Assessing the undiscovered resources of uranium and thorium in Mamuju, West Sulawesi

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Abstract. The exploration of nuclear minerals in Mamuju, West Sulawesi has been started in 2013 by the Center for Nuclear Minerals Technology (CNMT) – Badan Tenaga Nuklir Nasional (BATAN). There is a strong indication of uranium (U) and thorium (Th) minerals occurrences in the location. To follow the exploration result up, a resources assessment is needed. Due to the limited early exploration data, the concept of undiscovered resources can be used. Of all resource assessment methods suggested by International Atomic Energy Agency (IAEA), Energy Research and Development Administration (ERDA) method is the most appropriate method to be applied in the Mamuju case. In this research, Pocos de Caldas, Brazil (Osamu Utsumi Mine for U reference and Morro do Ferro Area for Th reference) was selected as control area due to its similarity on the geological condition and its more-advanced exploration stage compared to Mamuju. All the parameters for the assessment can be determined with the ERDA method based on the available information of the control area.

1. Introduction

CNMT-BATAN has started the exploration of nuclear minerals in Mamuju, West Sulawesi in 2013. After some passing years, enough evidence of the occurrence of U and Th mineralization in the location is indicated. To level the exploration stage up, an assessment of the number of resources is required.

The Mamuju area consists of hills and mountains with steep slopes. Hills in the study area are cone-formed and crater exist in some locations [1–3]. The exploration in Mamuju is still in the early stage so that the obtained data are still regional-scaled and quite simple. Those data would produce the value with a low certainty level if they were used to assess the resources. One of the resource types which can be assessed by using early-stage exploration data is the undiscovered resource. This resource is not quite usual in the mineral industry but more often applied for governmental affairs and inter-agency communication in both policymaking and commercial matters. By generating undiscovered resources of U and Th, the exploration in Mamuju can be leveled up to a more detailed exploration and the resource assessment result can be used as the early basis of exploration policymaking. Hence, this paper has the objective to assess the parameters for U and Th undiscovered resources in Mamuju using the most suitable method based on the available data.

2. The Geology of Study Area

Based on the results of geological mapping and petrographical observation, geology of Mamuju area consists of, from the oldest to the youngest, plutonic rocks, older sedimentary rocks, volcanic rocks, and younger sedimentary rocks [1–4]. The plutonic rocks were observed at Ampalas River in Ampalas Village, Kalukku District. The older sedimentary rocks exposed in this area are volcano-sedimentary in
the form of clays and sandstones. The volcanic rocks vary greatly in their either type or composition. According to regional geological data, volcanic rocks that existed in the study area consist of Talaya Volcanic Rocks and Adang Volcanic Rocks. In this study, Adang Volcanic Rocks are the only ones to discuss. Based on the results of satellite image interpretation and field geological mapping, Adang Volcanic Rocks can be classified into seven rock units, they are Tapalang, Ampalas, Adang, Malunda, Karampuang, Sumare, and Labuan Rano complexes. The younger sedimentary rocks are dominated by volcanlastic products and carbonate rocks [1–5]. Figure 1 displays the geological map of Mamuju [4].

Generally, radioactive minerals are associated with felsic plutonic and volcanic rocks. Usually, U exists in the facies which is rich in vesicular and trachytic structures as well as volcanic breccia and spherulite glass. The enrichment of radioactive elements could also occur in mafic rocks. Leucite-basalt-composed volcanic rocks are formed in a potassic environment by magma with continental composition [6]. Mamuju Regency is the area with the highest radioactivity in Indonesia. The radioactivity there could reach the value of 2800 nSv/h. That high radioactivity value was mostly found in the area composed of volcanic rocks, especially Adang Volcanic Rocks. It was inferred that the high radioactivity was the result of the natural decay of radioactive minerals (containing U and Th). Because of their high abundances in nature, gamma ray intensity produced by the decay of U and Th can be easily detected by gamma-ray spectrometer. The calor produced by the fission reaction of isotope U-235 is the prime source of energy in nuclear power plant. [2,7].

According to the newest literature from IAEA which refers to the occurrences of the world’s U and Th deposits, the exploration concept in Mamuju can be directed to volcanic and surficial deposit types. By using the concept, U could be accumulated on structural planes (structure-bound), bedding planes (strata-bound), or as volcano-sedimentary rocks [8,9]. The forming of U in volcanic rocks depends on the U extraction that occurred in felsic volcanic rocks during the transport of hydrothermal fluids and accumulation. The concentration of U in volcanic rocks increases in proportion to the increase in felsic content of the rocks [10]. The occurrences of radioactive minerals in Mamuju are related to the existence of intermediate-mafic Adang Volcanic Rocks. That thing might happen because of the advanced magma differentiation of the volcanic rocks [1,2,4].

[Figure 1. The geological map of Mamuju (modified from [4]).]
Some results obtained from geological and radiometric surveys of Mamuju are:

- U and Th minerals-bearing formation is Adang Volcanic Rocks;
- mostly consists of phonolite lava, autoclastic breccias (composed of phonolite), and limestones (clastic and reefal);
- regional structures are NE-SW and N-S-directed, it is inferred that the structures control the U and Th mineralizations;
- U and Th minerals’ host rocks are phonolite-composed lava and autoclastic breccias;
- mean U and Th equivalent concentrations are 123 ppm and 416 ppm, consecutively; and
- there are three possibilities of mineralization mechanism: hydrothermal alteration (Hulu Mamuju, Taan, Pengasaan, Hulu Ampalas), dissolution and sedimentation by meteoric water (Botteng), and supergene enrichment (Ahu, Takandeang).

3. Basic Theory

Generally, a resource (mineral deposit, in this case) is a concentration of naturally occurring material in such form and amount that economic extraction is currently or potentially feasible [11]. There are some organizations which made the classification of resource. Table 1 attaches some resource classifications, especially which are related to nuclear minerals [12]. The undiscovered resource is an undiscovered body of mineral-bearing material whose existence is surmised from broad (regional) knowledge and theory [13]. Undiscovered resource intersects with some other terminologies, like potential resources, hypothetical resources, and speculative resources [12]. Assessment of undiscovered resources is significant to conduct for advanced exploration planning, economic evaluation, and land management since the assessment provides information of the indication of mineral resource occurrences in the prospect area [11,14–16].

| Agency | Resource Classes                      |
|--------|---------------------------------------|
| DOE (1974-1982) | Reserves | Probable Potential Resources | Possible and Speculative Potential Resources |
| DOE (1983-current) | Reasonably Assured Resources (RAR) | Estimated Additional Resources (EAR) | Speculative Resources |
| DOI | Identified | Measured Reserves | Indicated Reserves | Inferred Reserves | Hypothetical | Speculative |
| NEA/IAEA | Reasonably Assured Resources (RAR) | Estimated Additional Resources 1 (EAR=I) | Estimated Additional Resources II (EAR=II) | Speculative Resources (SR) |

There are many methods to assess the undiscovered resource. Based on the data processing technique, there are qualitative methods (involving the delineation and ranking of prospective areas based on the potential level of mineral occurrence) and quantitative methods (estimating the tonnage of mineral to determine the geologically permissive area). Based on the data connecting technique, there are deterministic methods (premised on the causality between the tonnage of commodity and one or more geological features affecting to commodity) and probabilistic methods (connecting the tonnage of the commodity to geological features probabilistically). Based on the reference, there are data-driven method (premised on the geoscientific data in the study area) and knowledge-driven method (using conceptual geological models comprising geological features which support the mineralization) [11,14,15,18–21]. The probabilistic method is more prevalent to use in undiscovered resource assessment of various metal commodities [22], such as Platinum Group Elements (PGE) [23], Volcanic Massive Sulfides (VMS) [24], porphyry copper [25], and graphite [26]. Table 2 attaches the list of undiscovered resource assessment methods recommended by IAEA therewith the characteristics. [15].
4. Methodology

Based on the exploration condition and data availability, the criteria of resource assessment method required are:

- quantitative: to produce the exact value of undiscovered resources as the reference for the next-stage exploration;
- probabilistic: due to the absence of adequate grade and tonnage data to be assessed deterministically;
- subjective: due to the inadequate data to generate objective model, geological and radiometric data are the only available data;
- data- and knowledge-driven: to prove the knowledge of the experts by geological and radiometric data obtained in the field;
- appropriate for greenfield: so that the method can accommodate the area with limited data; and
- spatial: because the only available data are maps and the expected results are maps too.

Of all the methods attached in Table 2, three methods comply with all the criteria required; they are Energy Research and Development Administration (ERDA) method, National Uranium Resources Evaluation (NURE) method, and the Deposit-Size Frequency (DSF) method [13,14]. ERDA method was selected to assess the undiscovered resources in Mamuju due to the consideration that the method is the most simple and can be adjusted to the available data. NURE and DSF methods are not appropriate enough to be applied since there are some unavailable parameters in both methods’ formulas.

Most of the methods need the control area as the comparator of conditions to the study area being researched [18,20,27,28]. The control area is a geographical location where the mineralization, geological characteristics and parameters of the deposits, notably resources and average grades, have been well studied [15].

In the ERDA method, the undiscovered resource is termed a Potential Resource (PR). ERDA method has the following formula:

\[ PR = N \cdot F \cdot U \cdot T \]

Parameter N is the extent of the favorable area. A favorable area is a geographical location according to research data has geological features which bring an advantage to mineralization [13]. In this study, the favorable area was defined as the rocks unit according to field observation and laboratory test is proven to contain U and/or Th minerals. Parameter N was given in the m² unit.

Parameter F is the fraction of area favorability. This parameter represents the level of similarity between the study area and the control area. F was obtained by conducting the comparative study of
geological conditions in both areas. A more similar condition means higher F. Parameter F was stated in the form of percentage fraction.

Parameter U is the fraction of unexplored area. This parameter implies the ratio of exploration stage between the study area and control area. U was acquired by undertaking the comparative study of the exploration stage in both areas. As the study area approaches the exploration stage of the control area, the higher U is. Parameter U was given in the form of a percentage fraction.

Parameter T is the density of mineralization. This parameter reflects how many mineral tonnages in a certain extent of the area. To determine this parameter, a literature study respecting mining activity in the control area was conducted. Parameter T was stated in the ton/m² unit.

After all the parameters were attained, PR could be assessed. It should be made sure that the units of all parameters were fit to the convention in the paragraphs above. By using Equation 1, PR was obtained in tons.

5. The Selection of Control Area
In this research, Pocos de Caldas, Brazil, was selected as the control area to the study area in Mamuju, Indonesia. Pocos de Caldas was selected due to its similarity in geological conditions and its more advanced exploration stage compared to Mamuju. Actually, among other alkaline volcanic complexes, only Pocos de Caldas associated with volcanogenic U deposit. Respecting to the exploration stage, two locations have been researched deeply in Pocos de Caldas, are Osamu Utsumi Mine (U potential site) and Morro do Ferro Area (Th potential site).

The alkaline complex of Pocos de Caldas is situated in the southern part of the State of Minas Gerais close to the boundary with the State of Sao Paulo. The complex is roughly circular and covers an area of about 1000 km². The complex is situated on a plateau and is essentially saucer-shaped in a cross-section reflecting the configuration of the collapsed caldera. The elevations vary from 1300 m in the central part of the depression to about 1600 m around the periphery [29].

The radioactive material occurs in rocks known as caldasite which is a mixture of zirconium oxide (baddeleyite) and zirconium silicate (zircon). For many years, all U exploration was focused on the caldasite deposits since it was thought that U could be extracted economically from refractory ores [29]. About 85 alkaline intrusive bodies are known in Brazil. These vary considerably concerning their age, size, and geographical distribution [30].

The complex is characterized by a wide variety of rock types which has given rise to the hypothesis of varied injections of magma accompanied by differentiation phenomena. The most common rock types belong to the family of the nepheline syenites, and in order of decreasing importance, these include tinguites, phonolites, nepheline syenites, foyaites, lujaurites, and chibinites. The complex has a strong agpaitic tendency. Besides the above are found rocks of volcanic origin such as tuffs, agglomerates, ashes, and breccias. In the central part of the complex, the rocks have been highly altered by intense potassic metasomatism [29].

6. Parameters Assessment for Undiscovered Resources
Parameter N (the extent of the favorable area) was determined by delineating the areas which are proven to contain U and/or Th minerals (Adang Volcanic Rocks) based on the geological observation and have > 100 ppm equivalent U concentration based on radiometric measurement (100 ppm is a boundary value proposed by the experts in many best practices). From delineation, as many as three areas were obtained to be favorable. Area 1 consisted of Ahu, Pengasaan, Taan, Takandeang, Orobatu, and Botteng sectors. Area 2 consisted of Bebanga and Ampalas sectors. Area 3 consisted of the Hulu Mamuju sector. The extents of Area 1, Area 2, and Area 3 were 104,560,000 m²; 165,720,000 m²; and 4,580,000 m², respectively. Favorable area maps of Mamuju and their extents in m² (parameter N) are displayed in Figure 2.
After parameter N was obtained, a comparative study of geological conditions between the study area (all exploration sectors of Mamuju) and the control area (the whole Pocos de Caldas) was conducted. Parameter F (the fraction of area favorability) was obtained by scoring the similarity of geological conditions in both areas. A more similar condition means a higher score. The score was given in the form of a percentage fraction. The comparative study results in an F value of 0.66. Table 3 attaches the result of parameter F determination.

As parameter F was obtained, a comparative study of the exploration stage between study area (all exploration sectors of Mamuju) and control area (Osamu Utsumi Mine for U reference and Morro do Ferro Area for Th reference) was undertaken. Parameter U (the fraction of unexplored area) was obtained by scoring the percentage of the study area’s exploration stage to the control area’s exploration stage. Parameter U was given in the form of percentage fraction as well as parameter F. The comparative study results in the U value of 0.34 for U and 0.41 for Th. Table 4 attaches the result of parameter U determination.

The last parameter required in the ERDA method is T (the density of mineralization). T is the ratio of the control area’s deposit tonnage (in ton) to the extent of the control area (in m$^2$). The tonnage and the extent of the control area were obtained through the literature study respecting the mining activity in Osamu Utsumi Mine and Morro do Ferro Area. The tonnage of U in Osamu Utsumi Mine was as many as 21,800 tons (in form of U$_3$O$_8$) in an area extent of 20,000,000 m$^2$. The tonnage of Th in the Morro do Ferro Area was as many as 17,500 tons (in form of ThO$_2$) in an area extent of 3,140,000 m$^2$. Parameter T was determined as many as 0.0011 for U and 0.0056 for Th. Table 5 attaches the result of parameter T determination.

Figure 2. The determination of parameter N.
Table 3. The determination of parameter F (summarized from [1–5,29,31,32]).

| Parameter | Mamuju, Indonesia | Pocos de Caldas, Brazil | F |
|-----------|------------------|------------------------|---|
| Regional Parameter | | | 0.5 |
| Tectonic setting | situated on the edge of Eurasia continental plate. | situated on the center of South America continental plate. | 0.6 |
| Stratigraphy | from older to younger, Mamuju is composed by Latanadjing Fm (metamorphic rocks), Talaya Volcanic Rocks (autoclastic breccia, tuff, lava), Adang Volcanic Rocks (tuff, lava, autoclastic breccia), intrusive rocks (granite, diorite), Mamuju Fm (limestone), Tapalang Mb, aluvium deposits. | from older to younger, Pocos de Caldas is composed by hujairut,chibitin, tuff and pyroclastic rocks, fyayite, tinguita, phonolite, and potassic rocks. | 0.5 |
| Structure | ring fault system, composing caldera, NE-SW dominant strikes | reverse faults, fault/joint lineaments, NE-SW dominant strike | 0.5 |
| Geomorphology | mountains and hills | caldera | 0.4 |
| Climate | tropical | tropical | 0.9 |
| Local Parameter | | | |
| Mineralization type | volcanic, surficial | volcanic, surficial | 0.9 |
| Source rocks | Middle Miocene - Upper Miocene phonolites | Upper Cretaceous caldasites | 0.4 |
| Mineral transportation | hydrothermal fluids flow, meteoric water flow | hydrothermal fluids flow, meteoric water flow | 0.9 |
| Host rocks | phonolite | phonolite and nepheline syenite | 0.9 |
| Mineral trap | structural | structural | 0.9 |
| Mineral/element products | primary (thorite, thorianite, davidite), secondary (gummite, autunite) | primary (pitchblende, U black oxides, thorite), secondary (pitchblende, U black oxides, thorite) | 0.4 |
| Preservation of mineral deposits | chemical weathering | chemical weathering | 0.9 |
| Mean F (0-1) | | | 0.66 |

Table 4. The determination of parameter U (summarized from [1–5,29,31,32]).

| Exploration activity | Mamuju (all sectors) | Osamu Utsumi Mine (OUM) | Morro do Ferro Area (MFA) | Mamuju to OUM percentage | Mamuju to MFA percentage |
|---------------------|----------------------|--------------------------|---------------------------|--------------------------|--------------------------|
| A. Geological survey | 1:25000 scale | 1:1000 scale | 1:5000 scale | 0.5 | 0.6 |
| B. Geochemical survey | 1:25000 scale | 1:1000 scale | 1:5000 scale | 0.5 | 0.6 |
| C. Geophysical survey | | | | | |
| 1. Radiometric mapping | 200 m grid | 25 m grid | 50 m grid | 0.25 | 0.3 |
| 2. Geomagnetic mapping | 2 km grid | 250 m grid | 500 m grid | 0.25 | 0.3 |
| 3. Geophysical logging | spectral gamma ray | spectral gamma ray | spectral gamma ray | 0.25 | 0.3 |
| 3. Geophysical logging | logging, 80 m average depth | logging, 150 m average depth | logging, 220 m average depth | 0.5 | 0.6 |
| E. Technological survey | 5 spots / 10 km2, 80 m average depth | 5 spots / 10 km2, 120 m average depth | | | |
| F. Topographic mapping | 1:25000 scale | 1:1000 scale | 1:5000 scale | 0.25 | 0.3 |
| G. Laboratory analysis | | | | | |
| 1. XRF | 1:25000 scale | 1:1000 scale | 1:5000 scale | 0.25 | 0.3 |
| 2. Fluorometry | 1:25000 scale | 1:1000 scale | 1:5000 scale | 0.25 | 0.3 |
| 3. Petrography | 1:25000 scale | 1:1000 scale | 1:5000 scale | 0.25 | 0.3 |
| 4. Micrography | 1:25000 scale | 1:1000 scale | 1:5000 scale | 0.25 | 0.3 |
| Mean U (0-1) | | | | 0.34 | 0.41 |

Table 5. The determination of parameter T (summarized from [29,31–33]).

| Control area | U3O8 tonnage (ton) | ThO2 tonnage (ton) | The extent of control area (m²) | T U (ton/m²) | T Th (ton/m²) |
|--------------|-------------------|-------------------|---------------------------------|--------------|--------------|
| Osamu Utsumi Mine | 21,800 | 17,500 | 20,000,000 | 0.0011 | 0.0056 |
| Morro do Ferro Area | 3,140,000 | | | |

From the analysis above, it is known that the most suitable undiscovered resource assessment method is the ERDA method and the parameters for the assessment can be determined by selecting the appropriate control area. Furthermore, the potential resource can be obtained from the parameters. The selected control area, Pocos de Caldas in Brazil has a similar geological condition as Mamuju Area. Pocos de Caldas is even more suitable for being a control area as it has areas for both U and Th mineralizations, which are the exploration target of CNMT BATAN in Mamuju Area. All the parameters in the ERDA method, except N, are largely affected by the exploration of the control area. Thus, the potential resource of U and Th in Mamuju Area obtained from the assessment can be a basis for the continuation decision of exploration in the area, but for a more confident resource to assess the economic...
potential of the deposit, more advanced exploration method for identified resource estimation should be done.

7. Conclusion
The required criteria of the method to assess the undiscovered resources of Mamuju are quantitative, probabilistic, subjective, data- and knowledge-driven, appropriate for greenfield, and spatial. The method which meets all those criteria is the ERDA method. The favorable target to assess in Mamuju is Adang Volcanic Rocks which is proven to contain U and/or Th minerals and the area on the formation which has > 100 ppm U equivalent concentration. Pocos de Caldas in Brazil was selected as the control area to Mamuju due to its similarity in the geological conditions and its more advanced exploration stage. All the parameters for the assessment can be determined with the ERDA method based on the available information of the control area.

8. Recommendation
To increase the certainty level of the U and Th resources assessed in Mamuju, it is necessary to upgrade the exploration stage by expanding and detailing all kinds of exploration activity.

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