Atom Indonesia Vol. 49 No. 3 (2023) 177 - 184

Atom Indonesia

Journal homepage: http://aij.batan.go.id

Uncovering the Distribution Zones of Uranium and Thorium in Bangka Island

Ngadenin[1], R. Fauzi[2*], H. Syaeful[1], K. S. Widana[1], I. G. Sukadana[1], F. D. Indrastomo[1], Widodo[3]

[1]Research Center for Nuclear Fuel Cycle and Radioactive Waste Technology, National Research and Innovation Agency (BRIN), KST B.J. Habibie, South Tangerang 15310, Indonesia
[2]Research Center for Geological Resources, National Research and Innovation Agency (BRIN), KST Samaun Samadikun, Bandung 40135, Indonesia
[3]Indonesian Nuclear Technology Polytechnic, National Research and Innovation Agency (BRIN), KSE Achmad Baiquni, Yogyakarta 55281, Indonesia

ARTICLE INFO

Article history:
Received 2 January 2023
Received in revised form 25 July 2023
Accepted 28 July 2023

Keywords:
Uranium
Thorium
Radiometry
Mineralogy
Radioactive mineral
Bangka

ABSTRACT

Radioactive minerals, especially containing uranium and thorium, can be used as a core element of nuclear fuel. Bangka Island is located in The Southeast Asian Tin Belt where it has a large uranium and thorium potential. The purpose of this study is to delineate distribution zone of uranium and thorium in Bangka Island. The study methods consist of radiometric measurement and mapping, petrographic analysis, and mineralogical analysis of pan concentrate samples. Based on radiometric measurement, positive anomaly value of equivalent uranium (eU) is ranging from 5-15 ppm while of equivalent thorium (eTh) is ranging from 45-75 ppm. The result of petrographic analysis from several outcrops of Klabat Granite indicated that there are monazites found in several samples of Mangkol Granite and of Bebuluh Granite. Radioactive mineral indication also can be identified as pleochroic halo within biotite in samples of Pelangas Granite and Menumbing Granite. Based on the result of mineralogical analysis of pan concentrate samples, it was identified that monazites can be found in all samples. Monazites constitute the percentages ranging from 2.82-10.66 %. Zircon also can be identified with percentages ranging from 9.13-76.75 % while ilmenite and magnetite minerals have average percentages of 24.09 % and 5.97 %, respectively. Favorable zones can be delineated in outcrops of Klabat Granite, Ranggam Formation and alluvial deposits in northern, northwestern, northeastern, central, and southeastern parts of Bangka Island. The occurrences of monazites in those lithological units are the main factors of high radioactivity in Bangka Island. Based on petrographic and mineralogical composition, those granite bodies which are correlated with Klabat Granite are mostly associated with ilmenite series with S-Type granitic rocks.

INTRODUCTION

Nuclear energy is one of the most efficient source of energy. Nuclear energy can be established on various environments and also can provides enormous power continuously without significant carbon emissions and air pollutants [1]. Nuclear power could decrease carbon emissions and reduce dependency on fossil fuels [2-4]. Compared with other energy sources, the energy generated from a six-gram uranium pellet is equivalent with 1 ton of coal [5]. Nuclear energy is relatively much more efficient than other conventional energy sources, such as coal, oil, or natural gas. Indonesia needs to introduce nuclear power to improve the atmospheric environment and to support sustainable energy growth [6]. The utilization of nuclear energy could significantly support the number of energy consumption ratio from New and Renewable Energy sources (NRE) in Indonesia on a large scale [7].

Radioactive mineral, especially uranium, can be used as a core element of nuclear fuel [8]. Other radioactive element such as thorium is also

---

[*] Corresponding author.
E-mail address: rach021@brin.go.id
DOI: https://doi.org/10.55981/aij.2023.1288

considered as potential fuel that could complement uranium. Some of uranium minerals are pitchblende, uraninite, carnotite, and autunite [9]. Naturally, thorium occurred in particular minerals such as thorite, thorianite, monazite, zircon, xenotime, and allanite [10-13]. Thorium resource is more abundant than uranium in nature, with the average concentration of thorium in the earth's crust estimated to be about three times that of uranium [14]. There are two pilot plants for radioactive mineral processing in West Bangka and Jakarta,each have capacity of 50 kg monazite per batch [1,15]. Considering its importance as strategic minerals, it is necessary to identify the national availability of radioactive minerals. Those identifications should focus on several regions in Indonesia where those have abundant potential for radioactive minerals.

Bangka Island is located in The Southeast Asian Tin Belt where it is a north-south elongate zone 2,800 km long and 400 km wide, extending from Myanmar - Thailand - Malaysia to the Indonesian Tin Islands of Riau Islands and Bangka Belitung (Fig. 1) [16-21]. These regions have a large uranium and thorium potentials. Previous studies have been conducted to assess uranium and thorium occurrences in certain locations in Bangka. Uranium and thorium occurrences are mostly associated with abundance of particular minerals, such as monazite, xenotime, zircon, ilmenite, anatase, and other accessory minerals of cassiterite [22-26]. Those minerals can be identified not only in weathered granite but also in alluvium which can be considered for resource estimation [27-29].

The study area is located in the entire of Bangka Island. Based on its potential for radioactive mineral occurrence in Bangka Island, further studies to determine favorable zone of uranium and thorium are crucial as it will provide significant impact for planning and decision making of nuclear geology research. National Nuclear Energy Agency (BATAN), presently become a part of National Research and Innovation Agency (BRIN), has been conducting several nuclear geology studies in Bangka since 2009. Those data will be compiled and analyzed thoroughly in order to complement this study.

The purpose of this study is to delineate distribution zone of uranium and thorium in Bangka Island. This delineation, which is based on mineralogy and geochemical analyses as well as radiometric measurement, can identify certain favorable zones of uranium and thorium in Bangka Island. As a result, this study could provide an insightful overview of radioactive mineral potential and provide reference of prospect sector for further exploration stage in the study area.

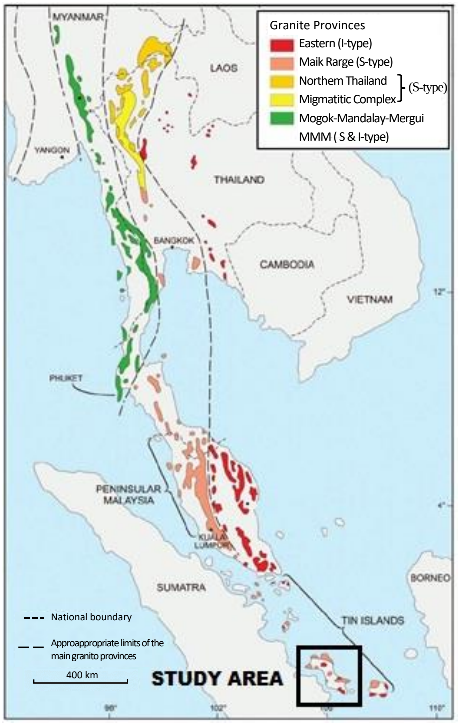

Fig. 1. The Southeast Asian Tin Belt [20,21].

Regional geology

Based on Regional Geology Map of Northern Bangka and Southern Bangka, lithology of Bangka Island is composed of several formations of metamorphic rock, metasedimentary rock, plutonic rock, and quaternary deposit. Stratigraphically from the oldest to the youngest, the study area consists of Pemali Metamorphic Complex, Penyabung Diabase, Tanjunggenting Formation, Klabat Granite, Ranggam Formation, quartz sand, swamp deposits, and alluvium [30,31].

Pemali Metamorphic Complex mainly consists of phyllite, schist, and quartzite. Phyllite is characterized by brownish grey, foliated with quartz veins. Schist is characterized by greenish grey, foliated, jointed, locally having vein filled with quartz or iron oxide, alternates with quartzite. Quartzite is characterized by dirty white, brownish, mineralogy consists of quartz and feldspar, fine-medium grain sized. This complex was deposited in Permian or Carbon.

Penyabung Diabase mainly consists of diabase which is jointed and faulted, intruded by younger Klabat Granite. This unit is presumed to be formed in Permian Age. Tanjunggenting Formation mainly consists of alternation of sandstone and claystone. Sandstone is characterized by brownish grey, fine-medium grain sized, well sorted, hard, having sediment structures of cross bedding and ripple mark and also locally lenses of limestone. Claystone is characterized by brownish grey, having locally lenses of fine-grained sandstone. There are mollusk fossils found in limestone fragment. This formation was deposited during Triassic age.

Klabat Granite mainly consists of granite, granodiorite, adamellite, diorite, and quartz diorite which were formed during Late Triassic. Ranggam Formation mainly consists of alternation of sandstone, claystone, tuffaceous claystone with intercalation of thin layers of siltstone and organic matter, characterized by well-bedded, parallel-lamination and cross-bedding, having fossil fragments such as mollusk which indicates that the age is not older than Late Miocene. Holocene formation consists of quartz sand, swamp deposits, and alluvium.

The majority of structure patterns which were developed in Bangka Island are NNE-SSW trending faults and NNW-SSE trending faults [32]. The regional geological map of Bangka Island is depicted in Fig. 2.

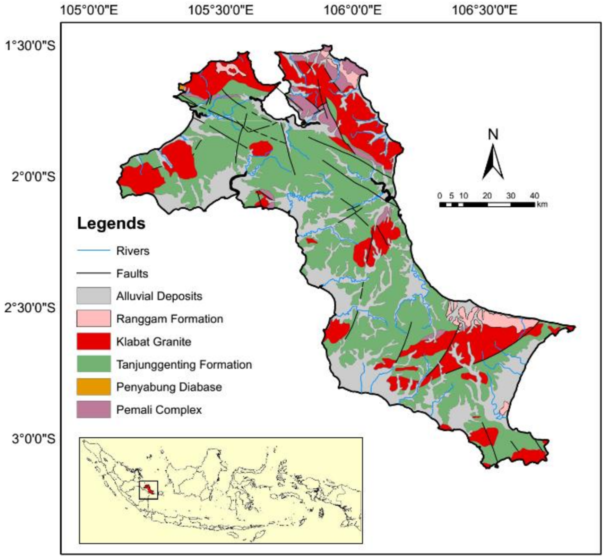

Fig. 2. Regional geology map of Bangka Island [30,31].

METHODOLOGY

The study was conducted by compiling various exploration data in the whole island of Bangka that has been conducted by BATAN since 2009. The study methods consist of radiometric measurement and mapping, petrographic analysis, and mineralogical analysis of pan concentrate samples.

Radiometric measurement and mapping were conducted for identifying the equivalent radioactivity value of gamma rays from uranium (U), thorium (Th), and potassium (K) decay chain reactions. Radiometric measurement and mapping are common methods for detecting uranium or thorium anomaly [33,34]. This method uses portable handheld spectrometer along traverses in study area. The device used in this method is gamma-ray spectrometer Radiation Solution-125 (RS-125) (Fig. 3). Principally, this device uses 103 cm^3 Thallium-doped Sodium Iodide or NaI(TI) detector that is able to read K, U, Th, dose rate, and total count in every measurement [35]. Those data would be positioned precisely by linking to GPS device that can provide the value of measurement and its coordinate. Subsequently, the measurement data is projected on radioelement map after it has been statistically processed.

Fig. 3. Gamma-ray spectrometer of RS-125.

The radiometric measurement data from previous studies in West Bangka Regency [36], South Bangka Regency, Central Bangka Regency, Bangka Regency, and Pangkal Pinang City [37] are compiled in this study.

The purpose of petrographic analysis is to identify mineralogy of particular sample, especially related to radioactive minerals. The samples were processed into thin section to be analyzed using polarization microscope Petrographic analysis was conducted in six granite samples which were representing all of granite outcrops in Bangka Island. Petrographic analyses data from previous studies in West Bangka Regency [36], South Bangka Regency [38] were compiled in this study while samples from Central Bangka Regency and Pangkal Pinang City [39] were re-analyzed.

Mineralogical analyses of pan concentrate samples are conducted to identify the occurrences of certain minerals from alluvial deposits in the vicinity of granite outcrops. 13 pan concentrate samples were sorted based on its density and then were analyzed using microscope. The analyses of pan concentrate samples are compiled from previous studies in West Bangka Regency [36], and South Bangka Regency [38] while other samples from West Bangka Regency [39], Central Bangka Regency and Pangkal Pinang City [40] were re-analyzed. The traverse and sampling location of study area are shown in Fig. 4.

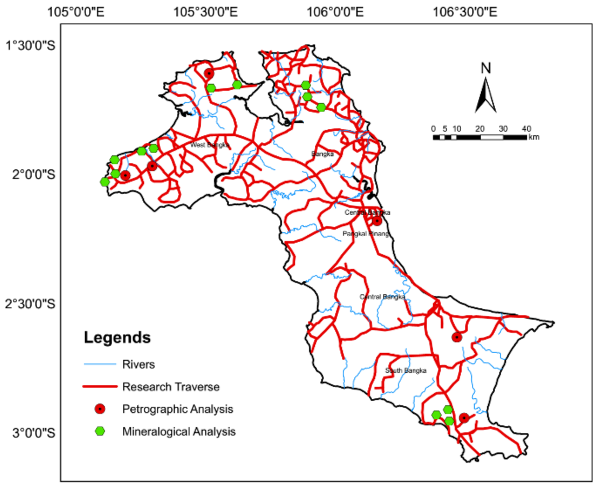

Fig. 4. Traverse and sampling location map [36-40].

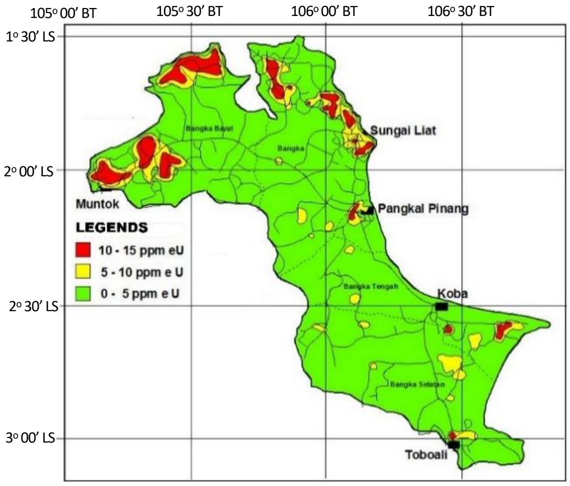

Fig. 5. Radioelement map of equivalent uranium.

RESULTS AND DISCUSSION

Equivalent uranium measurement and mapping

Uranium concentration measurement data showed that the value of equivalent uranium (eU) concentration in outcrops of Pemali Complex ranges from 0-5 ppm, the eU value of Tanjunggenting Formation ranges from 0-5 ppm, the eU value of Klabat Granite ranges from 5-15 ppm, the eU value of Ranggam Formation ranges from 0-15 ppm, while the eU value of alluvium deposit ranges from 0-5 ppm (Fig. 5).

Favorable zone was determined by its distinguished anomaly of eU concentration. Those measurement values are relatively higher compared with normal U concentration in granite (4 ppm), while normal U concentration in sandstone is 1.5 ppm. The anomaly cut-off of eU concentration is three times of 4 ppm eU, which is 12 ppm [41,42]. Therefore, favorable zone of uranium can be delineated in Klabat Granite and its vicinities in northern, northwestern, northeastern, central, and southeastern parts of Bangka Island.

It is interpreted that Klabat Granite is uranium-bearing granite. Uranium might substitute thorium in monazite minerals (($(Ce,La,Th)PO_4$)) because those elements have similar ion radius. There are some favorable zones in Ranggam Formation where it is situated in the vicinity of Klabat Granite which have significant anomaly of eU. Favorable zones in Ranggam Formation are affected by occurrences of reworked monazite or other uranium-bearing mineral from nearby granite which have become the fragments of sandstone in this formation. Favorable zone map of uranium in study area is shown in Fig. 6.

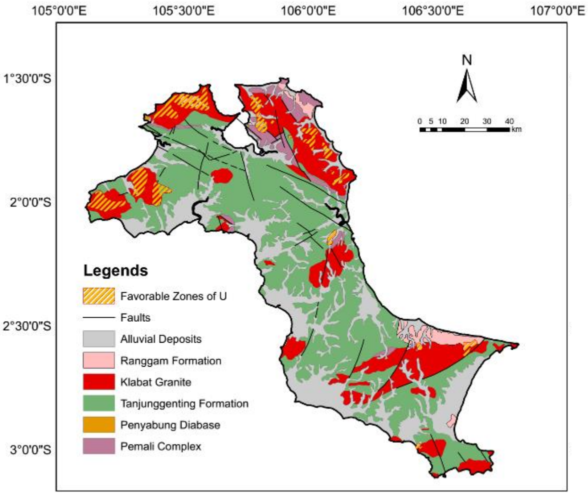

Fig. 6. Favorable zone map of uranium.

Equivalent thorium measurement and mapping

Thorium concentration measurement data showed that the value of equivalent thorium (eTh) concentration in outcrops of Pemali Complex ranges from 0-15 ppm, the eTh value of Tanjunggenting Formation ranges from 0-15 ppm, the eTh value of Klabat Granite ranges from 30-75 ppm, the eTh value of Ranggam Formation ranges from 15-60 ppm, while the eTh value of alluvium deposit ranges from 0-60 ppm (Fig. 7).

Relatively higher eTh concentration compared with normal Th concentration in granite is 15 ppm while normal U concentration in sandstone is 5 ppm [41,42] can be found in several parts in study area. Favorable zone of 45-75 ppm eTh can be delineated in certain parts of Klabat Granite, Ranggam Formation and alluvial deposits in northern, northwestern, northeastern, central, southern and southeastern parts of Bangka Island.

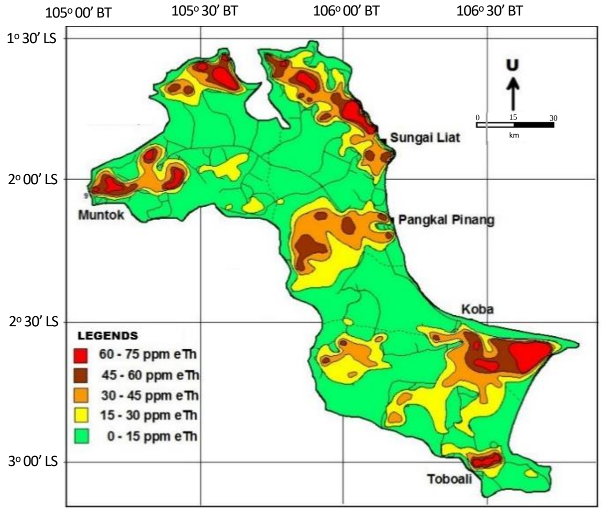

Fig. 7. Radioelement map of equivalent thorium.

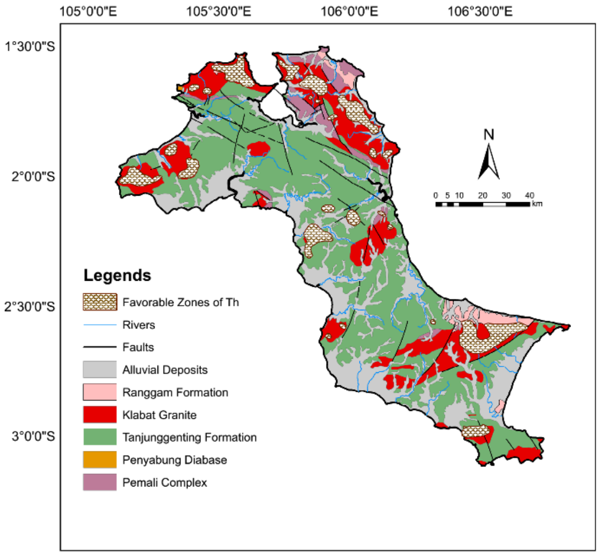

Fig. 8. Favorable zone map of thorium.

It is interpreted that Klabat Granite, Ranggam Formation, and alluvial deposits also have significant occurrences of thorium-bearing minerals. In order to confirm those kinds of radioactive minerals, mineralogy analyses are conducted which will be discussed on the next subsection. Favorable zone map of thorium in study area is shown in Fig. 8.

Favorable zone which has positive anomaly of radioactivity could not be found in Pemali Metamorphic Complex and Tanjunggenting Formation because these lithological units are mostly consisting of phyllite and schist which can be categorized as low-grade metamorphism rocks [43] and metasedimentary rocks. These types of rocks tend to have minimum probability to accumulate radioactive mineral. Radioactive mineral, especially monazite, mostly formed in medium-high grade metamorphism rocks [44-47]. Same condition also applies to Penyabung Diabase which did not has any radioactive mineral occurrence due to its characteristic of mafic mineral while uranium and thorium bearing minerals only deposited in intermediate to felsic rocks [48-51].

Petrographic analysis

Petrographic analyses are conducted to six representative samples of Klabat Granite outcrops which were obtained from several locations in the entire of Bangka Island. Those samples are Jebus Granite, Pelangas Granite, Menumbing Granite, Mangkol Granite, Bebuluh Granite, and Toboali Granite. The results of petrographic analysis are shown in Table 1 and Figs. 9-11.

The result of petrographic analysis indicated that there are monazites found in several samples of Mangkol Granite from Pangkal Pinang and of Bebuluh Granite from Central Bangka. Radioactive mineral indication can also be identified as pleochroic halo within biotite in samples of Pelangas Granite and Menumbing Granite. Both of them are originated from West Bangka. Pleochroic halo is a zone of radiation damage caused by radioactivity of certain crystals within the host crystal structure [52]. Those effects are most likely influenced by the occurrence of monazite. Two samples do not have any indication of radioactive mineral which are samples of Jebus Granite from West Bangka and Toboali Granite from South Bangka.

Table 1. Petrographic analysis of granite samples updated from [36,38,39].

No.	Sample location	Rock name	Main minerals	Other minerals	Radioactive minerals
1.	Jebus, West Bangka (**Fig. 9**)	Biotite-granite	Quartz 45 %, orthoclase 20 %, plagioclase 7 %, biotite 9 %.	Cordierite 7 %, sericite 5 %, chlorite 3 %, iron oxide 4 %.	-
2.	Pelangas, West Bangka (**Fig. 9**)	Biotite-granite	Quartz 40 %, orthoclase 30 %, plagioclase 9 %, biotite 8 %, muscovite 1 %.	Sericite 5 %, cordierite 3 %, chlorite 3 %, iron oxide 2 %.	Pleochroic halos in biotite
3.	Menumbing, West Bangka (**Fig. 10**)	Biotite-granite	Quartz 34 %, orthoclase 24.7 %, plagioclase 2.7 %, biotite 5.7 %, muscovite 1 %.	Sericite 21.3 %, chlorite 5.3 %, cordierite 3.7 %, iron oxide 2 %.	Pleochroic halos in biotite
4.	Mangkol, Pangkal Pinang (**Fig. 10**)	Granite	Quartz 70 %, orthoclase 20 %, plagioclase 5 %, biotite 4 %, hornblende 0.4 %.	Opaque mineral 0.1 %.	Monazite 0.5 %
5.	Bebuluh, Central Bangka (**Fig. 11**)	Granite	Quartz 60 %, orthoclase 30 %, plagioclase 5 %, biotite 2.9 %, hornblende 1 %.	Opaque mineral 0.1 %.	Monazite 0.5 % and zircon 0.5 %
6.	Toboali, South Bangka (**Fig. 11**)	Granite	Quartz 55 %, orthoclase 30 %, plagioclase 9.95 %, biotite 3 %, hornblende 2 %.	Opaque mineral 0.05 %.	-

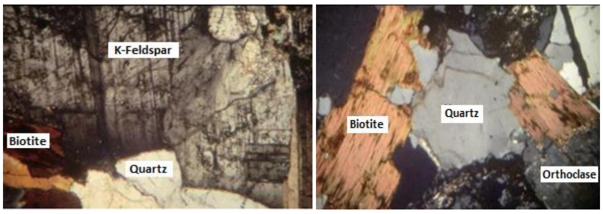

Fig. 9. Thin section image of Jebus Granite (left) and Pelangas Granite (right) (cross nicol, 120 x magnification).

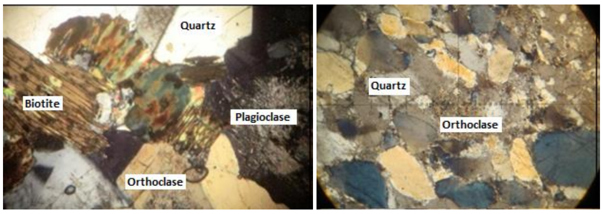

Fig. 10. Thin section image of Menumbing Granite (left) and Mangkol Granite (right) (cross nicol, 120 x magnification).

Fig. 11. Thin section image of Bebuluh Granite (left) and Toboali Granite (right) (cross nicol, 120 x magnification).

Mineralogical analysis of pan concentrate samples

Thirteen samples of pan concentrates were obtained from several locations of alluvial deposits in the vicinity of granite outcrops in Toboali Granite, Sungai Liat Granite, Menumbing Granite, Jebus Granite, and Pelangas Granite. The result of mineralogical analysis is shown in Table 2.

Monazites can be identified in all pan concentrate samples. Monazites constitute the percentages ranging from 2.82-10.66 %. It is interpreted that those monazite minerals accumulate as rework or erosional product of Klabat Granite Group which were deposited in nearby alluvial deposits. The result of petrographic analysis confirmed the occurrence of monazite in samples from several outcrops of Klabat Granite. Other radioactive minerals such as zircon also can be identified that has percentages ranging from 9.13-76.75 %.

Ilmenite and magnetite minerals also can be identified in all samples with various compositions. The percentages of ilmenites are various between 5.07-56.93 % (average value of 24.09 %) while magnetite are between 0.17-3.71 % (average value of 5.97 %). It is determined that ilmenite occurs much more than magnetite in those samples. Based on the assumption that those pan concentrate samples are rework products of Klabat Granite, therefore it can be interpreted that Klabat Granite is ilmenite-type granite. Ilmenite-type granite has significant potential for radioactive mineral occurrence [53,54].

Based on the result of petrographic analysis and mineralogical analysis, monazite occurrences in several granite samples indicate that those granites can be categorized as Type-S granite. It is confirmed with previous studies that Bebuluh Granite, Toboali Granite, and Menumbing Granite are Type-S granite [55,56]. Type-S granite has significant potential for radioactive mineral occurrences that may contain high concentration of uranium (0.13 wt%) and thorium (>1.0 wt%) [57].

Table 2. Mineralogical analyses of pan concentrate samples updated from [36,38-40].

Sample	Location	Cassiterite (%)	Monazite (%)	Zircon (%)	Magnetite (%)	Ilmenite (%)	Hematite (%)	Rutile (%)	Anatase (%)	Tourmaline (%)	Fluorite (%)	Garnet (%)	Hornblende (%)	Biotite (%)	Pyrite (%)	Quartz (%)
1/MB	South Bangka	2.051	5.14	38.23	0.407	20.702	18.031	1.251	0.857	0.462	0	0	5.149	0	0.381	7.339
2/MB		4.11	6.06	44.84	0.45	17.7	19.95	0.59	0.55	0	0.31	0.52	2.06	0	0	2.86
3/MB		4.58	6.47	50.9	0.42	14.18	13.87	0.92	1.14	0	0	0.35	5.31	0.32	0	1.54
4/MB	Bangka	5.06	4.11	9.13	1.97	28.16	19.82	0.45	0.8	0	0.24	0	25.02	0	4.18	1.06
5/MB		17.27	5.5	21.44	0.63	44.82	0.51	0.2	0.58	0	0.12	0	5.06	0	0.32	3.55
6/MB		3.68	5.1	27.86	1.34	56.93	0.77	0.26	0.29	0	0	0	2.08	0	0	1.69
7/MB	West Bangka	6.91	6.1	33.77	0.65	16.47	1.1	0.42	0.47	0	0.49	0	31.95	0	0	1.67
8/MB		10.68	9.35	4.98	0.95	31.01	0.51	0.38	0.53	0	0	0	24.71	0	0	16.91
9/MB		5.51	10.66	44.25	0.17	25.25	0.49	0	0.51	0	0	0	11.21	0	0	1.85
10/MB		10.46	4.47	44.07	3.71	32.31	1.28	0	0.45	0	0	0	1.94	0	0	1.31
11/MB		17.75	7.75	31.89	2.46	10.71	0.94	0.8	0.37	0	0	0	23.58	0	0	3.78
12/MB		11.91	3.01	76.75	0.47	5.07	0.22	0.47	0.19	0	0.09	0	0.92	0	0	0.9
13/MB		23.86	2.82	60.26	0.38	9.82	0.18	0.18	0.16	0	0.06	0	0.97	0	0	1.32

CONCLUSION

There are positive anomalies of equivalent uranium ranging from 5-15 ppm and of equivalent thorium ranging from 45-75 ppm. Favorable zones of uranium and thorium can be delineated in northern, northwestern, northeastern, central, and southeastern parts of Bangka Island. Monazite, a radioactive-bearing mineral, can be identified by petrographic and mineralogical analysis in granite samples that have composition up to 0.5 % and 10.66 %, respectively. Another radioactive-bearing mineral such as zircon constitute up to 76.75 % of pan concentrate sample.

The occurrences of monazites in those lithological units have become the main factor of high radioactivity in Bangka Island. Based on petrographic and mineralogical composition, those granite bodies which are correlated with Klabat Granite mostly resemble ilmenite series with S-Type granitic rocks. Compared with other areas with similar characteristic, particular granite outcrop sites and its vicinity in Bangka Island have a significant potential for radioactive mineral resources. It is necessary to conduct more specific and more comprehensive study in order to assess the mineral deposition model of uranium and thorium in this area.

ACKNOWLEDGMENT

The authors would like to thank to BATAN which has transformed into Research Organization for Nuclear Energy – National Research and Innovation Agency (ORTN-BRIN) for providing opportunity and funds to carry out this study.

AUTHOR CONTRIBUTION

All authors equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

REFERENCES

1. Ngadenin, H. Syaeful, K. S. Widana *et al.*, 50 Years of Uranium Exploration in Indonesia, BRIN Publisher, Jakarta (2022) 142. (in Indonesian)
2. Danish, B. Zhang, Z. Wang *et al.*, Nat. Hazards **90** (2018) 27.
3. M. K. Khan, S. F. Babar, B. Oryani *et al.*, Environ. Sci. Pollut. Res. Int. **29** (2022) 622.
4. M. Luqman, N. Ahmad and K. Bakhsh, Renewable Energy **139 (**2019) 1299.
5. L. Feng, IOP Conf. Ser.: Earth Environ. Sci. **621** (2021) 12068.
6. I. Cho, S. Oh, S. Kim *et al.*, Nucl. Eng. Technol. **53 (**2021) 314.
7. S. Santosa, K. Khotimah, I. W. S. Andani *et al.*, IOP Conf. Ser.: Earth Environ. Sci. **753** (2021) 12050.
8. R. Fauzi, Widodo, Ngadenin *et al.*, Indones. Assoc. Geol. J. **1** (2021) 111.
9. B. M. T. C. Peluzo and E. Kraka Int. J. Mol. Sci. **23** (2022) 4655.
10. M. A. Williams, D. E. Kelsey, T. Baggs *et al.*, Lithos **320-321** (2018) 222.
11. M. A. Ali, A. E. A. Gawad and M. M. Ghoneim, Acta Geol. Sin. Engl. Ed. **95** (2021) 1568.
12. S. Y. Ratnayake, Assessment of the fate and behavior of naturally occurring thorium and uranium in the environment of central Sri Lanka, Dr. rer. nat. Dissertation, Karlsruher Instituts für Technologie (2021).
13. R. Irzon, Eksplorium **39** (2018) 1. (in Indonesian)
14. I. Guagliardi, D. Zuzolo, S. Albanese *et al.*, J. Geochem. Explor. **212 (**2020) 106508.
15. Ministry of Energy and Mineral Resources, The Potential of Rare Earth Metals in Indonesia, Center for Mineral Resources, Coal, and Geothermal Energy, Bandung (2019) 114. (in Indonesian)
16. R. D. Nugraheni, D. Sunjaya and M. Burhannudinnur, Int. J. Sci. Technol. Res. **9** (2020) 1506.
17. F. Deon, J. Asian Earth Sci. **217** (2021) 104844.
18. T. Wang, Y. Tong, H. Huang *et al.*, Earth Sci. Rev. **237** (2023) 104298.
19. Y. Wang, X. Qian, Y. Zhang *et al.*, Lithos, **398-399** (2021) 106336.
20. M. O. Schwartz, S. S. Rajah, A. K. Askury *et al.*, Earth Sci. Rev. **38** (1995) 95.
21. W. J. McCourt, M. J. Crow, E. J. Cobbing *et al.*, Geol. Soc. **106** (1996) 321.
22. C. S. Subasinghe, A. S. Ratnayake, B. Roser *et al.*, Arabian J. Geosci. **15** (2022) 1616.
23. M. M. S. C. Pinto, M. M. V. G. Silva, A. M. R. Neiva *et al.*, Geosci. **8** (2018) 95.
24. A. M. Osman, R. A. Seif, R. M. Attia *et al.*, J. Phys. Conf. Ser. **2305** (2022) 012030.

25. Ngadenin, R. Fauzi and Widodo, Buletin Sumber Daya Geologi **17** (2022) 97. (in Indonesian)
26. K. Zglinicki, R. Małek, K. Szamałek *et al.*, Miner. **12** (2022) 44.
27. G. J. Simandl, R. O. Burt, D. L. Trueman *et al.*, Geosci. Can. **45** (2018) 85.
28. N. M. Batapola, N. P. Dushyantha, H. M. R. Premasiri *et al.,* J. Asian Earth Sci. **200** (2020) 104475.
29. K. S. Widana, I. Rosianna, D. Kamajati *et al.*, AIP Conf. Proc. **2517** (2023) 020008.
30. S. A. Mangga and B. Djamal, Geological Map of the North Bangka Sheet, Sumatera, Geological Research and Development Center, Bandung (1994) 1.
31. U. Margono, R. J. B. Supandjono and E. Partoyo, Geological Map of the South Bangka Sheet, Sumatera, Geological Research and Development Center, Bandung (1995) 1.
32. Ngadenin, H. Syaeful, K. S. Widana *et al.*, Jurnal Pengembangan Energi Nuklir **16** (2014) 13. (in Indonesian)
33. S. Ghosal, S. Agrahari, D. Banerjee *et al.*, Chemosphere **283** (2021) 131221.
34. S. K. Haldar, *Exploration Geophysics*, in: Mineral Exploration: Principles and Applications Second Edition, S. K. Haldar (Ed.), Elsevier, Cambridge (2018) 103.
35. I. G. Sukadana, I. W. Warmada, A. Harijoko *et al.*, IOP Conf. Ser.: Earth Environ. Sci. **819** (2021) 12030.
36. Ngadenin, H. Syaeful, K. S. Widana *et al.*, Eksplorium **35** (2014) 69. (in Indonesian)
37. Ngadenin, K. S. Widana and Widodo, Internal Report: Inventory of Thorium Resources Potential in Bangka, Bangka Belitung Province, Center for Nuclear Minerals Technology, Jakarta (2013) 1. (in Indonesian)
38. H. Syaeful, L. Subiantoro and Suprapto, Internal Report: Initial Assessment of Uranium and Thorium Prospects in Bangka Belitung, Center for Nuclear Minerals Technology, Jakarta (2009) 1. (in Indonesian)
39. F. D. Indrastomo, I. G. Sukadana and Sudarto, Internal Report: Inventory of Thorium Resources Potential in Bangka Regency, Center for Nuclear Minerals Technology, Jakarta (2011) 1. (in Indonesian)
40. Ngadenin, F. D. Indrastomo and Widodo, Internal Report: Inventory of Thorium Resources Potential in Central Bangka and Pangkal Pinang, Center for Nuclear Minerals Technology, Jakarta (2010) 1. (in Indonesian)
41. X. Hu, X. Yang, Z. Wu *et al.*, Ore Geol. Rev. **141 (**2022) 104668.
42. S. Patra, U. P. Sharma, K. Kumar *et al.*, Curr. Sci. **124** (2023) 253.
43. D. Alderton and S. A. Elias, Encyclopedia of Geology Volume 1-6, 2nd ed., Academic Press, London (2021) 1.
44. E. M. Renda, P. D. Gonzalez, H. Vizan *et al.*, J. South Am. Earth Sci. **106 (**2021) 103045.
45. P. S. D. S. Gorayeb, M. A. Galarza and E. D. O. Menezes, J. South Am. Earth Sci. **121** (2023) 104093.
46. P. Hölttä, H. Huhma, Y. Lahaye *et al.*, Int. Geol. Rev. **62** (2020) 360.
47. A. C. Tangari, E. L. Pera, S. Ando *et al.*, Catena **197** (2021) 104998.
48. W. Cakrabuana, R. C. Ciputra, and H. Syaeful, IOP Conf. Ser.: Earth Environ. Sci. **851** (2021) 12041.
49. P. Zhang, F. Li, Z. Liu *et al.*, Geol. J. **57** (2022) 3829.
50. C. Bonnettia, X. Liua, M. Cuney *et al.*, Ore Geol. Rev. **122 (**2020) 103514.
51. A. E. A. Gawad, M. M. Ghoneim, A. El-Taher *et al.*, Arabian J. Geosci. **14** (2021) 1356.
52. S. Kos, M. Dolenec, J. Lux *et al.*, Miner. **10** (2020) 325.
53. S. Collao, F. Stange, L. Hernández *et al.*, Int. J. Geosci. **10** (2019) 632.
54. C. Cruz, H. Sant'Ovaia and F. Noronha, Geol. Acta **18** (2020) 1.
55. K. S. Widana, Eksplorium **34** (2013) 75. (in Indonesian)
56. K. D. Saksama and Ngadenin, Eksplorium **34** (2013) 137.
57. K. Zglinicki, K. Szamałek and S. Wołkowicz Miner. **11** (2021) 352.