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Hydrogeochemical characteristics and terrestrial radiation of geothermal spring attractions in Central and Western Thailand

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ABSTRACT: The main objectives of this study were to evaluate the geochemical characteristics, reservoir temperatures (related to the natural ambient gamma radiation levels), and natural background radiation levels of the geothermal spring attractions in Central and Western Thailand. The hydrochemical properties of the geothermal waters revealed that K^+-Na^+ bicarbonate dominates the geochemistry of these hot spring waters. Due to their chemical characteristics, the geothermal waters reflect the homogeneity of the geological formations, which indicates that limestone originated and mixed with shallow groundwater/freshwater. On the other hand, no significant correlations were found between the reservoir temperatures and naturally occurring background radiation levels. The natural background radiation levels were investigated at the main pool and 10 m from the main pool. In addition, the annual effective dose equivalent (AEDE) and excess lifetime cancer risk (ELCR) would be considered in the areas with low natural background radiation levels. The highest averages for the AEDEs and the ELCRs were discovered in the Ratchaburi Hot Spring (RB1), at approximately 0.48 and 1.90 mSv/year, respectively. Although the ELCR is slightly higher than the annual average effective dose (1.45 mSv/year) due to the natural background radiation, a preventive strategy should be considered to protect the effects on visitors' health.

KEYWORDS: hot spring, geothermal attraction, geochemistry, geothermal reservoir, terrestrial radiation

INTRODUCTION

Geothermal spring landscapes are unique natural tourist attractions when fluids heated by heat sources from deep inside the Earth's surface spurt out of the Earth's surface under certain geological and hydrogeological conditions [1–3]. By focusing on Thailand's geothermal attractions, at least 20 hot springs have become world-famous tourism landscapes [4, 5]. For instance, Fang Hot Spring (the country's only geothermal power plant) of Chiang Mai Province, Saline Hot Spring (Khlong Thom) of Krabi Province, and Hin Dad Hot Spring (Thong Pha Phum) of Kanchanaburi Province are the most-visited hot springs in Southeast Asia [4, 5].

One of the main purposes of studies that monitored the geochemical hazards of geothermal springs would be to alert users (e.g., workers and travelers) because most geothermal springs have highly variable chemical compositions and anomalous element accumulations (either natural or anthropogenic) [6, 7]. Although the particular physical and chemical properties of the geothermal waters may be their natural origins from meteoric waters caused by precipitation, the absence of negative side effects for users is equally attractive [8, 9]. Because geothermal waters are highly influenced by the surface water and groundwater environments [9, 10], it is necessary to mention that such water chemical compositions are an essential parameter that provides the key to understanding the important roles in local geologic processes and where hot waters have come from and previously were [9, 10]. This research differs from geothermal exploration that studies the structure and geological setting, and it also differs from tourism science, which is economic development. However, it interacts as both cause and effect with those of the disciplines mentioned earlier due to their point of convergence as health and safety of users [7, 9]. Moreover, the studies also include trace element compositions and reservoir temperatures of the geothermal waters [6, 9]. It is important to identify the qualities and types of geothermal waters, as well as the reservoir temperatures, that are possibly related to the natural background radiation levels [9, 11]. Therefore, the properties of the geothermal waters could signify health risks and affect users of the natural pools and spas (bathing), an essential part of the development of geothermal attractions in Thailand.

Besides, hazards of high background radiation levels in the geothermal attractions must be considered. Most of the reports of different geothermal locations around the world have focused on workers and frequent travelers in geothermal spring areas who are not only exposed to low radiation doses and long-term background radiation but also not aware of any negative effects [11–13]. For example, Ramsar in Iran, Guarapari in Brazil, Kerala in India, Yangjiang in China, and parts of the Flinders Ranges in South

Australia are locations with these high background levels [11, 13]. In particular, gamma radiation is a form of high-frequency ionizing radiation. Gamma rays are mainly produced by radium (Ra-226), as this natural radionuclide is one of the primordial radioactive elements in the Earth's crust [11–13]. The concentrations of dissolved radon (Rn-222) in geothermal waters are related to variables such as flow rates and reservoir temperatures [14, 15]. Geothermal springs in non-volcanic areas (e.g., Thailand and West Malaysia) have been considered as areas with high background radiation levels, which are mainly caused by gamma radiation sources [3, 4]. In most cases, radioactivity is present at very low levels without any discernible risks to humans, especially where the areas are used for health and recreational purposes [2, 9]. The challenges of studying the radiation hazards in geothermal spring areas are the probability of gamma radiation emissions from the natural radioactive substances found in their geological compositions and the geothermal reservoir characteristics [14, 15]. Moreover, gamma radiation is highly interrelated with the aquifer components and local geological structures of the geothermal areas where hot springs occur [13, 14]. Therefore, consideration of the effective gamma radiation doses emitted from these geothermal springs is necessary to provide protection instructions to the users of these places.

Therefore, this study aimed to evaluate the unusual chemical properties, reservoir temperatures (related to natural background gamma radiation levels), and naturally occurring background radiation in Central and Western Thailand together with health risk assessments of radiation exposures. These measures are important for the promotion of geothermal springs located in the two regions as Thailand's unique geothermal attractions.

MATERIALS AND METHODS

Site descriptions

The site-specific selection of the geothermal attractions in Central and Western Thailand among the top tourist destinations consisted of seven hot springs located in five geothermal provinces: Uthai Thani (UT1), Kamphaeng Phet (KP1), Kanchanaburi (KC2 and KC3), Ratchaburi (RB1 and RB2), and Phetchaburi (PT1). Most travelers prefer to use these geothermal springs for recreational and therapeutic objectives, while the local authorities work with visitors for at least eight hours a day in these hot spring places.

The geological settings of Central and Western Thailand indicate that the two regions share a boundary (Fig. S1). The field observations show mountainous terrain in the northern part and the alluvial floodplain between west and east [16, 17] (Fig. S1). The overall topographic expression suggests that the region of the previous uplift, with strong strike-slip control, has been eroded considerably [17–19], and continuingly slow subsidence has resulted in gradual infilling and onlap of the topography by recently deposited sediments [18, 19]. Furthermore, the major faults of Central and Western Thailand. which include the Mae Ping Fault Zone (PFZ), Three Pagoda Fault Zone (TPFZ), and Sri Swat Fault Zone (SSFZ), are oriented in a parallel manner in the same NW-SE direction [19, 20] (Fig. S1). The MPFZ is located through eastern Myanmar onward to the border zone of North-Western Thailand and across the northern part of Central Thailand (Fig. S1) [19]. These faults move parallel to the strike of the fault plane with a total length of approximately 230 km [16]. In contrast, the TPFZ and the SSFZ were considered to have a left-lateral strike-slip faults with the Mawlamyine District (Myanmar) across the central region (Bangkok) [17–19]. Moreover, these faults show more or less NW-SE orientations and continue from eastern Myanmar to Western Thailand (e.g., Uthai Thani, Kanchanaburi, and Ratchaburi Provinces) [19, 20].

The local geology of the seven geothermal springs in Central and Western Thailand is represented by the specific sites of the geothermal provinces as follows. The Kamphaeng Phet geothermal spring (KP1) is influenced by the MPFZ, which is situated within the area of Quaternary sediments and sedimentary rock [19]. The Uthai Thani geothermal spring (UT1), located near the north-east of the SSFZ, is approximately 4 km [19, 21]. A hot spring site was discovered between Quaternary Sediments and Granite (Triassic) with oriented grains of feldspar, tourmaline, and quartz [20, 21]. The Kanchanaburi geothermal springs (KC2 and KC3), which were discovered in the vicinity of the TPFZ, are approximately 5 km in the north-eastern direction [16, 17]. These hot springs are located in the Quaternary alluvium of the Kwai River [16, 17]. The bedrock consists of sandstone/siltstone (Jurassic) and limestone/dolomitic limestone (Permian) [16, 17]. The Ratchaburi hot springs (RB1 and RB1), which are located west of the TPFZ, are approximately 10 km [22, 23]. The geothermal springs arise from granites (Cretaceous), which consist of biotite-hornblende granite and porphyritic granodiorite [19, 22]. The Phetchaburi geothermal spring (PT1) was discovered in an area that consists of sandstones (Devonian-Carboniferous) and lithic sandstones with (brown) fine-grained shale [22, 23].

Samples and analytical methods

Seven geothermal waters, located in five geothermal provinces of Central and Western Thailand, were examined in February 2021 (Table 1). Unstable parameters, the exit temperatures and the pH values, were measured at the sampling sites by using a thermometer and a pH meter, respectively. The hot water samples were stored in 2000-ml polyethylene bottles that had

Table 1 pH, exit temperature (Ex. T), and concentrations of cations and anions (mg/l) in the seven geothermal springs in Central and Western Thailand.

Hot spring	UTM (47P)		Ex. T	pH	TDS	Cation (mg/l)						Anion (mg/l)			
	East (m)	North (m)	(°C)		(mg/l)	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe^{2+}	Mn^{2+}	SiO_2	Cl^-	SO_4^{2-}	HCO_3^-
Kamphaeng Phet (KP1)	550040	1841855	59	8.3	372	141	6.1	19	4	0.03	0.0	60	19	16.0	210
Uthai Thani (UT1)	555259	1696243	48	8.4	334	124	6.4	2	8	0.01	0.0	83	8	21.0	174
Kanchanaburi (KC2)	470346	1616846	44	7.5	596	14	4.0	384	207	0.07	0.0	32	6	105.0	346
Kanchanaburi (KC3)	474061	1608187	44	7.6	298	5	1.1	242	72	0.01	0.0	35	6	3.7	290
Ratchaburi (RB1)	526583	1494567	58	7.8	158	33	8.1	43	2	0.01	0.0	49	6	3.1	96
Ratchaburi (RB2)	544145	1465985	44	8.4	326	141	3.7	13	6	0.01	0.0	60	8	44.0	172
Phetchaburi (PT1)	565076	1454158	46	8.2	284	82	5.2	73	5	0.01	0.0	57	6	26.0	194

been rinsed with deionized water twice before being used. All samples were analyzed for the contents of total dissolved solids (TDS), cations (e.g., Na^+, K^+, Ca^{2+}, Mg^{2+}, Mn^{2+}), and anions (e.g., SiO_2, Cl^-, HCO_3^-) at the Laboratory of Water Analysis Co., Ltd. (ISO/IEC 17025:2017), Phra Nakhon Si Ayutthaya, Thailand. The suggested methods for analyzing these elements are summarized in [24]: Fe^{2+} – Phenanthroline, Ca^{2+}, and Mg^{2+} – EDTA Titrimetric Method; Na^+ – Direct Nitrous Oxide-Acetylene Flame Method; K^+ – Direct Air-Acetylene Flame Method; SO_4^{2-} – Turbidimetric, Cl^-, and SiO_2 – in-house Method; F^- – SPADNS Method; and HCO_3^- – Titration Method. The limits of detection are the smallest concentrations of the analytes in the geothermal waters that can be reliably determined and range between 0.005 mg/l and 1 mg/l.

Effective dose measurement

The effective radiation doses were evaluated at seven geothermal spring sites mentioned above. Provision of information to the users of these hot springs is considered necessary as they are the most popular tourist destinations in the regions. A radiation Alert® Ranger dosimeter, which was optimized to detect low levels of natural background radiation, was used to measure the gamma radiation levels. All study sites were located at two points – in the main (natural) pool and at a distance of 10 m from the main pool. The dosimeter was manufactured according to the MIL-45208-A standard and calibrated using the ANSI-Z-540 standard. The instrument was tested for accuracies that are traceable to the National Institute of Standards and Technology. The accuracies were typically within ± 15% of the readings relative to Cs137. The operating range of this dosimeter was 0.01 to 1000 μSv/h for a response time of 3 s.

RESULTS AND DISCUSSION

Hydrogeochemical properties of hot spring waters

The geothermal springs in Central and Western Thailand had exit temperatures that ranged from 44 to 59 °C (Table 1). The pH values ranged between 7.5 and 8.4 indicating the degree of alkalinity of the waters. High Na^+ contents were determined in UT1 (124 mg/l), KP1 (141 mg/l), and RB2 (141 mg/l), which may be due to the reactions of meteoric waters with carbonate rocks and the ion exchange in the aquifers. In contrast, the K^+ and Mg^{2+} contents were relatively low, approximately 1.1–8.1 mg/l and 2–8 mg/l, respectively (with exception of KC2, 207 mg/l and KC3, 72 mg/l) as shown in Table 1. Moreover, the high Mg^{2+} concentrations in KC2 and KC3 may be related to sedimentary carbonate rocks, which are often found in association with limestone (Permian). The highest SiO_2 content was found in UT1, followed by KP1 and RB2, and reached as high as 83 mg/l (Table 1). On the other hand, relatively high Ca^{2+} contents (384 mg/l) were recorded at KC2 and KC3, with an average value of approximately 30 mg/l. The Mn^{2+} contents in all the hot spring samples were undetectable by the equipment used. For the anion concentrations, KC2 was characterized by exceptionally high HCO_3^- (346 mg/l) and SO_4^{2-} (105 mg/l) contents, with average values of 189 mg/l and 19 mg/l, respectively.

A classification of the geothermal waters in Central and Western Thailand was performed by using a Piper plot based on the cation-anion balances of the water-rock interactions [25] (Fig. 1). The results from four geothermal springs plotted near the Ca^{2+}-Mg^{2+}-HCO_3^- type (Fig. 1). However, other geothermal springs, which included UT1, KP1, and RB2; plotted in the Na^+-HCO_3^- type (Fig. 1). Nonetheless, both types of geothermal waters in the studied regions might have been influenced by the mixing process of groundwater in shallow reservoirs [26].

All triangular plots, which consisted of Cl^--SO_4^{2-}-HCO_3^-, SO_4^{2-}-Mg^{2+}-Na^+, and Mg^{2+}-Ca_2^+-(Na^++K^+), were used to map the hot spring types (Fig. 2). The diagrams showed that all of the hot spring samples were K^+-Na^+-bicarbonate-rich waters. Fig. 2a shows that the geothermal waters were enriched in the bicarbonate water field. Fig. 2b shows that hot water samples mainly plotted close to the Na^++K^+ field, excluding KC2 and KC3 which were characterized by high Ca^{2+} contents. In addition, most of the hot spring waters indicated Na^+ to SO_4^{2-} (Fig. 2c), which corresponded to the lower Mg^{2+} contents in geothermal reservoirs.

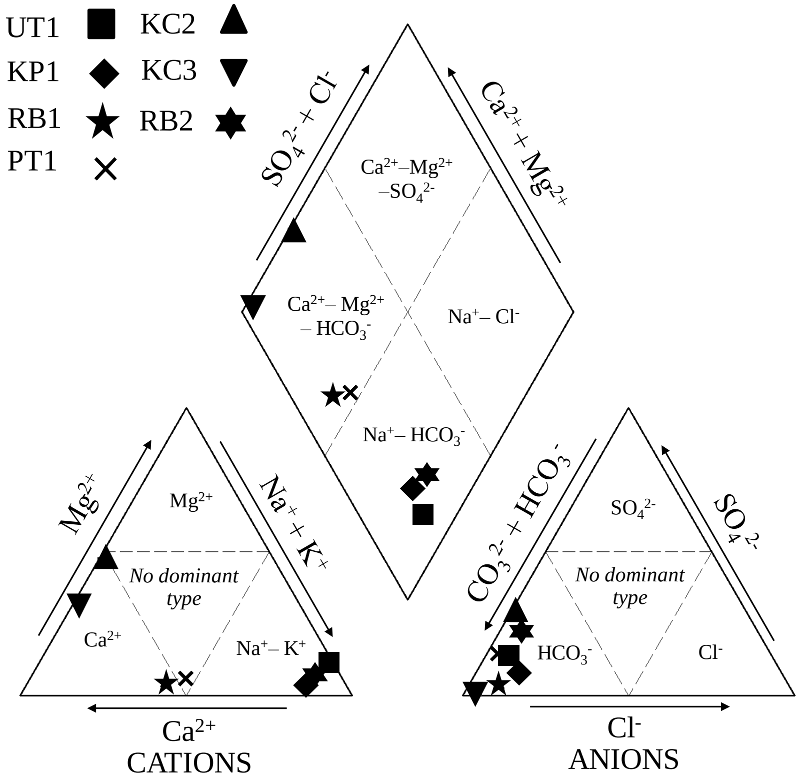

Fig. 1 Classification of the geothermal spring waters of all geothermal provinces by using a Piper diagram.

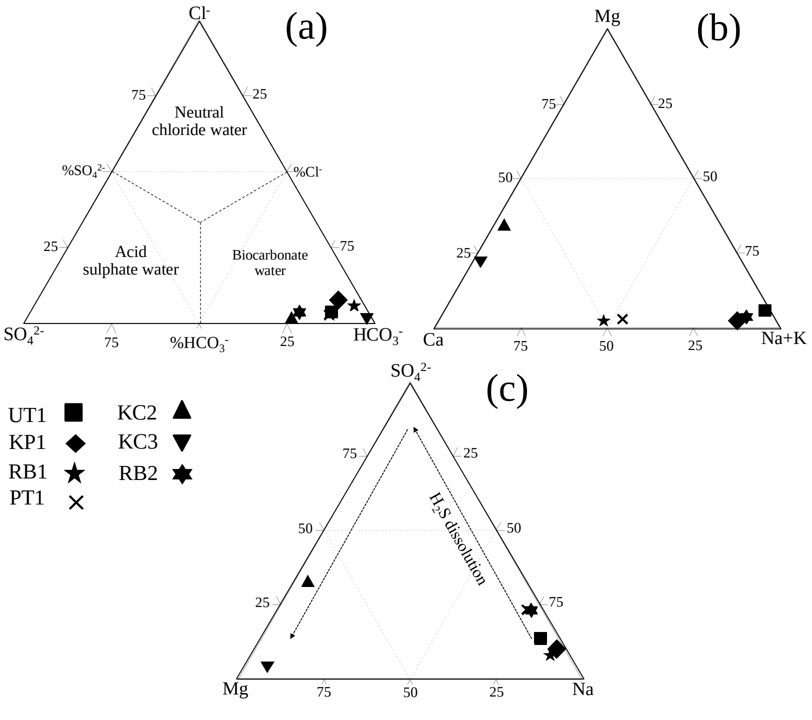

Fig. 2 Triangular plots for the major cations and anions: (a) all geothermal water samples plot in the bicarbonate waters; (b) half of hot water samples plot close to the Na+Ka field; and (c) the Na type of the studied hot springs is confirmed when most hot water samples plot close to the Na field.

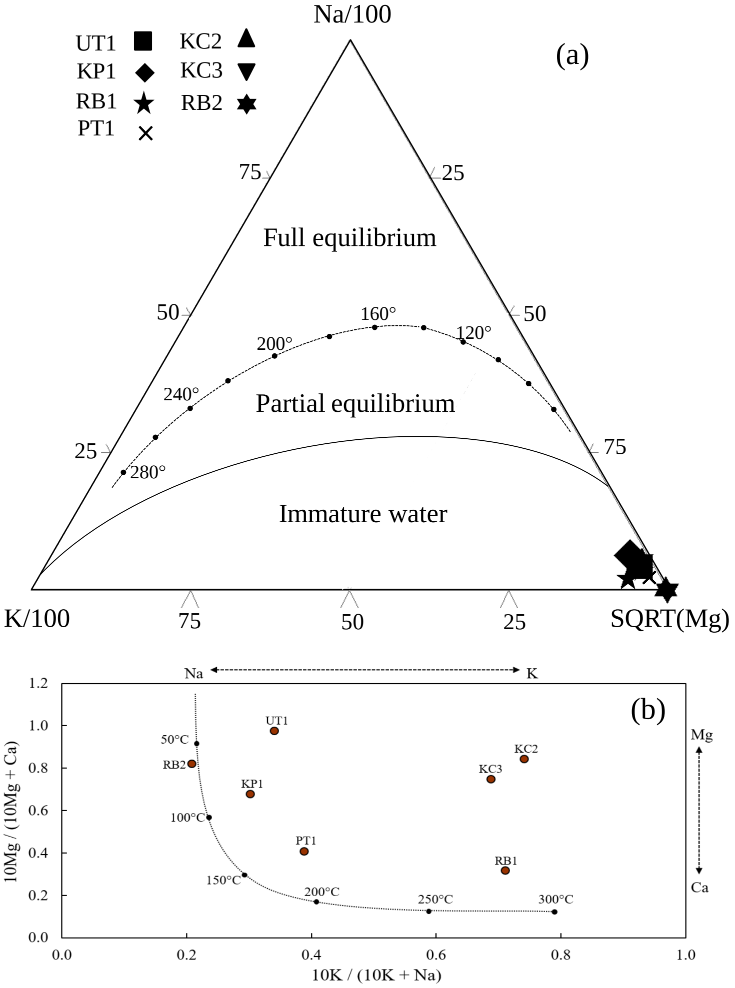

Fig. 3 The Na-K-Mg ternary and 10Mg/(10Mg+Ca) versus 10K/(10K+Na) binary plots indicate the geothermal water properties: (a) all hot spring samples plotted in the immature field and (b) hot water samples not indicating any equilibration between the rocks and the waters.

An aspect of the Na^+-K^+-Mg^{2+} ternary diagram indicated immature geothermal waters (Fig. 3a). The $10\,Mg^{2+}/(10\,Mg^{2+}+Ca^{2+})$ versus $10\,K^+/(10\,K^++Na^+)$ binary plot (Fig. 3b) exhibited similar behavior to the relationship shown in the Na^+-K^+-Mg^{2+} diagram (Fig. 3a). To date, it has been suggested that the hot waters (e.g., UT1 and KP1) are produced through dissolution of crustal rocks [27]. Besides, the resulting water-rock interactions increase the Na^+ contents, and the Cl^- compositions depend on the local geological settings and reservoir temperatures [26, 27].

Geological studies provide the geochemical signature of the geothermal waters in Central and Western Thailand showing that the highly permeable limestone formations and acidic solutions dissolve the limestones at depth [22, 23]. Except for the RB1 hot spring (HCO_3^-, 96 mg/l), all of the studied geothermal springs had relatively high HCO_3^- contents (172–346 mg/l), which suggested the presence of dissolved inorganic carbon in most groundwater/freshwater [26, 27]. The geochemical compositions of the geothermal waters in the limestone are generally characterized by relatively high HCO_3^- concentrations [22, 23]. These observations of the geochemical characteristics of the studied geothermal springs suggest waters that mix with the original hot water and local groundwater [26, 27].

Additionally, the geothermal waters in Central and Western Thailand exhibit low Cl^- contents (6–19 mg/l) when taken from the natural pools (hot spring sites), which reflect a lack of seawater mixing and no production of connate water at depth [27]. It is suggested that the geothermal waters are of meteoric origin and percolated into the geothermal reservoirs through local fractures [26]. Therefore, the different geochemical compositions in the geothermal waters can be related to the geological setting of the natural base rocks

Table 2 Reservoir temperatures computed from the SiO_2 and cation geothermometers.

Hot spring	Reservoir temperature (°C)			
	Quartz	Chalcedony	Na-K-Ca	K-Mg
Kamphaeng Phet (KP1)	111	81	137	659
Uthai Thani (UT1)	127	99	161	59
Kanchanaburi (KC2)	82	51	166	19
Kanchanaburi (KC3)	86	55	141	69
Ratchaburi (RB1)	101	71	193	80
Ratchaburi (RB2)	111	81	118	50
Phetchaburi (PT1)	108	79	136	59

and geothermal reservoir characteristics. Moreover, geothermal waters in Central and Western Thailand aren't higher than the recommended guidelines for the chemical aspects of drinking-water quality by the World Health Organization (WHO) [28].

Reservoir temperature estimation

Geothermal springs in non-volcanic areas are more likely to have elevated radiation levels, as shown by the high natural background radiation, due to the high uranium concentrations in the granites [9, 10]. As the heat produced in geothermal springs is released when the radionuclides decay, the temperatures in the geothermal reservoirs increases [9, 29]. The geothermal water is stored inside the fractures in granite geothermal reservoirs and dissolves uranium and other radionuclides into the hot water [29]. Consequently, the reservoir temperatures need to be determined by using geothermometers and computed by the chemical compositions of hot water [27]. Silica and cation geothermometers have been proposed to estimate the reservoir temperatures of the hot springs in Central and Western Thailand. Cation geothermometers (e.g., K-Mg and Na-K-Ca) are based on slow re-equilibration reactions [30, 31], while applying the silica concentrations found in solutions is based on fast re-equilibrating reactions [32]. It is suggested that cation geothermometers would be suitable for deep processing, which performed better than those in shallow geothermal reservoirs [30]. On the other hand, silica geothermometers, as a function of their fast re-equilibrating reactions, often compute estimated deep temperatures that are much lower than the actual temperatures in reservoirs [32, 33]. The expressions for the chemical geothermometers were inferred from quartz, chalcedony, K-Mg, and Na-K-Ca to compute the reservoir temperatures of hot springs as follows.

Silica geothermometers:

$$\text{Quartz; } \mathrm{T}(\mathrm{C}) = \frac{1309}{5.19 - \log[\mathrm{SiO_2}]} - 273.15$$

$$\text{Chalcedony; } \mathrm{T}(\mathrm{C}) = \frac{1112}{4.91 - \log[\mathrm{SiO_2}]} - 273.15$$

Cation geothermometers:

$$\text{K-Mg; } T(C) = \frac{4410}{14.0 - \log[K^2/Mg]} - 273.15$$

$$\text{Na-K-Ca; } T(C) = \frac{1647}{\log[\frac{Na}{K}] + \beta(\log[\frac{\sqrt{Ca}}{Na}] + 2.06) + 2.47} - 273.15$$

where $\beta = 4/3$ for $T < 100\,°C$; $\beta = 1/3$ for $T > 100\,°C$.

It is not surprising to obtain different reservoir temperature values for the same hot spring systems, as shown in Table 2 and Fig. 4. Preliminarily, the reservoir temperatures that were estimated by using silica geothermometers (e.g., quartz and chalcedony) were generally lower than those estimated by cation geothermometers (e.g., K-Mg and Na-K-Ca). In this study, the quartz-geothermometer temperatures ranged from 82 to 127 °C for KC2 and UT1. The temperatures that were calculated from the Na-K-Ca geothermometer were between 118 and 193 °C in RB2 and RB1.

Notably, the reservoir temperatures that were calculated by the K-Mg geothermometer matched well only for RB1 (Fig. 4). In contrast, the temperatures of other geothermal springs varied greatly in their K-Mg geothermometer values (e.g., KP1; 659 °C and KC2; 19 °C), which revealed that these hot waters have experienced groundwater-mixing processes [32, 33]. Moreover, the reservoir temperatures of KC2 and KC3 that were computed by the chalcedony geothermometer were much lower than those computed by the Na-K-Ca geothermometer, which suggests that the hot spring systems are controlled by the mixing processes of groundwater/freshwater [33, 34]. For the K-Mg geothermometer (Fig. 4), most of the geothermal springs provided inapplicable indicated reservoir temperatures, except for RB1, which should be realistic. Remarkably, the quartz geothermometer could provide the closest possible values to the actual values for the KC2 and KC3 hot springs (Fig. 4).

Effective dose from the natural radiation

The natural background radiation levels from the geothermal springs in Central and Western Thailand were determined, as summarized in Table 3. The users were exposed to high natural background radiation levels due to gamma radiation, either directly from the natural pools or when pumping the geothermal wells to fill the swimming pools. A concern is that the local authorities spend their entire working time in geothermal spring areas with long-term exposure to background radiation. The same situation is defined for a visitor when an adult spends at least three hours at a swimming pool or spa for recreational bathing once per month. The highest effective geothermal spring dose was observed at the RB1 hot spring, at approximately 4.86 mSv/year, while the lowest effective dose was found for the PT1 hot spring, which was approximately 1.00 mSv/year (Table 3). All hot spring

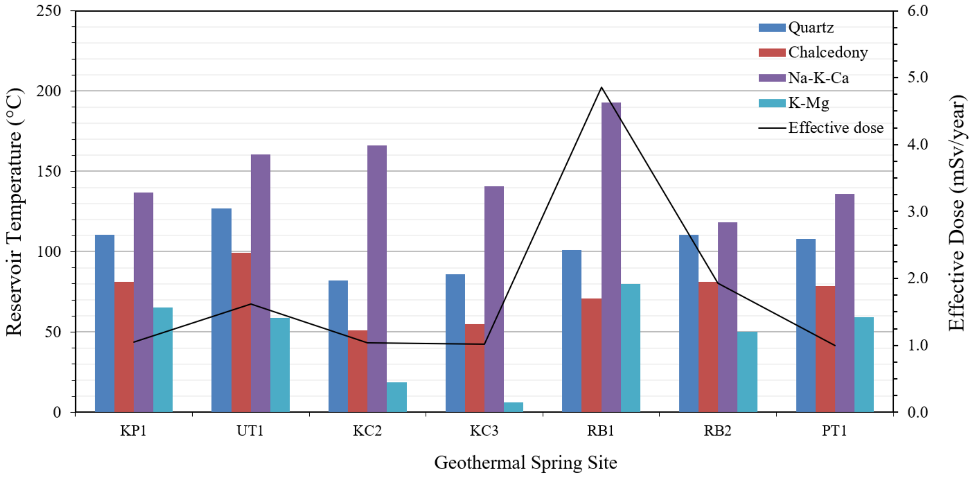

Fig. 4 Comparison between various geothermometers and the effective doses for all geothermal spring sites.

Table 3 The results of effective dose, annual effective dose equivalent (AEDE), and excess lifetime cancer risk (ELCR) at different geothermal springs in Central and Western Thailand.

Hot spring	Effective dose (µSv/h)		Main natural pool		
	main natural pool	10 m from natural pool	effective dose (mSv/year)	AEDE (mSv/year)	ELCR (mSv/year)
Uthai Thani (UT1)	0.185	0.183	1.62	0.16	0.64
Kamphaeng Phet (KP1)	0.119	0.118	1.05	0.10	0.41
Kanchanaburi (KC2)	0.119	0.116	1.04	0.10	0.41
Kanchanaburi (KC3)	0.116	0.113	1.02	0.09	0.40
Ratchaburi (RB1)	0.553	0.483	4.86	0.48	1.90
Ratchaburi (RB2)	0.220	0.213	1.93	0.19	0.76
Phetchaburi (PT1)	0.114	0.112	1.00	0.10	0.40

sites exhibited slightly higher effective doses at the main natural pools than at the 10 m distance from the main pool (Table 3). However, the natural background radiation doses varied at the different hot spring sites and were probably related to the hot water sources and reservoir temperatures [35, 36] (Fig. 4).

The formation of the RB1 hot spring is mainly based on granite, and the old mine in Ratchaburi Province contains valuable wolframite ore [16, 22]. Having a reasonable estimation of the geothermal reservoir temperature has a significant impact attributing to the high concentrations of radiogenic elements and, therefore, suggesting the generally above 120 °C temperatures [11, 14]. However, for the RB1 hot spring, the Na-K-Ca geothermometer determined that the temperature was relatively higher than the suggested temperatures (193 °C) (Fig. 4 and Table 2). On the other hand, the geothermometer, responded to the influences of the water-rock interactions on the chemistry of the geothermal spring, was influenced by the groundwater mixing process [8, 27]. Hence, a direct relationship between the natural background radiation levels and reservoir temperatures was not determined in the geothermal springs in Central and Western Thailand.

Furthermore, health risk assessments of the annual effective dose equivalent (AEDE) and excess lifetime cancer risk (ELCR) would be considered in areas with low natural background radiation (Table 3). The AEDEs were computed using the absorbed gamma dose rates received by residents living in the study area [12, 14, 37]. The outdoor effective doses are related to the dose conversion factor (0.7 Sv/Gy), occupancy factor (0.14), and time (8760 h) [12, 14, 38]. The AEDEs showed that the RB1 and the KC3 hot springs represented the maximum and the minimum doses, respectively (Table 3). For most of the geothermal spring attractions in Central and Western Thailand, the assessed AEDEs for the users of geothermal waters were much lower than the annual radiation dose limit (1.45 mSv/year) for members of the public, while the Ratchaburi (RB1) had a higher AEDE (4.86 mSv/year) than the limit. For the local authorities and spa workers, the estimated AEDEs may exceed the lower reference limit when considering geothermal areas with natural background radiation levels higher than 1 mSv/year [38,39]. The ELCRs, estimated based on the AEDEs, are considered to produce stochastic effects. The highest dose was approximately 1.90 mSv/year at RB1, which was slightly higher than the global average from natural radiation sources (e.g., 1.45 mSv/year) [38]. Similar situations for geothermal springs with high natural background radiation areas worldwide have been reported by the United Nations Scientific Committee on Effects of Atomic Radiation [39–41]: Iran (Ramsar, 10.21 mSv/year); Brazil (Guaranae, 5.52 mSv/year); India (Kerala, 3.82 mSv/year); and China (Yang Jiang, 3.51 mSv/year). However, these high natural background radiation levels have not formally been shown to cause any apparent harm to the local population [38,41]. In fact, the radiation from high natural background radiation levels presents a low risk, and the existence of radiation effects on health has not yet been proven [41,42]. Nevertheless, from a radiological point of view, using studied geothermal waters as examples of exposures to long-term background radiation could be problematic, given the possibility of exceeding the recommended annual committed effective dose [38,41].

CONCLUSION

The present study fully described the geochemical compositions and geothermal reservoir characteristics (related to natural background radiation levels) and measured the effective terrestrial radiation levels of the geothermal attractions in central and western Thailand. The chemical properties of the geothermal waters included the K^+-Na^+ bicarbonate-rich waters of whole water samples, which reflected homogeneity in the geological formations that consisted of limestones originated in deep settings. The clear disagreements between the qualitative chemical geothermometers and Na^+-K^+-Mg^{2+} ternary geothermal waters implied a disequilibrium with the associated reservoir rocks. Namely, the reservoirs of the geothermal springs could achieve groundwater/freshwater mixing with the original hot waters. For this reason, the different temperatures of the geothermal reservoirs in central and western Thailand were not suitable for predicting the effective doses in these geothermal springs.

On the other hand, the profile of the effective doses clearly showed high activity concentrations across Ratchaburi (RB1). At this site, a new finding related to the high background radiation area of hot springs in western Thailand was discovered. Although both the AEDE and ELCR in this area were slightly higher than the annual dose from natural radiation (global average), preventive measures should be considered by authorities, and they would include the length of time to stay for hours or days if there is no proper ventilation in order to track the indoor radiation. Therefore, to reduce the risk of radiation exposure, appropriate ventilation should be installed to dilute the radiation emitted from these hot springs.

Appendix A. Supplementary data

Supplementary data associated with this article can be found at http://dx.doi.org/10.2306/scienceasia1513-1874.2022.058.

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Appendix A. Supplementary data

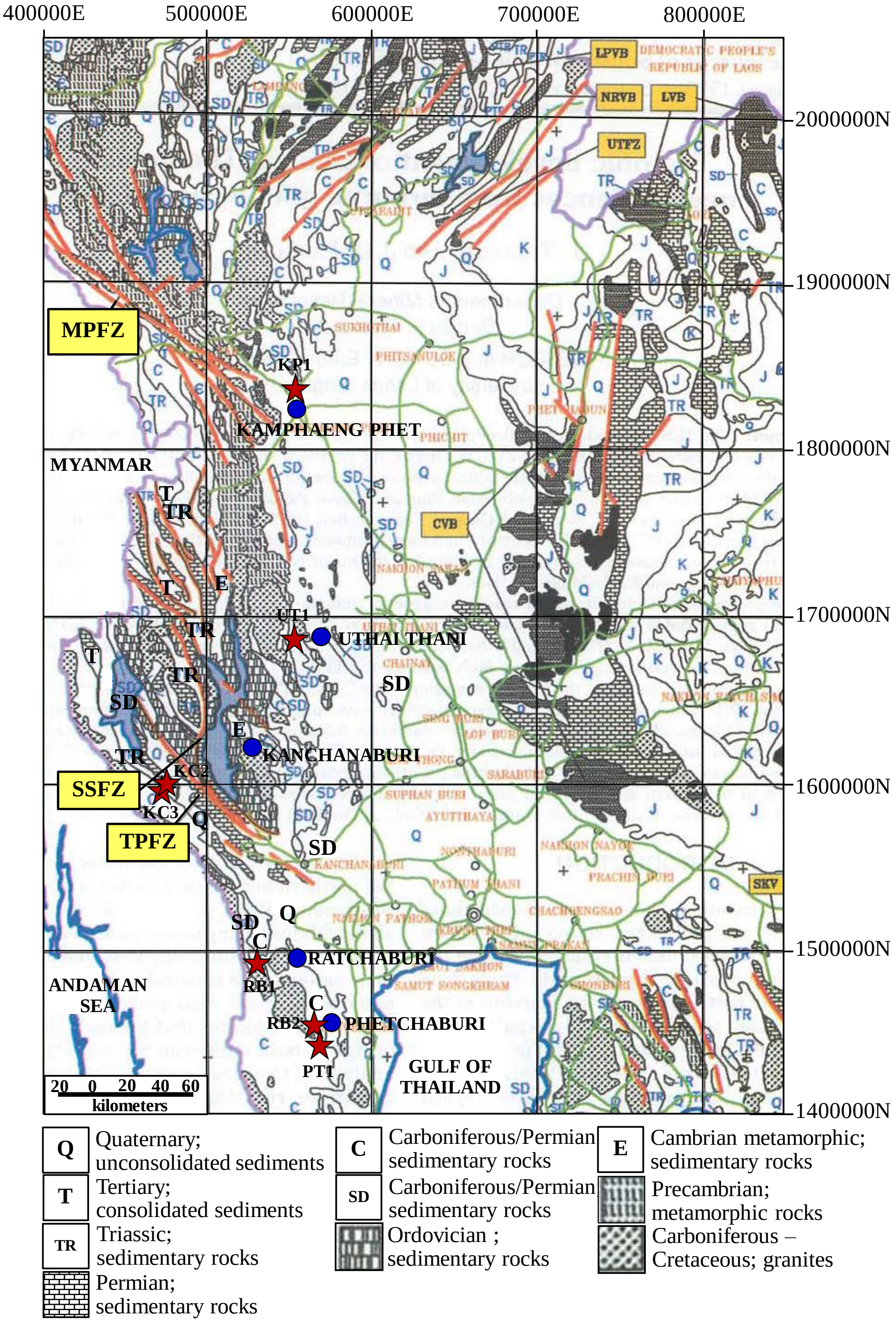

Fig. S1 Geological map of Central and Western Thailand showing the distribution of the seven geothermal springs (Uthai Thani, UT1; Kamphaeng Phet, KP1; Kanchanaburi, KC2 and KC3; Ratchaburi, RB1 and RB2; and Phetchaburi, PT1) as well as the trends of the Mae Ping Fault Zone (MPFZ), the Three Pagoda Fault Zone (TPFZ), and the Sri Swat Fault Zone (SSF).