RADIOLOGICAL ASSESSMENT OF GRANITE QUARRIES IN THE DJIDJA MUNICIPALITY, BENIN: AMBIENT GAMMA DOSE RATE MEASUREMENTS

G.D. HOUNDETOUNGAN[,**#], O.H. FACHINAN[**,***], S.B.M.G. ADJADOHOUN[*],M.B. ZINSOU[****], G. ABOGBO[*], B. AWEDE[*,**], M. ZOUNGRANA[*****], K.M. AMOUSSOU-GUENOU[*,**]*

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[*]Faculté des Sciences de la Santé, Université d'Abomey-Calavi, Bénin, [#]e-mail: fofodavid@yahoo.fr
[**]Centre de Recherche en Sciences Morphologiques et Fonctionnelles Humaines, École Doctorale des Sciences de la Santé, Université d'Abomey-Calavi, Bénin
[***]Institut de Formation en Soins Infirmiers et Obstétricaux, Université de Parakou, Bénin
[****]École Polytechnique d'Abomey-Calavi, Université d'Abomey-Calavi, Bénin
[*****]Université "Joseph Ki-Zerbo", Burkina Faso

Abstract. Granite formations are known sources of enhanced natural radioactivity that may contribute to external exposure. In Benin, information on environmental radiation levels remains scarce, particularly in granite quarrying zones. This study evaluated the ambient gamma dose equivalent rate and estimated the annual external effective dose in three granite quarries of the Djidja municipality. A cross-sectional survey was conducted during the fourth quarter of 2023 using a portable AT6101C(E) spectrometer coupled with a GPS for continuous geo-referenced data collection. Measurements were performed on foot within the quarries and by motorcycle in the surrounding residential areas. Data processing was carried out with ATAS Scanner©, RStudio, and Python, and annual effective doses were calculated from average dose rates according to ICRP recommendations. A total of 25,488 measurement points were collected. In the quarries, the ambient gamma dose equivalent rate ranged between 97.02–147.83 $nSv \cdot h^{-1}$, with a mean of 109 ± 10 $nSv \cdot h^{-1}$, while in residential areas the mean value was 50 ± 18 $nSv \cdot h^{-1}$. The corresponding annual effective doses were 0.20 ± 0.02 mSv for quarry workers and 0.09 ± 0.03 mSv for the general public. Although these doses are below ICRP limits, the results confirm the contribution of granite formations to ambient radioactivity and underscore the need for regular radiological monitoring in quarry environments. Furthermore, the findings highlight the importance of establishing a national radiological mapping program in Benin to support radiation protection policies.

Key words: Gamma dose rate, natural radiation exposure, radiation protection, granite quarries, Benin.

INTRODUCTION

The impact of ionizing radiation on human health and the environment is an increasing concern within the scientific community [20]. While radiological protection has historically focused on occupational exposure, it now extends to

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chronic environmental exposures of natural origin. Major nuclear accidents such as Chernobyl and Fukushima have reinforced the need for radiological monitoring that includes the general population [10, 21]. The biological effects of ionizing radiation depend on both dose and duration of exposure. High doses can induce deterministic effects such as acute radiation syndrome, whereas repeated low-dose exposures increase the risk of stochastic effects, including radiation-induced cancers [12, 17]. Rapidly proliferating tissues such as bone marrow and the gastrointestinal tract are particularly sensitive [7].

Monitoring ambient radioactivity is essential for the application of the ALARA principle (*As Low as Reasonably Achievable)* and for the prevention of avoidable exposures [12, 21]. International bodies recommend the establishment of radiological surveillance networks, especially in areas with specific geological features or high population density [9, 18]. Granite formations are known for their relatively high concentrations of natural radionuclides, which contribute to elevated ambient gamma dose rates [5, 19].

In sub-Saharan Africa, data on environmental radiation exposure remain scarce. In Benin, the regulatory framework for radiation protection has been strengthened with the establishment of the Regulatory Body of Radiation Protection, created under Law No. 2017-29 on radiological safety and nuclear security [3]. Nevertheless, few studies have assessed natural radioactivity levels in the country. Recent investigations in the Collines Department revealed relatively high ambient gamma dose rates in some quarries and schools [24]. In this context, the present study aims to evaluate the ambient gamma dose equivalent rate in three granite quarries of the Zou Department, southern Benin, in order to estimate the potential external exposure of quarry workers and surrounding populations.

STUDY AREA, MATERIALS, AND METHODS

STUDY AREA

The study was carried out in three granite quarries located in the Setto district of the Djidja municipality, Zou Department, Republic of Benin (West Africa). The geographic coordinates of Djidja are 7°29′51″ N and 2°4′27″ E. The Zou Department is characterized by gently undulating plateaus resting on a precambrian crystalline basement composed mainly of granites, gneisses, and migmatites. The landscape also includes isolated hills, exploited granitic zones (quarries), and alluvial lowlands.

The Djidja municipality, the largest in the department, hosts several granite quarries, including the three investigated in this study: Granite Carrière Bénin, Colas

Afrique, and Gravel Bénin Sarl. Ambient gamma dose equivalent rates were measured both within these quarries and in the surrounding areas of the Setto district, as well as in other sectors of the municipality, in order to assess the external exposure of nearby populations. Figure 1 shows the location of the granite quarries in the Djidja municipality.

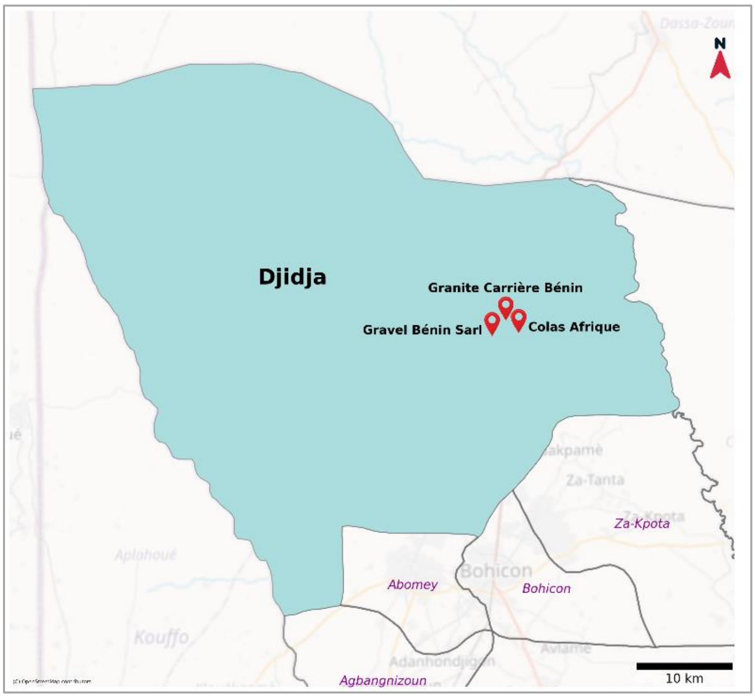

Fig. 1. Map showing the granite quarries in the Djidja municipality.
Source: base map from © OpenStreetMap contributors (ODbL) [15]. Additional data by authors.

MATERIALS AND METHODS

This was a cross-sectional descriptive and analytical study, carried out in two phases of data collection during the fourth quarter of 2023. The methodology was based on the measurement of ambient dose equivalent rate, denoted $\dot{H}^*(10)$, at a standardized height of one meter above ground level. This parameter, which corresponds to the dose in tissue located at a depth of 10 mm, provides a conservative estimate of the effective dose received by an exposed individual [11].

Measurements were performed using a field spectrometer AT6101C(E) (ATOMEX), equipped with a solid-state detector based on strontium iodide doped with europium, offering a typical energy resolution of 3.2 % for cesium-137. The system includes a BT-DU3 adapter for data transmission to a Nautiz X8 handheld computer (Fig. 2). The entire device, integrated into a portable backpack, allows for the simultaneous recording of dosimetric data and GPS coordinates, with real-time visualization on the embedded computer. The AT6101C(E) spectrometer was originally calibrated at the factory using certified gamma reference sources. In the field, it was employed under standard operating conditions, with regular background verifications conducted before measurements to ensure instrument stability.

Fig. 2. Photograph of the AT6101C(E) spectrometer used in this study to measure the ambient gamma dose equivalent rate.

These measurements were carried out using two approaches:

- On foot: within the granite quarries, in order to collect detailed data in areas likely to present elevated levels of natural radioactivity;
- In transit: by motorcycle, driven by a third party, at a maximum speed of 30 km/h, within the Setto district and across other neighborhoods of the Djidja municipality (Agondji, Djidja Centre, Dan, and Dohouimè).

Data analysis was performed using ATAS Scanner©, RStudio (version 4.3.1), and Python (version 3.12). The values initially recorded in $\mu Sv \cdot h^{-1}$ were converted into $nSv \cdot h^{-1}$ for better readability. Spatial distribution maps were generated from the GPS coordinates collected in the field and represented as scatter plots overlaid on a background map derived from an OpenStreetMap shapefile, used exclusively for geographical contextualization.

The annual external effective dose (*AEED*), expressed in millisieverts (mSv), was estimated from the mean hourly ambient gamma dose equivalent rate $\overline{\dot{H} * (10)}$, according to the formula:

$$AEED = \overline{\dot{H} \cdot (10)} \times 10^{-6} \times t \quad (1)$$

where hourly $\overline{\dot{H} \cdot (10)}$, is expressed in nanosieverts per hour (nSv·h^{-1}), t is the annual exposure time in hours (h), and the factor 10^{-6} converts nSv into mSv.

This estimation method follows the recommendations of the International Commission on Radiological Protection [12], which advocates the use of the ambient dose equivalent rate as a conservative proxy for the effective dose received by the public during external exposure to gamma radiation.

Two exposure scenarios were considered to estimate annual outdoor occupancy time:

- Residential areas along road axes: An outdoor occupancy factor of 20 % was applied, reflecting exposure along roads located in inhabited neighborhoods [9]. The resulting annual exposure time was $t = 365 \times 24 \times 0.2 = 1{,}752$ hours.
- Quarry workers: Occupational exposure was assumed, corresponding to 40 hours per week over 45 weeks per year, *i.e.*, $t = 40 \times 45 = 1{,}800$ hours, in accordance with Beninese labor legislation on legal working hours [2].

RESULTS

The results are presented in the following order: coverage of the surveyed areas, ambient gamma dose equivalent rates, and estimation of annual external effective doses.

COVERAGE OF THE SURVEYED AREAS

A total of 25,488 measurement points were recorded. In the Djidja municipality, the three granite quarries included in the study were systematically surveyed, with a total of 1,339 measurement points distributed as follows: 543 points for Colas Afrique, 501 points for Gravel Bénin Sarl, and 295 points for Granite Carrière Bénin. Outside the quarries, within the municipality of Djidja, 24,149 measurement points were collected. Figure 3 illustrates the coverage of the surveyed areas in the Djidja municipality.

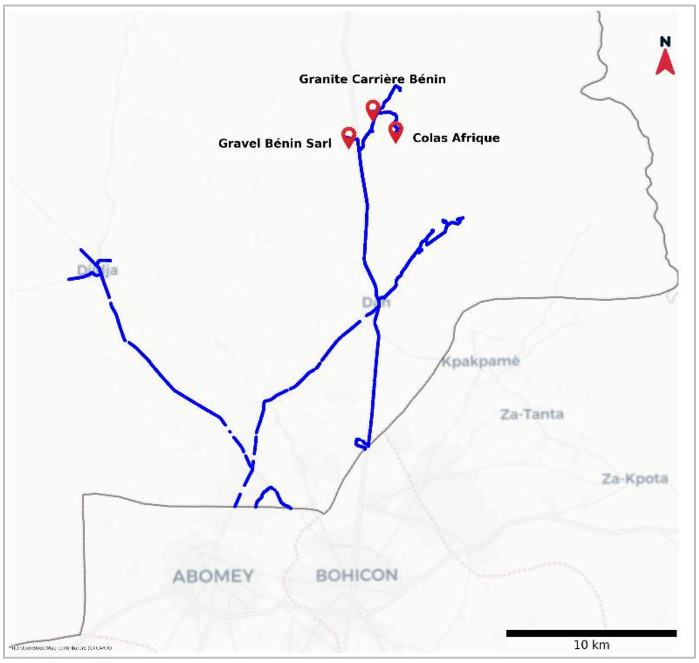

Fig. 3. Extent of surveyed areas (blue outline) in the Djidja municipality.
Source: base map from © OpenStreetMap contributors (ODbL) [15]. Additional data by authors.

AMBIENT GAMMA DOSE EQUIVALENT RATE

In the surveyed granite quarries, the mean ambient gamma dose equivalent rate was 109 ± 10 nSv·h^{-1}, with extreme values ranging from 97.02 to 147.83 nSv·h^{-1}. The maximum value was recorded at the Granite Carrière Bénin site. The values measured in the three quarries are presented in Table 1.

Table 1

Ambient gamma dose equivalent rate in the granite quarries of the Djidja municipality

Granite quarries	Ambient gamma dose equivalent rate (nSv·h^{-1})					
	Average	Standard deviation	Minimum	Maximum	2.5th percentile	97.5th percentile
Granite Carrière Bénin	116.78	9.54	97.84	147.83	101.74	134.66
Gravel Bénin Sarl	105.61	9.72	97.17	127.55	97.86	125.92
Colas Afrique	103.64	4.48	97.02	123.10	97.88	118.64

In the rest of the Djidja municipality, the mean ambient gamma dose equivalent rate was 50.35 ± 17.62 $nSv \cdot h^{-1}$, with minimum and maximum values of 11.50 and 108.28 $nSv \cdot h^{-1}$, respectively.

Among the districts surveyed within the Djidja municipality, Setto, which hosts the granite quarries, exhibited the highest mean ambient gamma dose equivalent rate. The mean values in the different districts of the municipality, along with their 95 % confidence intervals, are illustrated in Fig. 4.

The mean ambient gamma dose equivalent rate was significantly higher in Setto compared with the other districts of the Djidja municipality. Moreover, the lack of overlap between the confidence intervals suggests statistically significant differences in the mean gamma radiation levels recorded across the districts.

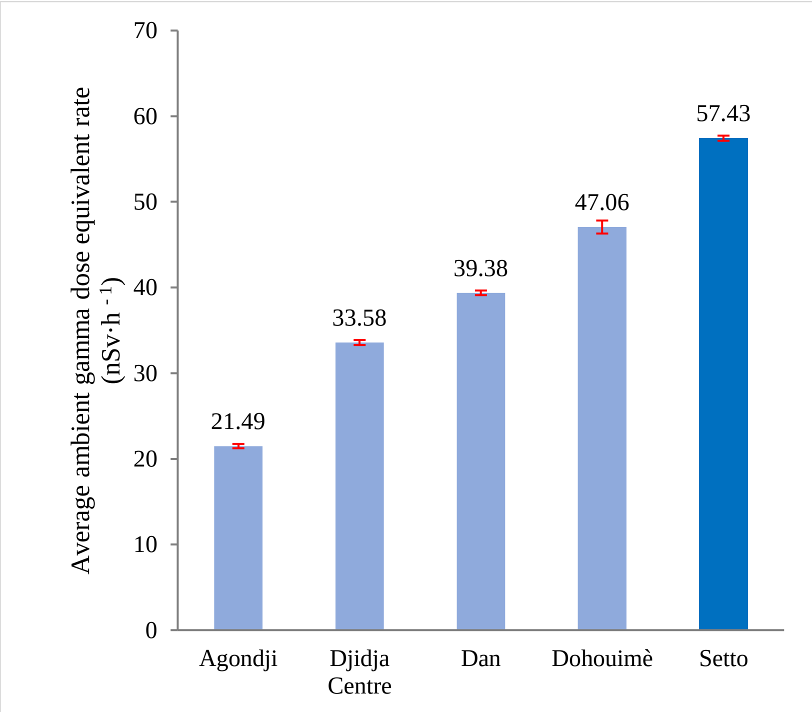

Fig. 4. Average ambient gamma dose equivalent rate across the districts of the Djidja municipality. The rate is higher in Setto, where granite quarries are located.

ESTIMATION OF ANNUAL EXTERNAL EFFECTIVE DOSES

In the granite quarries, the mean calculated annual external effective dose was 0.20 ± 0.02 mSv for workers. The estimated values for each quarry site are detailed in Table 2.

Table 2

Estimation of annual external effective doses in the granite quarries

Granite quarries	Annual external effective dose (mSv/year)	
	Average	Standard deviation
Granite Carrière Bénin	0.21	0.02
Gravel Bénin Sarl	0.19	0.02
Colas Afrique	0.19	0.01

The estimated annual external effective doses in the Djidja municipality, outside the granite quarries, averaged 0.09 ± 0.03 mSv/year, with minimum and maximum values of 0.02 and 0.19 mSv/year, respectively.

In the Setto district, where several granite quarries are located, the mean annual effective dose estimated from measurements taken along the road axes was 0.10 ± 0.03 mSv/year.

DISCUSSION

This study assessed ionizing radiation exposure in three granite quarries located in the Djidja municipality, southern Benin. The equipment used, the AT6101C(E) spectrometer, enabled mobile measurements of ambient gamma dose equivalent rates. Coupled with a GPS and integrated into a portable device, it allowed continuous and geo-referenced data collection. This approach has previously been employed in radiological mapping studies in Africa, notably in Benin [24] and Ghana [6], for the assessment of environmental exposures in granitic or mining contexts. Unlike indirect methods based on radionuclide quantification in soils, such as those used by Mbonou *et al*. in Nigeria [13], or by Bangou *et al*. in Burkina Faso [4], mobile spectrometry provides better spatial representativeness and a more direct evaluation of external exposure risks.

The ambient gamma dose equivalent rates recorded in the Djidja granite quarries (97.02–147.83 nSv·h^{-1}; mean 109 ± 10 nSv·h^{-1}) were significantly higher than those measured in residential areas of the municipality 50 ± 18 nSv·h^{-1}. Nonetheless, these values remain below those reported in the neighboring Collines Department, where a mean of 255 nSv·h^{-1} was observed [24]. Such disparities suggest differences in the geological composition of local granite formations. Comparable levels have been reported in other granitic regions, such as Egypt [5] and Nigeria [1], confirming that granite formations are environments with enhanced natural gamma radioactivity.

Regarding annual external effective doses, estimates in this study were (0.20 ± 0.02) mSv/year for quarry workers and 0.09 ± 0.03 mSv/year for the general population. These levels are lower than the global average of 0.87 mSv/year reported by UNSCEAR [19] and the ICRP limit of 1 mSv/year for the public [12]. However, the proximity of quarries to inhabited areas and the presence of workers with repeated exposure justify the implementation of continuous radiological monitoring. Indeed, local variations in radioactivity and potential radon accumulation may increase health risks, as previously reported in other mining contexts in West Africa [6, 8].

These findings highlight the relevance of establishing a national radiological mapping program in Benin, similar to initiatives carried out in India [16] and Cameroon [14], to identify areas with high radiological potential and to guide radiation protection policies.

Finally, some limitations must be acknowledged. Measurements were conducted only during the fourth quarter of 2023, without accounting for possible seasonal variations. Moreover, the study focused solely on external exposure and did not include radon inhalation, which is recognized as the main source of natural radiation exposure [13]. Additional studies integrating internal dosimetry and radon measurements are therefore necessary to provide a more comprehensive risk assessment.

CONCLUSION

This study indicates that gamma dose rates are elevated in granite quarries compared to residential areas in the Djidja municipality, highlighting the contribution of granitic geology to ambient natural radioactivity. Estimated annual effective doses for quarry workers and the general population remain below the limits recommended by the International Commission on Radiological Protection, indicating moderate exposure levels. Nevertheless, the persistent exposure of quarry workers and the proximity of inhabited areas underscore the need for systematic radiological monitoring, implementation of occupational safety measures, and the development of public awareness initiatives to support effective radiation protection policies.

Competing interests: The authors declare that there is no conflict of interest regarding the publication of this article.

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Declaration of generative AI and AI-assisted technologies in the writing process: Generative AI and AI-assisted technologies were used only to improve the readability and language of the manuscript. No AI tool was used for data collection, analysis, or interpretation. The authors take full responsibility for the content of this publication.

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