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Radiological Risk Assessment for the Population of Antsiranana II District, Madagascar, due to External Exposure to Natural Radioactivity in Volcanic Soil

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Abstract — *Public exposure to natural radiation sources is a fundamental aspect of public health protection. This study assesses the radiological hazards associated with soils in the Antsiranana II district, Madagascar, a region where the population has significant daily contact with soil for agricultural purposes and as a construction material. Activity concentrations of* ^{40}K, ^{238}U, *and* ^{232}Th *in 23 soil samples were utilized to calculate key radiological risk parameters. The radium equivalent activity (Raeq) ranged from 87 to 196 Bq.kg*$^{-1}$*, with a mean of 147 Bq.kg*$^{-1}$*, a value significantly below the international safety limit of 370 Bq.kg*$^{-1}$ *for building materials. The absorbed gamma dose rate in air (AGDR) was calculated at 67 ± 14 nGy.h*$^{-1}$*, slightly higher than the global average of 57 nGy.h*$^{-1}$*. Consequently, the mean annual effective dose rate (AEDR) received by the population from external soil exposure was estimated at 0.21 ± 0.04 mSv.y*$^{-1}$*, which is substantially lower than the public dose limit of 1 mSv.y*$^{-1}$ *recommended by the ICRP. The associated excess lifetime cancer risk (ELCR) was also found to be negligible. Despite the observed geological enrichment in uranium and thorium, this study concludes that the overall radiological risk to the population from external terrestrial radiation in the district is low and does not pose a significant public health threat. These findings provide a reassuring scientific baseline for local land management and public health monitoring, particularly in volcanically active regions.*

Keywords — *Soil radioactivity, Radium equivalent, Absorbed dose, Annual effective dose, Cancer risk, Radiation protection, Antsiranana II.*

I. INTRODUCTION

Human exposure to naturally occurring radioactive materials (NORM) is an unavoidable feature of life on Earth. Soil represents the primary source of external gamma radiation exposure for the population, contributing significantly to the total annual effective dose received by individuals (UNSCEAR, 2000). This exposure is directly linked to the concentrations of primordial radionuclides, specifically Potassium-40 (^{40}K) and the decay chains of Uranium-238 (^{238}U) and Thorium-232 (^{232}Th) (Rabesiranana, 2017; Donne *et al.*, 2021; Stolerie *et al.*, 2022; Rahelivao *et al.*, 2023; Ngoko *et al.*, 2024 & 2025; Tsilailay *et al.*, 2025).

In the district of Antsiranana II, Madagascar, the population is predominantly rural, living in close daily contact with the soil through agriculture and the use of earth-based building materials. A recent study established the geochemical baseline of this region, revealing that the volcanic soils of the Amber Mountain are naturally enriched in Uranium and Thorium compared to the world average, while being depleted in Potassium due to the specific volcanic petrology (Donne *et al.*, 2021; Tsilailay *et al.*, 2025). However, while the concentrations are now known, the radiological risk posed to the inhabitants remains unquantified.

Converting activity concentrations into tangible health risk parameters is very important for radiation protection and public health management. This is particularly relevant in volcanic regions where geological heterogeneity can lead to variable exposure levels (López-Pérez *et al.*, 2021). Therefore, this study builds upon previous geochemical findings to provide a comprehensive radiological risk assessment. The specific objectives are: (1) to calculate the Radium Equivalent activity (Ra_{eq}) to assess the suitability of soils as building materials; (2) to estimate the Absorbed Gamma Dose Rate (*AGDR*) in the air; (3) to determine the Annual Effective Dose Rate (*AEDR*) received by the population; and (4) to evaluate the Excess Lifetime Cancer Risk (*ELCR*). These results are then compared with international safety limits and data from other districts in the DIANA and SAVA regions to determine if the natural radioactivity in Antsiranana II poses a significant public health threat.

II. MATERIAL AND METHODS

2.1. Geological Description of the Study Area

The study was conducted in the District of Antsiranana II, located at the northern tip of Madagascar (Fig. 1). The district covers an area of 5,645 km² and surrounds the Amber Mountain massif. As detailed in our previous work (Tsilailay *et al.*, 2025), the geological context is dominated by this vast stratovolcano, composed mainly of mafic rocks (basalts, basanites) and pyroclastic deposits formed from the Miocene to the Quaternary. These volcanic formations rest on a sedimentary basement of Jurassic to Eocene age (marls, limestones, sandstones) (Besairie, 1970; Lemoine, 1906, Ségalen, 1956, Barat, 1958, Cucciniello *et al*., 2011; Donné *et al*., 2021). The resulting pedology is a complex mosaic of ferralitic and volcanic soils, which directly influences the distribution of natural radionuclides.

2.2. Sample Collection and Preparation

This study utilizes the radiological data obtained from 23 soil samples collected in July 2024, representative of the 23 rural communes of the district. The sampling methodology, geolocation, and preparation protocols are described in depth in Tsilailay *et al.* (2025).

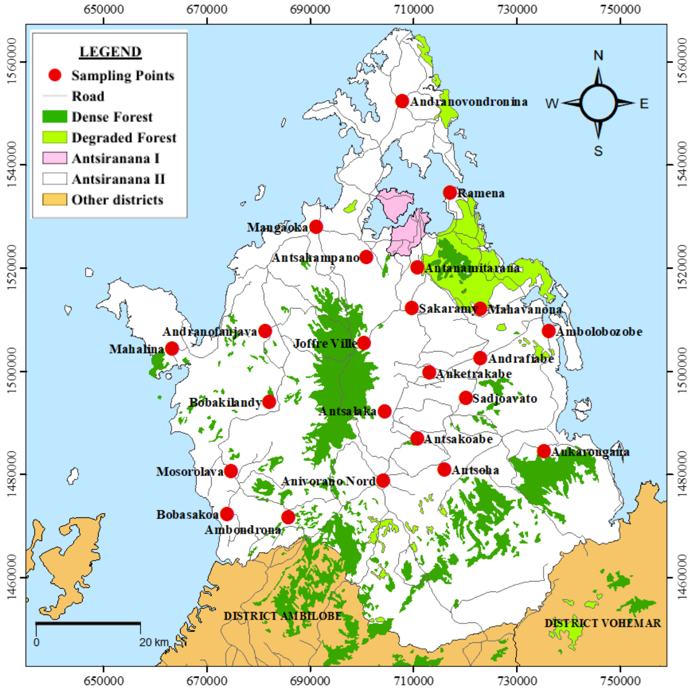

Fig. 1. Map of sampling points Location

Briefly, composite samples were taken from a depth of 30 cm in undisturbed areas, dried at 105°C, ground, and sealed in standard containers for gamma spectrometry analysis at the National Institute of Nuclear Sciences and Techniques (INSTN) in Antananarivo. The specific activities of ^{40}K, ^{238}U series and ^{232}Th series utilized for the risk calculations in this paper were determined using a NaI(Tl) detector after a secular equilibrium period of four weeks.

TABLE I. Geographic coordinates (Laborde system) of the soil sampling locations

Sample ID	Locality	Longitude (m)	Latitude (m)
Sam_01	Andrafiabe	723011.77	1502484.69
Sam_02	Antsakoabe	710761.02	1486885.07
Sam_03	Antsoha	716044.48	1480847.21
Sam_04	Anivorano Nord	704240.35	1478671.06
Sam_05	Bobasakoa	673923.98	1472230.68
Sam_06	Mosorolava	674765.56	1480475.39
Sam_07	Bobakilandy	682121.92	1493984.84
Sam_08	Ambondrona	685847.52	1471631.25
Sam_09	Ramena	717154.61	1534582.05
Sam_10	Mahavanona	719181.83	1512612.84
Sam_11	Antanamitarana	710750.21	1520064.04
Sam_12	Sakaramy	709769.79	1512220.67
Sam_13	Joffre Ville	700478.86	1505335.17
Sam_14	Antsahampano	700946.00	1522024.88
Sam_15	Sadjoavato	720184.90	1494724.01
Sam_16	Ankarongana	735260.73	1484376.72
Sam_17	Ambolobozobe	736629.65	1502500.17
Sam_18	Anketrakabe	713103.22	1499671.28
Sam_19	Andranofanjava	681337.59	1507710.73
Sam_20	Mangaoka	691141.79	1527907.40
Sam_21	Antsalaka	704475.52	1492220.09
Sam_22	Andranovondronina	707220.69	1553790.51
Sam_23	Mahalina	663297.85	1504377.30

Table I lists the 23 sampling points that cover all rural communes in the district. It confirms the study's wide geographical coverage, ensuring that the calculated risks are representative of the entire population of Antsiranana II.

2.3. Specific activity concentrations of ^{40}K, ^{238}U and ^{232}Th in soil

The activity concentrations of ^{40}K, ^{238}U series, and ^{232}Th series used in this study were determined from 23 soil samples collected in the Antsiranana II district. Measurements were performed using gamma-ray spectrometry, as detailed in our companion paper (Tsilailay *et al.,* 2025). These results are summarized in Table II.

TABLE II. Specific activity concentrations of natural radionuclides (^{40}K, ^{238}U series, ^{232}Th series) in soil samples from Antsiranana II

Sample ID	Specific activities ($Bq.kg^{-1}$)		
	^{40}K	^{238}U series	^{232}Th series
Sam_01	107 ± 10	40 ± 6	93 ± 9
Sam_02	123 ± 11	42 ± 6	60 ± 7
Sam_03	155 ± 12	68 ± 7	53 ± 6
Sam_04	187 ± 12	34 ± 6	97 ± 9
Sam_05	391 ± 16	29 ± 4	75 ± 8
Sam_06	246 ± 12	43 ± 6	47 ± 6
Sam_07	277 ± 13	78 ± 8	59 ± 6
Sam_08	161 ± 12	28 ± 4	33 ± 5
Sam_09	305 ± 12	65 ± 7	38 ± 5
Sam_10	147 ± 11	47 ± 6	62 ± 7
Sam_11	185 ± 12	55 ± 6	58 ± 6
Sam_12	180 ± 11	39 ± 5	40 ± 6
Sam_13	106 ± 10	33 ± 5	75 ± 7
Sam_14	323 ± 12	86 ± 8	60 ± 7
Sam_15	166 ± 11	37 ± 5	59 ± 6
Sam_16	107 ± 10	47 ± 6	82 ± 8
Sam_17	346 ± 12	40 ± 6	53 ± 6
Sam_18	212 ± 11	80 ± 8	86 ± 8
Sam_19	171 ± 11	31 ± 5	53 ± 6
Sam_20	113 ± 10	38 ± 5	48 ± 6
Sam_21	136 ± 10	50 ± 6	80 ± 8
Sam_22	130 ± 10	32 ± 5	34 ± 5
Sam_23	155 ± 11	32 ± 5	52 ± 6
Mean value ± SD	**194 ± 83**	**48 ± 19**	**61 ± 18**
(Min – Max)	**(106 – 391)**	**(28 – 86)**	**(33 – 97)**

SD: Standard Deviation

2.3.1. Radium Equivalent Activity (Ra_{eq})

The radium equivalent activity (Ra_{eq}) is a calculated sum of the hazards associated with ^{238}U, ^{232}Th and ^{40}K in a sample. It is crucial for evaluating the overall radiation hazards posed by various radionuclides present in the sample. It was calculated using the formula proposed by Beretka et Mathew (1985) (Eke *et al.,* 2024; Shi *et al.,* 2024; Mwimanzi *et al.,* 2025):

$$Ra_{eq} = A_U + 1.43 \times A_{Th} + 0.077 \times A_K \quad (1)$$

Where A_U, A_{Th}, and A_K are the activity concentrations in $Bq.kg^{-1}$ of ^{238}U, ^{232}Th and ^{40}K, respectively. The accepted safety threshold of Ra_{eq} is 370 Bq kg^{-1} (UNSCEAR, 2020).

2.3.2. Absorbed Gamma Dose Rate (AGDR)

The absorbed gamma dose rate at 1 m above the ground surface from the concentration of radionuclides in samples was computed using equation (2) (Eke *et al.,* 2024; Shi *et al.,* 2024; Mwimanzi *et al.,* 2025):

$$AGDR = 0.462 \times A_U + 0.604 \times A_{Th} + 0.0417 \times A_K \quad (2)$$

Where A_U, A_{Th} and A_K are defined as the activity concentrations in $Bq.kg^{-1}$ of ^{238}U, ^{232}Th and ^{40}K, respectively.

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2.3.3. Annual effective dose rate (AEDR)

The annual effective dose rate (*AEDR*) was calculated using equation (3) (Eke *et al.*, 2024; Shi *et al.*, 2024; Mwimanzi *et al.*, 2025):

$$AEDR = AGDR \times T \times Q \times \tau \times 10^{-6} \qquad (3)$$

Where Q is the conversion coefficient from absorbed dose to effective dose, with $Q = 0.7$ Sv·Gy^{-1}. τ represents the average occupancy factor, equal to 0.5. For this study, it is assumed that the individual spends approximately 50% of their time outside of a dwelling (Stolerie *et al.,* 2022). The annual exposure duration (T) is estimated at 8766 hours. An annual effective dose equivalent (*AEDE*) limit of 1 mSv·y^{-1} is considered acceptable for the general public (UNSCEAR, 2000).

2.3.4. Excess lifetime cancer risk (ELCR)

The *ELCR* was estimated using the formula (Eke *et al.*, 2024; Shi *et al.*, 2024; Mwimanzi *et al.*, 2025):

$$ELCR = AEDR \times DL \times RF \qquad (4)$$

Where DL is the average life expectancy (70 years), and RF is the risk factor (0.05 Sv^{-1}) for the general public (UNSCEAR, 2020).

2.4. Spatial mapping method

Surfer ® Version 30.1.218 and MS Excel 2019 software for Windows were used for making the spatial maps. In addition, the Kriging interpolation technique, a geostatistical method, was applied to create spatial distribution maps for radiological indices. This method provided a reliable estimation of values in unmeasured locations by considering both the distance and the degree of variation between measured data points, enhancing the accuracy of spatial analysis.

III. RESULTS AND DISCUSSION

3.1. Activity of radium equivalent (Raeq) and Absorbed Gamma Dose Rates(AGDR)

The calculated values for Radium Equivalent Activity (Raeq) and Absorbed Gamma Dose Rate (*AGDR*) are presented in Table III.

TABLE III. Radium Equivalent Activity (Ra_{eq}) and Absorbed Gamma Dose Rate (*AGDR*) calculated for the soil samples

Sample ID	Ra_{eq} (Bq.kg^{-1})	*AGDR* (nGy/h)
Sam_01	181 ± 14	79.1 ± 6.1
Sam_02	137 ± 12	60.8 ± 5.1
Sam_03	156 ± 11	69.9 ± 4.9
Sam_04	187 ± 14	82.1 ± 5.9
Sam_05	166 ± 12	75.0 ± 5.2
Sam_06	129 ± 11	58.5 ± 4.6
Sam_07	184 ± 12	83.2 ± 5.2
Sam_08	88 ± 8	39.6 ± 3.6
Sam_09	143 ± 10	65.7 ± 4.5
Sam_10	147 ± 12	65.3 ± 5.1
Sam_11	152 ± 11	68.2 ± 4.6
Sam_12	110 ± 10	49.7 ± 4.3
Sam_13	148 ± 11	65.0 ± 4.8
Sam_14	197 ± 13	89.4 ± 5.6
Sam_15	134 ± 10	59.7 ± 4.3
Sam_16	172 ± 13	75.7 ± 5.6
Sam_17	142 ± 11	64.9 ± 4.6
Sam_18	219 ± 14	97.7 ± 6.1
Sam_19	120 ± 10	53.5 ± 4.3
Sam_20	115 ± 10	51.3 ± 4.3
Sam_21	175 ± 13	77.1 ± 5.6
Sam_22	91 ± 9	40.7 ± 3.8
Sam_23	118 ± 10	52.7 ± 4.3
Mean ± SD	**148 ± 33**	**66.3 ± 14.6**
(Min – Max)	**(88 – 219)**	**(39.6 – 97.7)**
Word Recommended Value	**370**	**57**

Ra_{eq}: Radium Equivalent *AGDR*: Absorbed Gamma Dose Rates

The Ra_{eq} values range from (88 ± 8) to (219 ± 14) Bq.kg^{-1}, with a mean of (148 ± 33) Bq.kg^{-1}. Crucially, all samples are well below the safety limit of 370 Bq.kg^{-1} set by the OECD for building materials (UNSCEAR, 2000). This indicates that soils from Antsiranana II can be safely used for construction without posing a radiological hazard.

For the Absorbed Gamma Dose Rate is ranges from (39.6±3.6) to (97.7±6.1) nGy.h^{-1}, with a mean of (66.3±14.6) nGy.h^{-1}. This mean value is slightly higher than the world population-weighted average of 57 nGy.h^{-1} (UNSCEAR, 2000). This elevation is primarily driven by the higher thorium and uranium content in the volcanic soil (Tsilailay *et al.*, 2025).

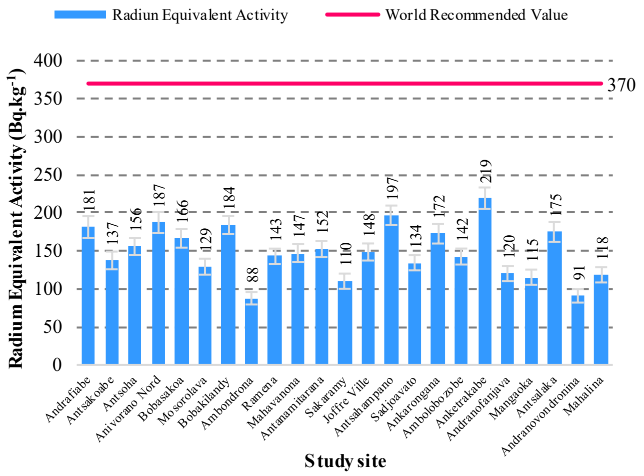

Fig. 2. Radium Equivalent Activity (Ra_{eq}) in soil samples compared to the world recommended maximum value (370 Bq.kg^{-1})

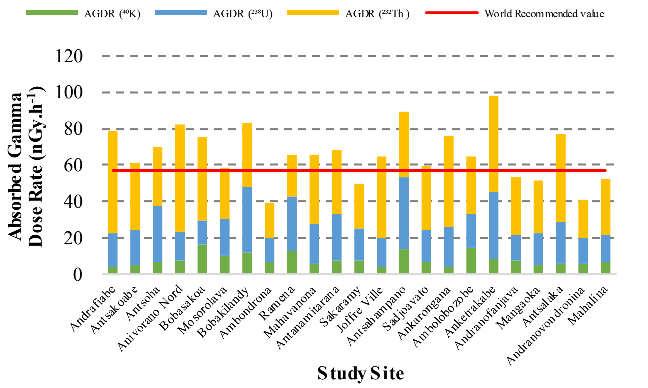

Fig. 3. Absorbed Gamma Dose Rates (*AGDR*) contributed by ^{40}K, ^{238}U, and ^{232}Th compared to the world average

Fig 2 illustrates that no commune exceeds the Ra_{eq} limit (red line). High values are observed in Anketrakabe and Antsahampano, but they remain within the safe zone.

Fig 3 and 4 demonstrate that while ^{40}K contributions are low, the combined dose from U and Th pushes the total *AGDR* above the world average for most samples. However, the excess is moderate and does not reach extreme values found in high background radiation areas, such as those reported in certain volcanic regions globally (Tzortzis *et al.*, 2003; López-Pérez *et al.*, 2021).

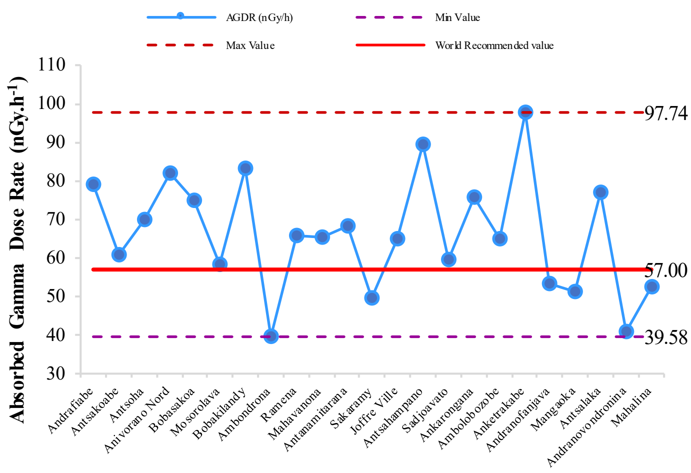

Fig. 4. Total Absorbed Gamma Dose Rate (*AGDR*) variations across sampling sites relative to world average (57 $nGy.h^{-1}$)

3.2. Annual Effective Dose Rates and Excess Lifetime Cancer Risk

The results of annual effective dose rates and Excess Lifetime Cancer Risk are shown in Table IV.

TABLE IV. Annual Effective Dose Rate (*AEDR*) and Excess Lifetime Cancer Risk (*ELCR*) for the population

Sample ID	AEDR (mSv/yr)	ELCR ($x10^{-3}$)
Sam_01	0.097 ± 0.008	0.34 ± 0.03
Sam_02	0.075 ± 0.006	0.26 ± 0.02
Sam_03	0.086 ± 0.006	0.30 ± 0.02
Sam_04	0.101 ± 0.007	0.35 ± 0.03
Sam_05	0.092 ± 0.006	0.32 ± 0.02
Sam_06	0.072 ± 0.006	0.25 ± 0.02
Sam_07	0.102 ± 0.006	0.36 ± 0.02
Sam_08	0.049 ± 0.004	0.17 ± 0.02
Sam_09	0.081 ± 0.005	0.28 ± 0.02
Sam_10	0.080 ± 0.006	0.28 ± 0.02
Sam_11	0.084 ± 0.006	0.29 ± 0.02
Sam_12	0.061 ± 0.005	0.21 ± 0.02
Sam_13	0.080 ± 0.006	0.28 ± 0.02
Sam_14	0.110 ± 0.007	0.38 ± 0.02
Sam_15	0.073 ± 0.005	0.26 ± 0.02
Sam_16	0.093 ± 0.007	0.33 ± 0.02
Sam_17	0.080 ± 0.006	0.28 ± 0.02
Sam_18	0.120 ± 0.007	0.42 ± 0.03
Sam_19	0.066 ± 0.005	0.23 ± 0.02
Sam_20	0.063 ± 0.005	0.22 ± 0.02
Sam_21	0.095 ± 0.007	0.33 ± 0.02
Sam_22	0.050 ± 0.005	0.17 ± 0.02
Sam_23	0.065 ± 0.005	0.23 ± 0.02
Mean ± SD	**0.081 ± 0.018**	**0.28 ± 0.06**
(Min – Max)	**(0.049 – 0.120)**	**(0.36 – 0.90)**
Word Recommended Value	**1**	**0.29**

AEDR: Annual Effective Dose Rates *ELCR*: Excess lifetime cancer risk

The Annual Effective Dose Rate varies between (0.049 ± 0.004) and (0.120 ± 0.007) $mSv.y^{-1}$, with a mean of (0.081 ± 0.018) $mSv.y^{-1}$. This is the most critical finding: despite the higher *AGDR*, the effective dose is drastically lower than the recommended public dose limit of 1 $mSv.y^{-1}$ (UNSCEAR, 2000).

The Excess Lifetime Cancer Risk averages 0.28×10^{-3}. This value is almost identical to the world average of 0.29×10^{-3}. This suggests that the probability of developing cancer due to natural soil radiation in this district is negligible and comparable to the global baseline. Fig 5 further illustrates that all *AEDR* values are significantly below the public exposure limit.

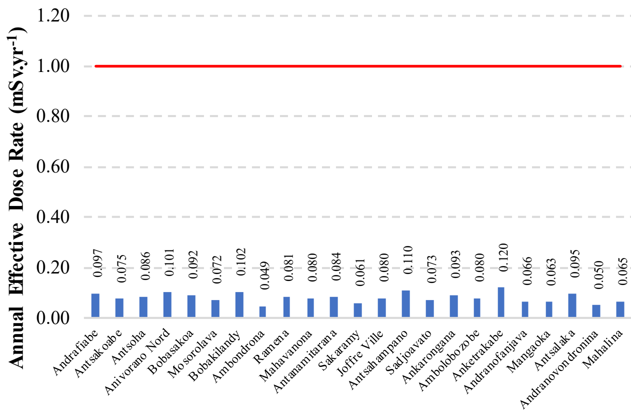

Fig. 5. Annual Effective Dose Rate (*AEDR*) for each commune compared to the public exposure limit (1 $mSv.y^{-1}$)

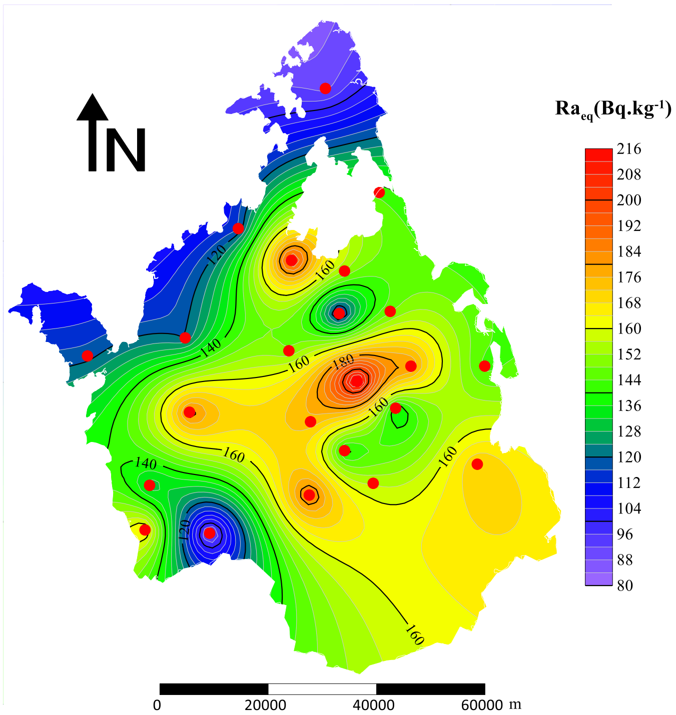

Fig. 6. Spatial distribution map of Radium Equivalent Activity (Ra_{eq}) in Antsiranana II

The interpolation maps (Fig. 6, 7 and 8) reveal a distinct spatial pattern. The highest risks (red zones) are concentrated in specific areas (likely corresponding to specific volcanic flows

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or older pedological formations rich in Th/U), while the coastal sedimentary areas generally show lower risks. These maps are valuable tools for local authorities to identify zones of slightly elevated exposure, although all remain within safe limits.

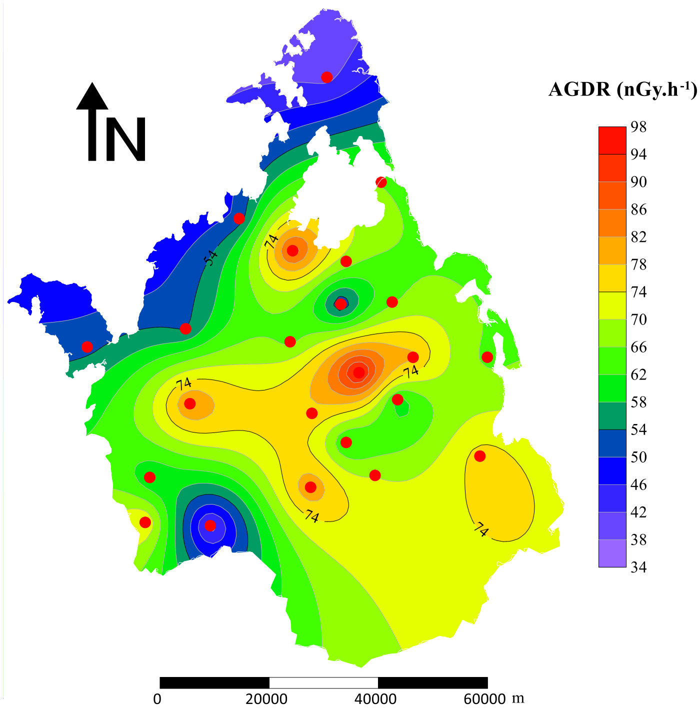

Fig. 7. Spatial distribution map of Absorbed Gamma Dose Rates (*AGDR*) in Antsiranana II

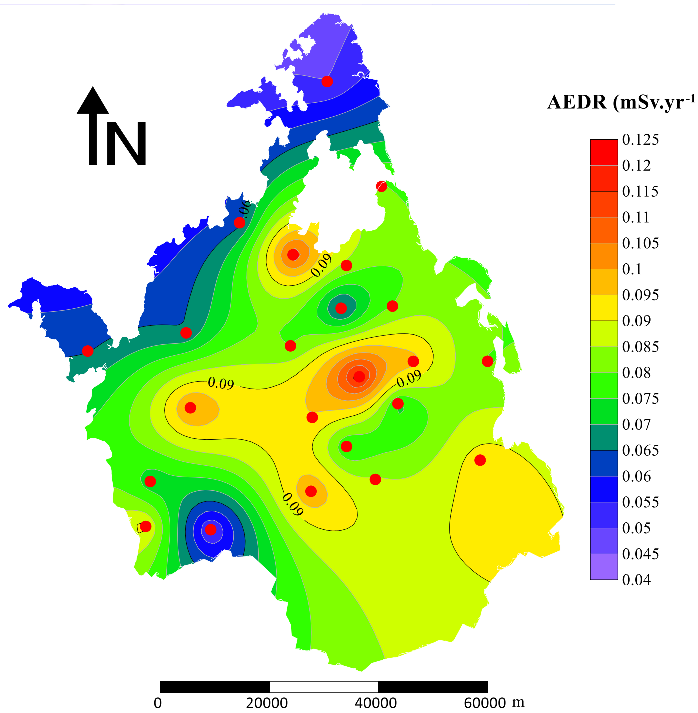

Fig. 8. Spatial distribution map of Annual Effective Dose Rates (*AEDR*) in Antsiranana II

Comparing the results with other districts in Northern Madagascar reveals the influence of regional geology on radiological risk (Table V).

TABLE V. Comparison of radiological hazard indices with other districts in the DIANA and SAVA regions

District	Ra_{eq} (Bq.kg^{-1})	AGDR (nGy/h)	AEDR (mSv/yr)	ELCR (x10^{-3})
Antsiranana II (Present study)	148,00	66,30	0,08	0,28
Ambilobe (Stolerie *et al.*, 2022)	120,00	58,00	0,18	0,50
Ambanja (Rahelivao *et al.*, 2023)	277,00	125,00	0,15	-
Antalaha (Ngoko *et al.*, 2024 & 2025)	133,00	58,00	0,18	0,53

The mean Ra_{eq} in Antsiranana II (148 Bq.kg^{-1}) is higher than in Ambilobe (120 Bq.kg^{-1}) and Antalaha (133 Bq.kg^{-1}), but significantly lower than in Ambanja (277 Bq.kg^{-1}). This disparity is explained by the geological substrate. Ambilobe is largely sedimentary, resulting in lower radioactivity. Ambanja, specifically the Ampasindava peninsula, contains granitic intrusions and specific mineralization (monazite) rich in Thorium, leading to much higher exposure levels (High Background Radiation Area). Antsiranana II occupies an intermediate position: its volcanic nature provides a moderate enrichment in actinides (U, Th) relative to sedimentary areas, but it lacks the heavy mineral accumulation found in Ambanja.

Consequently, while the risk in Antsiranana II is slightly above the global average, it does not constitute a radiological anomaly like Ambanja.

IV. Conclusion

This study successfully quantified the radiological risks associated with the volcanic soils of the Antsiranana II district, complementing the geochemical characterization previously published. The key findings are:

- ✓ The mean Radium Equivalent Activity of 148 Bq.kg^{-1} is well below the international safety limit of 370 Bq.kg^{-1}. This confirms that the soil in the district is radiologically safe for use as a building material for local dwellings.
- ✓ The Absorbed Gamma Dose Rate (mean 66.3 nGy.h^{-1}) is slightly above the world average (57 nGy.h^{-1}), reflecting the uranium and thorium enrichment of the Amber Mountain volcanic province.
- ✓ Despite the slightly elevated dose rate, the Annual Effective Dose Rate (mean 0.081 mSv.y^{-1}) remains well below the public exposure limit of 1 mSv.y^{-1}. Furthermore, the Excess Lifetime Cancer Risk (0.28 × 10^{-3}) is comparable to the global average, indicating a negligible health threat.

In summary, while the volcanic geology of Antsiranana II creates a distinct radiological signature higher than neighboring sedimentary districts (like Ambilobe), it does not pose a significant radiological health risk to the population. No specific radiation protection measures or restrictions on soil use are required in this district. These findings provide a reassuring scientific baseline for local land management and public health monitoring and contribute to a better understanding of natural radioactivity in volcanically active regions of Madagascar and beyond.

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