The Application of Geostatistical Analysis on Radiometric Mapping Data to Recognized the Uranium and Thorium Anomaly in West Sulawesi, Indonesia.

I Gde Sukadana¹ ²*, I Wayan Warmada², Agung Harijoko², Frederikus Dian Indrastomo¹, Heri Syaeful¹

¹Center for Nuclear Minerals Technology, National Nuclear Energy Agency of Indonesia
²Departemen of Geological Engineering, Gadjah Mada University, Indonesia

E-mail: sukadana@batan.go.id

Abstract. Mamuju Region in West Sulawesi, Indonesia is one of prospect area of uranium/thorium in Indonesia. High radiometric concentrations were located in Adang Volcanic Rocks. This formation is grouped as basaltic to intermediate rock and composed by lava, pyroclastic rocks, and tuff. Regional field radiometric mapping, including radiation dose rates, potassium, uranium, and thorium contents of soil and rock was conducted to identify the existence of radioactive minerals and prospect zones. Some radiometric anomalies are detected and probably related to hydrothermal alteration, leaching, and precipitation processes. Uranium anomaly (97,261 ppm) located in Mamuju River upstream, Botteng, Takandeang and Ahu area. The anomaly related to uranium leaching and precipitation processes in leucite basalt lava. Thorium anomaly (369,461 ppm) located in Pangasaan, Takandeang, Ahu, and Taan area. To expand this radiometric mapping, we characterized the reflectance of Landsat-8 imagery based on field measurement data. Based on circular structures identification, uranium/thorium anomaly are related to the existence of volcano vents on Adang Volcanic. Based on band rationing, high uranium contents distributed in the area with less ferromagnesian mineral, while thorium did not affect. These field based and remote sensing characterization results could be used as preliminary parameters to identify wide and detail prospects.

1. Introduction

Mamuju Region in West Sulawesi, Indonesia is one of prospect area of uranium and thorium exploration. High radioactivity dose rate are found from the environment radioactivity measurement conducted by BATAN in 2007-2014 (Iskandar and Kusdiana, 2014). The value of radioactivity dose rate 100-2,800 nSv/h which is the highest result in Indonesia (Syaeful et al., 2014). High radioactivity value in environment usually comes from the existence of the potassium (K), uranium (U), and thorium (Th) and their daughter decay in rock/soil. Radiometric mapping is one of important method to identify the distribution of radioelements in a wide area. In this study radiometric mapping was conducted in Mamuju Area with ±800 km² wide (Figure 1). This Area composed by Adang volcanic alkaline rocks (Sukadana et al., 2015). Specific mineral of uranium bearing minerals are davidite, gummite and autunite, and the thorium bearing minerals such as thorianite, thorite associate with rare earth elements (Sukadana et al., 2016). Radiometric measurements show the range of uranium equivalent (eU), thorium equivalent (eTh), potassium (K), and radiation dose rate values (Indrastomo et al., 2015). The results of these measurements can be a guide to determine the location of radioactive
mineral deposit. The mapping has been successfully delineated the area of NORM or the area with thorium and uranium anomaly. Thorium and uranium anomaly are related with multi-geological-process resulting the increase of grade into several element from its original state (Ielsch et al., 2017). The radiometric measurements data involve large amounts of data so that a way to process the data is needed so that it is easy for interpretation. The purpose of this study is to determine the anomaly value of radiometry measurements of soil / rock statistically so that the potential location of radioactive mineral deposits.

Figure 1. Research area location

The result of radiometric measurements can be classified on three class, which are background, normal value and anomalous value. The anomalous value will be compared with geochemical analysis data to cross check the validity of geostatistical analysis.

2. Regional Geology

Mamuju area as part of western arm of Sulawesi and consist of Volcano sedimentary rocks as the product of Paleocene to Pliocene magmatism in NW Sulawesi shows a progression from an older series with calc-alkaline/tholeiitic signatures (51–17 Ma) to a Younger series of mafic-intermediate high-K magmas (~14–5 Ma) and felsic K-rich calc-alkaline (CAK) magmas (9–2 Ma)(Elburg et al., 2003). Regional Geology of study area consists of Talaya Volcanic Rocks (Tmtv), Adang Volcanic Rocks (Tma), Mamuju Formation (Tmm), Tapalang Member of Mamuju Formation (Tmmt), Corraline Limestone (Ql), and Alluvial (Qa) (Figure 1). Talaya Volcanic rocks consist of andesitic-basaltic volcanic breccia, tuff and lava, with intercalations of sandstone and marl, locally coal. Adang Volcanic Rocks mainly consist of leucite basaltic lava and volcanic breccia, tuff, partly micaceous. Mamuju Formation deposited above Adang volcanic, consist of marl, calcarenite, coralline limestone
with tuff and sandstone intercalations, locally conglomerate, Mamuju Formation has interfingering relation with Tapalang Member which consist of Reef limestone, fragmental limestone, and marl (Ratman and Atmawinata, 1993). Based on landsat-8 analysis, the volcano stratigraphy of Mamuju area is classified into Talaya Crown and Mamuju Crown. The Talaya Crown consists of Mambi hummock, Malunda hummock, and Kalukku hummock, while Mamuju Crown consists of Botteng, Ahu, Tapalang, Adang, Ampalas, Sumare, and Labuhan Ranau hummock (Indrastomo et al., 2016). The Adang Volcanic complexes, composed of predominantly of leucite/ pseudo leucite-bearing trachytic tuff, lapilli-tuff, agglomerate volcanic breccia, volcanic-sedimentary products (volcaniclastics consisting of trachytic, phonolite and tepri phonolite)(Shaban et al., 2016). Based on the affinity of the rocks concluded that tectonic setting of magmatism formed in active continental margin (ACM)(Sukadana et al., 2015). According to the geological conditions Adang volcanic are interest area for radiometric measurement. The radiometric measurement using handheld gamma survey meter RS-125 was conducted in huge point and wide area. To make the best result and decision of the future exploration step, analysis and processing methods are needed.

Figure 2. Regional Geological Map of Research area (Ratman and Atmawinata, 1993)

3. Method and Data

The suitable methodology for preliminary screening, based on space of data are gamma ray method (IAEA, 2003). The conventional approach to the acquisition and processing of gamma ray spectrometric data is to monitor three or four relatively broad spectral windows (Figure 2). The K energy window monitors the 1.46 MeV gamma rays emitted by 40K. The U and Th energy windows monitor gamma ray emissions of decay products in the U and Th decay series. These windows are generally accepted as the most suitable for the measurement of K, U and Th.

The data acquisition are using portable hand-held gamma ray spectrometers are widely used in field studies, for exploration or environment survey. Portable threshold spectrometers have up to 100 cm$^3$ of
NaI(Tl) crystals as detectors, and several switch-operated energy thresholds. The threshold can be set to a low energy for total count measurement, and to energies slightly below the 1.46 MeV ($^{40}$K), 1.76 MeV ($^{214}$Bi) and 2.61 MeV ($^{208}$Tl) photopeak for K, U, and Th measurement, respectively (IAEA, 2003). The device used in survey is spectrometer Radiation Solution – 125. RS-125 device uses the same method as listed above, using 103 cm$^3$ Thalium doped Sodium Iodide or NaI(Tl) detector which capable to read K, U, Th, dose rate, and total count (TC) in every measurement. It is also can be directly linked to Bluetooth Global Positioning System (GPS) which can provide coordinate information during field measurement. The field measurement conducted by dynamic and static method, and in this study, data processing will be focused on dynamic measurement. The dynamic method conducted by setting the RS-125 radiometric device to automatically stored data in every 1 or 3 minutes (Indrastomo et al., 2015).

Figure 2. a) Typical gamma ray spectrum showing the positions of the conventional energy windows [5], b) Radiometry data distribution in area approx. 800 km$^2$

The precision of about 0.1% K, 0.4 ppm eU and 0.6 ppm eTh can be expected from field assays with a scintillation gamma ray spectrometer using a sampling time of 4 minutes. The main factors that reduce assay precision are the statistical nature of radioactivity, variable background radiation due to atmospheric radon, and the variable water content in rocks (Rouze et al., 2017).

Statistical data processing uses NCSS statistical software. The radiometric data is analyzed by using descriptive analysis to determine the correlation between data and their percentage values. The percentile values are used to determine background and threshold. The geostatistical data as the result of NCSS processing can be use in various purpose (Safari et al., 2013)

Data processing uses GIS based software. Map gridding using Inverse Distance Weighting (IDW) interpolation. The IDW interpolation method is used because it gives interpolation result more accurate than other (like kriging) (Pramono, 2008). The interpolation result is near to the minimum and maximum of original data. The interpolation uses a distance weighted average of data points to calculate grid values. Some parameters like cell size and search radius must be defined. Search radius defines the width and height of grid cell in distance unit. Since grid cells are square both width and height are specified with one value. When the cell size changed, the grid dimensions also changed.
4. Result

Data acquisition was conducted covering almost all the Mamuju area. The data base is the result of ground dynamic measurement. The space between data are not exactly the same distance because of the relief, time and the field condition. The total measurement points are 87,818 point with distribution as Figure 3.b. Statistical data processing uses NCSS statistical software. The radiometric data is analyzed by using descriptive analysis to determine the correlation between data and their percentage values (Table 1). The percentile values are used to determine background and threshold. Data population show the weight line intercepted with the data trend on percentile 25 and percentile 75. The percentile 25 value is defined as background, while percentile 75 is defined as threshold. The anomaly is the value more than percentile 75.

| Table | Min | Max  | Mean  | Median | Standard Deviation | Background (% 25) | Threshold (% 75) | Data Count |
|-------|-----|------|-------|--------|-------------------|------------------|----------------|------------|
| Dose (nSv/h) | 15.00 | 68934.300 | 913.720 | 696.000 | 1794.277 | 480.500 | 982.800 | 87818 |
| K (%) | 0.00 | 98.800 | 2.144 | 1.500 | 3.015 | 0.600 | 2.800 | 87818 |
| eU (ppm) | 0.00 | 2914.300 | 34.177 | 21.800 | 79.174 | 12.900 | 34.300 | 87818 |
| eTh (ppm) | 0.20 | 15511.400 | 201.653 | 156.100 | 399.495 | 105.000 | 222.600 | 87818 |

This interpolation uses 0.0025 cell size and 0.2 searching radius. After few experiments on determining the cell size, the 0.0025 parameter is the most realistic for large area as seen in Figure 1.b. (Mamuju area approx. 800 km² wide). The grid spacing is 145 x 161 resulting pixel sizes 270 x 270 m. There are only fewer noises from the calculation. The 0.2 searching radius parameter used to covers all the measurements area because the measurements location in the same geological setting. The interpolation results are seen in table 2 and Figure 3-6. The background and threshold values obtained from statistical percentile on table 1. Some area like Pengasaan, Botteng, Pasabu, Orobatu, Takandeang, Taan, and Bebanga are measured systemically in 200 m spacing. This area has high value of radiometry.

Based on geostatistical and GIS interpolation, the details data for each radioelement are below:

4.1. Radiation Dose Rate (DR).

Radiation dose rate measurement data has 87,818 point, with minimum measurements is 15 and the maximum value is 68,934 nSv/h. Based on geostatistical analysis, mean value of this data is 913.72 and median value is 696.0. Data processing resulted the figure 3.a, which are deflection of data trend (green lines) and the weight lines. The deviation standard value is 1,794.27 and the background data is < 480.5 nSv/h, from the line the result of threshold in 75% (percentile) of data is 982.8 nSv/h. Map processing using arc-GIS using IDW (inverse distance weight) interpolation resulted the minimum value 50 nSv/h, maximum value 26,769 nSv/h. The background value ranges from 50-480.5 nSv/h, the general value range from 480.5-982.8 nSv/h and the threshold value 982.8 nSv/h, so the anomaly value range are >982.8 nSv/h.
The result of the iso-radiometric map, there are some locations have radiometric anomalies, namely Ahu, Taan, Rantedoda, Takandeang, Hulu Mamuju, Botteng, Ampalas and Bebanga areas. Areas that have radiometric values contain potassium, thorium, and uranium. More detailed survey was conducted at this location to find out the potential at that location (Figure 3.b).

Figure 3. a) Radiometry data distribution in area approx. 800 km², b) Radiation dose rate interpolation in Mamuju Area. The anomalous area (red area) ranges from 982 to 26,769 nSv/h.

4.2. Potassium (%K)

Potassium data are reflected of the content of $^{40}$K in the rock/soil. Potassium acquisition data has 87,818 point, with minimum measurements is 0.00 and the maximum value is 98.80 %. Based on geostatistic analysis, mean value of this data is 2.144 and median value is 1.500. Data processing resulted the figure, which are deflection of data trend (green lines) and the weight lines (Figure 4.a.). The deviation standard value is 3.015 and the background data is < 0.6 %, from the line the result of threshold in 75% (percentile) of data is 2,800%. Map processing using arc-GIS using IDW (inverse distance weight) interpolation resulted the minimum value 0.2 %, maximum value 33.3%. The background value range from 0.6, the general value range from 0.6-2.8 % and the threshold value 2.8%, so the anomaly value range are 2.8-33.3%.

The result of the iso-potassium map, there are some locations have potassium anomalies value, namely Pengasaan, Tapalang low land, Mamuju-Rangas low land, Ampalas Area, Bebanga and Hulu Mamuju areas (Figure 4.b).
4.3. Uranium (ppm eU)

Uranium measurement data has 87,818 point, with minimum measurements is 0.00 and the maximum value is 2914.30 ppm. Based on geostatistic analysis, mean value of this data is 34.17 ppm and median value is 21.80 ppm. Data processing resulted the figure 5.a, which are deflection of data trend (green lines) and the weight lines. The deviation standard value is 79.17 and the background data less then 12.9 ppm, from the line the result of threshold in 75% (percentile) of data is 34.3 ppm ppm eU. Map processing using arc-GIS using IDW (inverse distance weight) interpolation resulted the minimum value 0.8, maximum value 984.2 ppm eU. The background value range from 12.9, the general value range from 12.9-34.3 and the threshold value 34.3 ppm eU, so the anomaly value range are 34.3-984.2 ppm eU.

The result of the iso-uranium map, there are some locations have uranium anomalies value, namely Ampalas, Hulu Mamuju, Takandeang, Ahu, Botteng and Taan Area (Figure 5.b).
4.4. Thorium (ppm eTh)

Thorium data is reflected the grade of thorium element in the rock or soil. Thorium is a radioactive element that has a decay that produces gamma rays, namely Tl with a gamma energy of 2.615 keV. The measurement data using RS 125 has been measured in 87,818 point, with minimum measurements is 0.20 and the maximum value is 15,511.4 ppm eTh. Based on geostatistical analysis, mean value of this data is 201.65 ppm and median value is 156.1 ppm. Data processing resulted the figure 6.a, which are deflection of data trend (green lines) and the weight lines. The deviation standard value is 399.49 and the background data is < 0.6 %, from the line the result of threshold in 75% (percentile) of data is 222.6. Map processing using arc-GIS using IDW (inverse distance weight) interpolation resulted the minimum value 8.7, maximum value 6,066. The background value ranges from <105, the general value range from 105,0-222.6 and the threshold value 222.6, so the anomaly value range are 222.6 – 6,066 ppm eTh. The result of the iso-thorium map, there are some locations have thorium anomalies value, namely Pengasaan, Tapalang low land, Mamuju-Rangas low land, Ampalas Area, Bebanga and Hulu Mamuju areas (Figure 6.b).
5. Discussion

Radioactive mineral surveys require the right data acquisition and processing to carry out the proper and efficient exploration stages. Geological survey is the initial stage of any mineral resource survey including radioactive mineral survey. In radioactive mineral surveys, radiometric methods are used. The radiometric method is carried out in accordance with the scale and availability of the survey tools to be used. At the regional stage, it is generally carried out by airborne surveys, with implementation that is faster and can cover a wider area (Rouze et al., 2017). In addition to detecting radioactive sources, airborne surveys are also used to explore the distribution of radionuclide contamination at the time of a nuclear accident (Masoudi et al., 2019). These methods should be combined and calibrated by the onsite measurement method or by ground check (Bourgeon et al., 2016). If it is not possible to carry out an airborne survey, then a systematic ground survey can be carried out. This activity is more effective because it can directly confirm the presence of radiometric anomalies in soil and rock. Ground survey radiometric data is in-situ radiometric data that reflects the radiometric conditions of soil / rock directly and can determine the background value of the area (Duarte et al., 2011). Ground survey data also can be combine by another geochemical data, such as stream sediment and soil/rock sampling (Guagliardi et al., 2020)

The results of field radiometric measurements using the RS-125 tool with the ground survey method are the most effective method at present. This radiometric measurement has been widely applied in various countries in preparing initial exploration data. Radiometric measurements in the Mamuju area have been carried out and compiled to cover the entire Mamuju area, so that it can be considered representative of the entire Mamuju area.

Geostatistical data processing using the NCSS program is considered to reflect data patterns that can be used as a basis for determining background values, thresholds, and anomalies. Furthermore, the results of geostatistical data processing are followed by making radiometric maps using Arc-Gis with the kriging method (Piccini et al., 2012). Radiometric iso maps are spatial data that can distinguish areas that have radioelement levels, which indicate the differences in the radioelement content on soil/rock in an area. The descriptive statistics also often using for radiometric data analysis (Adagunodo et al., 2018).

Figure 6. a) Thorium graphic of distribution, b) Thorium (ppm eTh) concentration interpolation in Mamuju Area.
The radiation dose rate anomaly is the reflection of the gamma ray emission from the soil / rock elements composition that emit radiation. Although there are many radioactive sources in nature, but the decay series that emit gamma radiation according to the gamma survey instrument are only the decay series of potassium (K), uranium (U) and thorium (K). The emission of gamma rays from the decay of the three elements causes a high/low rate of radiation dose rate (IAEA, 2003). In the research area, several areas that have high radiation dose rates cover almost the entire Mamuju area, especially the Ahu, Taan, Rantedoda, Takandeang, Hulu Mamuju, Botteng, Ampalas and Bebanga areas.

Potassium content in soil and rocks is a reflection of the presence of potassium-rich, both minerals in the fresh rock and weathering result and have been deposited elsewhere (Ryde, 1983). So that the distribution of potassium in the Mamuju area is spread over alkaline rocks and the distribution of weathered sediments of these alkaline rocks.

Areas that have potassium levels are scattered in areas composed of ultra-alkaline rocks to sedimentary rocks resulting from weathered sediment, including Mamuju upstream, upstream Ampalas, Rangas sedimentary areas, Mamuju lowlands, Tapalang lowlands and Kalukku lowlands.

Uranium anomaly area reflects the presence of uranium in soil / rock. The results of radiometric measurements and geostatistical processing, areas that have high uranium levels. Geochemical analysis using selected sample confirmed the high uranium concentrations of 539–128.699 Bq/kg (average: 22.882 Bq/kg), these area can be prospect are to uranium mineral exploration (Rosiani et al., 2020).

The thorium anomaly is scattered in several areas, especially in weathered rocks and forms the thick laterite. This occurs due to the formation of thorium enrichment as a stable element, while other elements have been leaching due to alteration and weathering processes. The was confirmed by geochemical analysis with high content of thorium until 471–288,639 Bq/kg (average: 33,549 Bq/kg)(Rosiani et al., 2020), those area have thorium exploration prospect.

6. Conclusion
Mamuju Region in West Sulawesi is a “green” field area of U/Th Exploration due to high radioactivity value The field measurement conducted by dynamic and static method using RS-125 can figure-out the distribution of dose rate, uranium, and thorium anomaly. Statistical data processing using NCSS statistical software is very sufficient to get background, normal and anomaly value. Data population show the weight line intercepted with the data trend on percentile 25 and percentile 75. The result of the iso-radiometric map, there are some locations have radiometric anomalies, namely Ahu, Taan, Rantedoda, Takandeang, Hulu Mamuju, Botteng, Ampalas and Bebanga areas. Areas that have radiometric values contain potassium, thorium, and uranium.

Acknowledgment
The authors would like to acknowledge Field work team of Exploration Division, and Head of Centre for Nuclear Minerals Technology-National Nuclear Nuclear Agency.

References
Adagunodo, T.A., Hammed, O.S., Usikalu, M.R., Ayara, W.A., and Ravisankar, R., 2018, Data on the radiometric survey over a kaolinitic terrain in Dahomey Basin, Nigeria: Data in Brief, v. 18, p. 814–822, doi:10.1016/j.dib.2018.03.088.

Bourgeon, M.A., Paoli, J.N., Jones, G., Villette, S., and Gée, C., 2016, Field radiometric calibration of a multispectral on-the-go sensor dedicated to the characterization of vineyard foliage: Computers and Electronics in Agriculture, v. 123, p. 184–194, doi:10.1016/j.compag.2016.02.019.

Duarte, P., Mateus, A., Paiva, I., Trindade, R., and Santos, P., 2011, Usefulness of systematic in situ gamma-ray surveys in the radiometric characterization of natural systems with poorly contrasting
geological features (examples from NE of Portugal): Applied Radiation and Isotopes, v. 69, p. 463–474, doi:10.1016/j.apradiso.2010.10.002.

Elburg, M., van Leeuwen, T., and Foden, J., 2003, Spatial and temporal isotopic domains of contrasting igneous suites in Western and Northern Sulawesi, Indonesia: Chemical Geology, v. 199, p. 243–276, doi:10.1016/S0009-2541(03)00084-6.

Guagliardi, I., Zuzolo, D., Albanese, S., Lima, A., Cerino, P., Pizzolante, A., Thombrane, M., De Vivo, B., and Cicchella, D., 2020, Uranium, thorium and potassium insights on Campania region (Italy) soils: Sources patterns based on compositional data analysis and fractal model: Journal of Geochemical Exploration, v. 212, p. 106508, doi:10.1016/j.gexplo.2020.106508.

IAEA, 2003, Mapping Using Gamma Ray: v. 4, 1549-1555. p., http://cdiac.esd.ornl.gov/oceans/GLODAP/glodap_pdfs/Thermohaline.web.pdf.

Ielsch, G., Cuney, M., Buscail, F., Rossi, F., Leon, A., and Cushing, M.E., 2017, Estimation and mapping of uranium content of geological units in France: Journal of Environmental Radioactivity, v. 166, p. 210–219, doi:10.1016/j.jenvrad.2016.05.022.

Indrastomo, F.D., Sukadana, I.G., Saepuloh, A., and H, A.H., 2015, Integrated Radiometric Mapping using Field Based and Remote Sensing Techniques for Uranium and Thorium Exploration at Mamuju Region, West Sulawesi, Indonesia:.

Indrastomo, F.D., Sukadana, I.G., Saepuloh, A., Harsolumakso, A.H., and Kamajati, D., 2016, Interpretasi Vulkanostratigrafi Daerah Mamuju Berdasarkan Analisis Citra Landsat-8: Eksplorium Buletin Pusat Teknologi Bahan Galian Nuklir, v. 36, http://journal.batan.go.id/index.php/eksplorium/article/view/2632 (accessed May 2016).

Iskandar, D., and Kusdiana, 2014, Peta Laju Dosis Radiasi Lingkungan Indonesia.pdf: Pusat Teknologi Keselamatan dan Metrologi Radiasi.

Masoudi, P., Le Coz, M., Cazala, C., and Saito, K., 2019, Spatial properties of soil analyses and airborne measurements for reconnaissance of soil contamination by 137 Cs after Fukushima nuclear accident in 2011: Journal of Environmental Radioactivity, v. 202, p. 74–84, doi:10.1016/j.jenvrad.2018.11.014.

Piccini, C., Marchetti, A., Farina, R., and Francaviglia, R., 2012, Application of indicator kriging to evaluate the probability of exceeding nitrate contamination thresholds: International Journal of Environmental Research, v. 6, p. 853–862.

Pramono, G.H., 2008, Akurasi Metode IDW dan Kriging untuk Interpolasi Sebaran Sedimen Tersuspensi di Maros, Sulawesi Selatan: Forum Geografi, v. 22, p. 145, doi:10.23917/forgeo.v22i2.4988.

Ratman, N., and Atmawinata, 1993, Lembar Peta Geologi Lembar Mamuju: Bandung, Pusat Penelitian dan Pengembangan Geologi.

Rosianna, I., Nugraha, E.D., Syauful, H., Putra, S., Hosoda, M., Akata, N., and Tokonami, S., 2020, Natural radioactivity of laterite and volcanic rock sample for radioactive mineral exploration in mamuju, indonesia: Geosciences (Switzerland), v. 10, p. 1–13, doi:10.3390/geosciences10090376.

Rouze, G.S., Morgan, C.L.S., and McBratney, A.B., 2017, Understanding the utility of aerial gamma radiometrics for mapping soil properties through proximal gamma surveys: Geoderma, v. 289, p. 185–195, doi:10.1016/j.geoderma.2016.12.004.

Ryde, N., 1983, Potassium-rich volcanic rocks of the muriah complex, java, indonesia: products of multiple magma sources? Journal of Volcanology and Geothermal Research, v. 18, p. 337–359.

Safari, Y., Esfandiarpour-boroujeni, I., Kamali, A., Salehi, M.H., and Bagheri-bodaghabadi, M., 2013, Qualitative Land Suitability Evaluation for Main Irrigated Crops in the Shahrekord Plain, Iran: A Geostatistical Approach Compared with Conventional Method: Pedosphere, v. 23, p. 767–778,
Shaban, G., Fadlin, F., and Priadi, B., 2016, Geochemical Signatures of Potassic to Sodic Adang Volcanics, Western Sulawesi: Implications for Their Tectonic Setting and Origin: Indonesian Journal on Geoscience, v. 3, p. 195–214, doi:10.17014/ijog.3.3.195-214.

Sukadana, I.G., Harijoko, A., and Setidjadji, L.D., 2015, Tataan Tektonika Batuan Gunung Api Di Komplek Adang, Kabupaten Mamuju, Propinsi Sulawesi Barat: Eksplorium, v. 36, p. 31–44, doi:10.17146/exsplorium.2015.36.1.2771.

Sukadana, I.G., Syaeful, H., Indrastomo, F.D., Widana, K.S., and Rakhma, E., 2016, Identification of Mineralization Type and Specific Radioactive Minerals in Mamuju, West Sulawesi: Journal of East China University of Technology, v. 39, p. 39–48.

Syaeful, H., Sukadana, I.G., and Sumaryanto, A., 2014, Radiometric Mapping for Naturally Occurring Radioactive Materials (NORM) Assessment in Mamuju, West Sulawesi: Atom Indonesia, v. 40, p. 33–39, http://aij.batang.go.id/index.php/aij/article/view/263 (accessed May 2016).