PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 6-8, 2023
SGP-TR-224

Preliminary Play Fairway Analysis of Geothermal Resources in Southern Thailand

Panupong Kongpet[1], Pitsanupong Kanjanapayont[1,2], Nicole Lautze3, Erin Wallin[3]

[1]Basin Analysis and Structural Evolution Research Unit (BASE RU), Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand

[2]M.Sc. Program in Petroleum Geoscience, Faculty of Science, Chulalongkorn University, Bangkok, 10330, Thailand

[3]Hawaii Groundwater & Geothermal Resource Center, University of Hawaii at Manoa, Honolulu, HI 96822, USA

6233033123@student.chula.ac.th

panupong2643@gmail.com

Keywords: Non-volcanic geothermal system, Low- to medium-enthalpy hot springs, Play fairway analysis, Southern Thailand

ABSTRACT

Southern Thailand is a non-volcanic area encompassing 70,000 km^2 that contains a reported 31 low- to medium- enthalpy hot springs. Dominant rock types are Paleozoic to Cenozoic sedimentary rock and Mesozoic granitic rock. The area is about 500 km east of the Andaman-Sumatra Subduction Zone resulting from the subduction of the Indian-Australian plate under the Eurasian plate. Two major active strike-slip faults exist within southern Thailand - the Ranong and Khlong Marui faults. Half of the 31 hot springs are located near these two fault zones and are related to contacts between the granitic body and Paleozoic-Cenozoic sedimentary rock unit. We use the relationship between hot springs, satellite gravity data, geologic maps, airborne magnetic data, and seismicity as key evidence to consider the geothermal resource potential of the area. Our goal is to apply the Play Fairway Analysis method for the first time in Thailand to evaluate geothermal resources. The required elements for a viable geothermal Play are heat (H) and permeability (P). To date, this preliminary study will: (1) map and contour the existing geology, geochemistry, and geophysics datasets of southern Thailand; (2) identify and rank datasets relevant to heat, and permeability, which we consider necessary for a viable geothermal play; (3) make a basic assessment of development viability, and (4) present a data collection plan. From a basic qualitative interpretation, geothermal systems in the study area are mainly controlled by the tectonic environment in terms of heat and permeability. The subsurface heat source results in the convection of hot fluid that transports heat from depth to the reservoir and surface via fluid pathways; faults and fractures, expressed in the form of hot springs. The consideration of high potential target areas is based on; 1) indicators of high heat anomalies including high exit temperatures and reservoir temperature hot springs, locations of high thermal conductivity rocks, and radio-active decayed granitic body; 2) indicators of high permeability that are low gravity anomaly and presence of hot springs; 3) faults, which relate to both anomalous high heat and high permeability. This study unveils potential future target areas for geothermal data collection and potential development for purposes including tourism, farming, and even geothermal electricity production in Ranong, Phang Nga, Surat Thani, and Yala geothermal provinces.

1. INTRODUCTION

Geothermal resources can provide renewable energy for sustainable development. Geothermal energy meets seven of the United Nations' Sustainable Development Goals (SDGs): number 1 (no poverty), number 7 (affordable and clean energy), number 8 (decent work and economic growth), number 9 (industry, innovation, and infrastructure), number 11 (sustainable cities and communities), number 12 (responsible consumption and production), and number 13 (climate action). To reveal the potential target areas for exploration and development of geothermal in Southern Thailand, the Play Fairway Analysis (PFA) method was used. PFA, originally developed in the oil and gas industry, entails identifying the characteristics required for a resource to exist; identifying and ranking the data that inform such characteristics in target area, or Fairway; and then systematically combining the disparate datasets to yield an internally consistent probability map of resource regions (Plays) that have a greater or lesser probability for a resource. The resource probability map is then used to define an assessment program capable of identifying viable resources within the Fairway in the most cost-effective manner (Lautze et al., 2017). For this study, the required elements for a viable geothermal Play are heat and permeability. Heat is needed for the resource to exist, and permeability is required so that fluids can be extracted and replenished in the subsurface. This preliminary study will: (1) map and contour the existing geology, geochemistry, and geophysics datasets of southern Thailand; (2) identify and rank datasets relevant to heat, and permeability, which we consider necessary for a viable geothermal play; (3) make a basic assessment of development viability, and (4) present a data collection plan.

2. BACKGROUND

2.1 Geothermal resources in Thailand

In recent years, Thailand has been deeply concerned about environmental issues and climate change. In COP27, the Thai government proposed reducing 40% of our carbon based emissions by 2030, carbon neutrality by 2050, and net zero carbon emissions by 2065. Geothermal may play an important component in achieving the goal. Thailand's first geothermal powerplant, Fang geothermal powerplant, is in Fang District, Chiang Mai Province, northern Thailand, and has a 0.3 MW generating capacity and subsurface water temperature of

130 °C. In 1978, the Electricity Generating Authority of Thailand (EGAT) studied and surveyed the geothermal power source in Fang District in collaboration with the Department of Mineral Resources and Chiang Mai Province and determined that the Fang District provided a viable resource for electricity production. Then, in 1989, EGAT began work on the Fang Geothermal Power Plant. In addition to power generation, geothermal energy is used to dry agricultural crops such as onion, garlic, longan, and chilli, and in the mineral bathing room, excess hot water is used for physical therapy.

2.2 Geological setting in the study area

Global data clearly show that Sundaland or Southeast Asia is a region with high surface heat flow (Artemieva & Mooney, 2001). Southern Thailand, the study area, is located within a high heat flow area. and covers an area, land, of approximately 70,000 km^2 and is located between longitudes 98°E and 102.2°E and latitudes 5.5° N and 11°N (Fig 1). Southern Thailand sits on the Eurasian plate where both sides of the eastern, Filipino plate, and the western, Indian-Australian plate, are move inward making a convergent plate boundary. From the geological map (Fig. 2), dominant rock types are Paleozoic to Cenozoic sedimentary rock, Mesozoic granitic rock, and Permian-Triassic volcanic rock. The area is about 500 km east of the Andaman-Sumatra Subduction Zone caused by subduction of the Indian-Australian plate under the Eurasian plate. Two major active strike-slip faults exist within southern Thailand - the Khlong Marui fault (KMZ) and Ranong faults (RF). These faults formed near the southern margin of a Late Cretaceous–Paleocene orogen and may have been influenced by variations in the rate of subduction ahead of India and Australia. North-south compression prior to reactivation of the subduction zone around southern Sundaland in the Eocene caused widespread deformation in the overriding plate, including sinistral transpression on the KMF and RF (Watkinson et al., 2008). Southern Thailand is a non-volcanic area, but still contains a reported 31 low- to medium-enthalpy hot springs with exit temperature from 40-80 °C and reservoir temperature from 70-145 °C (Ngansom & Dürrast, 2021). Half of the hot springs are located near these KMF and RF zones and are related to the contact between granitic bodies and Paleozoic-Cenozoic sedimentary rock units. The other half is not along KMF and RF zones. Some hot springs in southern Thailand (e.g., RN1) are in tourist areas, surrounded by concrete and small buildings with few to no geological features. However, geochemical survey, water collection, can still be done. Naturally occurring hot springs (e.g., RN4 and RN6) in the study area often exhibit sulfur smell, quartz precipitation, and shallow fractures. The springs also indicate a low-pressure system as demonstrated by boiling pools, versus high-pressure geysers where boiled water and hot steam indicate high-pressure resulting in eruptive behavior.

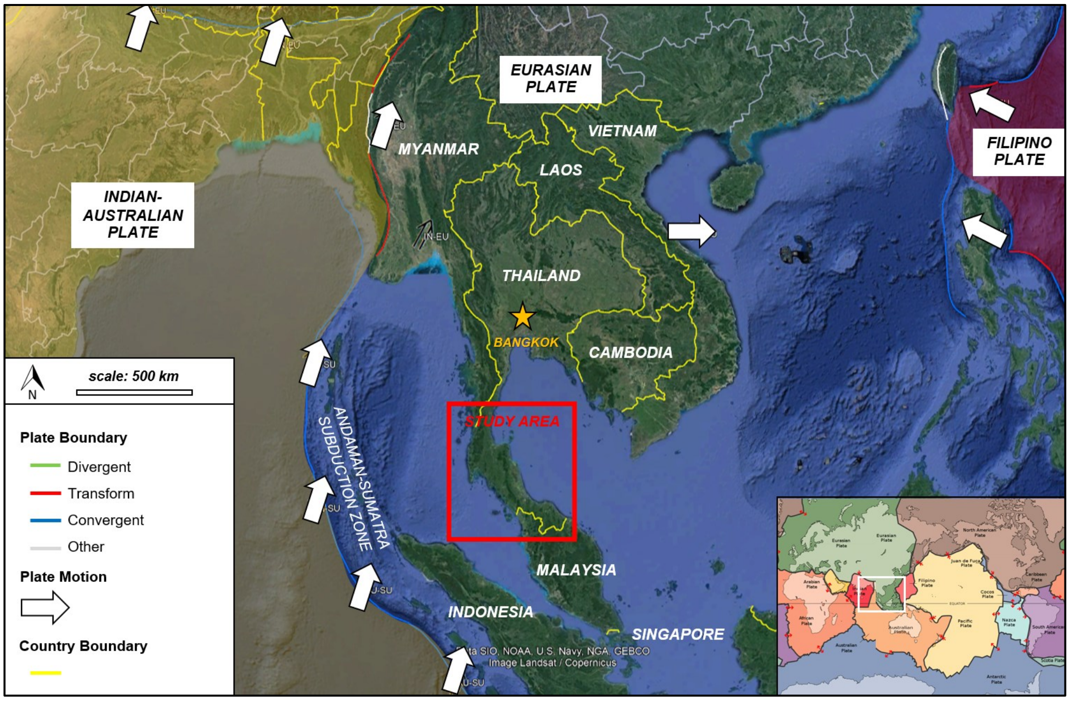

Figure 1: Tectonic orientation of Thailand. The study area, southern Thailand, is shown in the red square (modified from Google Earth and USGS).

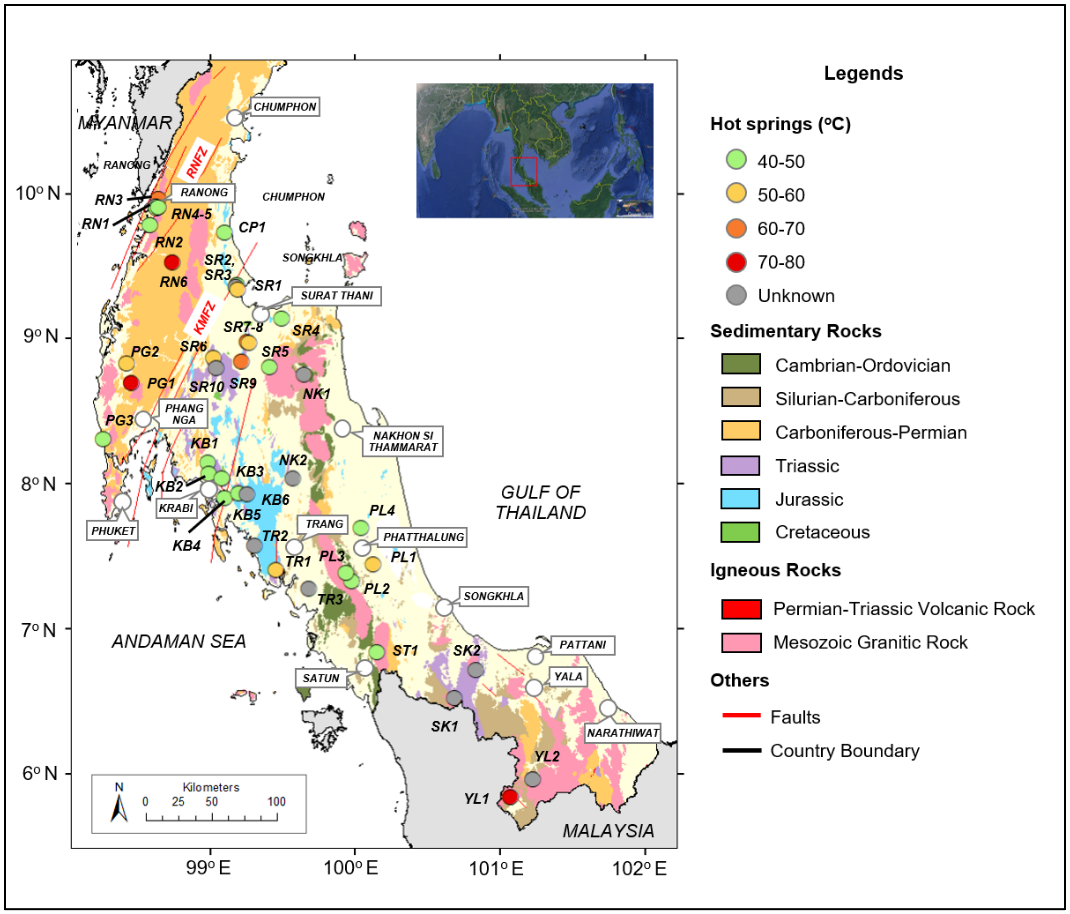

Figure 2: Geological map of southern Thailand (from Thailand's Department of Mineral Resources, 1999) showing rock units that range from Paleozoic to Cenozoic sedimentary rock and Mesozoic granitic rock. The hot spring distribution is modified after Ngansom & Dürrast (2021). The trends of the Ranong Fault zone (RF) and the Khlong Marui Fault zone (KMF) from Hinthong (1995) are shown in northeast-southwest trend red line.

3. METHODS

The method in this study followed the workflow in Fig 3. First, we mapped and contoured the existing data in southern Thailand in terms of geology, geophysics, and geochemistry. Second, we identified datasets relevant to geothermal heat and permeability, which include geologic maps, hot springs data, groundwater data, satellite gravity data, airborne magnetic data, and earthquake data. The authors identified proxies relevant to heat and permeability from each dataset. Each dataset was relatively ranked of reliability of how important the data are to indicating either heat or permeability, from 1 (low) to 5 (high). The numbers in parentheses indicate their ranking on a relative scale of 1–5, as derived by a method of 'expert elicitation' (Lautze et al., 2017). The evidence of heat anomaly and high permeability are explained below. This is followed by a basic assessment of development viability. Finally, a data collection plan for future exploration is presented.

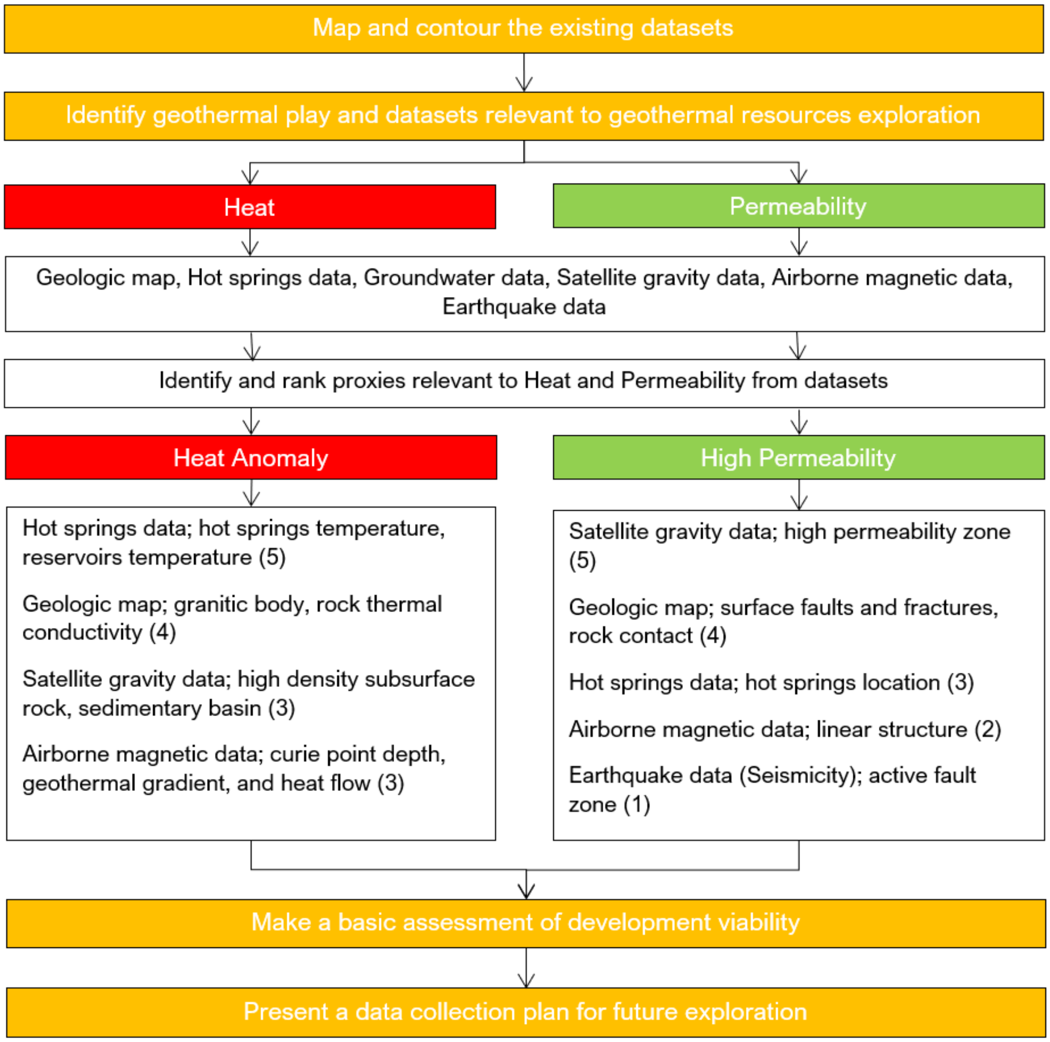

Figure 3: Flowchart showing workflow. The filled-colored boxes numbered 1–4, are main steps in this preliminary work. Each step will be discussed in the methods part. Step 2, identify geothermal play and datasets relevant to geothermal resources exploration, will be explained below.

Table 1: Summary of datasets used in this study, evidence they provide, and relative ranking of reliability, from 1 (low) to 5 (high).

Datasets	Evidence of high heat anomaly	Relative ranking of reliability, from 1 (low) to 5 (high)
Hot springs data; hot springs temperature, reservoirs temperature	High hot spring and reservoir temperature can indicate heat circulation in the subsurface	5
Geologic map; rock thermal conductivity, granitic body	Provide location of granitic body and each rock type where heat conductivity is different	4
Satellite gravity data; high density subsurface rock, moho depth	Possible location of subsurface granitic body or hot rock	3
Airborne magnetic data; curie point depth, geothermal gradient, and heat flow	Location where shallow curies point depth, and high geothermal gradient and heat flow indicate high potential resources	3

Datasets	Evidence of high permeability	Relative ranking of reliability, from 1 (low) to 5 (high)
Satellite gravity data; high permeability zone	Low values indicate high permeability within deeper structure	5
Geologic map; surface faults and fractures, rock contact	Area of where faults and fractures are dominated indicate high permeability zones in both surface and subsurface	4
Hot springs data; hot springs location	Where hot springs exist indicates high permeability	3
Airborne magnetic data; linear structure	Provide shallow-medium lineation structure such as fault or fracture which show zone of high permeability	2
Earthquake data (Seismicity); active fault zone	High seismicity occurs where the crust is already weak and permeable, or where fracture permeability is being enhanced	1

4. SOUTHERN THAILAND DATASETS

4.1 Southern Thailand datasets relevant to heat

Heat is a key element showing where the geothermal resources exist. In southern Thailand, a non-volcanic area, the resource heat can be indicated by hot rocks, decayed granitic body, elevated heat from extensional tectonic environments, and/or subduction related high heat anomaly. The evidence to reveal heat in the study area is as follows.

4.1.1 Hot springs data; hot springs temperature, reservoirs temperature

Hot springs data provides important evidence of where heat anomaly such as hot spring location, exit temperature of hot spring at the surface and geochemistry of hot spring; SiO_2 which is abundant in rocks and has a temperature-dependent solubility; therefore, elevated silica in groundwater has been widely used as a thermal indicator (Lautze et al., 2017a). Not only silica but also cations; Na, Ca, K, and Mg, can indicate subsurface heat and reservoir temperature in non-volcanic areas. These data are the most important to consider geothermal resources viability in non-volcanic areas (Ngansom & Dürrast 2021). The latter classifies geothermal resources into low- (below 100 °C) medium- (100–180 °C), and high-enthalpy (higher than 180 °C) fields. Low-enthalpy resources are used for direct heat use, e.g., for district heating, industrial or agricultural use often in combination with heat pumps. Medium- to high-enthalpy resources allow for power generation using different kinds of geothermal power plants (Sigfússon & Uihlein, 2015; Fink et al., 2022).

4.1.2 Geologic map; rock thermal conductivity, granitic body

Geology maps provide rock type and geology in this area to show the relationship between hot spring temperature and geological features. Thermal conductivity varies depending on the type of rock. Its variation in crystalline rock is narrow, whereas sedimentary rocks have a wider range. The maximum value of thermal conductivity in metamorphic rock (e.g., quartzite and schist) and sedimentary rocks (e.g., sandstone and limestone) are, relatively, higher than igneous rock (e.g., granite and diorite) (Shim & Park, 2013). In the same tectonic environment and amount of heat, high thermal conductivity rocks can allow heat more than low thermal conductivity. Therefore, groundwater above high thermal conductivity rocks would be easily heated. Geologic maps provide granitic body units on the surface from which we can further interpret subsurface granitic bodies in terms of rock properties and distribution. The subsurface granitic body in the area is believed by Thailand's Department of Mineral Resources to be one of the heat sources for the geothermal system by radioactive decay. It is still debated whether the amount of heat produced by granitic bodies is sufficient to boil water.

4.1.3 Satellite gravity data; high density subsurface rock

Density models from gravity data can show us density anomalies which might be hot rock or radio-active decayed granitic bodies in the deeper part of the subsurface. The gravity anomaly may indicate granitic bodies underground. Some geologists believe that radioactive decay from granite can generate heat at curtain depth. Moreover, large-scale variations in residual Bouguer gravity anomalies reflect how the Moho undulates, because the Moho represents the largest density boundary in the lithosphere (Li & Wang, 2016). The Bouguer gravity anomaly map (Fig. 4B) is from http://icgem.gfz-potsdam.de/calcgrid (Ince et al., 2019), using SGG-UGM-2 model (Liang et al., 2020).

4.1.4 Airborne magnetic data; curie point depth, geothermal gradient, and heat flow

Airborne magnetic data can be used to calculate and generate curie point depth by deriving the depth of the bottom of the magnetic body to the surface using a spectral analysis method originally from Spector & Grant (1970). The Curie point depth is the theoretical surface with a temperature of approximately 580 °C and can be used as an index of the bottom of a magnetic source due to ferromagnetic minerals converting to paramagnetic minerals (Hsieh et al., 2014). We can extend curie point depth to calculations of geothermal gradient and heat flow by using the heat conductivity factor in each location (e.g., Tanaka et al., 1999). Geothermal gradient and heat flow data could play an important role in heat distribution on a regional scale. We show residual magnetic field values (final total field- IGRF 1980) (Fig. 4C) from Thailand's Department of Mineral Resources, with surveying by Kenting Earth Science company during 1984-1990.

4.2 Southern Thailand datasets relevant to permeability

Permeability allows fluids to be extracted from and replenished in the subsurface. Subsurface permeability is associated with the ability to extract groundwater resources. Groundwater and permeability combined with heat can equate to a geothermal reservoir. Faults, fractures, and rock contact are direct evidence for permeability on a regional scale. Sedimentary basins can also show favorable location for geothermal system. Consideration of high permeability is based on presence of 1) faults and fractures; 2) rock contact; and 3) sedimentary basins. Evidence to reveal the permeability in the study area is as follows:

4.2.1 Satellite gravity data; high permeability zone

Gravity data can indicate deep structures, which may be otherwise hidden faults. It also shows the relationship between hot springs and fault structure and tectonic setting in the area. Gravity models provide density information, where higher density typically equates to lower permeability. Enhancing gravity data examining derivatives such as first total horizontal and vertical derivatives, and tilt derivative can also show deep structures, faults, and fractures.

4.2.2 Geologic map; surface fault and fracture, rock contact

Geologic maps provide rock contact and fault interpretations on the surface. This is the first tool that we use to interpret the relation between hot springs and geology of the area. Faults are important data to interpret the tectonic environment for geothermal exploration because faults are believed to be a main fluid pathway for hot springs. Understanding the fault in terms of rate, age, stress state, and strain helps us to understand favorable structural and tectonic setting for hot springs in geothermal system. We utilize fault data from Thailand's Department of Mineral Resources and Hinthong (1997).

4.2.3 Hot springs data; hot springs location

Hot springs data can be very useful in terms of permeability. The presence of hot springs is an indicator of fluid pathway where water can flow through the rock from underground to the surface. Fluid pathways are considered as; 1) deep faults which possibly cut deep to the mantle and geothermal resources reservoir; and 2) shallow fractures which cut reservoir through the surface.

4.2.4 Airborne magnetic data; linear structure

Enhancing airborne magnetic data, using similar methods to those performed with gravity data, can provide shallow-medium lineation structure such as faults and fractures, and rock contact.

4.2.5 Earthquake data (Seismicity); active fault zone

Earthquake data are an indicator of active faults in terms of location and depth which is useful for permeability consideration. In southern Thailand, there are very few earthquakes during human recordable times. The data source is from Earthquake Observation Division, Meteorological Department of Thailand.

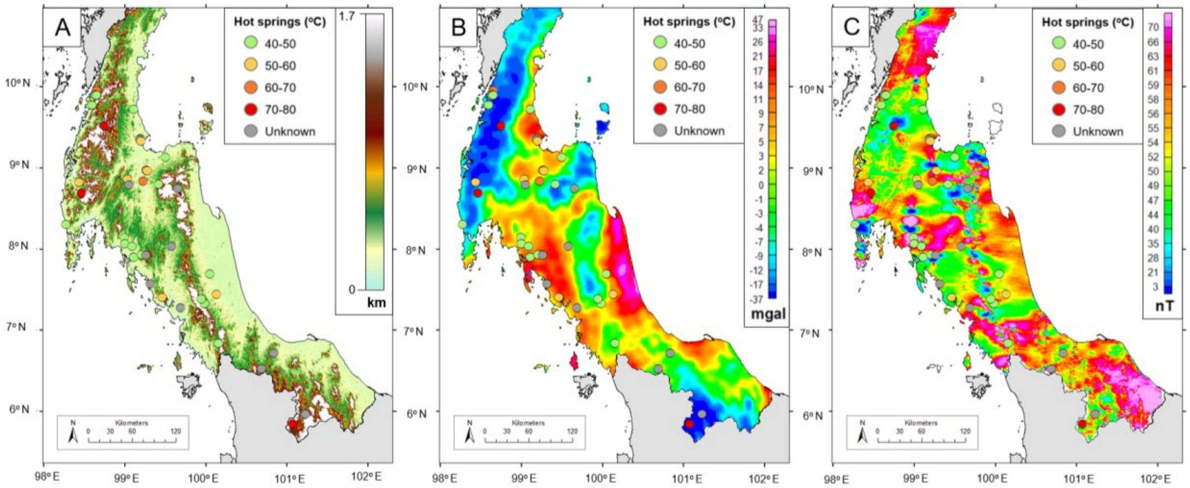

Figure 4: A. Digital Elevation Model (DEM) (Pailoplee, personal contact). B. Bouguer gravity anomaly map using SGG-UGM-2 model and grid stepping 0.1 (Ince et al., 2019; Liang et al., 2020). C. Residual magnetic field value (final total field- IGRF 1980) map (Thailand's Department of Mineral Resources).

5. RESULT AND DISCUSSION; BASIC QUALITATIVE INTERPRETATION/INITIAL FINDINGS

5.1 Evidence for elevated heat

Hot springs provide key evidence of surface heat and elevated heat in southern Thailand (Fig. 5). Of 31 hot springs, exit temperature ranges from 40-80 °C and reservoir temperature from quartz geothermometry ranges from 72.8 – 135.8 °C (Ngansom & Dürrast, 2021). These hot springs are direct evidence of the existence of a heat anomaly underground. The hot springs are usually located near faults. Faults in the area are believed to be strike-slip faults which were a compressional regime in the past and are an extensional regime in the present. These faults cut through the continental crust; thus, the heat anomalies are elevated. One of the heat sources is possibly from a radio-active decayed granitic body at depth. Metamorphic rock and sandstone basement rocks are high thermal conductivity which can easily conduct heat to the surface as expressed by heating groundwater and becoming hot springs. Sometimes heated groundwater has no pathway or enough pressure to the surface; such hot groundwaters have become reservoirs and high potential areas for geothermal resources. In some systems one reservoir can provide more than one hot spring. The reservoirs are usually located under or near the hot springs themselves. It is expected that there are many undiscovered hot springs in southern Thailand.

5.2 Evidence for elevated permeability

The relationship between hot springs location and bouguer gravity is evidence for elevated permeability. Most of the hot springs exist near or on low gravity anomalies. Low gravity anomalies indicate low density bodies under the surface. such as a magma chamber, hot rock, sedimentary basin, and deep fault and fracture zone. All earthquakes, 3-4 Magnitude at depth approximately 10 km (Fig. 6), showing active faults, were concentrated in the southwestern part of the KFZ in the Andaman Sea. In southern Thailand, these are interpreted as sedimentary basin or deep faut and fracture zone, thus, high permeability. High permeability zone underground would be a high potential area for underground water reservoir. If such a reservoir is combined with the presence of the hot springs, it would be a high potential area for geothermal resources. Hot springs cannot be a direct indicator for permeability, but they could help to identify the extent of the reservoir.

5.3 Qualitative interpretation for the target areas

Our preliminary qualitative interpretation of target areas is based on; 1) indicators of high heat anomaly that are high exit and reservoir temperature hot springs, locations of near high thermal conductivity rocks, and radio-active decayed granitic body (Fig. 5); 2) indicators of high permeability that are low gravity anomaly and presence of hot springs (Fig. 6); 3) faults relate to both high heat anomaly and high permeability. These three considerations provide high potential target areas which are shown in Fig. 7: Ranong, Phang Nga, Surat Thani, and Yala geothermal provinces.

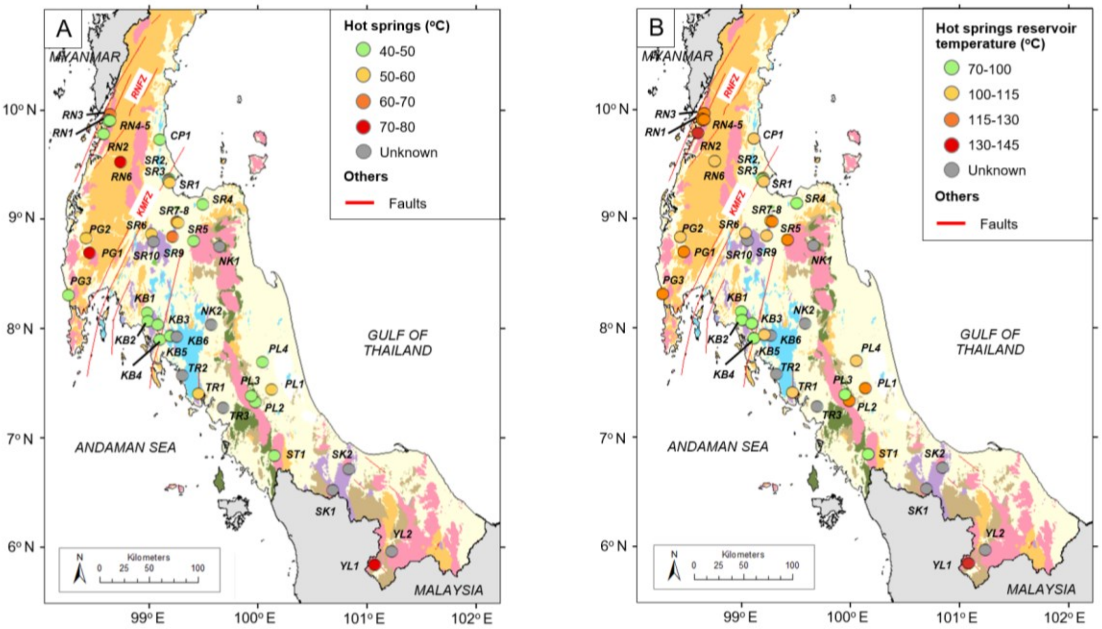

Figure 5: A. Geological map with exit temperature of the hot springs. B. Geological map with reservoir temperature of the hot springs.

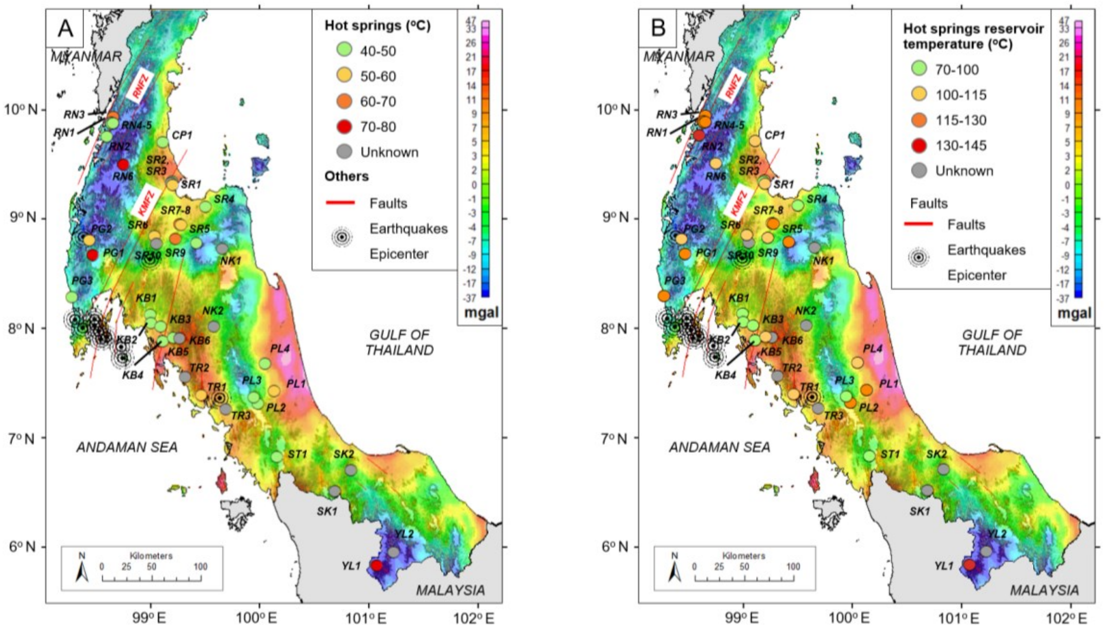

Figure 6: A. Bouguer gravity anomaly map with exit temperature of the hot springs, faults, and earthquakes B. Bouguer gravity anomaly map with reservoir temperature of the hot springs, faults, and earthquakes.

6. FURTHER STUDY; A DATA COLLECTION PLAN

This study so far is regional. For further study, specific geological, geophysical, and geochemical surveys are required. For example, an important method in the surface exploration of high potential geothermal areas are electrical and electromagnetic methods (Georgsson, 2013). Processing of airborne magnetic data is ongoing. This data will provide Curie point depth, thermal gradient, and heat flow, by calculating from residual magnetic field value (Fig. 5C). For the data collection plan, we not only considered the 2 factors which mentioned above, but also an economic factor in order to consider the accessibility of the resources, for example, as related to electricity usage in different areas, both rural and urban. From our preliminary qualitative interpretation, high priority target areas for the future exploration are in Ranong and Phang Nga, Surat Thani, and Yala. There are three main methods for field data collection: geological, geochemical, and geophysical. Firstly, detailed geological fieldwork is needed to map the rock units, faults, and fractures, and to collect rock samples for thin sections. This would be very helpful to understand tectonic regime (contraction, extension, or strike-slip) in the area. Secondly, collecting water samples from groundwater well would help to contour surface temperature and elements composition. The Na, K, Ca, Ng, SiO_2 geothermometers would provide the reservoir temperature. Thirdly, geophysical methods including airborne magnetic and satellite gravity would provide a regional study, followed by gravity and magnetotelluric survey in specific target areas. Drilling a temperature-gradient well would be a fourth important prospecting step that, if successful, could lead to development. Additionally, the quantitative interpretation using geostatistical methods would be useful for blind geothermal resources where there are no geothermal activities expression such as hot springs before starting a new collection plan. In Thailand, geothermal energy can be expected to support various economies such as tourism farming, manufacturing, construction, and even geothermal electricity production itself.

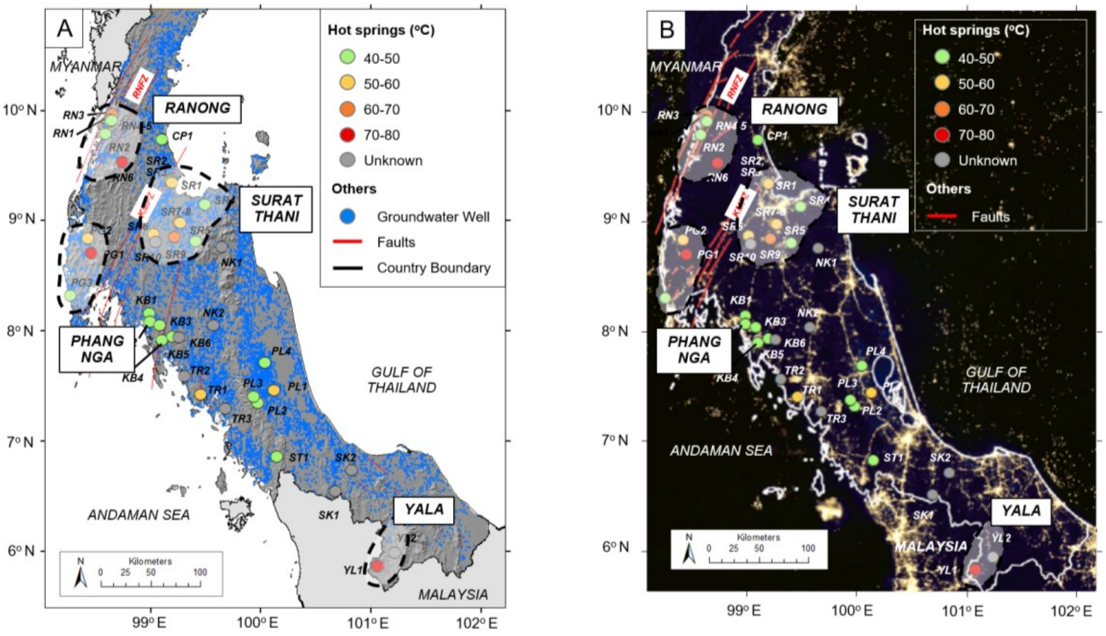

Figure 7: Location of high potential target areas which are Ranong, Phang Nga, Surat Thani, and Yala geothermal province. A. Groundwater well distribution (Groundwater Resources Management (Smart Pasutara), 2022). B. Southern Thailand at night to show urban area (modified after Jitmahantakul, 2013).

7. SUMMARY

The ultimate goal for geothermal exploration is to extract a natural subsurface heat resource for human usage that reduces our fossil fuel consumption. Although ultimately necessary, drilling is very expensive. This preliminary PFA is intended to reduce the risk associated with drilling by analyzing existing data and collecting new, less expensive data to refine drilling target areas. We also incorporate a development viability analysis that considers economics and accessibility of a resource should one be discovered. This preliminary PFA finds 4 high potential areas in Ranong, Phang Nga, Surat Thani, and Yala geothermal provinces. Development viability criteria, including assessment of the area, local government support, and demand for renewable energy will be used to consider future data collection plan. Datasets description as evidence of heat and permeability in this PFA can apply to non-volcanic area but still contain geothermal expressions. Given the presence of hot springs and warm groundwater across the Asia Pacific, a similar PFA method may also apply including in western and northern Thailand, Malaysia (Malay peninsula), Myanmar, Laos, Cambodia, Vietnam (Mainland Southeast Asia), and Taiwan.

ACKNOWLEDGEMENTS

We wish to thank Thailand's Department of Mineral Resources (DMR) that provided the geological map and airborne magnetic survey datasets. This work is supported by the Development and Promotion of Science and Technology Talents (DPST) Project Scholarship of Thailand. This work could not be done by the help of department of Geology, Faculty of Science, Chulalongkorn University and Hawai'i Groundwater & Geothermal Resources Center (HIGP).

REFERENCES

Artemieva, I. M., & Mooney, W. D. (2001). Thermal thickness and evolution of Precambrian lithosphere: A global study. Journal of Geophysical Research: Solid Earth, 106(B8), 16387-16414.

Earthquake Statistics. Earthquake Observation Division. (n.d.). Retrieved December 28, 2022, from https://earthquake.tmd.go.th/.

Fink, J., Heim, E., & Klitzsch, N. (2022). State of the art in deep geothermal energy in Europe: with focus on direct heating.

Georgsson, L. S. (2009). Geophysical methods used in geothermal exploration. Short Course on Surface Exploration for Geothermal Resources.

Groundwater Resources Management (Smart Pasutara). (n.d.). Retrieved December 28, 2022, from https://pasutara.dgr.go.th/api_well/api/FindWellAll.

Hinthong, C. (1995, January). The study of active faults in Thailand. In Proceedings of the annual technical 1995 conference on the progression and vision of mineral resources development (pp. 129-140).

Hsieh, H. H., Chen, C. H., Lin, P. Y., & Yen, H. Y. (2014). Curie point depth from spectral analysis of magnetic data in Taiwan. Journal of Asian Earth Sciences, 90, 26-33.

Ince, E. S., Barthelmes, F., Reißland, S., Elger, K., Förste, C., Flechtner, F., & Schuh, H. (2019). ICGEM–15 years of successful collection and distribution of global gravitational models, associated services, and future plans. Earth System Science Data, 11(2), 647-674.

Jitmahantakul, S. (2013, December 6). Actives Fault in Thailand. GeoThai.net. Retrieved December 28, 2022, from https://www.geothai.net/thailand-active-faults/.

Lautze, N., Thomas, D., Hinz, N., Apuzen-Ito, G., Frazer, N., & Waller, D. (2017). Play fairway analysis of geothermal resources across the State of Hawaii: 1. Geological, geophysical, and geochemical datasets. Geothermics, 70, 376-392.

Liang, W., Li, J., Xu, X., Zhang, S., & Zhao, Y. (2020). A high-resolution Earth's gravity field model SGG-UGM-2 from GOCE, GRACE, satellite altimetry, and EGM2008. Engineering, 6(8), 860-878.

Li, C. F., & Wang, J. (2016). Variations in Moho and Curie depths and heat flow in Eastern and Southeastern Asia. Marine Geophysical Research, 37(1), 1-20.

Ngansom, W., & Dürrast, H. (2021). Geochemical Characterization of Hot Spring Waters from Southern Thailand as the Base for Geothermal Energy Utilization. EnvironmentAsia, 14(3).

Shim, B. O., & Park, C. H. (2013). Ground thermal conductivity for (ground source heat pumps) GSHPs in Korea. Energy, 56, 167-174.

Sigfússon, B., & Uihlein, A. (2015). 2014 JRC geothermal energy status report.

Spector, A., & Grant, F. S. (1970). Statistical models for interpreting aeromagnetic data. Geophysics, 35(2), 293-302.

Tanaka, A., Okubo, Y., & Matsubayashi, O. (1999). Curie point depth based on spectrum analysis of the magnetic anomaly data in East and Southeast Asia. Tectonophysics, 306(3-4), 461-470.

Vimuktanandana, S. (1999). Geological Map of Thailand, 1:2,500,000. Bangkok: Geological Survey Division, Department of Mineral Resources.

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