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Investigation of Radioisotope count fluctuation and Shifts of Their Content Accumulation in Rock Minerals

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Abstract: The main problem studied in this study concerns the fluctuations in the number of radioisotopes and the shift in the center of their accumulation in rock minerals in Oesuu, Central Kupang after experiencing weathering a few years ago. The objectives of the study: determine the range of radioisotope counts in rock minerals in Oesuu Central Kupang after weathering several years ago, investigate the shift in the center of accumulation of radioisotope content in rock minerals in Oesuu Central Kupang by time-dependent radioisotope migration and decay processes. Research methods: observation, survey, mapping, analysis, and interpretation. Brief research procedures: Observations to determine the boundaries of the research site and create a grid, measure the background count around the survey location, measure the field data, correct the data, make three-dimensional curves and contours of the radioisotope radiation count, interpret and draw conclusions. Research result. The range of radioisotope radiation counts in rock minerals is 10 Counts per minute (cpm) to 107 cpm, and the results of the 2008 study were 9 cpm to 117 cpm. The distribution of the accumulation center of radioisotope content in rock minerals has shifted from the edge towards the center of the study site, which is most likely caused by radioisotope migration and accumulated by very strong cohesive forces between radioisotope elements contained in rock minerals.

Keywords: Fluctuation; Investigation; Rock Minerals; Radioisotope; Shift of their content.

Introduction

Radioisotopes contained in rock minerals are continuously undergoing decay or disintegration and migration and weathering (Djabou et al., 2022). Migration can occur hydrothermally, the occurrence of erosion, through local faults, wind gusts that carry radioactive dust from the center of the content to other places, there is a strong cohesive force between radioactive particles, and so on (L. Wang et al., 2022; Manikanda Bharath et al., 2022; C. Wang et al., 2022). The results of previous studies indicate that in Oesuu Central Kupang there is a radioisotope content in rock minerals with a count range between 9 counts per minute (cpm) to117 cpm) (Pasangka & Ngana, 2020).

The rock composition in Oesuu Cental Kupang is dominated by sedimentary rocks, which are thought to have formed since the occurrence of the island of Timor, namely the upward lifting of the continental Australian shelf by thrust. The accumulation of radioisotope content in rock minerals is mostly found in sedimentary rock types (Nunes et al., 2023; Wu et al., 2023; Fallatah & Khattab, 2023). A prospect area contains a radioisotope if the ratio of the background count to the field count is greater than one third (Wang (王夕露 et al., 2021; Aplin et al., 2017; Kang et al., 2020). Radioisotopes found in nature undergo spontaneous decay, weathering, and time-dependent migration.

The migration of radioisotopes contained in rock minerals can contaminate the surrounding environment with fluctuating doses of nuclear radiation at three levels of contamination which are high contamination, medium contamination, and low contamination (Tortorello et al., 2013; Ostoich et al., 2022; Gwynn et al., 2024; Smičiklas & Šljivić-Ivanović, 2016). The environment that can be contaminated includes the surrounding air, (Al Nabhani et al., 2016; Olszewski et al., 2015), soil (Machiraju et al., 2020; N et al., 2021); Küçükömeroğlu et al., 2021; Ba et al., 2022), and water (Noli et al., 2016). The decay that occurs can be in the form of single decay and series decay. Single decay and series decay satisfy the equation:

$$N = N_o e^{-\lambda t} \quad (1)$$

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$$N = N_o e^{-\lambda t} \quad (2)$$

Where n = 1, 2, 3, 4, etc.

$$C_1 = \frac{\lambda_1 \lambda_2 .... \lambda_{n-1} N_1^o}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)(.......)(\lambda_n - \lambda_1)} \quad (3)$$

$$N_n = C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t} + ... + C_n e^{-\lambda_n t} \quad (4)$$

N_o: Original number of atoms, N: Number of atoms after decaying t seconds, λ: decay constant, t: decay time, N_n: Number of atoms after nth decay.

Radioisotope decay includes alpha, beta, and gamma decay:

For alpha decay, decay reaction:

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He \quad (5)$$

Decay energy:

$$Q = K_a + K_d = (M_p - M_d - m_a)c^2 \text{ in unit MeV} \quad (6)$$

Where: ${}^{A}_{Z}X$: parent atomic mass, ${}^{A-4}_{Z-2}Y$: daughter atomic mass, ${}^{4}_{2}H_e$: alpha particle (Helium nucleus), Q = decay energy, K_a: alpha particle kinetic energy, K_d: the daughter's kinetic energy decays, M_o: parent atomic mass, M_d: atomic mass of daughter, m_a: atomic mass of alpha particle. For beta decay:

Positive beta decay: decay reaction:

$${}^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + e^{+} + \upsilon \quad (7)$$

Dcay energy:

$$Q_{\beta^+} = \left(M_Z - M_{Z-1} - 2m_e\right)c^2 \quad (8)$$

Negative beta decay: decay reaction:

$${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e^{-} + \bar{\upsilon} \quad (9)$$

Decay energy:

$$Q_{\beta^-} = \left(M_Z - M_{Z+1}\right)c^2 \quad (10)$$

Electron capture: Decay reaction:

$${}^{A}_{Z}X + {}_{-1}e \rightarrow {}_{Z-1}^{A}Y + \upsilon \quad (11)$$

Decay energy:

$$Q_{EC} = \left(m_Z - m_{Z-1} + m_e\right)c^2 \quad (12)$$

Where:

e^{+}: positron, υ : neutrino Q_{β^+} : positive beta decay energy c : speed of light, m_e: electron mass ${}_{-1}e$ e^{-}: negatron $\bar{\upsilon}$: anti-neutrino, Q_{EC} : decay energy of electron capture.

Alpha and beta radiation are types of non-electromagnetic radiation that can be deflected by electric and or magnetic fields, while gamma radiation is electromagnetic waves. The penetrating power of gamma radiation is higher than beta and alpha (Taftazani et al., 2013). Radioisotopes decay continuously which always depends on time, causing fluctuations in the range of radioisotope nuclear radiation contained in rock minerals. Nuclear radiation count of radioisotope content in rock minerals in nature can be measured by Geiger Muller detector and Gamma ray detector (Šešlak et al., 2017; Ebihara et al., 2022)..

Method

Research Instruments

The main tools used in this study consisted of: Geiger Muller detector type Radiolet-50, GPS, stop watch, and Roller.

Research Methods and Procedures

Research methods include observation, mapping, analysis, and interpretation. The research procedure includes: making observations to determine the boundaries of the research site and making a grid, measuring the background count around the survey location, measuring the amount of radioisotope radiation in the field according to the grid that has been made, correcting the field data with the background count, make three-dimensional curves and contours of radioisotope counts based on field data, determine the range of radioisotope counts, compare the three-dimensional curves and contours between the results of the study with the three-dimensional contours and contours of the results of the 2008 study, estimate the shift in the accumulation of content radioisotope in rock minerals, conclusions. Note: The size of the research location in 2008 corresponds to the size of the research location in 2022, the distance of the measuring points and the distance of the track are taken the same.

Result and Discussion

The results of the study in the form of radioisotope radiation counts in rock minerals in Oesuu Central Kupang, Timor Island, Indonesia are listed in Table 1.

Table 1. Radioisotope radiation counts in rock minerals at Oesuu in 2022

Track Distance (m)						
L_1	L_2	L_3	L_4	L_5	L_6	Description
28	17	11	17	16	43	Measuring point
29	20	24	27	27	35	Distance: 85.00 m
27	27	22	40	36	15	Track distance: 400.00 m
21	29	25	34	27	30	
44	23	15	30	29	29	Distance measurement point of
35	47	37	40	10	35	core area: 10.00 m
41	33	34	42	22	32	
47	91	14	36	37	50	Track distance core area: 40.00 m
49	73	17	53	12	48	
48	56	28	36	20	49	Size location study: 2.000.00 km
58	58	37	32	33	47	x 3.150.00 km
50	70	36	30	36	35	
32	84	38	28	40	44	Size core area: 200.00 m x 300.00 m
35	70	32	50	37	49	
49	94	30	56	40	31	
62	89	22	50	47	28	
37	67	26	45	55	56	
50	99	36	56	54	37	
47	87	37	36	53	29	
55	64	72	30	52	29	
31	77	44	32	35	11	
63	70	56	25	41	44	
44	89	41	37	58	36	
36	104	40	38	45	33	
50	107	34	31	37	49	
67	90	32	43	31	29	
28	106	33	18	52	14	
20	75	24	29	38	36	
14	47	29	46	32	22	
28	36	21	26	44	28	
18	37	21	15	20	24	
17	35	32	22	31	29	
27	26	27	27	37	27	
20	29	17	28	24	21	
15	24	18	11	23	10	
22	31	14	28	27	23	
10	28	06	15	25	26	
16	19	29	25	14	28	

Based on the data in Table 1, three-dimensional curves and contours of the radioisotope radiation count in rock minerals in Oesuu Cental Kupang, Timor Island, Indonesia are made by the surfer-13 program as shown in Figure 1 and Figure 3. Figure 2 and Figure 4 show three-dimensional curves and contours of the radioisotope radiation count in this study in 2008 at the same location with the same location and grid size as the location and research grid in 2022. The radiation count measuring instrument used in the two studies with different times (time interval of 14 years) was also the same, namely the Geiger Muller detector, the *Radiolet* - type 50). Snippets of research locations are shown in Figure 5a, Figure 5b, Figure 5c, and Figure 5d.

Table 2. Radioisotope radiation counts in rock minerals at Oesuu in 2008

Track Distance (m)						
L_1	L_2	L_3	L_4	L_5	L_6	Description
53	38	27	21	27	26	Measuring point distance: 85.00 m
45	39	30	14	17	37	
25	37	17	32	50	46	Track distance: 400.00 m
40	31	19	15	44	37	
39	54	33	25	40	19	Distance measurement point of
45	45	57	47	50	20	core area: 10.00 m
42	51	43	44	52	32	
60	57	91	24	46	47	Track distance core area: 40.00 m
58	59	73	27	63	22	
59	58	66	38	46	30	Size location study: 2.000.00 km x
57	68	68	47	42	43	3.150.00 km
45	60	80	46	40	46	
54	42	94	48	39	50	Size core area: 200.00 m x 300.00 m
59	45	80	42	60	47	
41	59	104	40	66	50	
38	72	99	32	60	57	
66	47	77	36	55	65	
47	60	109	46	66	64	
39	57	97	47	46	63	
39	65	74	82	40	62	
21	41	87	54	42	45	
54	73	80	66	35	51	
46	54	99	51	47	68	
43	46	114	50	48	55	
59	60	117	44	41	47	
39	77	100	42	53	41	
54	38	116	43	28	62	
46	30	85	34	19	48	
32	24	57	39	56	42	
38	18	46	31	36	54	
34	28	47	31	25	30	
39	27	45	42	32	41	
17	17	36	37	36	45	
31	30	39	27	18	9	
20	25	34	28	21	10	
9	32	41	24	18	17	
13	20	38	16	25	13	
18	26	29	19	12	24	

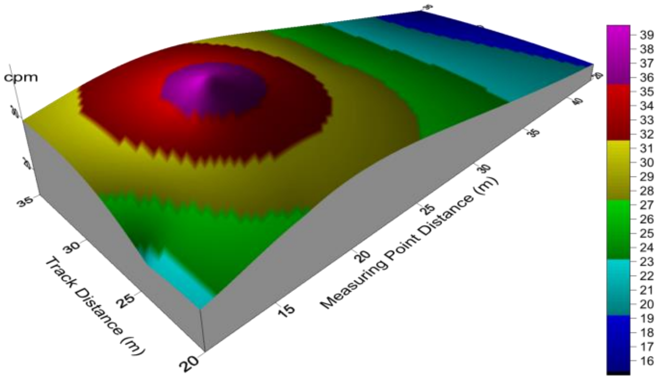

Figure 1. Three-dimensional curve of radioisotope count in rock minerals in Oesuu, Central Kupang

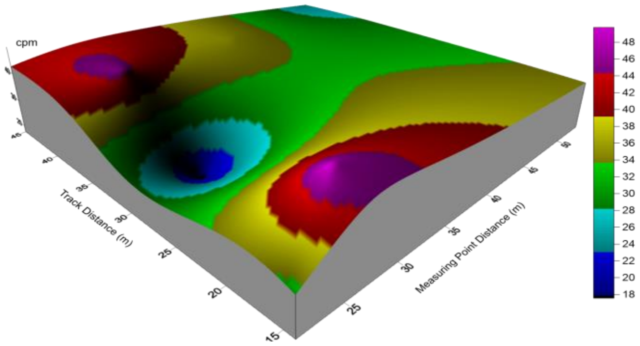

Figure 2. Three-dimensional curve of radioisotope content in rock minerals in previous studies

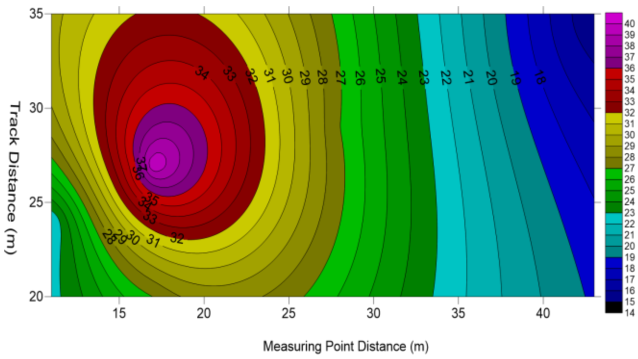

Figure 3. Contours of radioisotope count fluctuations in rock minerals in Oesuu, Central Kupang

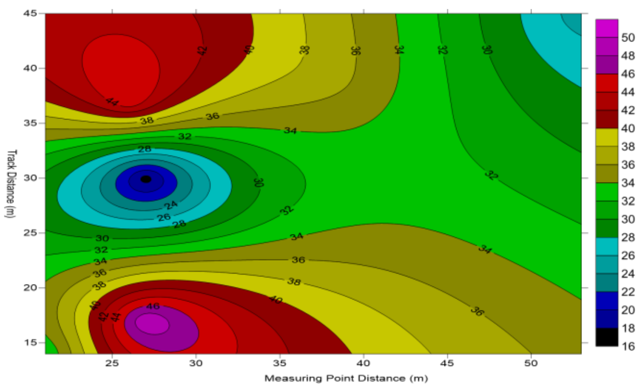

Figure 4. Contours of radioisotope count in rock minerals in in previous studies

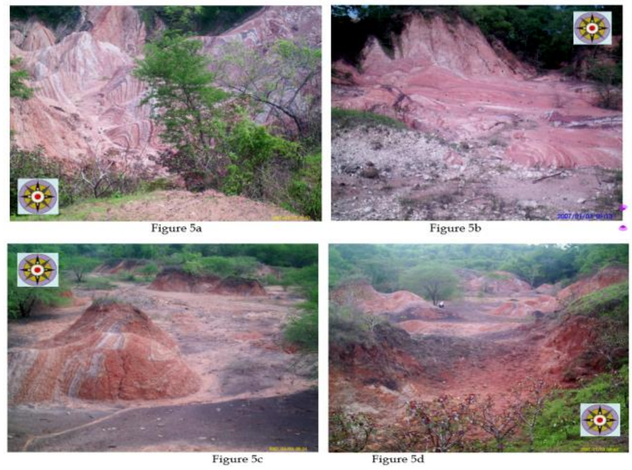

Figure 5. 5a, 5b, 5c, and 5d. Photo footage of the research location in Oesuu Central Kupang, Timor Island, Indonesia

Based on the data in Table 1, it can be stated that the radiation count of radioisotope content in rock mineral deposits in Oesuu Central Kupang, Timor Island, ranges from 10 cpm to 107 cpm. This shows that the amount of radioisotope radiation in rock mineral deposits changes every time and the size depends on the radioactive series that is formed at each change (Kallithrakas-Kontos et al., 2018; Rojas et al., 2020; Sharma et al., 2021; Molla et al., 2021). Figure 2 and Figure 4 show the distribution of radioisotope content in rock minerals in Oesuu Central Kupang, Timor Island, Indonesia, the results of a 2008 study.

In these images it is clear that the center of accumulation of radioisotope content in rock minerals is quite high distributed in the north and south on the right east of the research location. Figure 1 and Figure 3 show three-dimensional curves and distribution contours of radioisotope content in rock minerals in Oesuu Central Kupang, Indonesian Timor Island in 2022. Figure 1 and Figure 3 show the distribution of radioisotope content accumulation centers in rock minerals located in the eastern part center of the research location. If the two research results are compared, it is clear that there is a shift in the center of accumulation of radioisotope content in rock minerals from the north and south of the study site in the east in opposite directions so that the accumulation is concentrated in the center of the study site in the east (Su & Lim, 2023; Bartels et al., 2023; López-Pérez et al., 2022; Jiang et al., 2022; Rozhkova et al., 2022; Kazakis et al., 2022).

If the direction of the shift is observed carefully, it can be stated that the shift is most likely caused by the strong cohesive forces between minerals containing radioisotopes. Another possibility is the existence of hydrothermal migration, migration through faults, and migration through erosion of water flow and wind because the research location in the eastern part of the center has a low topography (Bonotto, 2017; Faganeli et al., 2017; Xarchoulakos et al., 2022; Bonotto & Oliveira, 2017; Navarro-Martinez et al., 2017).

Conclusion

Based on the description above, the following conclusions can be drawn. The range of radioisotope radiation counts in rock minerals is 10 cpm to 107 cpm, and the results of the 2008 study were 9 cpm to 117 cpm. The distribution of the center of accumulation of radioisotope content in rock minerals has shifted from the edge towards the center of the study site in the east of the research location, which is most likely caused by radioisotope migration and accumulated by very strong cohesion forces between radioisotope elements contained in rock minerals, migration hydrothermally, migration through local faults, weathering of rocks, and migration by erosion and wind.

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Author Contributions
B. P. ; is tasked with going into elementary school institutions to carry out observations and research. Apart from that, he is also responsible for carrying out data processing and writing scientific articles; I. G. P., is the supervisor and directed the author in the preparation of this scientific article.

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Conflicts of Interest
The author declares that he has no conflict of interest regarding the publication of this scientific article.

References

Al Nabhani, K., Khan, F., & Yang, M. (2016). Technologically Enhanced Naturally Occurring Radioactive Materials in oil and gas production: A silent killer. *Process Safety and Environmental Protection*, *99*, 237–247. https://doi.org/10.1016/j.psep.2015.09.014

Aplin, K. L., Briggs, A. A., Harrison, R. G., & Marlton, G. J. (2017). Measuring ionizing radiation in the atmosphere with a new balloon-borne detector. *Space Weather*, *15*(5), 663–672. https://doi.org/10.1002/2017SW001610

Ba, V. N., Phuong, H. T., Thien, B. N., Van Thang, N., Thu, H. N. P., & Loan, T. T. H. (2022). Variation of radioactivity and trace metal elements during the growth period of water spinach. *Journal of Radioanalytical and Nuclear Chemistry*, *331*(5), 2319–2329. https://doi.org/10.1007/s10967-022-08293-2

Bartels, C., Kersting, F., & Wolf, N. (2023). Testing Marx: Capital Accumulation, Income Inequality, and Socialism in Late Nineteenth-Century Germany. *Review of Economics and Statistics*, 1–44. https://doi.org/10.1162/rest_a_01305

Bonotto, D. M. (2017). The dissolved uranium concentration and 234U/238U activity ratio in groundwaters from spas of southeastern Brazil. *Journal of Environmental Radioactivity*, *166*, 142–151. https://doi.org/10.1016/j.jenvrad.2016.03.009

Bonotto, D. M., & Oliveira, A. M. M. A. D. (2017). Mobility indices and doses from 210Po and 210Pb activity concentrations data in Brazilian spas groundwaters. *Journal of Environmental Radioactivity*, *172*, 15–23. https://doi.org/10.1016/j.jenvrad.2017.03.006

Djabou, R. E., Mavon, Ch., Belafrites, A., & Groetz, J. E. (2022). Mining treatment effects on natural radioactivity and radiological hazard index assessment in phosphates and fertilizers used in Algeria. *Journal of Radioanalytical and Nuclear Chemistry*, *331*(5), 2081–2092. https://doi.org/10.1007/s10967-022-08258-5

Ebihara, M., Shirai, N., Kuwayama, J., & Toh, Y. (2022). High sensitivity determination of iridium contents in ultra-basic rocks by INAA with coincidence gamma-ray detection. *Nuclear Engineering and Technology*, *54*(2), 423–428. https://doi.org/10.1016/j.net.2021.08.010

Faganeli, J., Falnoga, I., Benedik, L., Jeran, Z., & Klun, K. (2017). Accumulation of 210 Po in coastal waters (Gulf of Trieste, northern Adriatic Sea). *Journal of Environmental Radioactivity*, *174*, 38–44. https://doi.org/10.1016/j.jenvrad.2016.07.018

Fallatah, O., & Khattab, M. R. (2023). Evaluation of Environmental Radioactivity and Hazard Impacts Saudi Arabia Granitic Rocks Used as Building Materials. *Minerals*, *13*(2), 165. https://doi.org/10.3390/min13020165

Gwynn, J. P., Hatje, V., Casacuberta, N., Sarin, M., & Osvath, I. (2024). The effect of climate change on sources of radionuclides to the marine environment. *Communications Earth & Environment*, *5*(1), 135. https://doi.org/10.1038/s43247-024-01241-w

Jiang, Q., Wang, Y., Cheng, J., Pan, Y., Ren, J., Leng, Y., Liu, Y., Bao, C., Wang, L., & Tuo, X. (2022). Sorption of cesium on surrounding granite of Chinese low- and medium-level nuclear waste repository in the groundwater environment. *Journal of Radioanalytical and Nuclear Chemistry*, *331*(5), 2069–2080. https://doi.org/10.1007/s10967-022-08280-7

Kallithrakas-Kontos, N. G., Xarchoulakos, D. C., Boultadaki, P., Potiriadis, C., & Kehagia, K. (2018). Selective Membrane Complexation and Uranium Isotopes Analysis in Tap Water and Seawater Samples. *Analytical Chemistry*, *90*(7), 4611–4615. https://doi.org/10.1021/acs.analchem.7b05115

Kang, H., Min, S., Seo, B., Roh, C., Hong, S., & Cheong, J. H. (2020). Low Energy Beta Emitter Measurement: A Review. *Chemosensors*, *8*(4), 106. https://doi.org/10.3390/chemosensors8040106

Kazakis, N., Busico, G., Ntona, M.-M., Philippou, K., Kaprara, E., Mitrakas, M., Bannenberg, M., Ioannidou, A., Pashalidis, I., Colombani, N., Mastrocicco, M., & Voudouris, K. (2022). The origin of Uranium in groundwater of the eastern Halkidiki region, northern Greece. *Science of The Total Environment*, *812*, 152445. https://doi.org/10.1016/j.scitotenv.2021.152445

Küçükömeroğlu, B., Şen, A., Duran, S. U., Çiriş, A., Taskin, H., & Ersoy, H. (2021). Determination of radioactivity level of water supply network in Trabzon province, Turkey. *Isotopes in Environmental and Health Studies*, *57*(6), 610–622. https://doi.org/10.1080/10256016.2021.1972996

López-Pérez, M., Martín-Luis, C., Catalán, A., & Salazar-Carballo, P. A. (2022). Estimation of radiation doses due to groundwater intake at a volcanic island: Tenerife (Canary Islands, Spain). *Food Control*, *135*, 108830. https://doi.org/10.1016/j.foodcont.2022.108830

Machiraju, P. V. S., Murty, V. V. K. P. L. N., & Shyamala, P. (2020). Distribution of uranium in drinking/ground waters in Narsipatnam Revenue Division of Visakhapatnam District of Andhra Pradesh, India and consequent ingestion dose. *Journal of Radioanalytical and Nuclear Chemistry*, *324*(3), 1109–1113. https://doi.org/10.1007/s10967-020-07134-4

Manikanda Bharath, K., Natesan, U., Chandrasekaran, S., & Srinivasalu, S. (2022). Determination of natural radionuclides and radioactive minerals in urban coastal zone of South India using Geospatial approach. *Journal of Radioanalytical and Nuclear Chemistry*, *331*(5), 2005–2018. https://doi.org/10.1007/s10967-022-08284-3

Molla, S., Jha, S. K., Rana, B. K., & Kulkarni, M. S. (2021). Disequilibrium of 226Ra, 210Pb, and 210Po in groundwater and soil around the Singhbhum region of Jharkhand, India. *Journal of Radioanalytical and Nuclear Chemistry*, *330*(3), 1243–1254. https://doi.org/10.1007/s10967-021-08055-6

N, D., Panda, B., S, C., M V, P., Singh, D. K., A L, R., & Sahoo, S. K. (2021). Spatio-temporal variations of Uranium in groundwater: Implication to the environment and human health. *Science of The Total Environment*, *775*, 145787. https://doi.org/10.1016/j.scitotenv.2021.145787

Navarro-Martinez, F., Salas Garcia, A., Sánchez-Martos, F., Baeza Espasa, A., Molina Sánchez, L., & Rodríguez Perulero, A. (2017). Radionuclides as natural tracers of the interaction between groundwater and surface water in the River Andarax, Spain. *Journal of Environmental Radioactivity*, *180*, 9–18. https://doi.org/10.1016/j.jenvrad.2017.09.015

Noli, F., Kazakis, N., Vargemezis, G., & Ioannidou, A. (2016). The uranium isotopes in the characterisation of groundwater in the Thermi-Vasilika region, northern Greece. *Isotopes in Environmental and Health Studies*, *52*(4–5), 405–413. https://doi.org/10.1080/10256016.2015.1119134

Nunes, L. J. R., Curado, A., & Lopes, S. I. (2023). The Relationship between Radon and Geology: Sources, Transport and Indoor Accumulation. *Applied Sciences*, *13*(13), 7460. https://doi.org/10.3390/app13137460

Olszewski, G., Boryło, A., & Skwarzec, B. (2015). Uranium (234U, 235U and 238U) contamination of the environment surrounding phosphogypsum waste heap in Wiślinka (northern Poland). *Journal of Environmental Radioactivity*, *146*, 56–66. https://doi.org/10.1016/j.jenvrad.2015.04.001

Ostoich, P., Beltcheva, M., Antonio Heredia Rojas, J., & Metcheva, R. (2022). Radionuclide Contamination as a Risk Factor in Terrestrial Ecosystems: Occurrence, Biological Risk, and Strategies for Remediation and Detoxification. In D. Junqueira Dorta & D. Palma De Oliveira (Eds.), *The Toxicity of Environmental Pollutants*. IntechOpen. https://doi.org/10.5772/intechopen.104468

Pasangka, B., & Ngana, F. R. (2020). Radiation Measurement Of Radioisotope In Mineral Deposit At Subdistrict Of Middle Kupang West Timor Island Indonesia. *Jurnal Fisika : Fisika Sains Dan Aplikasinya*, *5*(1), 78–86. https://doi.org/10.35508/fisa.v5i1.2388

Rojas, L. V., Dos Santos Júnior, J. A., Alvarado, J. A. C., Milan, M. O., Röllin, S., Amaral, R. S., Fernández, Z. H., & Do Nascimento Santos, J. M. (2020). Natural uranium isotopes and 226Ra in surface and groundwater from a basin of a semiarid region in Brazil. *Journal of Radioanalytical and Nuclear Chemistry*, *326*(2), 1081–1089. https://doi.org/10.1007/s10967-020-07393-1

Rozhkova, A. K., Kuzmenkova, N. V., Sibirtsev, A. M., Petrov, V. G., Shi, K. L., Hou, X. L., & Kalmykov, S. N. (2022). Simultaneous separation of actinides and technetium from large volumes of natural water for their determination. *Journal of Radioanalytical and*

Nuclear Chemistry, *331*(5), 2037–2044. https://doi.org/10.1007/s10967-022-08274-5

Šešlak, B., Vukanac, I., Kandić, A., Đurašević, M., Erić, M., Jevremović, A., & Benedik, L. (2017). Determination of 210Pb by direct gamma-ray spectrometry, beta counting via 210Bi and alpha-particle spectrometry via 210Po in coal, slag and ash samples from thermal power plant. *Journal of Radioanalytical and Nuclear Chemistry*, *311*(1), 719–726. https://doi.org/10.1007/s10967-016-5028-6

Sharma, D. B., Jha, V. N., Singh, S., Sethy, N. K., Sahoo, S. K., Jha, S. K., & Kulkarni, M. S. (2021). Distribution of 210Pb and 210Po in ground water around uranium mineralized area of Jaduguda, Jharkhand, India. *Journal of Radioanalytical and Nuclear Chemistry*, *327*(1), 217–227. https://doi.org/10.1007/s10967-020-07495-w

Smičiklas, I., & Šljivić-Ivanović, M. (2016). Radioactive Contamination of the Soil: Assessments of Pollutants Mobility with Implication to Remediation Strategies. In M. L. Larramendy & S. Soloneski (Eds.), *Soil Contamination – Current Consequences and Further Solutions*. InTech. https://doi.org/10.5772/64735

Su, X., & Lim, K. F. (2023). Capital accumulation, territoriality, and the reproduction of state sovereignty in China: Is this "new" state capitalism? *Environment and Planning A: Economy and Space*, *55*(3), 697–715. https://doi.org/10.1177/0308518X221093643

Taftazani, A., Sumining, S., & Muzakky, M. (2013). Sebaran radioaktivitas radionuklida alam dan faktor akumulasinya dalam air, sedimen dan tanaman di perairan sungai dan laut surabaya. *Ganendra Majalah IPTEK Nuklir*, *5*(2). https://doi.org/10.17146/gnd.2002.5.2.216

Tortorello, R., Widom, E., & Renwick, W. H. (2013). Use of uranium isotopes as a temporal and spatial tracer of nuclear contamination in the environment. *Journal of Environmental Radioactivity*, *124*, 287–300. https://doi.org/10.1016/j.jenvrad.2013.06.007

Wang, C., Myshkin, V. F., Khan, V. A., & Panamareva, A. N. (2022). A review of the migration of radioactive elements in clay minerals in the context of nuclear waste storage. *Journal of Radioanalytical and Nuclear Chemistry*, *331*(9), 3401–3426. https://doi.org/10.1007/s10967-022-08394-y

Wang, L., Cheng, J., Bao, C., Wang, Y., Jiang, Q., Pan, Y., Liu, Y., Hong, T., Tuo, X., & Leng, Y. (2022). Simulation of nuclide migration in a middle- and low-level radioactive waste repository based on GMS. *Journal of Radioanalytical and Nuclear Chemistry*, *331*(5), 2159–2167. https://doi.org/10.1007/s10967-022-08260-x

Wang (王夕露), X., Clark, A. M., Ellis, J., Ertel, A. F., Fields, B. D., Fry, B. J., Liu, Z., Miller, J. A., & Surman, R. (2021). R-Process Radioisotopes from Near-Earth Supernovae and Kilonovae. *The Astrophysical Journal*, *923*(2), 219. https://doi.org/10.3847/1538-4357/ac2d90

Wu, Y., Bai, X.-J., Shi, H.-S., He, L.-Y., & Qiu, H.-N. (2023). Dating of authigenic minerals in sedimentary rocks: A review. *Earth-Science Reviews*, *241*, 104443. https://doi.org/10.1016/j.earscirev.2023.104443

Xarchoulakos, D. C., Manoutsoglou, E., & Kallithrakas-Kontos, N. G. (2022). Distribution of uranium isotopes, 210Pb and 210Po in groundwaters of Crete- Greece. *Journal of Radioanalytical and Nuclear Chemistry*, *331*(11), 4685–4694. https://doi.org/10.1007/s10967-022-08578-6