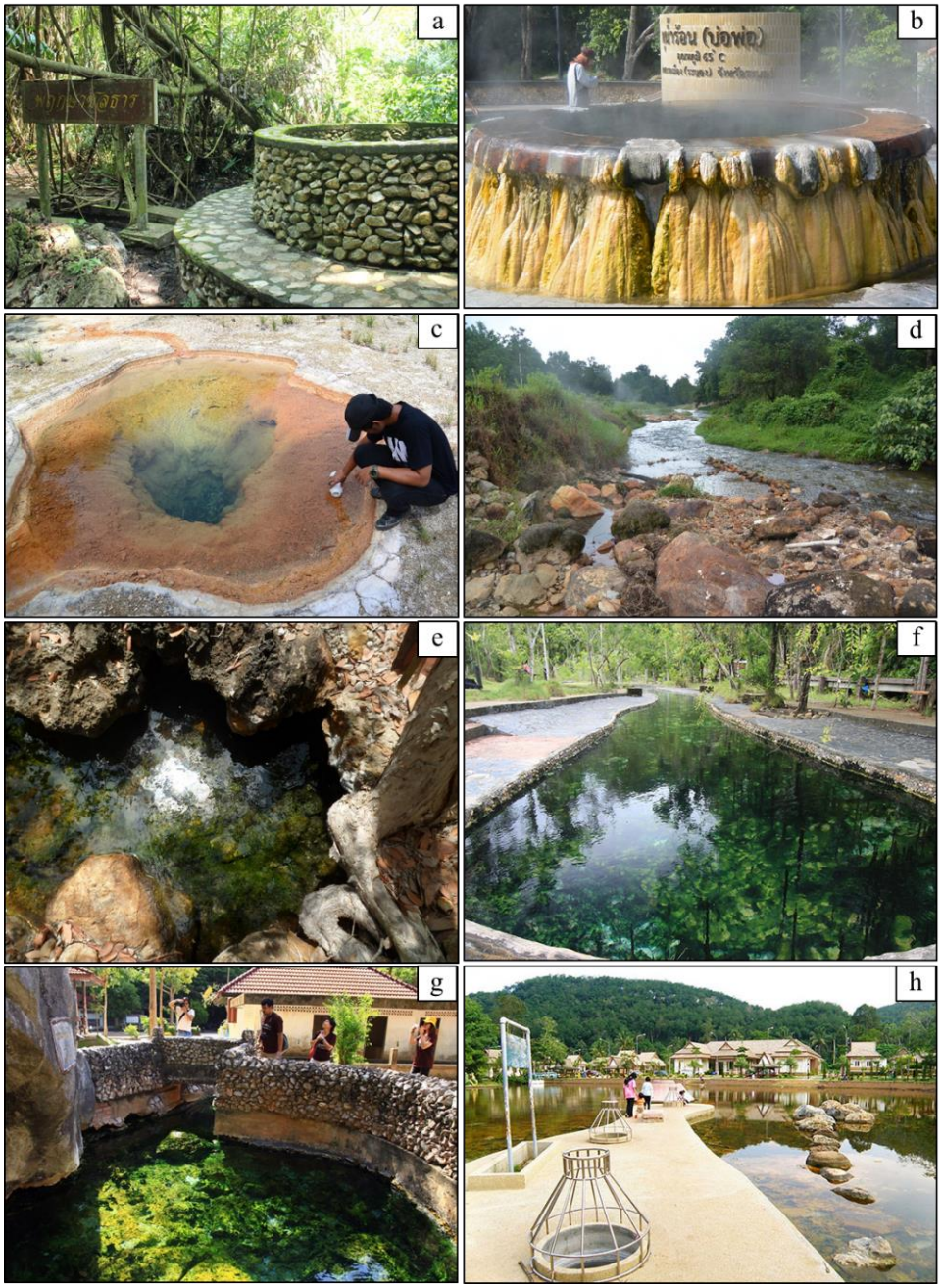

Figure 2: Geothermal hot springs in Southern Thailand; (a) Chumphon hot spring, (b) RN1 site of Ranong system, (c) SR7 site of Surat Thani system, (d) PG1 site of Phang Nga system, (e) KB4 site of Krabi system, (f) Trang hot spring, (g) PL1 site of Phatthalung system and (h) Yala hot spring.

Major cation and anion concentrations of all hot spring water samples were analyzed at the Central Equipment Division, Faculty of Science, Prince of Songkla University, Thailand, using standard procedures outlined in Eaton et al. (2005). Accuracy and precision of the laboratory measurements were computed by analyzing certified reference materials and by performing several replicas and dilutions of collected samples. Methods of analysis and detection limits of elements are summarized in Table 2. pH was measured with a standard pH meter; along with resistivity using a standard laboratory resistivity meter, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and SiO_2 concentrations were determined by ICP-OES; HCO_3^{-} concentration was determined by standard titration method. Although determination of bicarbonate concentration is preferable on site, it is also possible in the laboratory if time between sampling and analysis is not prolonged (Nicholson, 1993).

For selected water samples, the REEs were analyzed by ICP-MS on the PerkinElmer DRC II (Sciex, Canada) at the Department of Geochemistry, Geoscience Centre, University of Göttingen, Germany. This work focuses on the use of REEs in understanding water-rock interactions in hot spring systems, which imparts that the comparable REE signature to the hot spring water is related to that of the rocks through which the hot water flows. Data for representative rocks in the study area, granite and sedimentary rocks were gathered (Wu and Ishihara, 1994).

Table 1: Locations and surface discharge temperatures of geothermal hot spring systems in Southern Thailand.

Hot spring system	UTM (WGS-84), Zone 47		Surface Temperature (°C)
	East (m)	North (m)	
Chumphon: CP	512222	1075014	50
Ranong			
RN1	462169	1100516	65
RN2	460000	1094700	40
RN3	461030	1093400	45
RN4	462290	1094275	50
RN5	456192	1080300	46
RN6	470810	1060430	75
Surat Thani			
SR1	521107	1034893	45
SR2	520518	1033905	40
SR3	522412	1031459	60
SR4	555129	1009502	41
SR5	545897	972938	42
SR6	503522	979890	53
SR7	529417	991895	70
SR8	530806	991094	56
SR9	524947	977116	62
Phang Nga			
PG1	441455	960807	78
PG2	437870	975306	55
PG3	420496	918037	45
Krabi			
KB1	499622	900439	45
KB2	500183	891731	47
KB3	510462	888220	45
KB4	512329	873475	47
KB5	523171	876867	47
Trang: TR	551391	818787	52
Phatthalung			
PL1	625096	823266	57
PL2	608944	810077	46
PL3	604490	816432	50
PL4	615661	850513	41
Yala: YL	729730	646758	80

Table 2: Methods applied at the Central Equipment Division, Faculty of Science, Prince of Songkla University, Thailand, and detection limits of analyzed cations and anions.

Parameters	Method used	Detection limits (mg/L)
Fluoride, F^-	Photometric	0.1
Chloride, Cl^-	Argentometric	0.1
Iron, Fe^{2+}	Inductively Couple Plasma (ICP)-OES	0.005
Calcium, Ca^{2+}	Inductively Couple Plasma (ICP)-OES	0.01
Magnesium, Mg^{2+}	Inductively Couple Plasma (ICP)-OES	0.01
Potassium, K^+	Inductively Couple Plasma (ICP)-OES	0.01
Sodium, Na^+	Inductively Couple Plasma (ICP)-OES	0.005
Sulfate, SO_4^{2-}	Photometric	1
Bicarbonate, HCO_3^-	Titration	1
Dissolved silica, SiO_2	Inductively Couple Plasma (ICP)-OES	1

4. RESULTS AND DISCUSSION

4.1 Thermal Water properties

Altogether 30 hot spring water samples of eight geothermal systems in Southern Thailand were collected. Chemical analysis of major cations and anions, and also pH determination are shown in Table 1 and 3. pH values of all samples are in a range between 6.7 and 8.4. The concentration of the total dissolved solids (TDS) is in general moderate with some quite higher exceptions, SR1, SR3, KB2, KB4, and TR2; mostly related to higher Na^+ and Cl^- content and a minor extent of Ca^{2+}, K^+, and SO_4^{2-}. These five hot springs are all more or less influenced by shallower marine water ingression as their locations are relatively close to an estuary or a major river system connecting to the ocean.

Table 3: Surface temperatures, pH, concentrations of cations and anions and reservoir temperatures of hot springs in Southern Thailand.

Hot spring	Surface temp. (°C)	pH	Content (mg/L)					Geothermometer (°C)		
			TDS	Na^+	K^+	Ca^{2+}	SiO_2	Silica	Na-K	Na-K-Ca
CP1	50	7.8	580	63.50	6.80	89.50	64.20	114	223	154
RN1	65	8.3	330	48.40	2.80	44.10	79.30	125	174	128
RN2	40	8.3	330	46.40	3.20	44.10	75.50	122	187	135
RN3	45	8.4	330	46.90	3	44.30	72	120	181	132
RN4	50	8.2	240	46.10	2	17.80	87	130	155	121
RN5	46	8.3	310	51.30	3.50	28.10	111	130	155	122
RN6	75	8.1	580	63.50	6.80	89.50	64.20	143	186	139
SR1	45	7.7	13690	3850	1320	933	65	114	140	147
SR2	40	7.8	7180	1855	64.20	400	39	91	140	143
SR3	60	7.9	12610	3655	115	840	58.50	109	135	143
SR4	41	8.3	270	20.5	2.40	27.80	37.40	89	231	150
SR5	42	8.4	320	55.90	6.00	20.90	80.20	125	223	164
SR6	53	8.1	740	44.80	5.20	97.10	53.60	105	230	152
SR7	70	7.9	1980	64.50	13.60	381	60.70	111	291	177
SR8	56	7.2	62	59.70	12.80	69.60	66.30	115	292	192
SR9	62	6.8	1300	12.10	4.60	265	62	112	367	182
PG1	78	7.8	280	84.00	3.30	6.90	77.70	124	148	132
PG2	55	6.8	390	108.60	3.10	2.60	62.50	123	150	142
PG3	45	6.9	5100	1250	50.30	515	77	123	150	142
KB1	45	7.2	350	24.90	2.50	86.30	26.80	75	217	137
KB2	47	7.3	16120	4450	125	975	44.40	96	128	140
KB3	45	7.2	3300	986	22.10	382	25.50	73	115	115
KB4	47	7.2	20600	12500	395.50	833	32.10	82	134	147
KB5	47	7.0	480	2.30	1.30	86.30	61	111	426	182
TR1	52	7.1	590	79.10	2.80	82.10	61	111	142	111
PL1	57	7.7	265	39.10	3.70	45.50	25.50	73	212	146
PL2	46	8.0	255	72.90	3.20	3.00	84.30	128	156	142
PL3	50	8.0	240	69.70	3.20	5.10	73.60	121	158	139
PL4	41	6.9	418	21.70	2.90	21.90	38.90	90	243	159
YL1	80	7.8	330	76.60	6.40	16.70	97.60	136	202	159

Piper and Cl^--SO_4^{2-}-HCO_3^- diagrams were used to provide graphical displays of the major cation and anion chemistry for hot spring waters in Southern Thailand represented by Figure 3 and 4. The chemical composition of most hot spring water samples shows that waters are of Ca–Na–bicarbonate rich character, e.g. Ranong, Phang Nga, Surat Thani, and Trang geothermal systems. Moreover, the hot spring water samples are also classified as Ca^{2+}–Na^+–K^+–(Mg^{2+})–HCO_3^- water, except waters from Krabi (KB) and Surat Thani (SR) systems are characterized by high chloride concentrations.

The variation of concentrations of Na^+, K^+, Mg^{2+}, Ca^{2+} and SO_4^{2-} against the conservative component of Cl^-shown in Figure 5a to 5f exhibit for almost all parameter a positive proportion trend. Only HCO_3^- concentrations are scattered and show no correlation with Cl^-. Although the concentrations of Na and Mg cover a large range, the plots exhibit a progressively increasing trend. Consequently, most of the hot spring waters from southern region are taken part in the much longer and deeper flow path with lower concentrations of Cl^- than groundwater with higher values. Geochemical data in Table 3 and Figure 3 to 5 also indicate that

all geothermal systems in Southern Thailand experience mixing between the original hot waters from depth and meteoric waters of the shallow subsurface, but at different degree. Bicarbonate-rich chemistry represents the main characteristics of shallow groundwater aquifer; thus, evidence points to a rather extensive mixing in most cases.

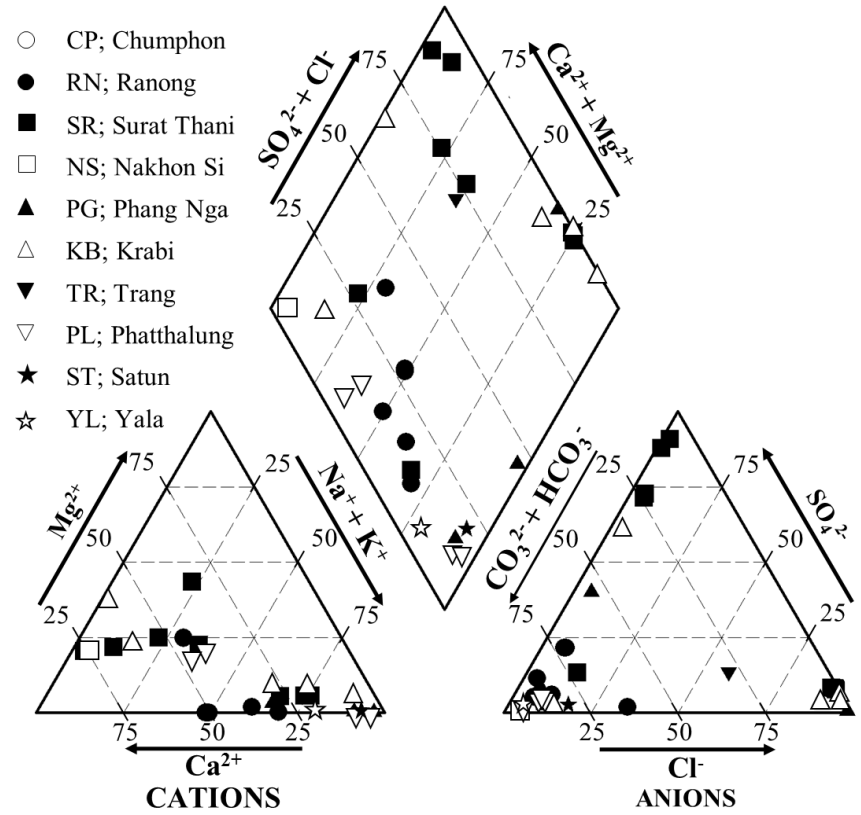

Figure 3: Piper diagram of hot spring water samples in Southern Thailand.

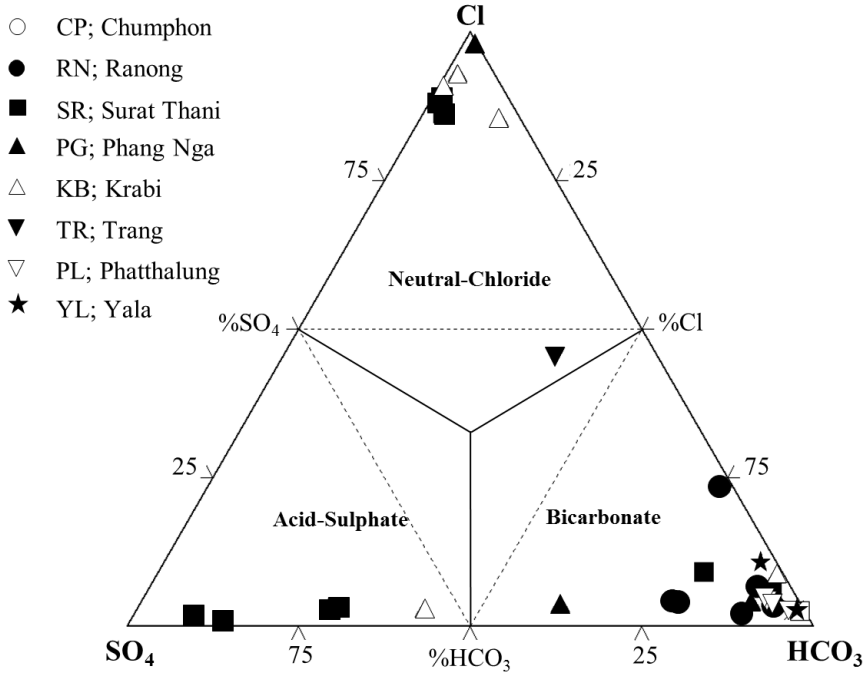

Figure 4: Cl-SO4-HCO3 diagram of water samples in Southern Thailand, most samples plot in the bicarbonate water region.

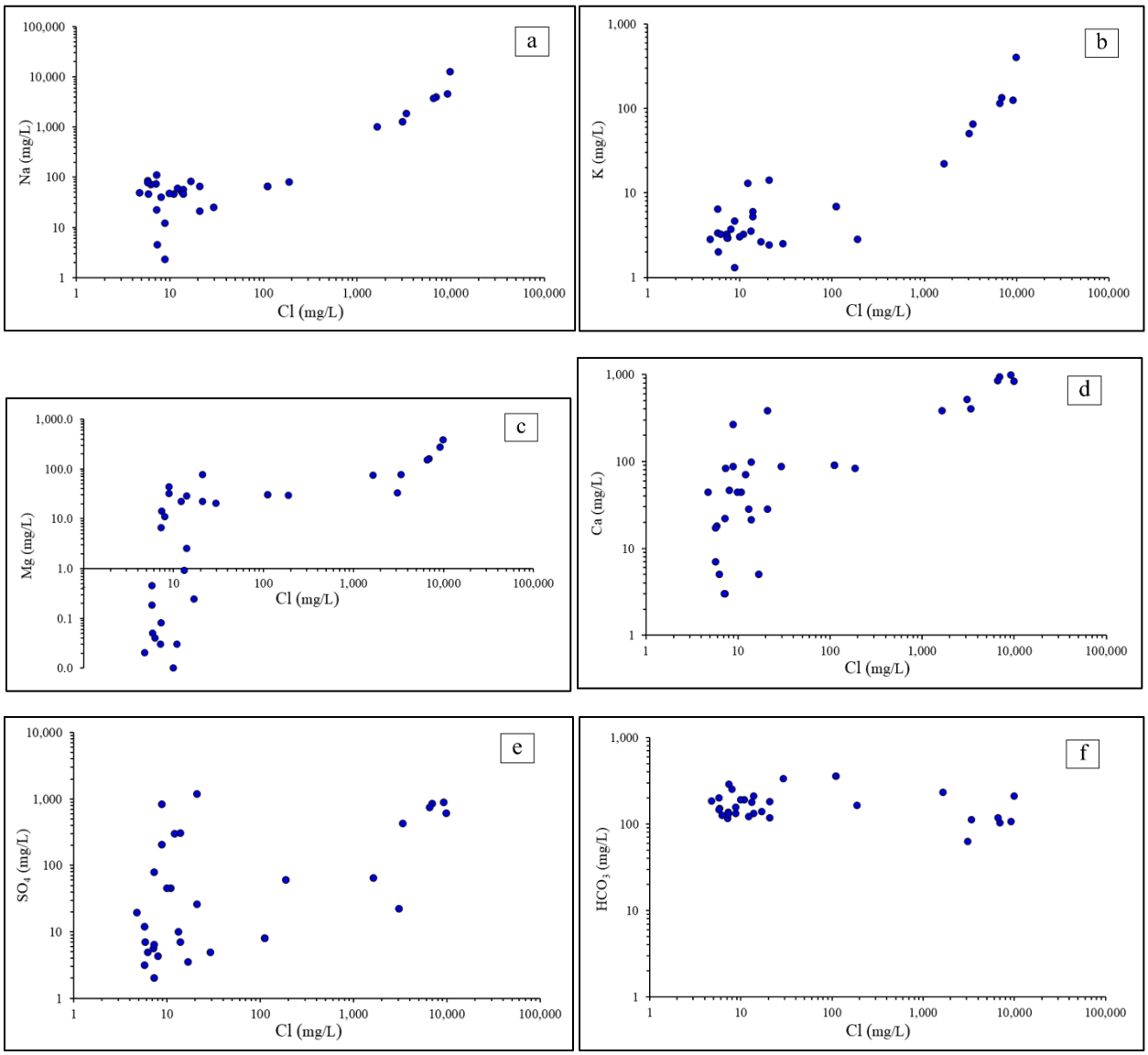

Figure 5: Variations of concentrations of major inorganic ions against the conservative component of Cl.

4.2 REE geochemistry of Southern Thailand

Rare-earth elements (REEs) were determined to differentiate main sources of water with depended on geological settings (Goldstein and Jacobsen 1988; Johannesson and Lyons 1994). In general, chondrite-normalized REE values of the two rock samples are higher than those of the hot spring waters (Table 4, Figure 6); however patterns of hot spring waters and rock samples are in main parts similar. For the REE patterns in parts acquired from hot spring water samples following three differentiation types can be separated; (a) a horizontal line for data having the same REE distributions as the chondritic meteorites, (b) positive slope for the normalized curve denotes material enriched in heavier lanthanides, and (c) negative slope for normalized curve indicates enrichment in lighter lanthanides (Figure 6). For PG 1 hot spring data, the heavier REEs (HREE) are less fractionated than the lighter REEs (LREE) in comparison to chondrite, with the LREEs almost forming a plateau at around 0.03. REE data from granites and sedimentary rock formations are shown in Table 4 and Fig 6. The granite is located north of the KMF zone, which allows a correlation of their REE data. As presented in Figure 6 the granites of the studied area were generated from source rocks which possess similar REE patterns to those of the analyzed sedimentary rocks. Possible the genesis of the studied granites which may be probably derived from partial melting of the source rocks possessing similar REE features to those of the analyzed sedimentary rocks of the area at various depths. A negative Eu anomaly for PG 1 and KB 5 might be explained through water-rock interaction at depth with rocks similar shown here. A positive Eu anomaly of the saline hot spring sample KB 4 indicates that the water is interacting with another rock formation not represented by the data here. A similar explanation holds for Ce as KB 4 here shows a negative anomaly.

Table 4: Concentrations of REEs of hot spring waters, granite and sedimentary rock sample.

REE	Rock Sample [a]		Hot Spring Water Sample [b]				
	Granite (43) DMR-1	Sedimentary Rock (47) 7711-3002-1	PG1	KB3	KB4	KB5	TR1
La	133.00	28.00	0.1590	0.0316	0.1116	0.0934	0.0250
Ce	270.00	60.00	0.2198	0.0173	0.0576	0.0958	0.0181
Pr	30.00	7.20	0.1144	0.0118	0.0660	0.0892	0.0210
Nd	93.00	26.00	0.0882	0.0100	0.0501	0.0734	0.0156
Sm	14.50	4.40	0.0554	0.0110	0.0419	0.0382	0.0044
Eu	0.88	1.10	0.0180	n.d.	0.0866	0.0132	n.d.
Gd	11.40	3.90	0.0395	0.0055	0.0539	0.0264	0.0032
Tb	1.20	0.60	0.0182	0.0062	0.0453	0.0257	0.0095
Dy	5.00	4.30	0.0264	0.0039	0.0310	0.0237	0.0034
Er	2.20	2.60	0.0211	0.0086	0.0224	0.0184	0.0073
Yb	2.10	2.90	0.0173	0.0072	0.0153	0.0162	0.0066
Lu	0.30	0.40	0.0156	0.0150	0.0201	0.0182	0.0078
Total	**563.58**	**141.40**	**0.7929**	**0.1281**	**0.6019**	**0.5318**	**0.1217**

[a] Data from Wu and Ishihara (1994); [b] this study; [c] n.d. – no data

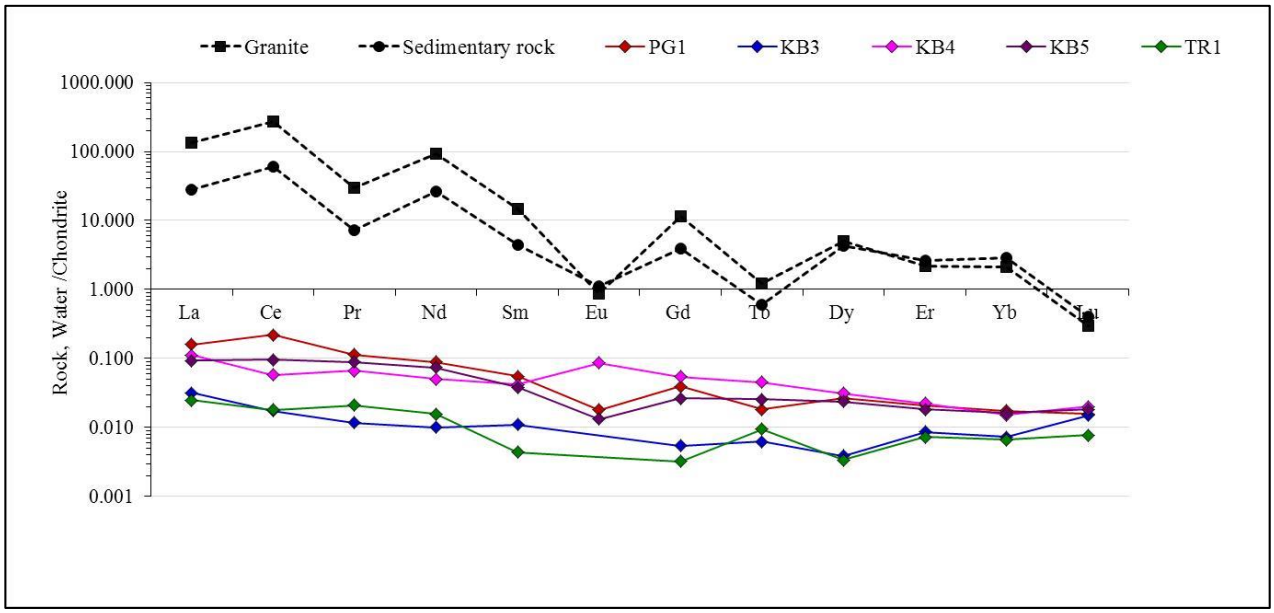

Figure 6: Chondrite-normalized plot of the REE concentrations of the PG hot spring system.

4.3 Geothermal Reservoir Temperature Estimates

Geothermal reservoir temperatures were estimated by utilizing the chemical water composition with silica and cation geothermometers, as shown in Table 3 and Figure 7. A silica geothermometer calculation is based on the solubility of quartz and chalcedony, which is widely used to estimate the subsurface temperature of geothermal systems (Fournier and Rowe, 1966). Cation geothermometers are calculated based on an ion-exchange reaction with the temperature-dependent equilibrium constant. The resulting Na–K geothermometer values for Ranong, Surat Thani and Krabi (KB4) geothermal system are of about 220 to 420 °C, which also represents the hottest sites. The Na-K-Ca geothermometer values are lower than those from the Na-K geothermometer, with values ranging from 150 to 180 °C; while the silica geothermometer based temperatures vary between 70 and 120 °C, which is lower than from the cation geothermometers for all geothermal systems. The main differences in the determined geothermal reservoir temperatures using different geothermometers can be explained by the mixing of hot water with shallow groundwater, which at some locations contains seawater related cations (Carotenuto et al., 2016). The silica geothermometer, therefore, seemingly provides more realistic values, although relatively low in comparison.

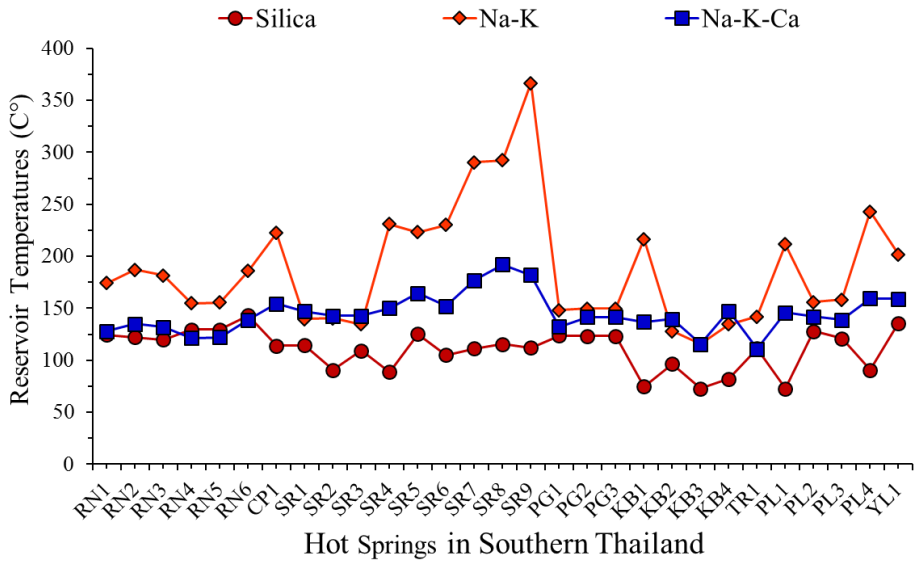

Figure 7: Geothermal reservoir temperatures of the hot spring systems (for abbreviations and locations see Table 3) inferred from silica, and Na–K and Na–K–Ca of the cation geothermometers.

5. CONCLUSION

Geothermal hot springs in Southern Thailand are characterized by medium to high surface discharge temperatures, combined with a wide concentration range of dissolved chemical compositions. Most of the hot spring waters are chemically similar and characterized as the sodium bicarbonate types, except waters from hot spring systems with ocean water influx. Surface temperatures range from 40 to 80°C, and pH values of all water samples are in a range between 6.7 and 8.4. Total dissolved solids (TDS) content is in general moderate with some quite high exceptions, SR1, SR3, KB2, KB4, and TR2; mostly related to higher Na^+ and Cl^- content and a minor extent of Ca^{2+}, K^+, and SO_4^{2-}. These five hot springs are all more or less influenced by shallower marine water ingression as their locations are relatively close to an estuary or a major river system connecting to the ocean. Most of the hot spring water samples are illustrated that waters are Ca–Na–bicarbonate rich waters and classified into Ca^{2+}–Na^+–K^+–(Mg^{2+})–HCO_3^- water, but excepted waters from Krabi (KB) and Surat Thani (SR) systems are indicated a high chloride concentration. Differences between silica and cation geothermometer values indicate mixing of the original hot waters with near-surface groundwaters. Silica geothermometers gave equilibrium temperatures ranging from 93 °C to 154 °C in the hot spring systems. From the geochemical data presented here following preliminary boundaries for all 30 hot springs representing geothermal systems in Southern Thailand can be given. The hot springs can be divided into four greater areas having similar geochemical characteristics: (1) Ranong and Phang Nga, (2) Surat Thani, (3) Krabi minus KB 4 and (4) others, incl. KB 4. Only the Ranong-Phang Nga Group has hot water with low contaminants, and data from the hot springs indicate a relatively high potential for energy generation. Further work also utilizing other methods has to prove that.

REFERENCES

Apollaro, C., Vespasiano, G., Rosa, R.D., Marini, L.: Use of mean residence time and flow rate of thermal waters to evaluate the volume of reservoir water contributing to the natural discharge and the related geothermal reservoir volume. Application to Northern Thailand hot springs, *Geothermics* **58**, (2015), 62–74.

Ármannsson, H., Ólafsson, M.: Geothermal sampling and analysis. Presented at Short Course II on Surface Exploration for Geothermal Resources, *Proceedings*, UNU-GTP and KenGen, at Lake Naivasha, Kenya (2007).

Arnórsson, J.O., Bjarnason, N., Giroud, N., Gunnarsson, I., Steffánsson, A.: Sampling and analysis of geothermal fluids, *Geofluids* **6**, (2006), 203–216.

Barr, S.M., Ratanasathein, B., Breen, D., Ramingwong, T., Sertsrivanit, S.: Hot springs and geothermal gradients in northern Thailand, *Geothermics*, **8**, (1979), 88–95.

Bunopas, S.: Paleogeographic history of Western Thailand and adjacent parts of Southeast Asia - A plate-tectonics interpretation. *Ph.D. Thesis*, Victoria. University of Wellington, New Zealand, (1982).

Carotenuto, A., Ciccolella, M., Massarotti, N., Mauro, A.: Models for thermo-fluid dynamic phenomena in low enthalpy geothermal energy systems: A review, *Renewable and Sustainable Energy Reviews*, **60**, (2016), 330–355.

Charusiri, C., Chaturongkawanich, S., Takashima, I., Kosiwan, S., Won-in, K., Cat, N.: Application of geothermal resources of Thailand, Vietnam, and Myanmar to tectonic settings, *Proceedings*, The World Geothermal Congress, Tohoku, Japan (2000).

Chaturongkawanich, S., Leevongchareon, S.: The geothermal resources of Changwat Ranong Southern Thailand, *Proceedings*, The World Geothermal Congress 2000, Kyushu-Tohoku, Japan, (2000).

Chinoroje, O.: Petrographic studies of Permian carbonates in southern Thailand, *Journal of Southeast Asian Earth Sciences* **8(1-4)**, (1993), 161–171.

Chuaviroj, S.: Geothermal development in Thailand, *Geothermics*, **17(2/3)**, (1988), 421-428.

Eaton, A. D., Clesceri, L. S., Rice, E. W., Greenberg, A. E., Franson, M. A. H.: Standard methods for the examination of water and wastewater: *Centennial edition*, American Public Health Association, Washington DC (2005).

Fournier, R.O., Rowe, J.J.: Estimation of underground temperatures from the silica content of water from hot springs and wet-steam wells, *Am. J. Sci.*, **264**, (1966), 685- 697.

Garson, M.S., Young, B., Mitchell, A.H.G., Tait, B.A.R.: The Geology of the Tin Belt in Peninsular Thailand around Phuket, Phangnga and Takua Pa. *Institute of Geological Sciences Overseas Memoir*, **1**, (1975), 112.

Goldstein, S.J., Jacobsen, S.B.: Rare earth elements in river waters, *Earth and Planetary Science Letters*, **89**, (1988), 35–47.

Huang, W.J., Wang, Y., Cai, W.J.: Methods, *Limnol. Oceanogr*, **10**, (2012), 711–717.

Johannesson, K.H., Lyons, W.B.: The rare earth element geochemistry of Mono Lake water and the importance of carbonate complexing, *Limnol. Oceanogr*, **39(5)**, (1994), 1141–1154.

Kanjanapayont, P.: Deformation style of the Mesozoic sedimentary rocks in southern Thailand, *Journal of Asian Earth Sciences*, **92**, (2014), 1–9.

Khawtawan, A., Lohawijarn, W., Tonnayopas, D.: Gravity Anomaly of Chaiya Geothermal Area, *Proceedings*, The International Conference on Applied Geophysics, Chiang Mai, Thailand (2004).

Khoonphunnarai, P., Lohawijarn, W., Duerrast, H.: Airborne Geophysical Anomaly of Ranong Geothermal Area, Thailand, *Proceedings*, The 7th National Graduate Research Conference, Surat Thani, Thailand (2007).

Korjedee, T.: Geothermal exploration and development in Thailand, *Proceedings*, The World Geothermal Congress, Kyushu-Tohoku, Japan (2002).

Ngansom, W., Durrast, H.: Saline hot spring in Krabi, Thailand: A unique geothermal system, *Society of Exploration Geophysicists*, (2016), 1949–4645.

Ngansom, W., Pirarai, K., Duerrast, H.: Geothermal Exploration in Phang Nga, Southern Thailand, *Proceedings*, The 15th World Renewable Energy Congress (WREC), Jakarta, Indonesia (2016).

Ngansom, W., Pirarai, K., Duerrast, H.: Integrated geoscientific investigations of the Phang Nga geothermal system, southern Thailand, *Society of Exploration Geophysicists*, (2017), 5427– 5431.

Nicholson, K.: Geothermal fluids. Springer-Verlag, Berlin, Heidelberg, New York, (1993), 263.

Polachan, S., Pradidtan, S., Tongtaow, C., Janmaha, S., Intarawijitr, K., Sangsuwan, C.: Development of Cenozoic basins in Thailand, *Marine and Petroleum Geology*, **8(1)**, (1991), 84–97.

Praserdvigai, S.: Geothermal development in Thailand, *Geothermics*, **15(5/6)**, (1986), 565-582.

Raksaskulwong, M.: Four decades of geothermal research and development in Thailand, *Proceedings*, The 9th Asian Geothermal Symposium, Kagoshima, Japan (2011).

Raksaskulwong, M.: Geothermal direct–use in southern Thailand, *Proceedings*, The 6th Asian Geothermal Symposium, Daejeon, South Korea (2004).

Raksaskulwong, M.: Thailand geothermal energy: development history and current status, *Proceedings*, The 8th Asian Geothermal Symposium, Hanoi, Vietnam (2008).

Ridd, M.F., Watkinson, I.: The Phuket-Slate Belt terrane: tectonic evolution and strike-slip emplacement of a major terrane on the Sundaland margin of Thailand and Myanmar, *Proceedings of the Geologists' Association*, **124(6)**, (2013), 994 –1010.

Ridd, M.F.: The Phuket Terrane: A Late Palaeozoic rift at the margin of Sibumasu, *Journal of Asian Earth Sciences*, **36(2–3)**, (2009), 238 – 251.

Ridd, M.F.: The role of strike-slip faults in the displacement of the Palaeotethys suture zone in Southeast Thailand, *Journal of Asian Earth Sciences*, **51**, (2012), 63–84.

Shi, X., Liu, S., Fang, X., Qiao, S., Khokiattiwong, S., Kornkanitnan, N.: Distribution of clay minerals in surface sediments of the western Gulf of Thailand: Sources and transport patterns, *Journal of Asian Earth Sciences*, **105**, (2015), 390–398.

Subtavewung, P., Raksaskulwong, M., Tulyatid J.: The Characteristics and classification of hot Springs in Thailand, *Proceedings*, The World Geothermal Congress, Antalya, Turkey (2005).

Wanakasem, S., Takabut, K.: Present status of Fang geothermal project, Thailand, *Geothermics*, **15(5/6)**, (1986), 583-587.

Watkinson, I., Elders, C., Hall, R.: The kinematic history of the Khlong Marui and Ranong Faults, southern Thailand, *Journal of Structural Geology*, **30(12)**, (2008), 1554–1571.