Natural radioactivity in the soil samples of Botswana

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ABSTRACT

Studies on concentrations of primordial radionuclides in soil samples of Botswana were carried out. Measurements were made by gamma spectrometry employing a 41% relative efficiency HPGe detector. The activity of ^{226}Ra was found to vary in the range 6.1–97.4 Bq kg^{-1} with a mean value of 34.8 Bq kg^{-1}, ^{232}Th in 7.4–110.0 Bq kg^{-1} with a mean value of 41.8 Bq kg^{-1} and that of ^{40}K between 33.5 and 1085.7 Bq kg^{-1} with a mean value of 432.7 Bq kg^{-1} in surface soils. Existence of strong correlations in the distributions of these radionuclides indicates that an individual result for any one of the radionuclide is a good predictor of the concentration of the other. The mean value of effective dose, due to the ^{238}U series, ^{232}Th series and ^{40}K in soil, was 0.07 mSV. The results of the present study are compared with the literature values reported for other normal background regions of the world and discussed.

Keywords:
Radioactivity
Botswana
Gamma spectrometry
Absorbed dose
Effective dose

1. Introduction

The knowledge of distribution of radionuclides and radioactivity levels in the environment is important for assessing the radiation exposure to the population. The two prominent sources of external radiation are cosmic rays and terrestrial gamma rays. Terrestrial gamma rays are essentially due to radionuclides belonging to ^{238}U and ^{232}Th series and singly occurring ^{40}K that are present in the earth's crust.

Measurements of radioactivity in soils of Botswana were not carried out so far. However, radiometric studies through aerial surveys have been carried out with main emphasis on finding diamond resources (Ranganai et al., 2006). Botswana is endowed with a variety of minerals, especially diamonds, which contribute enormously to the economic progress of the country. However, extensive mining operations can degrade the environment affecting the human population in the surrounding vicinity.

Also, the large scale mining activities have the potential to enhance the background radiation levels prevailing in the region. Since systematic studies on radiation levels and radionuclides concentration were not carried out so far for Botswana, there was a need for a detailed study aimed at establishing baseline data on background radiation levels. Therefore, a systematic study on these aspects was initiated. This paper reports the initial results of ^{226}Ra, ^{232}Th and ^{40}K activities in soil samples collected along Gaborone–Lobatse–Kanye–Jwaneng road. Jwaneng diamond mine is the world's largest open pit diamond mine. The population density in the region selected for the present study is higher when compared to other regions.

2. Geology of the study area

The simplified regional geological and structural setting of the area is shown in Fig. 1. Archaean (Kaapvaal craton) basement terrain mainly comprising the Gaborone granite complex and the Kanye volcanic formation, unconformably overlain by early Proterozoic (sedimentary) rocks that are in turn partly covered by Karoo sands and calcrete. The oldest rocks traversed by the sampling route are the late Archaean Kanye Volcanic Formation (KVF) of fine-grained felsites that has a widespread distribution in southeastern Botswana and is best exposed in the hills between Lobatse, Gaborone and Kanye (Fig. 1; Aldiss et al., 1989; Carney et al., 1994). The Kanye felsites are closely associated with, and partly intruded by, the major, late Archaean to early Proterozoic Gaborone Granite Complex (GGC) that dominates the geology of the area. The GGC is composed of a multi-phase granitic batholith with a central rapakivi-textured core called the Thamaga granite, followed by the medium-grained granites marginal facies Kgale granite and the equigranular Ndhandhe microgranite at the periphery of the complex. Both the KVF and the GGC are (unconformably) overlain by the ~2.7 Ga Lobatse Volcanic Group (LVG), a volcano-sedimentary sequence (Ventersdorp Supergroup)

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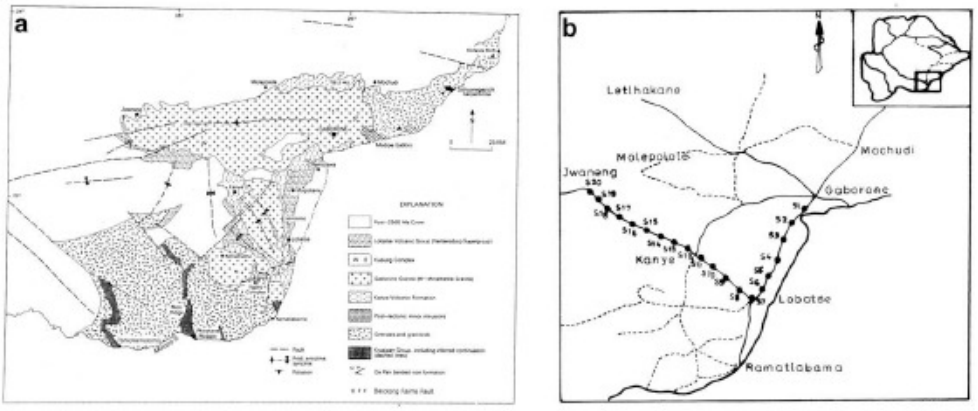

Fig. 1. (a) Simplified geology of southeastern Botswana. (b) Locations of soil sampling along the Gaborone–Lobatse–Kanye–Jwaneng main road.

which is widely distributed in neighbouring South Africa (Fig. 1). The best exposures in Botswana occur at the eastern margin of the GGC, in the range of hills between Ramotswa and Lobatse where the unit comprises a diverse assemblage of acid to intermediate lavas, associated pyroclastics, and fine to coarse-grained sediments (Carney et al., 1994). Transvaal Supergroup (Taupone) dolomite and some syenites intrusions around Jwaneng – the Jwaneng diamondiferous kimberlite itself is hosted by a dolomite–sandstone–shale succession within granitic country rock. The Gaborone granite complex contains relatively large concentrations of potassium (K), uranium (U), and thorium (Th) (Downey, 1996; Wormald and Downey, 1999; Ranganai et al., 2006), the three most abundant, naturally occurring radioactive elements on earth.

3. Materials and methods

3.1. Sample collection

Soil samples were collected from 20 sampling stations along Gaborone–Lobatse–Kanye–Jwaneng road (Fig. 1b). The names of the sampling stations are given in column 2 of Table 1. Samples were collected along this road since the terminal point of the present study is Jwaneng where there are large scale open pit diamond mining activities going on. For soil samples, undisturbed level surfaces situated sufficiently away from public roads and buildings were selected. About 1 m^2 area was marked and the top layer of the soil (0–5 cm depth) was collected after removing plant materials such as litter, root, etc.

Table 1
^{226}Ra, ^{232}Th and ^{40}K activity concentrations in soil samples of Botswana.

Sample code	Name of the sampling station	Activity (Bq kg^{-1})			Absorbed dose (nGy h^{-1})			Total absorbed dose (nGy h^{-1})	Effective dose (mSv)
		^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K		
S1	Metsemaswaane river bridge	36.6 ± 0.7[a]	50.8 ± 0.9	645.1 ± 11.6	16.9	30.7	26.9	74.5	0.09
S2	Boatle	48.3 ± 0.8	53.9 ± 1.2	581.0 ± 10.9	22.3	32.6	24.2	79.1	0.10
S3	Waste disposal site	24.8 ± 0.5	27.0 ± 0.7	274.6 ± 5.9	11.5	16.3	11.5	39.2	0.05
S4	Baratane hill	66.9 ± 1.0	68.5 ± 1.3	792.6 ± 14.5	30.9	41.4	33.1	105.3	0.13
S5	Nywane dam	27.2 ± 0.6	35.4 ± 0.8	373.6 ± 7.5	12.6	21.4	15.6	49.5	0.06
S6	Lobaste tile factory junction	41.2 ± 0.7	49.0 ± 1.0	326.6 ± 6.9	19.0	29.6	13.6	62.2	0.08
S7	Lobaste Jwaneng junction	56.8 ± 0.8	57.1 ± 1.2	556.7 ± 10.5	26.2	34.5	23.2	83.9	0.10
S8	Molapowabojwang	49.9 ± 0.8	60.9 ± 1.2	910.0 ± 15.4	23.1	36.8	37.9	97.8	0.12
S9	20 km from Lobatse–Jwaneng junction	47.8 ± 0.8	79.1 ± 1.3	963.0 ± 16.0	22.1	47.8	40.2	110.0	0.13
S10	30 km from Lobatse–Jwaneng junction	49.1 ± 1.2	69.0 ± 1.7	662.7 ± 14.8	22.7	41.7	27.6	92.0	0.11
S11	Kanye	97.4 ± 1.1	110.0 ± 1.5	1085.7 ± 18.0	45.0	66.4	45.3	156.7	0.19
S12	Mheelo river bridge	38.0 ± 0.7	48.9 ± 1.0	939.7 ± 16.0	17.6	29.5	39.2	86.3	0.11
S13	20 km from Kanye	19.4 ± 0.5	22.3 ± 0.6	55.6 ± 2.6	9.0	13.5	2.3	24.8	0.03
S14	30 km from Kanye	15.9 ± 0.5	19.7 ± 0.6	77.0 ± 3.0	7.3	11.9	3.2	22.5	0.03
S15	40 km from Kanye	14.4 ± 0.5	18.8 ± 0.6	164.9 ± 4.5	6.7	11.4	6.9	24.9	0.03
S16	50 km from Kanye	18.3 ± 0.4	18.7 ± 0.6	77.4 ± 2.9	8.5	11.3	3.2	23.0	0.03
S17	60 km from Kanye	8.1 ± 0.5	8.9 ± 0.7	37.4 ± 3.3	3.7	5.4	1.6	10.7	0.01
S18	70 km from Kanye	13.8 ± 0.4	16.2 ± 0.6	59.7 ± 2.8	6.4	9.8	2.5	18.6	0.02
S19	80 km from Kanye	16.3 ± 0.5	13.7 ± 0.6	37.0 ± 2.5	7.5	8.3	1.5	17.3	0.02
S20	Jwaneng	6.1 ± 0.8	7.4 ± 0.4	33.5 ± 2.1	2.8	4.5	1.4	8.7	0.01
	Range	6.1–97.4	7.4–110.0	33.5–1085.7	2.8–45.0	4.5–66.4	1.4–45.3	8.7–156.7	0.01–0.19
	Mean	34.8	41.8	432.7	16.1	25.2	18.0	59.4	0.07
	SD	23.0	27.5	368.1	10.6	16.6	15.4	41.4	0.05

[a] ± Value indicates the error associated with the measurement.

3.2. Sample processing

The samples were processed following the standard procedures (EML Procedure Manual, 1983). Soils were well mixed after removing extraneous materials such as roots, mat portions, pieces of stones and gravel. Samples were weighed and then dried in an oven at 105 °C overnight and re-weighed to find the water content. After mixing thoroughly, the samples were shaken in a sieve shaker and particle sizes of <250 microns were obtained. Sieved samples were sealed in 300 ml plastic containers and stored for a minimum period of 30 d to allow ^{226}Ra to come into equilibrium with its daughters. Proper sealing was ensured by providing double seal to the lid of the container to avoid ^{222}Rn escaping out.

3.3. Activity determination

The concentrations of ^{226}Ra, ^{232}Th and ^{40}K were determined by gamma spectrometry employing a 41% relative efficiency n-type HPGe detector (Canberra, USA). This facility is available at University Science Instrumentation Centre, Mangalore University, India. The detector was enclosed in a graded lead shield (Model 747, Canberra, USA). The detector was connected to the DSA-1000 (Canberra, USA – which has built in detector HV bias supply, ADC and 16 K MCA) for data acquisition and spectrum was analyzed by GENIE-2000 software. The detector efficiency calibration was performed by using the IAEA quality assurance reference materials: RG U-238, RG Th-232, RG K-1 and SOIL-6 procured from IAEA. The standard materials and samples were taken in containers of same size and type so that detection geometry remained the same. Samples were counted long enough (60,000 s) to reduce the counting error. The ^{226}Ra activity was evaluated from the weighted mean of the activities of three photopeaks of ^{214}Bi (609.3, 1120.3 and 1764.5 keV) and one of ^{214}Pb (352.0 keV) after applying Compton corrections. In the case of ^{232}Th one photopeak of ^{228}Ac (911.2 keV) and two photopeaks of ^{208}Tl (583.1 and 2614.5 keV) were used in the same way. The activity of ^{40}K was derived from the 1460.8 keV gamma line of this isotope (Karunakara et al., 2001). The Minimum Detection Levels (MDL) for the gamma spectrometer system used in the present study were 0.2 Bq kg^{-1}, 0.3 Bq kg^{-1} and 1.2 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively for a counting time of 60,000 s and a sample weight of 0.3 kg.

4. Results and discussions

The results of soil radioactivity measurement are presented in Table 1. The ^{226}Ra concentration varied in the range 6.1–97.4 Bq kg^{-1} with a mean of 34.8 Bq kg^{-1}, ^{232}Th in the range 7.4–110.0 Bq kg^{-1} with a mean of 41.8 Bq kg^{-1} and ^{40}K in the range 33.5–1085.7 Bq kg^{-1} with a mean of 432.7 Bq kg^{-1}.

It is interesting to note that the soil samples of the Metsemaswaane (very near to Gaborone) – Kanye section (sample code No. S1 to S12) showed higher concentrations of ^{226}Ra, ^{232}Th and ^{40}K when compared to the Mheelo–Jwaneng section (sample No. S13–S20). For example, the mean value of ^{226}Ra concentration in soil samples collected from Metsemaswaane – Kanye section is 48.7 Bq kg^{-1} and the same for the soil samples collected from Mheelo–Jwaneng section is 14.0 Bq kg^{-1}. This variation is more predominant in the case of ^{40}K, the mean value (675.9 Bq kg^{-1}) for the Metsemaswaane – Kanye section is 10 times higher when compared to the mean value (67.8 Bq kg^{-1}) of concentration in soil samples of Mheelo–Jwaneng section. As discussed earlier in Section 2, examinations of geological maps of the study area show that the region between Lobatse and Kanye correspond to areas underlain by granitic rocks with relatively thin soil cover (Key, 1983; Aldiss et al., 1989). The higher values in Gaborone–Kanye are attributed to the Gaborone granite which extends upto the starting point of Kanye. It is well known that, granites contain high concentration of uranium, thorium and potassium (Ivanovich and Harmon, 1982). The uranium and thorium are incorporated in to the rocks in the crystallization of the last magmas and residual solutions, since their large ionic radii stop them from crystallizing out in the early silicates. The lower concentration of these radionuclides in the region from Kanye to Jwaneng is due to the fact that the soil in this region is purely sedimental type, which is known to contain lower concentrations of ^{238}U, ^{232}Th and ^{40}K when compared to soil of granitic origin.

4.1. Absorbed dose rates

From the results of ^{226}Ra, ^{232}Th and ^{40}K activities in the surface soil (Table 1) the gamma dose rates in air were calculated using the dose coefficients (nGy h^{-1} per Bq kg^{-1}) 0.462, 0.604 and 0.0417 given in UNSCEAR (2000) for ^{226}Ra sub-series, ^{232}Th series and ^{40}K respectively and by assuming secular equilibrium between ^{238}U and ^{226}Ra. The absorbed dose is given by:

$$D = [(0.462 \times A_{Ra}) + (0.604 \times A_{Th}) + (0.0417 \times A_K)]\ \text{nGy h}^{-1}$$

where, A_{Ra}, A_{Th} and A_K are the concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in Bq kg^{-1}.

It may be noted that about 98% of the external dose from ^{238}U series is delivered by ^{226}Ra sub-series. Therefore, the disequilibrium, if any, between ^{226}Ra and ^{238}U does not affect the dose estimation from the measurement of ^{226}Ra. The absorbed dose values thus calculated are presented in Columns 6–9 of Table 1. The total absorbed dose delivered by these radionuclides ranged in 8.7–156.7 nGy h^{-1} with a mean value of 59.4 nGy h^{-1} which is comparable with the world average value of 51 nGy h^{-1} (UNSCEAR, 2000). The annual effective dose to the population due to the soil radioactivity was estimated using the dose coefficient (0.7 SvGy^{-1}) and occupancy factor (0.2) for outdoors given in UNSCEAR (2000). The effective doses thus calculated (presented in Column 10 of Table 1) are found to vary in the range 0.01–0.19 mSv with a mean of 0.07 mSv. The mean value of effective dose obtained in the present study is exactly same as that given (0.07 mSv) in UNSCEAR (2000) for worldwide representative value.

The percentage contributions of ^{238}U, ^{232}Th and ^{40}K to the external dose rates in air were also calculated. The mean values are 29.6, 45.1, and 25.3% for ^{238}U, ^{232}Th and ^{40}K, respectively. Karunakara et al. (2001) have reported these percentage contributions to be 40.2, 42.3 and 17.5% due to ^{238}U, ^{232}Th and ^{40}K, respectively for Kaiga, India. Mishra and Sadasivan (1971) have reported these percentage contributions in the order of 17.7, 33.6 and 48.7 due to ^{238}U, ^{232}Th and ^{40}K, respectively for Indian environs. UNSCEAR (1982) has reported the worldwide average values for the relative contributions from ^{238}U, ^{232}Th and ^{40}K gamma dose rates in air to be about 25%, 40% and 35%, respectively.

4.2. Comparison of the results with other countries

The concentration of ^{226}Ra, ^{232}Th and ^{40}K observed in the present study is compared with those reported for the normal background regions of other countries in Table 2. It is evident from the table that the concentrations observed in soils of Botswana are comparable to those reported for worldwide range and average values (UNSCEAR, 2000) and also to the values reported for European, Asian, South and North American countries (Anagnostakis et al., 1996; Baeza et al., 1992; McAualy and Moran, 1988; Merdanoglu and Altinsoy, 2006; Weng, 1996; Yang et al.,

Table 2
Comparison of ^{226}Ra, ^{232}Th and ^{40}K concentrations of soil samples of Botswana with that reported for other countries.

^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})	Region	Reference
6.1–7.4 (34.8)	7.4–110.0 (41.8)	33.5–1085.7 (432.7)	Botswana	Present study
8.2–68.4 (30.6)	5.9–77.2 (38.2)	14.6–344.9 (152.2)	West Coast of India	Karunakara et al. (2005)
7.8–152.0 (31)	17.5–158.3 (63)	43–766 (394)	All India average	Kamath et al. (1996)
1–238 (25)	1–193 (21)	12–1570 (360)	Greece	Anagnostakis et al. (1996)
13–165 (46)	7–204 (49)	48–1586 (650)	Spain	Baeza et al. (1992)
6–98 (33)	2–88 (28)	15–990 (310)	Japan	Megumi et al. (1988)
100–200 (60)	3–60 (26)	40–800 (350)	Ireland	McAualy and Moran (1988)
8.0–160.0 (40)	4–130 (35)	100–700 (370)	USA	Myrick et al. (1983)
82.32–166.99 (115)	151.91–275.63 (192)	1015.48–1484.93 (1207)	Turkey	Merdanoglu and Altinsoy (2006)
45–48 (31)	3–38 (32)	42–1100 (480)	Namibia	Steinhausler and Lettner (1992)
5–64 (17)	2–96 (18)	29–6590 (320)	Egypt	UNSCEAR (2000)
36	14.8–44.4	148–814	Taiwan	Weng (1996)
40.2–442 (112)	32.6–88.1 (71.5)	440–913 (672)	China	Yang et al. (2005)
8–160 (32)	4–130 (40)	100–700 (420)	World average	UNSCEAR (2000)

Values given in the parenthesis are mean values.

2005; Karunakara et al., 2005; Kamath et al., 1996; Myrick et al., 1983; Steinhausler and Lettner, 1992; UNSCEAR, 2000).

4.3. Correlation studies

In order to find the extent of the existence of these radioactive nuclides together at a particular place, correlation studies were performed between the combinations of radionuclides like ^{226}Ra & ^{232}Th, ^{232}Th & ^{40}K and ^{228}Ra & ^{40}K. A very good correlation was observed between the activities of ^{226}Ra and ^{232}Th with a significant positive correlation coefficient ($R = 0.96$, $N = 20$). Similarly, strong correlations were also observed between ^{226}Ra and ^{40}K ($R = 0.86$) and ^{232}Th & ^{40}K ($R = 0.92$). The strong correlations between the activities indicate that the individual result for any one of the radionuclide concentration in each pair is a good predictor of the concentration of the other.

4.4. Activity ratios

The ^{226}Ra/^{232}Th and ^{226}Ra/^{40}K concentration ratios were evaluated from the measured values of activity concentrations. The mean values of ^{226}Ra/^{232}Th and ^{226}Ra/^{40}K ratios were 0.83 and 0.08, respectively. These are comparable to the mean values reported for the soils of Greece ($1.10 \pm 44\%$ and $0.06 \pm 56\%$, Anagnostakis et al., 1996), USA (1.15 and 0.11, UNSCEAR, 1993), India (1.42 and 0.26, Karunakara et al., 2001) and China (0.76 and 0.06, UNSCEAR, 1993).

5. Conclusions

Although the study has not covered the entire country of Botswana this is the first report on the data on radionuclides in soil of Botswana. The results show that the concentrations of ^{226}Ra, ^{232}Th and ^{40}K in soil of Botswana are comparable to the reported worldwide range and mean values. More detailed study covering different regions of Botswana is in progress.

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