Feasibility of Handheld BGO Gamma-Ray Spectrometer to Evaluate U and Th in Phosphate Ore Mining Area: A Case Study

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Abstract: Equivalent uranium (eU in ppm), equivalent thorium (eTh in ppm), and potassium (K%) concentrations were assessed in soil using hand-held (in-situ) BGO (Bismuth Germanium Oxide) gamma-ray spectrometer in phosphate ore mining area. Soil samples were collected from the same locations of in-situ measurements. Gamma-ray spectrometers based on HPGe detectors, for in-laboratory measurements, were exploited to investigate and compare the activity concentrations in Bq/kg dry weight of ^{238}U, ^{226}Ra, ^{228}Ra (^{232}Th) and ^{40}K, in soil samples, with the obtained results of in-situ measurements. In some cases, it was not possible to correlate both in-Situ and in-laboratory (in-lab) measurements especially in case of ^{238}U and eU. While the correlation between ^{226}Ra and eU was possible with careful consideration of the essential differences between in-situ and in-lab measurements such as sample-detector configurations, detectors characterization, and ^{222}Rn emanation. Finally, hand-held spectrometers could be considered a very effective equipment to measure eU (^{214}Bi) and eTh (^{208}Tl) in quantitive/ semi-quantitive that could be correlated to U and Th series, respectively, in a very specific conditions of ensuring series' secular equilibrium.

Keywords: In-situ; BGO; Handheld gamma-ray spectrometer; HPGe; Phosphate mining.

1 Introduction

Uranium and thorium are found in the earth's crust. Their concentrations varied widely all over the world based on the rock types along with their origin. Both of them form a series, which end with ^{206}Pb and ^{208}Pb for ^{238}U and ^{232}Th series, respectively. Uranium-238 and thorium-232 are alpha emitters with the absence of well pronounced gamma-ray emissions. Uranium -238 could be generally assessed via the gamma-ray emission of its successor ^{234m}Pa at 1001.03 keV; 1.067 % [1,2]. Thorium-232 could be assessed, after ensuring secular equilibrium, using the gamma-ray emissions from its successor ^{228}Ac at 338.32 keV (11.27%) and 911.2 keV (25.8%) or from ^{220}Rn successor ^{208}Tl at 2614.5 keV (99.75%). However, in order to assess ^{226}Ra as an indicative of the ^{238}U, it is necessary to achieve secular equilibrium between ^{238}U, ^{226}Ra and its direct progeny ^{222}Rn, and in turn, ^{222}Rn achieves secular equilibrium with its successors ^{214}Pb and ^{214}Bi that their gamma energy transitions are well pronounced. One advantage of some geological, i.e. formations environments is the existence of (to a certain degree) secular equilibrium between the grandparent radionuclides (e.g., ^{238}U and ^{232}Th), and their progenies. This should help in the accurate assessment of these radionuclides via measuring their progenies. As long as no aggressive chemical weathering and/or physical interferences are applied to the ore's environment, equilibrium is often achieved between the ^{238}U and it grand-daughters ^{226}Ra & ^{222}Rn. Similarly, ^{232}Th and ^{228}Ac often are in secular equilibrium.

The quantification of the radioactive inventories (e.g., U and Th) during uranium bearing ore mining via traditional radiochemical procedures e.g. gamma spectrometry is a long process starting from sampling ending with the specific activity measurement using radioactivity counting systems and/or spectrometers. Each step in this processes is both costly and time consuming. On the contrary, the handheld spectrometers based on different radiation detectors such as NaI (Tl) and BGO (Bismuth Germinate Oxide) could be used for in-situ measurement in a relatively short measuring time (0.5-30 min.). They are based mainly on the quantification of both ^{238}U and ^{232}Th via their successors ^{226}Ra (via^{214}Pb and/or ^{214}Bi) and ^{228}Ra respectively. They are simple, user-friendly, and effective tools for measuring the activity concentrations of ^{226}Ra as

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equivalent uranium (eU) in ppm, ^{228}Ra (^{208}Tl) as equivalent thorium (eTh) in ppm and ^{40}K as K%. Accordingly, the existence of equilibrium is very crucial otherwise the data will be misleading.

These techniques are used widely in U exploration field as well as geological and geophysical techniques applications that make them highly variable and well accepted techniques in order to evaluate the ^{238}U series and ^{232}Th series inventories especially within any U bearing ore such as U and P ore mining.

This work aims at evaluating the feasibility of using handheld BGO gamma-ray spectrometry for evaluating the activity concentration of ^{238}U and/or ^{232}Th series radionuclides in soil. In-situ measurements in phosphate mining area using handheld BGO gamma-ray spectrometer were compared against laboratory measurements of prepared soil samples using well-shielded and carefully-calibrated HPGe gamma ray spectrometer.

2 Experimental Works

2.1 Area of Study

The selected area of study is near and within Hazm Al-Jalamid phosphate mining area. The mining activities have been going on for few years. The field measurements using handheld BGO gamma-ray spectrometer as well as Gamma-ray spectrometry for soil (using template technique) or phosphate rock samples collected from the same field measurement sites. I think it should be (Thirty-two) sites were selected to evaluate U and Th inventories using both field measurements and laboratory-based measurements using handheld BGO and HPGe gamma-ray spectrometry, respectively. Collected samples for gamma-ray spectrometry were dried at 110 ^{o}C, mechanically crushed, mixed and sieved through a 2 mm mesh. Portions of the dried samples were transferred to polyethylene beakers of 100 ml capacity and sealed for about 4 weeks to reach secular equilibrium between ^{226}Ra and ^{228}Ra and their progenies. For analytical quality control, a reference sediment sample (IAEA-384) and soil samples (IAEA-326 and IAEA-327) from the International Atomic Energy Agency (IAEA) were analyzed to ensure both the accuracy and precision of the measurements.

2.2 Handheld BGO Gamma-Ray Spectrometry for in-Situ Measurements

Handheld RS-300 gamma-ray spectrometer based on BGO detector of 6.3 cubic inch (Radiation Solutions Inc, 386 Watline Ave, Mississauga, Ontario, Canada, L4Z 1X2) where its performance is higher than the comparable volume of NaI (Tl) detectors as survey meter and/or spectrometer. It offers an integrated design with full weather protection, large detector, ease of use and the highest sensitivity in the market segment. This detector is capable for radioactivity full assay with data in eU (ppm),

eTh (ppm) and K%, no radioactive sources are required for proper operation. The spectrometer is calibrated using international standards developed by the Geological Survey of Canada (GSC) that are traceable to the IAEA in Vienna [3,4]. These standards ensure consistent, accurate estimates of U, Th and K. Uranium-238 series, ^{232}Th series and ^{40}K are the main source of terrestrial gamma radiation [5].

The spectrometer was mounted down on the ground where it was set for measurement time of 2 min. The measured eU (ppm), eTh (ppm) and K% were recorded. The RS-230 BGO Super-Spec portable handheld unit spectrometer with high accuracy, and its average probable measurement errors was about 5%. The main factors that reduce assay precision are the statistical nature of radioactivity, variable background radiation due to atmospheric radon, and the variable water content in rocks. Determination of radionuclides content was based on the stripping technique of gamma-ray spectrometry. Potassium-40 content was calculated based on its gamma rays at 1460.8 keV. Uranium-238 (eU) was calculated based on the energy transition of ^{226}Ra-^{222}Rn successor ^{214}Bi at 1764 keV while ^{232}Th$_{eq}$ was calculated based on the energy transition of its successor ^{208}Tl at 2614 keV. Results were expressed in ppm, where 1ppm by weight, of ^{238}U is equivalent to 12.35 Bq/kg, and 1 ppm of ^{232}Th is equivalent to 4.06 Bq/kg. Potassium-40 was expressed in percentage where 1% of natural potassium is equivalent to 313 Bq/kg of ^{40}K [3].

2.2 HPGe Gamma-ray Spectrometry for Laboratory Measurements

Two extended range High Purity Germanium (HPGe) detectors (Canberra Model GX4018) of about 47 % relative efficiency and 1.8 keV FWHM (energy resolution) at 1332 keV gamma-ray energy line of ^{60}Co were simultaneously used. They were associated with preamplifier model 2002CSL, amplifier model 2025, 16 k digital multichannel analyzer multiport II and Genie-2000 gamma-ray spectrometry software. The detectors are mounted on a vertical cryostat model 7935SL with liquid nitrogen Dewar and surrounded by a 10 cm lead shield, which is internally layered by a copper sheet. The energy calibration of the spectrometers was performed using ^{137}Cs and ^{60}Co point sources. Then it was reconfirmed using the multiple energy lines of ^{226}Ra (^{214}Pb-^{214}Bi) point source, using the most intense gamma-ray energy lines such as 186.21 (3.59%), 351.9 (35.6%), 609.3 (45.5%), 1120.3 (14.9%), 1764.5 (15.3%) and 2204.21 (4.9%) keV. The efficiency calibration of the HPGe gamma-ray spectrometer was carried out using the relative efficiency method. The method exploits ^{226}Ra point source and KCl solutions (1 gm KCl = 16.28 Bq of ^{40}K) as a standardization solution. This relative efficiency method is explained in details by [6].

3 Results and Discussion

The concentration of eU and eTh in ppm (mg/kg), and K%, measured by handheld BGO gamma-ray spectrometer and

their calculated activity concentration of [238]U, [232]Th and [40]K in Bq/kg were given in table 1 and 2, respectively. The concentrations of eU and eTh in ppm were calculated using the BGO hand-held spectrometer photopeak of [214]Bi (1764 keV) and [208]Tl (2614 keV). Conversion factor values (Bq/kg)/ppm) of 12.35 and 4.06, respectively were exploited in order to calculate their mass concentrations (ppm) [3]. The measured eU and eTh concentrations were actually represented by [214]Bi (successor of [226]Ra) and [208]Tl (successor of [228]Ac), respectively. The activity concentration of [238]U, [226]Ra, [228]Ra ([232]Th) and [40]K (Bq/kg dry weight) in soil samples, measured using HPGe gamma-ray spectrometers were given in table 3.

The correlation between the activity concentration of [238]U (eU), [232]Th (eTh) and [40]K via in-situ measurement, and [238]U, [226]Ra, [228]Ra and [40]K via laboratory measurement were given in Fig 1. It is obvious that there were not consistent trends regarding the correlations between in-situ and in-laboratory measurements. Even the correlations coefficients (Pearson's coefficient, R) showed week correlation as given in table 4 and shown in Fig. 1. The activity ratios of in-field and in-laboratory of U, Th, Ra and K isotopes were given in table 5. While their descriptive statistical parameters were given in table 6.

It is very crucial to understand the scientific as well as the technical details of both handheld and laboratory gamma-ray spectrometers that were based on BGO and HPGe detectors, respectively. Both are very helpful and relatively accurate but their effectiveness and accuracy will depend on the aim of measurements.

It is highly challenging to establish a solid comparison between the in-situ and laboratory measurements regarding their capabilities. The gamma spectrometric determinations using the HPGe are highly reliable measurements which were directed towards a specific aliquot of soil samples and a very specific sample-detector geometry's full energy peak efficiency calibration. Usually, samples follow standard procedures for the assessment of their radionuclides inventories. The process often begins with samples drying, homogenization, pulverization and sieving. Additionally, the samples are measured in a specified standard volume containers' geometry. This measurements criteria, offer a higher degree of precession due to the eliminations of many sources of errors (samples' geometry, self-attenuation, humidity, and peak's calculations). Although, the laboratory measurement are costly and time consuming but they offer the most accurate mean to determine the activity concentration of specific radionuclide with high accuracy

and precision.

Even with that accurate and precise analytical data, another issue would arise regarding whether the collected soil samples representative or not. It is well known that the in-situ measurements consider area averaging activity concentrations, while laboratory measurements are often related to a specific spot surface soil aliquot. Theoretically, if the soil samples were representative and assuming the accuracy of both in-situ and laboratory analyses, both set of data should be most probably matched with little fluctuations considering the measurements' errors. On the other hand, the hand-held gamma-ray spectrometers could be very useful in many situations and field studies. However, the measurement's reliability might suffer from several factors which could effectively jeopardize it. The irregular terrain of the measured surface could be a major factor. Also, the moisture content and rock matrices could, they could play an essential role in the self-attenuation fluctuations during the measurements. Additionally, the lack of equilibrium between the series' members ([238]U-series and [232]Th-series) could pose another factor of uncertainty.

The measurement of the eU is achieved, as mentioned before, through the assessment of its successor [226]Ra via [214]Bi using the energy transition of 1764.49 keV (15.4%). So the assessment of eU should achieve several phases of equilibrium processes. Under certain circumstances, these equilibriums can be jeopardized causing potential discrepancies in the member's values and resulting in obvious errors in the eU determination. Weathering conditions could cause disequilibrium between [238]U and [226]Ra. Escape of the radon ([222]Rn) as a gas (intermediate member between [226]Ra and [214]Bi) could results in major uncertainties in the assessment of [226]Ra. Accordingly soils, soil aggregates, and partially milled ore materials could be all good candidates for radon escape process. Additionally, the rock's hardness, integrity, and porosity could play an important role to certain extent in the variable rates of radon escape from the rocks matrices. Accordingly, the lack of reasonable correlation between for the current study area could be attributed mainly to the disturbance of equilibrium between [222]Rn and [226]Ra in the studies samples.

It is expected that the hand-held gamma ray spectrometers would effectively perform in areas were rocks are non-weathered, non-porous and are relatively flat. Users of those spectrometers should be more careful when establishing conclusions based on their measurements. Confirmatory measurements for some selected samples using HPGe could be highly recommended afterward.

Table 1: The concentration of equivalent uranium (eU) and equivalent thorium (eTh) in ppm, potassium percentage (K %) measured by handheld BGO gamma-ray spectrometer.

Ser.	Code	eU	eTh	K	Ser.	Code	eU	eTh	K
		ppm		%			ppm		%
1	S1F4	1.8	2.6	0.5	17	S17F42	1.9	3.4	0.4
2	S2F6	2.3	3.9	0.7	18	S18F43	2.6	3.5	0.6

3	S3F11	3.3	1.3	0.1	19	S19F44	2.4	4.0	0.6
4	S4F12	3.4	0.4	0.1	20	S20F45	1.8	4.2	0.5
5	S5F30	2.2	1.6	0.4	21	S21F46	2.8	2.9	0.3
6	S6F31	2.2	3.4	0.5	22	S22F47	2.5	2.6	0.4
7	S7F32	1.9	4.1	0.5	23	S23F48	2.4	3.3	0.4
8	S8F33	8.1	4.5	0.7	24	S24F49	1.9	3.0	0.5
9	S9F34	2.1	3.6	0.5	25	S25F50	5.8	4.6	0.5
10	S10F35	2.5	3.4	0.5	26	S26F51	5.9	3.3	0.7
11	S11F27	2.6	4.9	0.9	27	S27F52	3.0	3.6	0.4
12	S12F37	3.2	3.4	0.5	28	S28F53	3.1	3.9	0.7
13	S13F38	2.9	3.6	0.5	29	S29F54	2.3	2.8	0.8
14	S14F39	2.4	3.9	0.2	30	S30F55	3.9	6.6	0.8
15	S15F40	3.8	5.4	1.0	31	S31F56	2.5	1.8	0.5
16	S16F41	2.2	2.7	0.7	32	S32F57	1.8	3.6	0.6

Table 2: Calculated activity concentration in Bq/kg of ^{238}U, ^{232}Th and ^{40}K based on the eU, eTh and K% concentrations measured using handheld BGO gamma-ray spectrometer.

Ser.	Code	U-238	Th-232	K-40	Ser.	Code	U-238	Th-232	K-40
1	S1F4	22.3	10.6	156.5	17	S17F42	23.6	13.8	125.2
2	S2F6	28.5	15.8	219.1	18	S18F43	32.2	14.2	187.8
3	S3F11	40.9	5.3	31.3	19	S19F44	29.8	16.2	187.8
4	S4F12	42.2	1.6	31.3	20	S20F45	22.3	17.1	156.5
5	S5F30	27.3	6.5	125.2	21	S21F46	34.7	11.8	93.9
6	S6F31	27.3	13.8	156.5	22	S22F47	31.0	10.6	125.2
7	S7F32	23.6	16.6	156.5	23	S23F48	29.8	13.4	125.2
8	S8F33	100.4	18.3	219.1	24	S24F49	23.6	12.2	156.5
9	S9F34	26.0	14.6	156.5	25	S25F50	71.9	18.7	156.5
10	S10F35	31.0	13.8	156.5	26	S26F51	73.2	13.4	219.1
11	S11F27	32.2	19.9	281.7	27	S27F52	37.2	14.6	125.2
12	S12F37	39.7	13.8	156.5	28	S28F53	38.4	15.8	219.1
13	S13F38	36.0	14.6	156.5	29	S29F54	28.5	11.4	250.4
14	S14F39	29.8	15.8	62.6	30	S30F55	48.4	26.8	250.4
15	S15F40	47.1	21.9	313	31	S31F56	31.0	7.3	156.5
16	S16F41	27.3	11.0	219.1	32	S32F57	22.3	14.6	187.8

+ 1 ppm U = 12.4 Bq ^{238}U/kg, 1 ppm Th= 4.06 Bq ^{232}Th/kg, 1% K = 313 ^{40}K/kg (UNSCEAR, 2000)

Table 3: Activity concentration of ^{238}U, ^{226}Ra, ^{228}Ra (^{232}Th) and ^{40}K (Bq/kg dry weight) in soil samples from phosphate mining region, measured by HPGe gamma-ray spectrometry.

Ser.	Code	U-238			Ra-226			Ra-228			K-40		
1	S1F4	22.8	±	4.72	23.6	±	3.6	25.9	±	4.5	257.7	±	7.4
2	S2F6	19.4	±	4.59	26.3	±	6.1	29.1	±	7.2	341.4	±	11.5
3	S3F11	12.3	±	2.59	17.3	±	2.6	20.8	±	3.4	191.0	±	5.3
4	S4F12	12.4	±	3.28	22.8	±	4.9	20.7	±	5.8	211.6	±	9.7
5	S5F30	14	±	3.18	20.8	±	3.0	21.4	±	3.8	186.2	±	5.7
6	S6F31	18.6	±	4.19	22.0	±	5.4	26.8	±	5.9	213.0	±	9.9
7	S7F32	19.3	±	3.48	21.1	±	2.8	23.3	±	3.4	259.1	±	5.9
8	S8F33	6.2	±	5.00	230.5	±	11.1	354.2	±	12.2	182.0	±	12.5
9	S9F34	24.6	±	5.68	22.9	±	4.4	25.0	±	5.3	280.3	±	9.3
10	S10F35	18.3	±	3.21	19.5	±	2.5	21.3	±	3.0	208.1	±	4.9
11	S11F27	30.2	±	4.71	25.2	±	3.1	28.8	±	3.9	299.1	±	6.6
12	S12F37	20.7	±	3.85	20.9	±	23.0	20.9	±	3.5	190.6	±	5.5
13	S13F38	35.2	±	6.82	27.2	±	4.5	31.7	±	5.4	334.1	±	9.5
14	S14F39	5.0	±	1.1	9.7	±	2.5	9.9	±	3.2	107.4	±	4.8
15	S15F40	-		-	-		-	-		-	-		-

16	S16F41	11.6	±	2.8	10.4	±	2.4	9.7	±	2.9	98.7	±	4.4
17	S17F42	31.3	±	4.9	24.9	±	3.1	25.8	±	3.8	264.9	±	6.3
18	S18F43	17.0	±	3.3	21.2	±	2.7	20.5	±	3.3	193.3	±	5.0
19	S19F44	19.5	±	3.2	24.3	±	4.1	22.3	±	4.6	254.0	±	6.6
20	S20F45	8.4	±	2.3	23.4	±	4.5	24.9	±	5.4	314.7	±	8.6
21	S21F46	-		-	-		-	-		-	-		-
22	S22F47	12.9	±	2.3	13.9	±	3.1	15.7	±	3.7	128.1	±	5.8
23	S23F48	14.7	±	4.8	24.2	±	5.7	25.2	±	6.7	246.2	±	10.7
24	S24F49	21.7	±	3.9	24.7	±	3.2	27.9	±	4.0	282.3	±	6.7
25	S25F50	10.0	±	2.8	23.4	±	4.2	25.7	±	5.6	269.8	±	9.1
26	S26F51	11.5	±	3.0	21.9	±	4.6	19.8	±	5.3	207.9	±	7.9
27	S27F52	-		-	-		-	-		-	-		-
28	S28F53	15.3	±	5.5	19.6	±	5.9	20.2	±	7.2	197.8	±	11.0
29	S29F54	18.8	±	3.8	20.4	±	3.1	22.7	±	3.7	256.8	±	6.6
30	S30F55	13.7	±	2.7	22.3	±	4.1	24.4	±	4.8	294.2	±	8.3
31	S31F56	13.9	±	3.3	22.5	±	4.4	19.3	±	5.2	216.5	±	8.3
32	S32F57	-		-	-		-	-		-	-		-

Table 4: Pearson's correlation coefficients of activity concentrations of in-situ measured ^{238}U, ^{232}Th and ^{40}K, and laboratory measured ^{238}U, ^{226}Ra, ^{228}Ra and ^{40}K.

	U-238*	Th-232*	K-40*	U-238	Ra-226	Ra-228	K-40
U-238*	1	0.26	0.20	-0.42	0.70	0.70	-0.13
Sig.	--	0.16	0.27	0.03	0.00	0.00	0.50
Th-232*	0.26	1	0.66	0.08	0.20	0.21	0.38
Sig.	0.16	--	0.00	0.68	0.30	0.29	0.05
K-40*	0.20	0.66	1	0.20	0.20	0.20	0.30
Sig.	0.27	0.00	--	0.30	0.30	0.32	0.12
U-238	-0.42	0.08	0.20	1	-0.24	-0.25	0.56
Sig.	0.03	0.68	0.30	--	0.23	0.21	0.00
Ra-226	0.70	0.20	0.20	-0.24	1	1.00	-0.06
Sig.	0.00	0.30	0.30	0.23	--	0.00	0.75
Ra-228	0.70	0.21	0.20	-0.25	1.00	1	-0.08
Sig.	0.00	0.29	0.32	0.21	0.00	--	0.67
K-40	-0.13	0.38	0.30	0.56	-0.06	-0.08	1
Sig.	0.50	0.05	0.12	0.00	0.75	0.67	--

*In-Situ measured activity concentration of U (eU), Th (eTh) and K using handheld BGO gamma-ray spectrometer.

Table 5: Activity concentration ratios of ^{238}U (eU), ^{232}Th (eTh) and ^{40}K (K), and ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K using handheld BGO gamma-ray spectrometry (In-Situ) and laboratory HPGe gamma-ray spectrometry (Lab), respectively, ^{238}U (eU)/ ^{226}Ra, ^{238}U (eU)/^{238}U, ^{232}Th (eTh)/^{228}Ra, ^{40}K (K)/^{40}K.

Ser.	Code	^{238}U (eU)/^{226}Ra	^{238}U (eU)/^{238}U	^{232}Th (eTh/^{228}Ra	^{40}K (K)/^{40}K	Ser.	Code	^{238}U (eU)/^{226}Ra	^{238}U (eU)/^{238}U	^{232}Th (eTh/^{228}Ra	^{40}K (K)/^{40}K
1	S1F4	0.94	0.98	0.41	0.61	17	S17F42	0.95	0.75	0.53	0.47
2	S2F6	1.09	1.47	0.54	0.64	18	S18F43	1.52	1.90	0.69	0.97
3	S3F11	2.37	3.33	0.25	0.16	19	S19F44	1.23	1.53	0.73	0.74
4	S4F12	1.85	3.41	0.08	0.15	20	S20F45	0.96	2.67	0.68	0.50
5	S5F30	1.31	1.95	0.30	0.67	21	S21F46				
6	S6F31	1.24	1.47	0.52	0.73	22	S22F47	2.23	2.40	0.67	0.98
7	S7F32	1.12	1.22	0.71	0.60	23	S23F48	1.23	2.02	0.53	0.51
8	S8F33	0.44	16.34	0.05	1.20	24	S24F49	0.96	1.08	0.44	0.55
9	S9F34	1.14	1.06	0.59	0.56	25	S25F50	3.07	7.23	0.73	0.58
10	S10F35	1.59	1.69	0.65	0.75	26	S26F51	3.35	6.35	0.68	1.05

11	S11F27	1.28	1.07	0.69	0.94	27	S27F52				
12	S12F37	1.90	1.92	0.66	0.82	28	S28F53	1.97	2.51	0.78	1.11
13	S13F38	1.32	1.02	0.46	0.47	29	S29F54	1.40	1.52	0.50	0.98
14	S14F39	3.08	5.95	1.61	0.58	30	S30F55	2.17	3.52	1.10	0.85
15	S15F40					31	S31F56	1.38	2.23	0.38	0.72
16	S16F41	2.62	2.36	1.13	2.22	32	S32F57				

Table 6: Descriptive statistics of activity concentration ratios of ^{238}U (eU), ^{232}Th (eTh) and ^{40}K (K), and ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K using handheld BGO gamma-ray spectrometry (In-Situ) and laboratory HPGe gamma-ray spectrometry (Lab), respectively, ^{238}U (eU)/ ^{226}Ra, ^{238}U (eU)/^{238}U, ^{232}Th (eTh)/^{228}Ra, ^{40}K (K)/^{40}K.

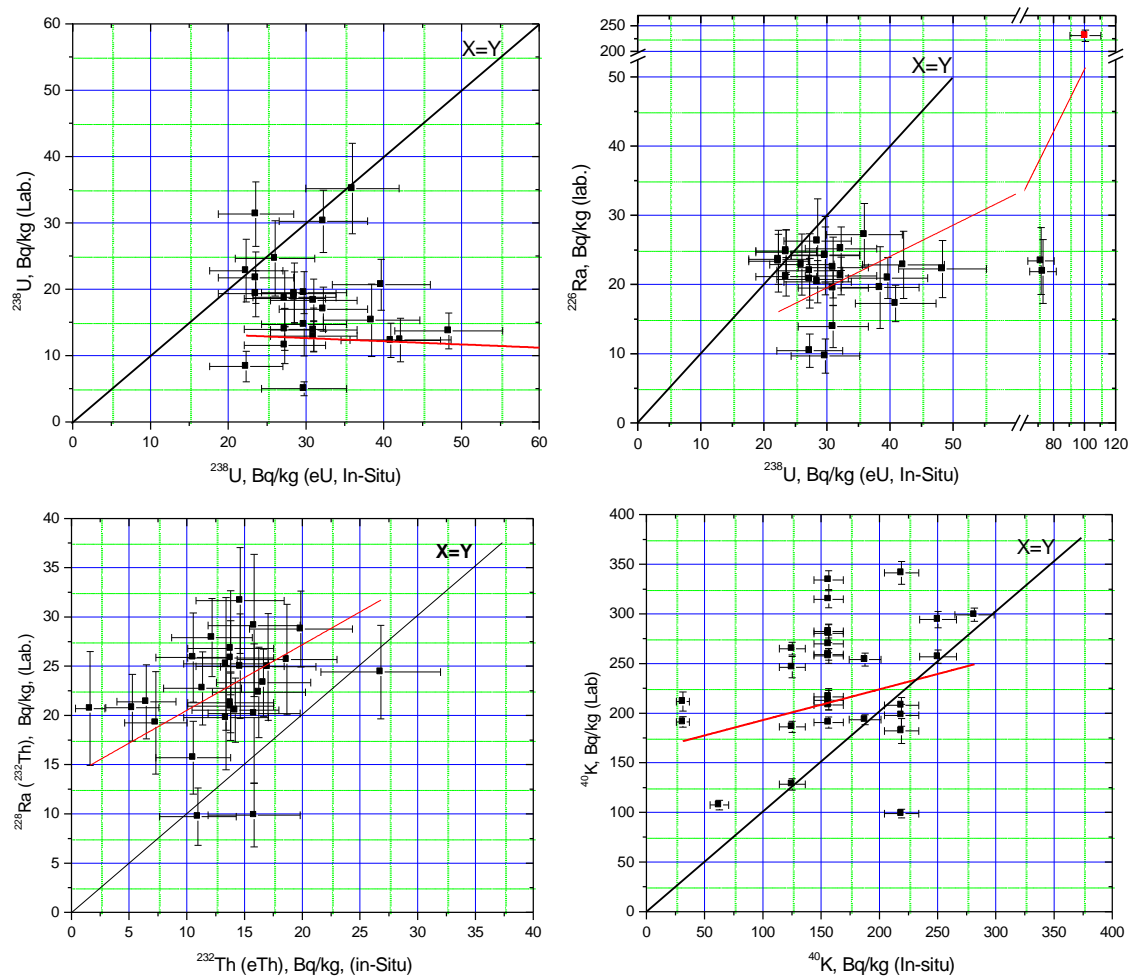|	eU/Ra-226	eU/U-238	eTh/Ra-228	K*/K-40
Mean	1.63	2.89	0.61	0.75
Stand. Error	0.14	0.59	0.06	0.07
Stand. Deviation	0.73	3.10	0.31	0.38
Minimum	0.44	0.75	0.05	0.15
Maximum	3.35	16.34	1.61	2.22
Count	28	28	28	28

Fig.1: The correlations between the activity concentrations (Bq/kg) of ^{238}U (eU), ^{232}Th (eTh) and ^{40}K (K), and ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K using handheld BGO gamma-ray spectrometry (In-Situ) and laboratory HPGe gamma-ray spectrometry (Lab), respectively.
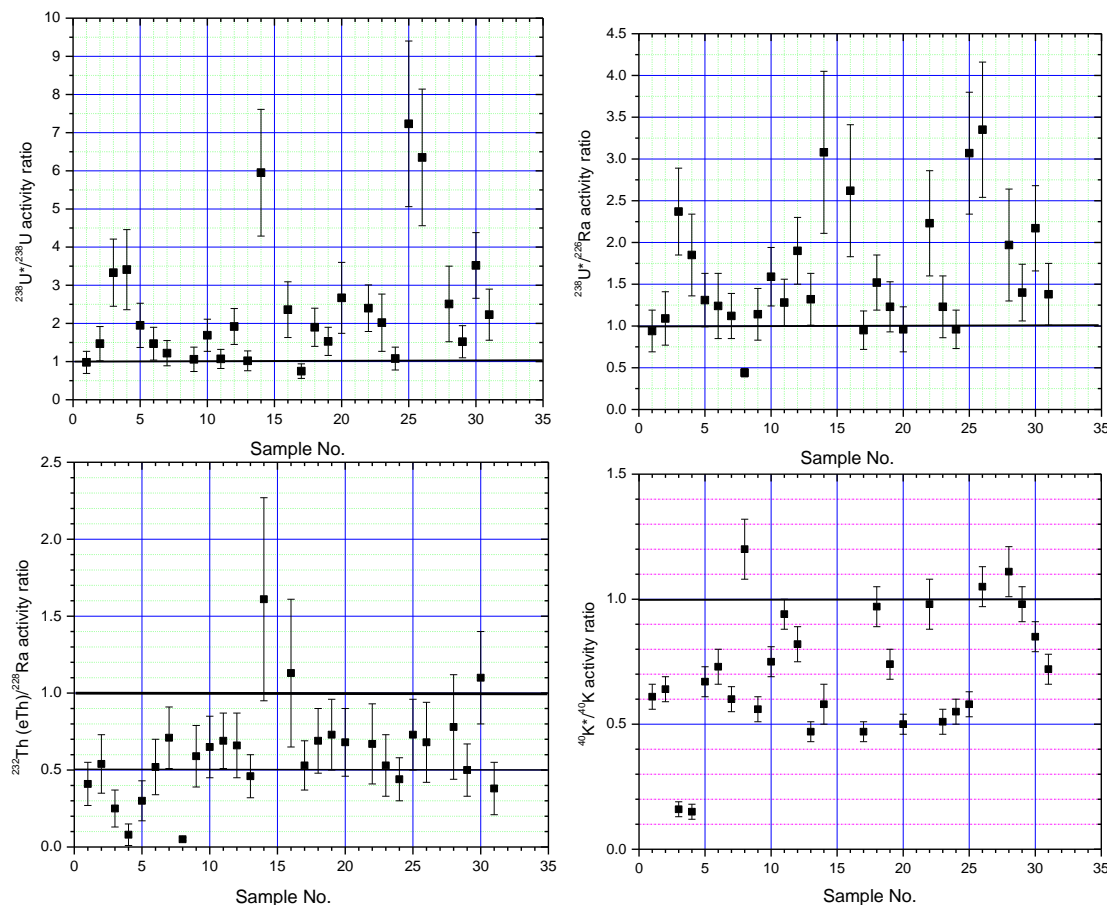
Fig. 2: Activity concentration ratios of ^{238}U (eU), ^{232}Th (eTh) and ^{40}K (K), and ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K using handheld BGO gamma-ray spectrometry (In-Situ) and laboratory HPGe gamma-ray spectrometry (Lab), respectively, ^{238}U (eU)/ ^{226}Ra, ^{238}U (eU)/^{238}U, ^{232}Th (eTh)/^{228}Ra, ^{40}K (K)/^{40}K.

4 Conclusions

Handheld gamma-ray spectrometers were widely used in various fields such as geological studies, ore exploration and radioecological studies. Our study revealed that comparing the measurements of radioactivity concentration of eU, eTh and K via in-situ handheld BGO gamma-ray spectrometer with that of ^{238}U, ^{226}Ra, ^{232}Th, ^{226}Ra, and ^{40}K via in laboratory HPGe gamma-ray spectrometers was highly challenging. Although most published data and user of handheld gamma-ray spectrometers express eU and eTh as an equivalent to activity concentration of ^{238}U and ^{232}Th, respectively, which is not correct. Other factors were made this comparison barely practical and/or scientifically possible such as sample-detector geometry, detectors characterization, variability of in-field humidity, radon (^{222}Rn) and thoron (^{220}Rn) gas escape, and U and Th series disequilibrium. Finally handheld gamma-ray spectrometers were a powerful tool for both practical and scientific applications and their out data should be carefully used

where for example eU and eTh concentrations would be related to ^{214}Bi and ^{208}Tl, and not to ^{238}U and ^{232}Th, respectively.

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