Radiogenic heat production of S-type and I-type granite rocks in Bangka Island, Indonesia

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Abstract

Radiogenic heat production (RHP) has been investigated from wide types of rocks based on regional setting and metamorphism grade. In this study, we analyze the abundance of heat-producing elements (U, Th, K) and Radiogenic Heat Production (RHP) on I-type and S-type granite rocks in Bangka Island, one of the main provinces in Tin Belt Island. The average U, Th, and K concentrations for both S-type and I-types granite are 10.27 ppm, 79.6 ppm, 3.1%, and 87.79 ppm, 99.2 ppm, and 1.93 % respectively. The highest concentration of U (681.22 ppm) and Th (99.2 ppm) are found in Pangkal Pinang and K (3.79%) in West Bangka. We analyze that the RHP average for I-type granite is higher at 27.87 (N=17, range from 12.97 to 550.28) than S-type with 8.43 (N=11, range from 4.93 to 12.64). The Th/U ratio shows an exponential correlation with RHP and classifies S-type granite tectonic discriminant as continental collision and I-type granite as a continental arc.

Keywords: Continental lithosphere; I-type granite; radiogenic heat production; S-type granite, Th/U ratio

1. Introduction

Radiogenic Heat Production (RHP) is a major key to studying the temperature and heat flow of the crust and mantle of the earth (Sclater *et al.*, 1980), whereas RHP contains information about the relation between tectonic age and evolution of the earth's crust. Radiogenic heat is mostly produced by the existence of radioactive elements in the igneous rocks both volcano and plutonic rocks (Singh & Vallinayagam, 2016). Thorium, Uranium, and Potassium are widely discovered in granite and have been studied by numerous researchers (He *et al*., 2010; Zhang *et al*., 2020) for their contribution to radiogenic heat production. These elements were processed in the mantle but are concentrated mainly in the crust.

In the uppermost crust, heat distribution is mostly controlled by Uranium & Thorium hence the upper mantle is controlled by potassium (Cermak & Bodri, 1991). The heat generated by radioactive in the continental crust (roughly equally granodiorite & granulite) contains about 10%

of the total outflow, whereas oceanic crust and mantle are 0.15% and 30% respectively (Brown & Musset, 1993).

Radiogenic heat generation in granite has been analyzed by numerous researchers (Artemeiva *et al.*, 2017; Hasterok *et al*., 2019; Veikkolainen *et al.,* 2019). The Th/U ratio of granite can be used to explain the geodynamic evolution and represent the genesis of continental arc magmas (Maden & Akaryali, 2015). Moreover, studies on radioactive heat generation have been applied to igneous, metamorphic, and sedimentary rocks (Hasterok *et al.,* 2018; Jaupart *et al.,* 2016). Overall, researchers provide information on heat production as general compiled data from different continental settings and tend to relate it to variations of lithology and regional settings. Unfortunately, research on the same rock type (e.g granite as one of the most promising radioactive element hosts) is hardly analyzed due to the rare granite in regional studies. Meanwhile, a vast variety of granite can be easily found on Bangka Island, Indonesia.

Bangka is one of the main provinces in the Southeast Asia granite tin belt extending from Burma, Malaysian peninsular, to Tin Islands (Riau Archipelago & Bangka Island). Thorium in Bangka Island granite has been investigated (Ngadenin *et al.,* 2014) from 41 samples leading to thorium exploration potential. Furthermore, granite in Central and Northern Bangka are identified as I-type which is indicated by the significant presence of magnetite, magnesian, and more primitive, while S-type in South and West Bangka is indicated by high K_2O and the abundance of biotite, muscovite and cordierite (Widana, 2013).

In this study, we investigate radiogenic heat production (RHP) on granite in West-South Bangka and Central-North Bangka. The goal of this study is to examine the correlation between RHP and magmatic types of granite rocks in Bangka Island, S-type, and I-type. This study's objective is intriguing since we found little research reference of granite's RHP based on its types.

2. Geological Setting

Bangka Island is a part of the South East Asia tin belt from Malaya peninsula, Riau islands, Bangka and Belitung Island to West Kalimantan. Regional granites have been classified into four provinces; the main range province (S type granite mainly Triassic age), the eastern province (permo-triassic of I type granite), the western – peninsular Thailand-Burma (mostly S type with smaller I type of Cretaceous age) and the north Thailand migmatite province with S type of Triassic age (Hutchison, 1977).

The granitoid of Bangka island is a combination of the main range province and eastern province (Schwartz *et al.,* 1995). The main range overlaps in time with the eastern province produced at different source regions and mobilized within the same crustal segment (Barber *et al.,* 2005). Magmatic sources of Southern Bangka granite are mixed of crust and mantle with Calc-Alkaline affinity, whereas Northern Bangka granite sources are characterized as crust products with high-K calc-alkaline affinity (Widana & Priadi, 2015). The forming of S type affinity is in continental acr-post-collisional and I type Calc-Alkalic is related to subduction with the prototype as a product of hydrous, mafic igneous, and metamorphic rocks (Roberts & Clemens, 1993). The tectonic activity was subduction of Paleo-Thetys oceanic from Perm to Trias period followed by the collision of Sibumasu (Siam-Burma-Malaysia-Sumatra) block with East Malaya. This collision along Bentong Raub Suture lead to magmatic activity and the forming of I and S type in Bangka Island (Metcalfe, 2000).

3. Method

The interest in calculating radiogenic heat production in Bangka Island comes from the previous research (Ngadenin & Karunianto, 2016; Ngadenin *et al.,* 2014). The granite rocks were sampled from outcrop as representative of the Klabat granite formation which geologically controls Bangka Island (Figure 1). Granites were crushed and pulverized into powder form (>200 mesh) in an agitate mortar. Samples were analyzed by X-Ray Fluorescence to characterize major and trace elements. Samples in powder form were then dried in an oven at 100℃ for 24 h. Dry samples were put into polities capsule to perform Analysis Activation Neutron (AAN) for characterizing Thorium & Uranium in Pusdiklat- National Nuclear Energy Agency of Indonesia after irradiated in Siwabessy Reactor in Serpong. The result of both methods will be used to study petrogenesis (Widana & Priadi, 2015) and the heat production of granite. Meanwhile, radioactive elements of samples in this study are time-independent, so another method that permits the simultaneous determination of the sample's radionuclide such as Gamma ray-spectrometry is not used.

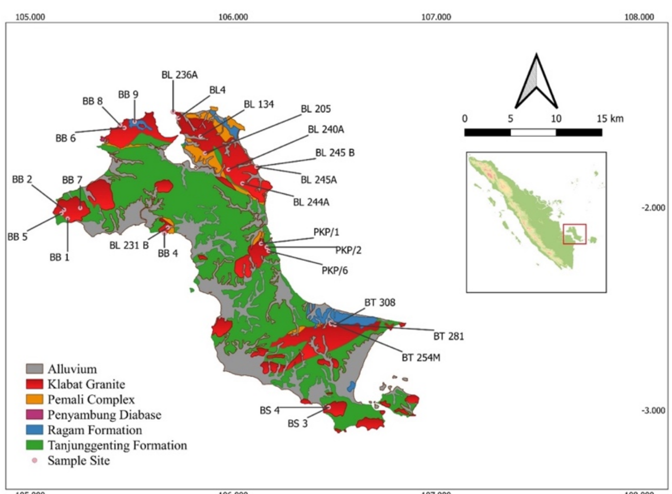

Fig. 1. The major granite body and sample data collection area

Uranium, Thorium, and Potassium concentrations in granite decay are converted to energy. The energy emitted from the radioactive decay process yield kinetic energy from α β particles and the γ radiation contributed to heat produced in rocks. So, radiogenic heat production (RHP) can be calculated by considering Uranium, Thorium, and Potassium concentrations of rocks (Rybach, 1988):

$$RHP = \rho(9.52\ C_U + 2.56C_{Th} + 3.48C_K)10^{-5} \quad (1)$$

where ρ is the bulk density of granite which is 2.7 kg/m^3, C_U and C_{Th} are concentrations of Uranium & Thorium in ppm and C_K is for Potassium in %.

4. Result and discussion

4.1 Radiogenic Heat Production (RHP) of S-type granite and I-type granites

Radiogenic heat production (RHP) is a petrophysical quantity resulting from the decay of radioactive elements in the earth's crust and mantle which leads to terrestrial heat flow in some areas of the earth. The crustal granite in West Bangka and South Bangka shows lower average radiogenic heat production than crustal-mantle mixed granite in Central and North Bangka as shown in

Table 1 and Table 2. The S-type granites show the highest concentration of U (21 ppm); Th (112 ppm); and K (18.3 %) which were found in BB1, BB7, and BB9 respectively. In I-type granite, the highest concentration of U (681 ppm); Th (99.2 ppm); and K (3.55%) were found in PKP/10B and BL 240A respectively. The concentration of radioactive elements in I-type is quite interesting; especially from 17 samples show the average U and Th are 87.79 ppm, 65.68ppm respectively. But as we investigate the average concentration of K, S-type granite investigation provides a higher value (average 3.1 %) than I-type (average 1.93 %).

Table 1. Heat production of S-type Granite from South Bangka (sample code: BS) and West Bangka (sample code: BB)

Sample	Coordinate		U (ppm)	Th (ppm)	K %	Th/U	RHP (μWm^{-3}) due to			Total RHP (μWm^{-3})
	X	Y					U	Th	K	
BS 3	106.471636	-2.986242	5.2	70	2.69	13.46	1.34	4.84	0.25	6.43
BS 4	106.470726	-2.986166	4.5	74	3.03	16.44	1.16	5.11	0.28	6.56
BB 1	105,18475	-2,05448	21	96	3.3	4.57	5.40	6.64	0.31	12.34
BB 2	105,16751	-2,01155	13	96	3.04	7.38	3.34	6.64	0.29	10.26
BB 4	105,66141	-2,12664	15	76	2.76	5.06	3.86	5.25	0.26	9.37
BB 5	105,15464	-2,02829	7	89	2.91	12.71	1.80	6.15	0.27	8.22
BB 6	105,46443	-1,60748	10	66	3.46	6.6	2.57	4.56	0.33	7.46
BB 7	105,24668	-2,00251	18	112	2.88	6.22	4.63	7.74	0.27	12.64
BB 8	105,44384	-1,59371	6	62	3.15	10.33	1.54	4.29	0.30	6.12
BB 9	105,51457	-1,57725	3	55	3.79	18.33	0.77	3.80	0.36	4.93
Average			10.27	79.6	3.101	10.11	2.64	5.50	0.29	8.43

Granites from South and West Bangka are characterized by abundances of Uranium ranging from 3 ppm to 21 ppm, from 55 ppm to 112 ppm for Thorium, and from 2.69 % to 3,79 % for

Potassium. The mean values for uranium, thorium, and potassium are 10.27 ppm, 79.6 ppm, and 3.101% respectively. Thorium gives the biggest contribution to RHP, followed by Uranium and Potassium. The highest thorium concentration is found on sample BB7 with 112 ppm. The major minerals in this sample are quartz-rich granite, K-feldspar, biotite, and cordiorite, while the minor mineral is plagioclase and muscovite as accessory mineral (Refaat *et al.,* 1978).

The RHP of S-type granite indicates a higher average than continental crust rock's RHP. Furthermore, there are some correlations between U and Th to RHP, but they tend to not correlate between K and RHP for S-type. The best-fitting linear relation between U and RHP is a linear correlation with a coefficient 0.92 for S granite and 0.99. Th graphic shows a good correlation for S-type with 0.83 with linear regression, but Th curve for I-type exponential trend with 0.82 correlation. Even though the correlation is clear, Th data are somewhat scattered around the trend, especially for sample BB 1 with 96 ppm of Th. The data is influenced by a relatively high U concentration of 21 ppm, whereas the same concentration of Th for BB 1 has 13 ppm of U. K curve for I-type shows an exponential trend due to the absence of K in BT 308 and PKP/1 samples.

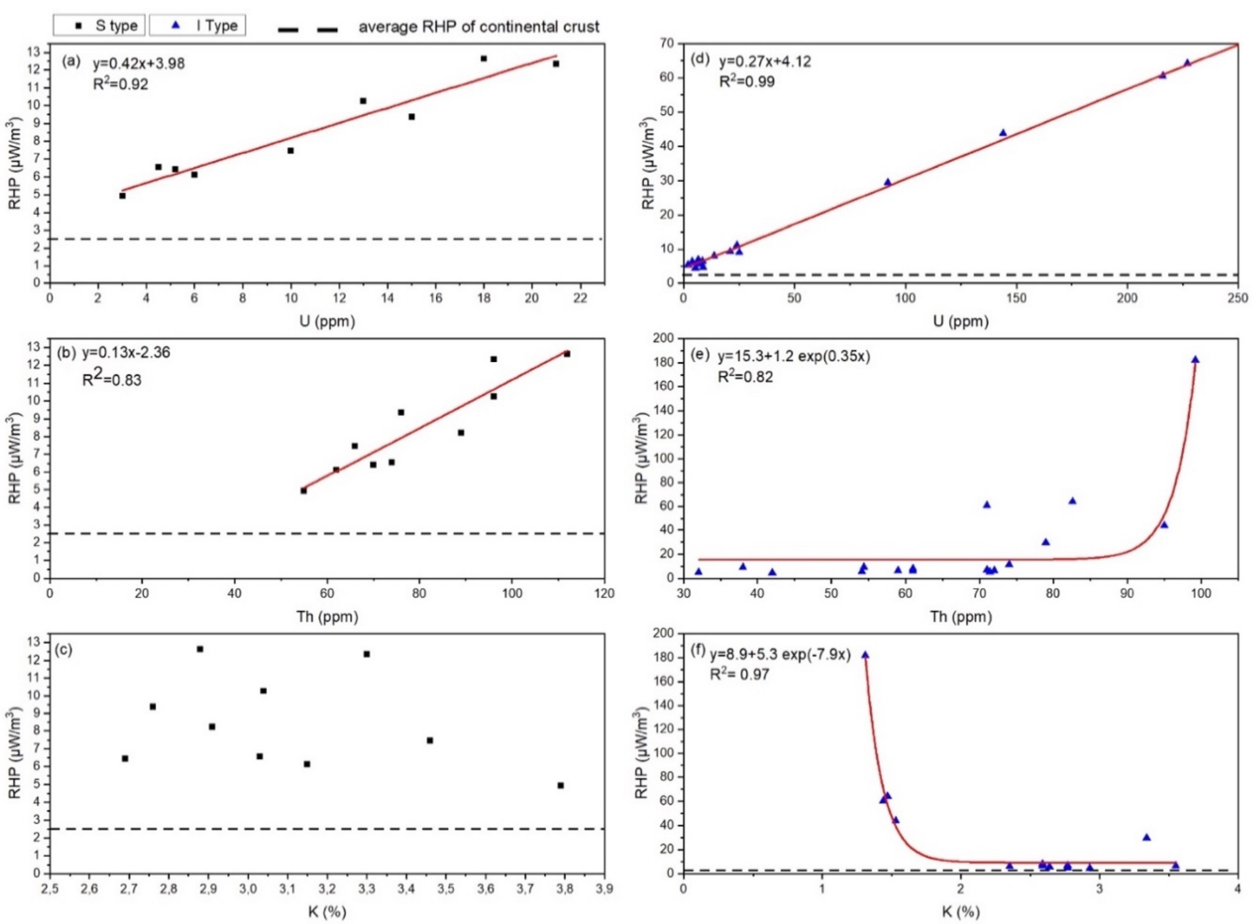

Fig. 2. Plots of U, Th, and K versus Radiogenic heat production sorted by S type (a-c) and I type granite (d-e). The horizontal dash line is presented as the average RHP on the continental crust (Taylor & McLenna, 1985)

The U, Th, and K concentrations of I-type granite are given in Table 3 and plotted in Figure 2 related to RHP. Generally, the relationship of RHP to U and Th is increasing linearly for S-type, and I-type RHP to U is increasing linearly but to Th is increasing exponentially. Meanwhile, the relationship of RHP to K decreases exponentially for I-type, and no good pattern for S-type. It means that for S-type and I-type the higher concentration of U and Th, the higher radiogenic heat production, but not for Pottasium K. Total abundance of U concentration range from 2 ppm to 681 ppm, 32 ppm to 99.2 ppm for Th and 0.07% to 3.55% for K. The average concentrations for U, Th and K are 87.79 ppm, 65.7ppm, and 1.93 % respectively.

Anomaly in this region is represented by the concentration of U and Th in sample PKP/10B with 681 ppm and 99.2 ppm which produce 550.28 RHP. This value is the highest among all the data on Bangka Island. Data obtained from 7 samples (Irvani & Pitulima, 2017), U and Th concentrations range from 6.7 ppm to 200.7 ppm and 30.3 ppm to 197 ppm respectively. Th of PKP/10B sample is also higher than the previous study on the same region. Data from Ngadenin *et al* (2014) revealed that Th concentration range from 23.5 ppm to 78.5 ppm of Th with 42.0 ppm on average. K concentration is relatively low compared to S-type granite with 1.93 %, where K concentration from two samples, BT 308 and PKP/1 are negligible. The average RHP value is 27.28 which is higher than S type RHP average.

Table 2. Heat production of I-type granite from North Bangka (sample code: BL), Central Bangka (sample code: BT), and Pangkalpinang (sample code: PKP)

Samples	Coordinate		U ppm	Th ppm	K %	Th/U	RHP $(\mu\mathrm{Wm}^{-3})$ due to			Total RHP $(\mu\mathrm{Wm}^{-3})$
	X	Y					U	Th	K	
BL4	105,729740	-1,558996	6.6	71	2.77	10.76	4.04	11.68	247.78	263.50
BL 134	105,839026	-1,649234	13.8	61	2.59	4.42	8.45	10.04	231.68	250.16
BL 205	105,861200	-1,732480	7	61	2.35	8.71	4.28	10.04	210.21	224.53
BL 231 B	105,677880	-2,098920	5.3	42	2.93	7.92	3.24	6.91	262.09	272.24
BL 236A	105,704440	-1,528120	92	79	3.34	0.86	56.30	13.00	298.76	368.07
BL 240A	105,976740	-1,813410	3.9	72	3.55	18.46	2.39	11.85	317.55	331.78
BL 244A	106,045560	-1,881340	8.8	32	2.77	3.64	5.39	5.27	247.78	258.43
BL 245A	106,114790	-1,799550	8.5	59	2.59	6.94	5.20	9.71	231.68	246.59
BL 245 B	106,114790	-1,799550	6.6	54.1	2.64	8.20	4.04	8.90	236.15	249.09
BT 254P	106,480170	-2,568000	144	95	1.53	0.66	88.13	15.63	136.86	240.62
BT254M	106,480170	-2,568000	227	82.6	1.47	0.36	138.92	13.59	131.49	284.01
BT 281	106,48212	-2,57532	24	74	0.07	3.08	14.69	12.18	6.26	33.13
BT 308	106,501840	-2,578870	2	71.4	0	35.70	1.22	11.75	0.00	12.97
PKP/1	106,137160	-2,178770	25	38	0	1.52	15.30	6.25	0.00	21.55
PKP/2	106,164880	-2,195530	21	54.4	1.34	2.59	12.85	8.95	119.86	141.67
PKP/6	106,174620	-2,214750	216	71	1.44	0.33	132.19	11.68	128.81	272.68
PKP/10B	106,134917	-2,185250	681	99.2	1.31	0.15	416.77	16.33	117.18	550.28
	Average		87.79	65.7	1.93	6.72	22.566	4.540	0.181	27.288

4.2 Th/U ratio of I-type and S-type granites

Uranium and Thorium concentration varies with granite types and shows that I-type produces higher RHP than S-type. Furthermore, we carried out heat production from some areas all around the world. Table 3 clearly shows that I type granites from Central and North Bangka have high RHP from all the data. RHP enrichment usually occurs on the upper continental crustal rocks as a product of partial melting on the subducted crust (Vilà *et al.,* 2010). Thus, we investigate the origin of magmatism and tectonic setting by characterizing Th/U ratio of samples.

Table 3. The heat produced compared to other published data. The data shows that Central - North Bangka shows high heat production

Type of rocks - Location	**Heat Production**				**Reference**
	due to U	**due to Th**	**due to K**	**Total**	
S type Granite -West and South Bangka	2.64	5.50	0.29	8.43	This study
I type Granite - Central and North Bangka	22.56	4.54	0.18	27.29	This Study
Granite - Sweden	1.19	1.03	0.31	2.53	(Veikkolainen *et al.,* 2019)
Rhyolite – Western Rajashtan (India)	2.09	2.22	0.4	4.70	(Singh and Vallinayagam, 2016)
Granite – Achatau (Russia)	2.44	2.87	0.40	5.71	(Khutorskoy and Polyak, 2016)
Mudstone – Gonghe Basen (Northeastern Tibetan Plateau)	0.80	0.95	0.20	1.96	(Zhang *et al.,* 2020)
Granite – Gonghe Basen (Northeastern Tibetan Plateau)	2.64	5.50	0.29	8.43	(Zhang *et al.,* 2020)

Characterization of S type granite based on Th/U ratio (Figure 3a) is shown by relatively high Th/U ratio range from 4.57 to 18.33, meanwhile I-type granite (Figure 3b) Th/U ratio range from 0.15 to 35.7. The distribution of RHP and Th/U shows a negative exponential correlation with coefficients of 0.65 and 0.96 for S type and I type granite respectively. For S-type, the data are scattered around the trend line. The anomaly in this data is shown by PKP/10B, PKLP 6, BT 254M, BT 245P, BL 236A with ratios 0.15, 0.33, 0.36, 0.66, and 0.86 respectively. Based on *Friedrich et al.* (1987), at lower Th/U ratios, the U concentration related to uraninite increases up to 80% for Th/U=1. Theoretically, Uraninite will contribute to high RHP based on their concentration where in this data, the lowest Th/U tends to have the highest U. On the other hand, Uranium is located in monazites with Th/U ratios exceeding 4. The low Th/U ratio on I types of data produces an exponential plot with a correlation coefficient 0.96, while some S-type data are not fit to exponential trend due to the >1 Th/U ratio.

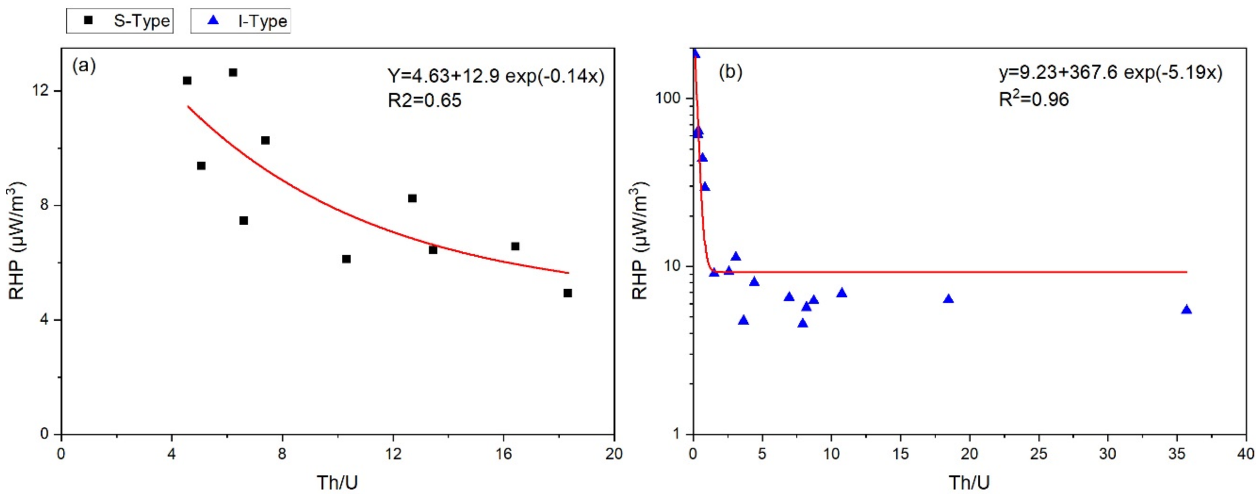

Fig. 3. Characterization of (a) S type and (b) I type granite based on Th/U ratio

A Th/U ratio higher than 1 is normally produced from mantle-derived volcanic rocks as mid-ocean ridge basalts and continental materials (Maden & Akaryali, 2015). Th/U ranges from 3 to 7 (Wasserburg *et al.,* 1964) and is normally classified into continental crust material, which in this research is mostly found in I-type granite with an average 6.72. This result is fairly close to Th/U ratio when compared to the typical ratio for continental crust value of 5 (Paul *et al.,* 2003). The Th/U ratio > 8 is classified as the limit for continental crust characteristics which differs granite of West Bangka and South Bangka. Based on Widana & Priadi (2015), granitoid in Bangka Island were produced from two sources, shoshonitik for Belinyu and Central Bangka and crust for South and West Bangka. This source different can be interpreted as a magmatic episode from different geodynamics on continental margin as a product of subduction and collision. S-type granites from West Bangka and South Bangka are classified as Eurasia continental collision products, whereas I-type granites from Central Bangka, Pangkal Pinang, and North Bangka as continental arc products (Chappell and White, 2001).

5. Conclusions

Radiogenic heat production (RHP) has been determined by calculating the concentration of Uranium, Thorium, and Potassium within Bangka Island's granite. In this study, we evaluate RHP based on the type of granite; S-type from South Bangka and West Bangka, I type from North Bangka, Pangkal pinang, and Central Bangka. The S-type granite shows lower RHP than I-type granite with an average 8.43 μWm^{-3} and 27.28 μWm^{-3} respectively. We also investigate RHP of granite based on the type by comparing with other published data, we get the same result where S-type produces lower RHP than I-type.

We evaluate Th/U ratio from both types for investigating tectonic settings and magmatic sources. Th/U and RHP show the same exponential trend for both types, with remarkable fitting for I-type plot but unfortunately poor for S-type due to lack of data. Th/U ratio classifies S-type granite as a continental collision product from partial melting of metasedimentary source rock in collisional zones (Artemeiva *et al.,* 2017). I-type granite is classified as continental arcs from partial metling of the igneous protolith. But, it remains an open question whether RHP on each type from different regional settings shows similar behavior.

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