Natural Radioactivity Measurements in Soil, External Dose and Radiological Hazard Assessment in the Uranium and Thorium Bearing Region of Lolodorf, Cameroon

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The level of natural radioactivity has been evaluated for soil samples collected from the uranium and thorium bearing region of Lolodorf in the southwestern Cameroon. Specific activities of $^{226}$Ra, $^{232}$Th and $^{40}$K in these soil samples were determined using γ-ray spectrometry with sodium iodide (NaI(Tl)) detector. The specific activities for the whole study areas where consist of five inhabited localities were compared with the world average and permissible recommended limits. Specific activities of $^{226}$Ra, $^{232}$Th and $^{40}$K ranged from 5–120, 2–170 and 50–253 Bq kg$^{-1}$, with average values of 22±2, 37±6 and 98±7 Bq kg$^{-1}$, respectively. The average values of absorbed dose rate in air ($D_a$), external effective dose ($E_{ext}$), radium equivalent activity ($Ra_{eq}$), external hazard index ($H_{ext}$) and representative level index ($I_γ$) were 36.7±5.0 nGy h$^{-1}$, 0.29±0.04 mSv y$^{-1}$, 83±14 Bq kg$^{-1}$, 0.22±0.03 and 0.58±0.10 respectively, which, were lower than their recommended values. Although this study shows that radioactivity level is normal in the study areas, except some areas where the uranium and potassium anomalies had been found by previous investigations, the possibility of developing cancer cases among individuals must not be neglected. The soil from the sampling areas in this study can be used safely as building materials apart from some points within Ngombas and Kribi.

Key Words: uranium, thorium, soil, NaI detector, specific activity, air absorbed dose, radiological hazard

1. Introduction

The human body is unavoidably and continuously exposed to natural background radiation, which is considered as association of cosmic rays and, above all, γ-ray radiations emitted by radionuclides such as the potassium-40 and the members of the radioactive decay chains of uranium-238 and thorium-232 series. These primordial radionuclides, which have existed since the creation of the solar system, are present at various degrees in the environment, especially in rocks, soils, beach sands, river beds and sediments. Uranium-238, $^{232}$Th and $^{40}$K are the most abundant naturally occurring radionuclides in the earth’s crust and contribute, respectively, on average 55.8%, 14% and 13.8% on the dose. External exposure of the public to terrestrial γ-ray radiation is the second largest contributor with 0.48 mSv, i.e. 20% of the total annual dose (2.4 mSv) per inhabitant due to natural sources, next to inhalation of radon (internal exposure) accounting for 48% (1.15 mSv) of this dose.
The radioactivity level in the soil depends mainly on geographic and geologic conditions. The activity concentrations of radionuclides in the soil provide basic or fundamental data of radioactive isotopes with an effect on human health, plants and animals. Situations of chronic exposure of the public to radiation are defined on the basis of the annual effective dose received. This effective annual dose is low, medium and high when it is less than or equal to 5, 20 and 50 mSv yr\(^{-1}\), respectively. It is well known that chronic exposure to even low-level radiation of natural origin (\(\leq 5\) mSv yr\(^{-1}\)) could be the cause of DNA damage causing certain cancers (lungs, etc.) and hereditary mutations. Knowledge of the level of radionuclide distribution in the environment is therefore necessary because it provides radiological information of the local environment.

Many studies have been carried out world widely to determine the level of natural radioactivity. As far as Cameroon is concerned, in the uranium region of Poli in northern Cameroon, Saidou et al. measured natural radioactivity and assessed total dose received by the public. Their result showed that the inhalation of radon and the ingestion of \(^{210}\)Pb and \(^{210}\)Po contained in the foodstuffs constitute the most contribution to the annual effective dose. Saidou et al. also investigated radiological exposure of the public in the oil bearing area of the Bakassi Peninsula. The results revealed a high dose exposure to the public (34.6 mSv yr\(^{-1}\)) by natural radiation. Ele Abiama et al. carried out preliminary studies in the high background radiation of southwestern region of Cameroon, in particular at the uranium and potassium anomalies points within Ngombas, Awanda and Bikoue localities. These studies have shown high radioactivity level in the soil and in rock. More recently, Dallou et al. and Ngoa Engola et al. evaluated natural radiation exposure to the public in the gold mining areas of Eastern Cameroon, particularly in Batouri and Betare-Oya. Results obtained pointed out that soils investigated could be safely used for building constructions.

The objectives of this work is to study natural radiation exposure to the public in the inhabited areas of the uranium and thorium bearing region of Lolodorf (southwestern Cameroon), typically at Eska, Akongo, Kribi, Ngombas and Awanda in order to contribute to the country’s radiological mapping. Compared to previous studies in the same region, the present work doesn’t take into account of the uranium and potassium anomaly points. Most of them are out of the inhabited areas. After sampling and conditioning, measurements of the natural radioactivity in the soil were carried out using the NaI (TI) detector. The external radiation dose of the public and the related radiological hazard were assessed.

2. Materials and methods

2.1 Study area

The uranium and thorium bearing region of Lolodorf is shown in Fig. 1. Seventeen points within the villages of Ngombas, Awanda, Bikoue and Madon in this region were highlighted with anomalies of uranium and potassium through geological and radiometric surveys conducted from 1978 to 1985 by the French Office of Geological and Mining Research. This part of Cameroon belongs to the Equatorial tropical zone, in which geological base formations consist of shale, gneiss, basalt and granite, leading to specific ferralitic soils types. These soils are rich in minerals features such as the hematites \((\text{Fe}_2\text{O}_3)\) that contain the Fe(III) and goethite which is an iron oxide \((\text{FeO(OH)})\) of yellow-red color containing, Fe(II) (deep-red). Temperatures vary between 25 and 26\(^\circ\)C with two rainy seasons and two dry seasons. The alternance of dry season and rainy season is ensured by the Inter Tropical Front (FIT) created by the movement of dry air masses (harmattan and trade winds) from Sahara (Center of high pressure) in the African continent.
to the West coast of the Gulf Guinea (Center of low pressure) and the rise in opposite direction wet air masses (the monsoons). The annual rainfall range is 1500–2000 mm, with a relative humidity of 70–80% recorded throughout the year. The total population is estimated to be about 300,000. Most people in this area live in houses that use the surrounding soil as a building material.

2.2 Sample collection and conditioning
Fifty-seven surface soil samples were taken randomly in five inhabited localities (Eseka, Akongo, Kribi, Ngombas and Awanda) in the uranium and thorium bearing area of Lolodorf. At each identified sampling point, an area of about 1 m × 1 m was marked. The marked surface area was then cleaned by removing foreign bodies such as humus layer, stones, herbs and roots using a flat-blade shovel. About 2 kg of soil sample was collected by mixing the soil taken from about 5 cm depth from every corner of the marked surface and at its center. The soil samples collected were stored in sealed polythene containers, properly labeled, and then taken to the Institute of Geological and Mining Research, Yaounde, Cameroon for the radioactivity measurements. The samples were oven dried at 70°C for 2 days to ensure that moisture is completely gone. Then each sample was crushed, homogenized, sieved with a 2 mm pore sieve, weighed and conditioned in 500 mL Marinelli beakers which were sealed for a period of 4 weeks to reach secular equilibrium which the rates of decay of the daughters, 214Bi and 228Ac, are equal to that of the parents, 226Ra and 228Ra, respectively.

2.3 Gamma-ray spectrometry
2.3.1 Experimental set-up and detector calibration
γ-ray spectrometry measurements of soil samples were performed with a Canberra NaI(Tl) detector.
(Model 802) with a crystal size of 7.6 cm × 7.6 cm and a resolution of 7.5% at 667 keV housed in a thick lead shield (5 cm) to minimize background radiation. The detector is coupled with a computer based Multichannel Analyzer (MCA) which was used for the data acquisition and analysis of gamma spectra.

The energy calibration of detector was carried out using multi-γ-ray standard point sources $^{60}$Co (1173.2 and 1332.5 keV), $^{137}$Cs (661.9 keV), $^{54}$Mn (834.8 keV), $^{22}$Na (511 and 1274.5 keV), $^{133}$Ba (383.9 keV) and $^{152}$Eu (1407.5, 1112, 1086, 778.6, 121.8 and 344.2 keV). For efficiency calibration, a customer supplied 500 mL Marinelli Beaker-resin volume source containing $^{155}$Eu, $^{57}$Co, $^{113}$Sn, $^{137}$Cs, $^{54}$Mn and $^{65}$Zn emitting γ-rays in the range of 60–1115.5 keV was used.

This Model 802 plugs directly into the Model 2007 Tube Base which provides power for the photomultiplier tube. Treatment of the data was carried out using GENIE 2000 software. Each sample was counted for 100,000 s to reduce the statistical uncertainty. The minimum detectable activities of NaI (Tl) detector system for $^{40}$K, $^{226}$Ra and $^{232}$Th are 1.10, 0.74 and 0.43 Bq kg$^{-1}$ respectively for a counting time of 100,000 s.

2·3·2 Specific activities of $^{226}$Ra, $^{232}$Th and $^{40}$K, and related uncertainty

The specific activity (Bq kg$^{-1}$) and related uncertainty which is the standard deviation of a given radionuclide in the spectrum were calculated by the following equations (1 and 2),

$$A_i = \frac{C_i}{\varepsilon(E) \times P \times M_i \times t_c}$$

(1)

$$\mu_d = \sqrt{\left(\frac{\mu_C}{C_i}\right)^2 + \left(\frac{\mu_P}{P}\right)^2 + \left(\frac{\mu_M}{M_i}\right)^2 + \left(\frac{\mu_e}{E}\right)^2}$$

(2)

Where $C_i$ is the net area under photo peak at energy $E$ (keV), $\varepsilon(E)$ is the efficiency of detector at particular γ-ray energy $E$, $P$ is the γ-ray emission probability at energy $E$, $M_i$ is the sample weight (kg), $t_c$ is the counting time (seconds) and $\mu$ is the standard deviation. The specific activities for $^{226}$Ra were evaluated from the three γ-ray lines obtained from photopits $^{214}$Bi (609.3 keV (44.8%), 1120 keV (15.1%) and 1764.5 keV (15.8%)), while specific activities of $^{232}$Th were calculated from the average value of the two γ-ray lines obtained from the photopits of $^{228}$Ac (911.6 keV (26.6%) and 969.1 keV (16.6%)), by assuming radioactive equilibrium with $^{232}$Th and $^{228}$Ra (from $^{228}$Ac). Specific activities of $^{40}$K were determined using its single γ-line of energy (1460.8 keV (10.67%)).

2·3·3 Adsorbed dose rate and contribution of $^{226}$Ra, $^{232}$Th and $^{40}$K to absorbed dose rate

Absorbed dose rate in air ($D_a$) usually expresses the health effects of γ-ray radiation from the natural radioactive sources in the environment. $D_a$ values at the high 1 m above the ground were calculated from the measured specific activities of $^{226}$Ra, $^{232}$Th, and $^{40}$K by using the following equation (3),

$$D_a (\text{nGy h}^{-1}) = 0.462 \times A_{Ra} + 0.604 \times A_{Th} + 0.0417 \times A_{K}$$

(3)

Where $A_{Ra}$, $A_{Th}$ and $A_{K}$ are specific activities of $^{226}$Ra, $^{232}$Th and $^{40}$K, respectively. The conversion factors of dose rate for $^{238}$U and $^{232}$Th series and $^{40}$K are, respectively, 0.462, 0.604 and 0.0417, expressed in nGy h$^{-1}$ per Bq kg$^{-1}$.

2·4 External annual effective dose

The external effective dose received annually by an adult person indoor and outdoor dwelling in the study area was calculated by converting the absorbed dose as presented by the equation (4) proposed by Saïdou et al.15)

$$E_{ext} = F_c \left[ (1 - F_{occ}) + F_{occ} F_b \right] \times D_a \times t$$

(4)

where $F_c$ is the conversion coefficient of $0.7 \times 10^{-6}$ mSv nGy$^{-1}$, $F_{occ}$ is the indoor occupancy factor of 0.6, which implies that people spend 40%
of the time outdoors. However, since the materials used in the construction of most of buildings contain radionuclides, the average factor $F_b$ of 1.4 was applied to take into account their contribution and estimate the indoor rate.15) $D_a$ (nGy h$^{-1}$) is absorbed dose rate in air for each analyzed sample.

2.5 Radium equivalent activity

Expressed in Bq kg$^{-1}$, radium equivalent activity ($Ra_{eq}$) is a single quantity which describes the $\gamma$-ray output from different mixture of $^{226}$Ra, $^{232}$Th and $^{40}$K in the soil. In addition, due to disequilibrium of $^{226}$Ra and its decay products, distribution of the naturally occurring radionuclides in the soil is not homogeneous. $Ra_{eq}$ is thus used to compare uniformity of specific activity of samples containing different amounts of $^{226}$Ra, $^{232}$Th and $^{40}$K. The $Ra_{eq}$ values are obtained from the equation (5).25)

$$Ra_{eq} = A_{Ra} + 1.43 \times A_{Th} + 0.077 \times A_{K}$$

where $A_{Ra}$, $A_{Th}$ and $A_{K}$ are the specific activities of $^{226}$Ra, $^{232}$Th and $^{40}$K in Bq kg$^{-1}$, respectively. The radium equivalent activity is based on the fact that 370 Bq kg$^{-1}$ of $^{226}$Ra, 259 Bq kg$^{-1}$ of $^{232}$Th and 4810 Bq kg$^{-1}$ of $^{40}$K were assumed to produce the same gamma ray dose rate. The maximum allowed $Ra_{eq}$ value is 370 Bq kg$^{-1}$ which corresponds to the annual effective dose of 1.5 mSv$^{-1}$ higher than that recommended by ICRP27) for the general public (1 mSv).

2.6 External hazard index

The soil studieds is used locally as the main building material. In order to ensure if external $\gamma$-ray radiation dose from this building material is insignificant and does not exceed acceptable maximum values ($\leq 1$), evaluation of external hazard index $H_{ex}$ was widely used. $H_{ex}$ is given by the following equation28) (6),

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_{K}}{4810}$$

where $A_{Ra}$, $A_{Th}$ and $A_{K}$ are the specific activities of $^{226}$Ra, $^{232}$Th and $^{40}$K in Bq kg$^{-1}$, respectively. The external hazard index must be less than unity so that the annual effective dose due to radioactivity in the materials will be limited to 1.5 mSv$^{-1}$.29)

2.7 Representative level index

To assess the hazardous level of the $\gamma$-ray radiation in the human body from natural radionuclides, representative level index ($I_{\gamma}$) is generally used.30, 31) To keep the radiation exposure neglected, this index value must be less than unity. So this index can be used for quality control and monitoring of the $\gamma$-ray radiation external dose accumulated in the body. I$_{\gamma}$ was calculated from the following33, 34) equation (7),

$$I_{\gamma} = \frac{A_{Ra}}{150Bq~kg^{-1}} + \frac{A_{Th}}{100Bq~kg^{-1}} + \frac{A_{K}}{1500Bq~kg^{-1}}$$

where $A_{Ra}$, $A_{Th}$ and $A_{K}$ are the specific activities of $^{226}$Ra, $^{232}$Th and $^{40}$K in Bq kg$^{-1}$, respectively. The quantities 150, 100 and 1500 Bq kg$^{-1}$ are the corresponding factors for a dose criterion of 0.3 mSv$^{-1}$ for radium, thorium and potassium, respectively.35) There exists a correlation between $I_{\gamma}$ and annual dose rate. When the value of $I_{\gamma}$ is 1, it corresponds to a dose rate criterion of 0.3 mSv$^{-1}$ and $I_{\gamma}$ is less than 3 corresponds to dose rate of 1 mSv$^{-1}$. Thus, $I_{\gamma}$ should be used only as a screening tool for identifying materials which might be of concern to be used as building materials.51) Soils with $I_{\gamma}$ > 3 are prohibited to be used as construction materials as they correspond to doses greater than that permitted to the public (1 mSv$^{-1}$).35)

3. Results and discussion

3.1 Specific activities of $^{226}$Ra, $^{232}$Th and $^{40}$K

Specific activities of the three most important radionuclides $^{226}$Ra, $^{232}$Th and $^{40}$K in the soil samples
collected (Eseka, Ngombas, Awanda, Akongo and Kribi) are presented in Table 1. Activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K ranged from $5 \pm 1$ to $120 \pm 11$ Bq kg$^{-1}$, from $2 \pm 1$ to $170 \pm 38$ Bq kg$^{-1}$ and from $50 \pm 11$ to $253 \pm 54$ Bq kg$^{-1}$, respectively, with average values of $22 \pm 2$, $37 \pm 6$ and $98 \pm 7$ Bq kg$^{-1}$, respectively. The following average activity concentrations were obtained for the same sites using in-situ $\gamma$-ray measurements made by Bineng et al.:

- $^{238}$U: $26 \pm 2$ Bq kg$^{-1}$, $33 \pm 7$ Bq kg$^{-1}$ and $153 \pm 19$ Bq kg$^{-1}$ for Eseka; $44 \pm 12$ Bq kg$^{-1}$, $66 \pm 22$ Bq kg$^{-1}$ and $153 \pm 19$ Bq kg$^{-1}$ for Ngombas; $22 \pm 2$ Bq kg$^{-1}$, $32 \pm 2$ Bq kg$^{-1}$ and $125 \pm 5$ Bq kg$^{-1}$ for Awanda; $28 \pm 3$ Bq kg$^{-1}$, $50 \pm 9$ Bq kg$^{-1}$ and $113 \pm 5$ Bq kg$^{-1}$ for Akongo and $30 \pm 11$ Bq kg$^{-1}$, $41 \pm 20$ Bq kg$^{-1}$ and $130 \pm 15$ Bq kg$^{-1}$ for Kribi. The slight difference between laboratory and in situ measurements results could be explained by the fact that radioactivity measured in the laboratory is value for soil samples collected from surfaces limited 1 m$^2$ area, while the in situ gamma spectrometry gives a concentration representing the source in the horizontal plane within a radius of 70 m approximately.

Abiama et al. evaluated specific activities (in laboratory) of $^{226}$Ra, $^{232}$Th and $^{40}$K in soil samples from Ngombas and Awanda by using a Hyper Pure Germanium detector (HPGe) $\gamma$-ray spectrometry. The average specific activities were $0.206 \pm 0.002$ kBq kg$^{-1}$, $0.582 \pm 0.04$ kBq kg$^{-1}$ and $0.552 \pm 0.04$ kBq kg$^{-1}$ (Ngombas), and $0.134 \pm 0.012$ kBq kg$^{-1}$, $0.466 \pm 0.03$ kBq kg$^{-1}$ and $0.888 \pm 0.064$ kBq kg$^{-1}$ (Awanda) for $^{226}$Ra, $^{232}$Th and $^{40}$K, respectively. These specific activities are 7–10 times higher than the values found in the present work. This large difference could be explained by the fact that, sampling for the two studies was not done at the same areas. For this study, sampling was carried out exclusively in the inhabited area while for study reported by Ele Abiama et al., sampling was carried out in the uranium and potassium anomaly points which are rarely occupied by the population.

$^{226}$Ra, $^{232}$Th and $^{40}$K mean specific activities of the whole study area were found to be lower than the world average values of 33, 45 and 420 Bq kg$^{-1}$, respectively. In Table 1, one observes that the localities of Ngombas and Akongo present an average activity concentration of $^{232}$Th higher than the corresponding world average value. According to Ele Abiama et al., this high specific activity of $^{232}$Th is justified by the occurrence of thorium and uranium bearing minerals (zircon, apatite, monazite, uranothorite, uraninite, thorite) in some points within these areas.

| Location | Number of samples | Activity concentration in Bq kg$^{-1}$ |
|----------|------------------|-------------------------------------|
|          |                  | $^{226}$Ra | $^{232}$Th | $^{40}$K |
| Eseka    | 16               | $15 \pm 1$ | $21 \pm 3$ | $89 \pm 13$ |
|          |                  | $(6 - 25)$ | $(2 - 52)$ | $(51 - 253)$ |
| Ngombas  | 13               | $25 \pm 0$ | $51 \pm 14$ | $119 \pm 3$ |
|          |                  | $(15 - 54)$ | $(19 - 170)$ | $(75 - 223)$ |
| Awanda   | 5                | $15 \pm 1$ | $35 \pm 3$ | $88 \pm 2$ |
|          |                  | $(13 - 17)$ | $(26 - 42)$ | $(84 - 95)$ |
| Akongo   | 6                | $20 \pm 2$ | $46 \pm 3$ | $109 \pm 7$ |
|          |                  | $(14 - 24)$ | $(40 - 58)$ | $(92 - 133)$ |
| Kribi    | 17               | $33 \pm 7$ | $34 \pm 8$ | $83 \pm 8$ |
|          |                  | $(5 - 120)$ | $(6 - 126)$ | $(50 - 204)$ |
| Whole Area | 57             | $22 \pm 2$ | $37 \pm 6$ | $98 \pm 7$ |
|          |                  | $(5 - 120)$ | $(2 - 170)$ | $(50 - 253)$ |
Average specific activities of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ found in soil samples in the whole study area are presented in Fig. 2. Radium-226 was the smallest specific activity compared with those of the $^{232}\text{Th}$ and $^{40}\text{K}$ in this area. Fig. 3 shows the comparison of average specific activities of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ depending on the sampling sites. Among all these sites, Kribi has the largest average specific activities of $^{226}\text{Ra}$ and Ngombas has the largest one of $^{232}\text{Th}$ and $^{40}\text{K}$, respectively.

To evaluate enrichment and depletion processes of the soils sampled, analyses of the correlation between specific activities of primordial radionuclides were carried out. Fig. 4 presents the correlations between $^{226}\text{Ra}$ and $^{232}\text{Th}$, $^{232}\text{Th}$ and $^{40}\text{K}$, and $^{40}\text{K}$ and $^{226}\text{Ra}$. A good correlation was observed between $^{226}\text{Ra}$ and $^{232}\text{Th}$ with a correlation coefficient of 0.738 illustrating certain proximity between $^{226}\text{Ra}$ and $^{232}\text{Th}$ (two-variable correlation test). For the other two cases ($^{232}\text{Th}$ and $^{40}\text{K}$, and $^{40}\text{K}$ and $^{226}\text{Ra}$), there is a weak correlation. This can be explained by the fact that the contents of uranium, thorium and potassium in soils are related to their respective geochemical properties and difference of minerals including them. The presence of some radioactive minerals (uranothorite, uraninite, thorite) could explain the relative high correlation of uranium and thorium.

### 3.2 Adsorbed dose rate, contribution of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ to adsorbed dose rate and external annual effective dose

Table 2 shows mean values of the air absorbed
dose rate, the contribution of $^{226}$Ra, $^{232}$Th and $^{40}$K to the absorbed dose rate and finally the annual effective dose per sampling site. The mean absorbed dose rate per site found in soil samples varied from 23.0 to 47.3 nGy h$^{-1}$ with an overall average value of 36.7 ± 5.0 nGy h$^{-1}$ (Table 2). This weighted mean value (36.7 ± 5.0 nGy h$^{-1}$) represents 63% of the world average corresponding value (59 nGy h$^{-1}$).\[^{39}\] Thus, external radiation exposure for population in the whole study area due to soils is therefore insignificant. Thorium-232 (61.3%) is found to be the main contributor of the air absorbed dose rate.

Fig. 5 shows the average absorbed dose rate in air of each site. The average values for Eseka, Ngombas, Awanda, Akongo and Kribi were 23.0±2.5, 47.3±10.3, 32.0±2.0, 41.4±2.3 and 37.0±8.0 nGy h$^{-1}$, respectively. These values are very similar to those obtained by in-situ gamma spectrometry. In fact Bineng et al.\[^{36}\] found by in situ gamma measurements the mean absorbed dose rate values of 28.3±2.0 nGy h$^{-1}$ (Eseka), 60±17 nGy h$^{-1}$ (Ngombas), 31±2 nGy h$^{-1}$ (Awanda), 44.4±6.0 nGy h$^{-1}$ (Akongo), 39±14 nGy h$^{-1}$ (Kribi). Ele Abiama et al.\[^{16}\] obtained at uranium and potassium anomaly points of Ngombas and Awanda 338±24 and 315±16 nGy h$^{-1}$, respectively. These dose rate values were found to be very high compared to that obtained in this work.

Fig. 6 shows the contribution of air absorbed dose rate per site sampled for each primordial radionu-

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\begin{array}{|c|c|c|c|c|c|c|c|c|}
\hline
\text{Location} & \text{Number of sampling Points} & \text{Mean Absorbed dose rate in air (nGy h}^{-1}\text{)} & \text{Contribution to the Absorbed dose rate (\%)} & \text{External effective dose (mSv y}^{-1}\text{)} \\
\hline
\text{Eseka} & 16 & 3.7 & 6.7 & 12.6 & 23.0±2.5 & 16.1 & 29.1 & 54.8 & 0.18±0.02 & 0.08 - 0.38 \\
\text{Ngombas} & 13 & 4.9 & 11.6 & 30.8 & 47.3±10.3 & 10.4 & 24.5 & 65.1 & 0.38±0.08 & 0.18 - 1.09 \\
\text{Awanda} & 5 & 3.7 & 6.9 & 21.3 & 32.0±2.0 & 11.6 & 21.6 & 66.8 & 0.26±0.02 & 0.20 - 0.30 \\
\text{Akongo} & 6 & 4.5 & 9.1 & 27.8 & 41.4±2.3 & 10.9 & 22.0 & 67.1 & 0.33±0.02 & 0.28 - 0.40 \\
\text{Kribi} & 17 & 3.5 & 15.4 & 21.0 & 37.0±8.0 & 8.8 & 38.9 & 53.0 & 0.32±0.06 & 0.07 - 1.08 \\
\hline
\text{Whole study area} & 57 & 4.1 & 9.9 & 22.7 & 36.7±5.0 & 11.5 & 27.2 & 61.3 & 0.29±0.04 & 0.08 - 1.09 \\
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\end{array}
\]
clides. For the whole study area, Ngombas, Kribi and Ngombas are the major contributors in $^{40}\text{K}$ (24.3%), $^{226}\text{Ra}$ (31%) and $^{232}\text{Th}$ (27.1%) of the air absorbed dose rate respectively.

The external annual effective dose was assessed using equation (4). Table 2 presents the dose values obtained within the framework of this study. For Eseka, Ngombas, Awanda, Akongo and Kribi, external annual effective dose ranged from 0.08 to 0.38 mSv y$^{-1}$, 0.18 to 1.09 mSv y$^{-1}$, 0.20 to 0.30 mSv y$^{-1}$, 0.28 to 0.40 mSv y$^{-1}$ and 0.07 to 1.08 mSv y$^{-1}$, respectively, with mean values 0.18 ± 0.02 mSv y$^{-1}$, 0.38 ± 0.08 mSv y$^{-1}$, 0.26 ± 0.02 mSv y$^{-1}$, 0.33 ± 0.02 mSv y$^{-1}$ and 0.32 ± 0.06 mSv y$^{-1}$, respectively. These average dose values are well below the world average (0.5 mSv y$^{-1}$). However, there are some peak values at Ngombas (1.09 mSv y$^{-1}$) and Kribi (1.08 mSv y$^{-1}$) which should be studied in more detail. The average value of annual effective dose for this study was 0.29 ± 0.04 mSv y$^{-1}$ and ranged from 0.08 to 1.09 mSv y$^{-1}$. This average value is slightly smaller than those determined by Bineng et al. (submitted) and Ele Abiama et al. (0.41 mSv y$^{-1}$).

### 3.3 Radium equivalent activity, external hazard index, representative level index and excess lifetime cancer risk

Table 3 shows radiological hazards for each site and for the whole study area. The average values of radium equivalent activity ($R_{\text{eq}}$) for Eseka, Ngombas, Awanda, Akongo and Kribi sites were 51 ± 8, 107 ± 18, 72 ± 12, 94 ± 16 and 89 ± 16 Bq kg$^{-1}$, respectively. Ngombas had the largest calculated $R_{\text{eq}}$ value while Eseka presented the smallest value. In addition, for the whole study area, $R_{\text{eq}}$ varied from 51 (Eseka) to 107 Bq kg$^{-1}$ (Ngombas) with an average value of 83 ± 14 Bq kg$^{-1}$. The $R_{\text{eq}}$ values obtained in this work (Table 3) are all smaller than the maximum recommended by OECD (0.5 mSv y$^{-1}$) for building materials.

External hazard index ($H_{\text{ex}}$) varied from 0.05 to 0.3 for Eseka, from 0.14 to 0.85 for Ngombas, from 0.15 to 0.22 for Awanda, from 0.22 to 0.31 for Akongo and from 0.05 to 0.82 for Kribi with an average value of 0.14 ± 0.02, 0.29 ± 0.04, 0.20 ± 0.03, 0.25 ± 0.04 and 0.24 ± 0.04, respectively. As shown in Table 3, the average value of all the study area is 0.22 ± 0.03. Compared to the recommended limit value (unit), all $H_{\text{ex}}$ values obtained in this work were smaller. This means that the analyzed soils do not have significant radiological hazards to local population and therefore sampled soils can be used as building materials.

The values of the representative level index ($I_7$) for all sites are presented in Table 3. $I_7$ values varied from 0.15 to 0.76, 0.36 to 2.21, 0.41 to 0.58, 0.57 to 0.8 and 0.14 to 2.10 for Eseka, Ngombas, Awanda, Akongo and Kribi sites, respectively, with average values of 0.36 ± 0.06, 0.76 ± 0.12, 0.51 ± 0.09,
0.66±0.11 and 0.62±0.11, respectively. Thus for the whole study area, $I_\gamma$ average value was 0.58±0.10 and varied from 0.36 to 0.76. Apart from the peaks observed at Ngombas (2.21) and Kribi (2.10), all $I_\gamma$ values found in this study are below 3, therefore, the dose received by the public does not pose significant health hazards.

4. Conclusion

Activity concentrations of primordial radionuclides in soil samples collected from different sites of Lolodorf uranium and thorium bearing area were measured using NaI(Tl) based $\gamma$-ray spectrometry technique and the related radiation hazards were assessed. For the whole study area, average specific activities of $^{226}$Ra, $^{232}$Th and $^{40}$K are 22±2, 37±6 and 98±7 Bq kg$^{-1}$, respectively. $^{226}$Ra, $^{232}$Th and $^{40}$K mean specific activities of the whole study area were found to be lower than the world average values. Ngombas and Akongo localities showed an average specific activity of $^{232}$Th higher than the corresponding world average value. The mean value of the total air absorbed dose rate and external annual effective dose was, respectively, 36.7±5.02 nGy h$^{-1}$ and 0.29±0.04 mSv y$^{-1}$ which were below the corresponding world average values of 59 nGy h$^{-1}$ and 0.5 mSv y$^{-1}$, respectively. Thorium-232 (61.3) was found to be the main contributor to the air absorbed dose rate.

The radium equivalent activity, external hazard index and representative level index have indicated lower values than the unacceptable limit. Indoor measurements of radon, thoron and their progeny radionuclides will be carried out for better dose assessment in this part of Cameroon.

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