

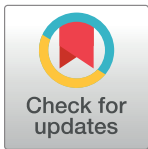
RESEARCH ARTICLE

The presence of radioactive heavy minerals in prospecting trenches and concomitant occupational exposure

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OPEN ACCESS

Citation: Hanfi MYM, Masoud MS, Sayyed MI, Khandaker MU, Faruque MRI, Bradley DA, et al. (2021) The presence of radioactive heavy minerals in prospecting trenches and concomitant occupational exposure. *PLoS ONE* 16(3): e0249329. <https://doi.org/10.1371/journal.pone.0249329>

Editor: Flavio Manoel Rodrigues Da Silva Júnior, Universidade Federal do Rio Grande - FURG, BRAZIL

Received: October 27, 2020

Accepted: March 15, 2021

Published: March 31, 2021

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Data Availability Statement: All relevant data are provided within the manuscript.

Funding: This work was supported by Research Universiti Grant, Universiti Kebangsaan Malaysia, Dana Impak Perdana (DIP), code: 2020-018.

Competing interests: The authors declare no conflict of interest.

Abstract

Uranium, perhaps the most strategically important component of heavy minerals, finds particular significance in the nuclear industry. In prospecting trenches, the radioactivity of ²³⁸U and ²³²Th provides a good signature of the presence of heavy minerals. In the work herein, the activity concentrations of several key primordial radionuclides (²³⁸U, ²³²Th, and ⁴⁰K) were measured in prospecting trenches (each of the latter being of approximately the same geometry and physical situation). All of these are located in the Seila area of the South Eastern desert of Egypt. A recently introduced industry standard, the portable hand-held RS-230 BGO gamma-ray spectrometer (1024 channels) was employed in the study. Based on the measured data, the trenches were classified as either non-regulated (U activity less than 1000 Bq kg⁻¹) or regulated (with ²³⁸U activity more than 1000 Bq kg⁻¹). Several radiological hazard parameters were calculated, statistical analysis also being performed to examine correlations between the origins of the radionuclides and their influence on the calculated values. While the radioactivity and hazard parameters exceed United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) guided limits, the mean annual effective doses of 0.49 and 1.4 mSv y⁻¹ in non-regulated and regulated trenches respectively remain well below the International Commission on Radiological Protection (ICRP) recommended 20 mSv/y maximum occupational limit. This investigation reveals that the studied area contains high uranium content, suitable for extraction of U-minerals for use in the nuclear fuel cycle.

1. Introduction

The radioactivity of the living environment is contributed to by terrestrial and extra-terrestrial sources. Terrestrial natural radionuclides (^{238}U , ^{232}Th and their progeny, and ^{40}K) exist in all ground formations, forming the main sources of external gamma radiation exposure to humans [1–3]. Extra-terrestrial sources such as cosmogenic radionuclides (^{36}Cl , ^{32}Si , ^{26}Al , ^{14}C , ^{10}Be , ^7Be and ^3H) exist at trace levels, forming a minor part of radiation exposure to humans, albeit at levels varying with altitude and location. About 96% of the total radiation dose to the world population is from these natural sources, while 4% arises from anthropogenic sources [2, 4]. Elevated levels of environmental radiation are contributed to by igneous rocks such as granite, with lower levels typically being associated with sedimentary rocks. Both are used as essential raw materials for building material purposes, landfill etc. The presence of terrestrial radionuclides in raw materials used for constructional intent may pose radiation risks within the living environment [5].

Prospecting for and research on important minerals is being carried out in many parts of the world. Uranium mining in particular is unique in that currently the ores represent the only source of nuclear fuel for nuclear power production [6, 7]. In uranium prospecting, the principal sources of occupational exposure are inhaled radon, thoron, and their respective progenies from the ^{238}U and ^{232}Th series, along with the associated external irradiation gamma rays [8–12].

Uranium ore deposits in Egypt are found in several areas, including El-Missikate and El-Erediya (in the Central Eastern Desert of Egypt), Gable Gattar (in the North Eastern Desert of Egypt), Abu Rusheid, El Seila and Um Ara (in the South Eastern Desert of Egypt), and Abu Zeneima (South of Sinai) [13, 14]. While numerous studies around the world, including in Egypt, have concerned determination of radiation levels in various trenches or ores as indicators of mineral deposits [15–23], no such investigation has been found for the trenches of the El Seila area of Egypt.

The nomadic El-Bishariya tribe inhabit areas around Seila, practicing a pastoral life-style within this region of the South East Desert. The area is also one with occurrences in the granites of natural uranium, U_{Nat} . Over the past several decades, with guidance offered under programmes of the International Atomic Energy Agency (IAEA), Egypt has paid great attention to the possibility of using nuclear energy to produce electricity. The responsible national authorities examining justification of such process includes the Nuclear Materials Authority (NMA), undertaking exploration for radioactive raw materials. The NMA has established an exploration project to evaluate and extract radioactive raw materials, primarily from uranium-bearing heavy minerals. Accordingly, many open trenches have been created, workers consequently being exposed, not least from the external gamma radiation from the terrestrial radionuclides, either at site or during transportation. Most of the trenches have been located in mountainous or relatively uneven areas, drilling and transportation of the heavy minerals accordingly representing a relatively difficult task. Moreover, weathering, aeration and rock fracturing processes lead to stream sediments, concentrated in various wadis and tributaries, further contributing to radiation exposures, both to surrounding dwellers as well as personnel working in the various prospecting processes.

The present work forms the first such study determining terrestrial radionuclide concentrations and estimating the concomitant radiation exposure inside these particular open prospecting trenches. Several radiological parameters such as the radium equivalent activity Ra_{eq} (Bq kg^{-1}), absorbed dose rate in air D (nGy h^{-1}), and the annual effective dose AED (mSv y^{-1}) have been estimated, seeking evaluation of radiation risk, most particularly to trench workers. Details of the study are presented in the following sections.

2. Materials and methods

2.1 Environmental setting of the prospecting trenches

The prospecting trenches in the area of Seila are located between latitudes $22^{\circ} 13' 48'' - 22^{\circ} 18' 36''$ N and longitudes $36^{\circ} 10' 12'' - 36^{\circ} 18' 36''$ E (Fig 1). The granite within these trenches are large highly weathered entities, exposed within low-to-moderately separated hills, being coarse-grained, and pink to pinkish-grey in colour. It is mainly composed of quartz, K-feldspar, plagioclase, biotite, and rare muscovite and is characterized by the presence of iron and manganese oxides filling joints and fractures, indicating Fe and Mn mineralization. The area is further intruded by fine-grained granite, occurring as sheets and dykes trending north-west (NW) to south-east (SE). This granite, dissected by basic dykes, are massive, fine-grained, and range in colour from greyish-green to dark grey, mostly trending east-north-east (ENE) to west-south-west (WSW), usually injected along the extension planes. The southern part of the coarse-grained granite is dissected by a barren quartz vein trending ENE-WSW, extending for more than 600 m, the widest parts ranging from 1 to 10 m [24]. This area is the one in which most of the granite trenches are distributed, perpendicular to the ENE-WSW shear zone. The length of these trenches range from 10 m to 15 m, with width from 5 m to 8 m, and depth of 5–6 m [25, 26].

2.2. Sampling method and experimental measurements

A portable, industry-standard RS-230 BGO gamma-ray spectrometer was used to determine the terrestrial radionuclides content in the trenches, popular in uranium exploration. This handheld instrument has been reported to offer convenience and affordability, comparison being

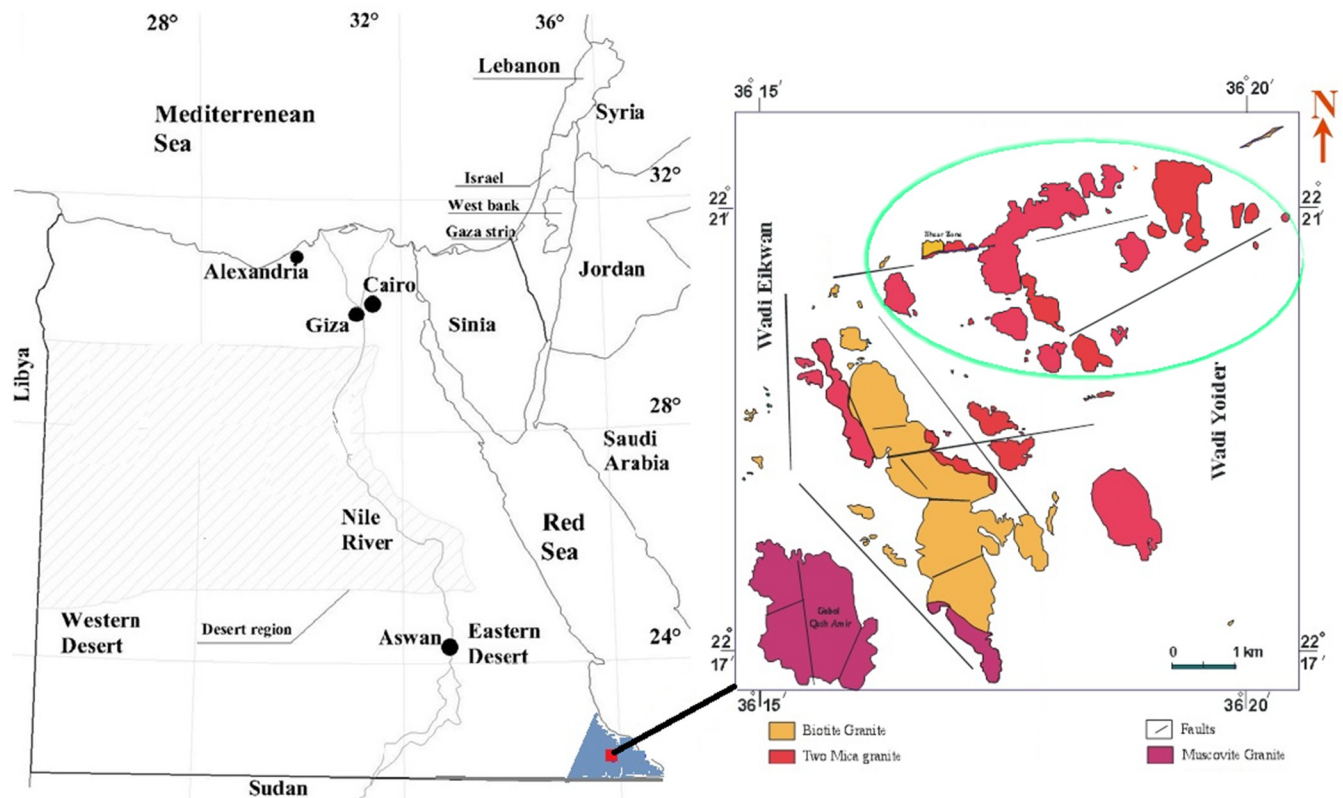


Fig 1. [a] Map of Egypt with the investigated area, [b] the geological map of the Seila area together with the distribution of prospecting trenches [27].

<https://doi.org/10.1371/journal.pone.0249329.g001>

made against that of a number of other portable units [28]. Terraplus (2013) showed that a 120 s duration RS-230 BGO measurement provides comparable quality to that performed using the much larger 21 in³ NaI portable detector. The spectrometer auto-stabilizes on the naturally occurring radioactivity (K, U, & Th) and does not require any test sources [29].

The present study was carried out as a field study for many regions in Egypt by the Nuclear Materials Authority (NMA). The first and second authors are working in the NMA. This work was done as a part of their MSc. thesis. The area of interest is not restricted or under control, and it is open for measurement by any researchers. The samples were not collected from the prospecting trenches, instead a portable gamma-ray spectroscopy (RS-230) was employed. The RS-230 builds up with a 6.3 in³ (103 cm³) high density bismuth germinate oxide (BGO) detector. The main characteristics is the recording of readout result rapidly, which facilitates repeated measurements within a short period.

A total of 20 trenches have been studied, obtaining 30 s duration direct readings of ²³⁸U, ²³²Th, and ⁴⁰K, recorded in ppm, recorded four times for each trench in order to obtain good statistics. The RS-230 BGO spectrometer also provides a measure of the percentage of potassium in the trenches. The radiological measurements were defined by the activity concentration (Bq kg⁻¹) instead of content (ppm) [28], both listed in Table 1.

Following the recommendation of the IAEA [30], the measured activity concentrations of terrestrial radionuclides in the prospecting trenches have been divided into two categories, non-regulated and regulated. For this, the IAEA has established reference values of 1 Bq/g for radioactive material ²³⁸U and ²³²Th, and 10 Bq/g for ⁴⁰K; above these values the radioactive material is recommended to be regulated [30].

2.2.1 Assessment of radiation hazard. The key radiological hazard indices were: radium equivalent activity (Bq kg⁻¹), absorbed dose rate (nGy h⁻¹), and annual effective dose (mSv y⁻¹), seeking to evaluate the radiation risk to occupationally exposed workers.

2.2.2 Radium equivalent activity (Ra_{eq}). This index is related to the external gamma-ray exposure and internal dose due to alpha particles, the following formula being used [31]:

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

with A_U , A_{Th} , and A_K the activity concentrations of uranium, thorium, and potassium in Bq kg⁻¹. The weights are based on the estimated dose of 370 Bq kg⁻¹ for ²³⁸U, 259 Bq kg⁻¹ for ²³²Th, and 4810 Bq kg⁻¹ for ⁴⁰K [32].

2.2.3 Absorbed dose rate. The absorbed dose rate D (nGy h⁻¹) is conventionally determined by assessing the gamma-ray exposure at 1 m above the ground surface. This value can be calculated by using the following equation [28, 33]:

$$D(nGy h^{-1}) = 0.427A_U + 0.662A_{Th} + 0.043A_K \quad (2)$$

2.2.4 Annual effective dose. To assess the occupational radiation exposure due to natural radioactivity inside the open prospecting trenches, the annual effective dose (AED) was estimated in mSv y⁻¹, the following equation being used [1]:

$$AED(mSv y^{-1}) = D(nGy h^{-1}) \times 2000 \times 1(Sv Gy^{-1}) \quad (3)$$

Table 1. Conversion of radioelement content to activity concentration (Bq kg⁻¹).

Radioelement	Content	Activity concentration (Bq kg ⁻¹)
⁴⁰ K	1% K in rock	313
²³⁸ U	1 ppm U in rock	12.4
²³² Th	1 ppm Th in rock	4.06

<https://doi.org/10.1371/journal.pone.0249329.t001>

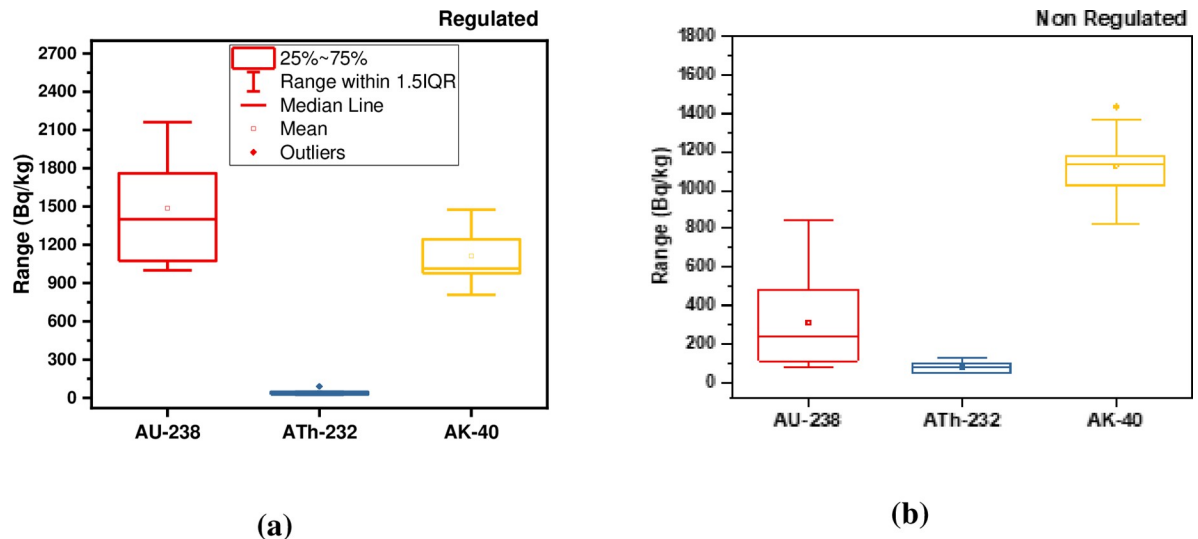


Fig 2. Box and whisker plot of ^{238}U , ^{232}Th , and ^{40}K activity concentrations (Bq kg^{-1}) in: (a) the regulated trenches and; (b) non-regulated trenches.

<https://doi.org/10.1371/journal.pone.0249329.g002>

where the duration of occupational exposure is taken to be 2000 h/y, with a conversion factor of 1 Sv Gy^{-1} for whole-body exposures.

2.3. Statistical analysis

Variation in radionuclide activity, in terms of mean and standard deviation was assessed, also data normality, use being made of a one-way analysis of variance (ANOVA-1). SPSS software (SPSS, 2006) was used to test the means by Duncan's multiple ranges at $P < 0.05$.

3. Results and discussion

The studied trenches are approximately of the same geometry and physical condition. The average activity concentrations in the two types of trenches (non-regulated and regulated) are shown in Fig 2. For non-regulated trenches, the mean activity concentrations of ^{238}U , ^{232}Th and ^{40}K are 313, 76, 1131 Bq kg^{-1} with ranges (49 to 510 Bq kg^{-1}), (42 to 126 Bq kg^{-1}), and (805 to 1477 Bq kg^{-1}) respectively. For regulated trenches, the average activity concentrations are 1487, 42, 1112 Bq kg^{-1} with ranges (1100 to 2163 Bq kg^{-1}), (25 to 92 Bq kg^{-1}), and (805 to 1435 Bq kg^{-1}) for ^{238}U , ^{232}Th and ^{40}K respectively.

Overall, the highest activity concentrations of ^{238}U , ^{232}Th , and ^{40}K have been found to be 2163 ± 126 , 126 ± 5 , and $1476 \pm 120 \text{ Bq kg}^{-1}$, respectively, while the respective lowest values were observed to be 49 ± 3 , 25 ± 2 , and $805 \pm 15 \text{ Bq kg}^{-1}$. These values, other than some small values for ^{232}Th , are greater than the UNSCEAR reported reference values of 33, 45, and 412 Bq kg^{-1} for uranium, thorium, and potassium [1]. The various terrestrial radionuclide concentration values in the different prospecting trenches are reflective of geological formation variability, the granite rocks in the studied trenches being considered uriferous granite in that they contain at least twice the Clarke value [34]. The normal probability of ^{238}U , ^{232}Th , and ^{40}K activity concentrations in the studied regulated and non-regulated prospecting trenches are presented in Fig 3.

The calculated radium equivalent activity (Ra_{eq}) values for each studied trenches (both regulated and non-regulated) are presented in Fig 4. The Ra_{eq} values ranging from 282 to 1004 Bq kg^{-1} with a mean of 510 Bq kg^{-1} for the non-regulated prospecting trenches. In the regulated

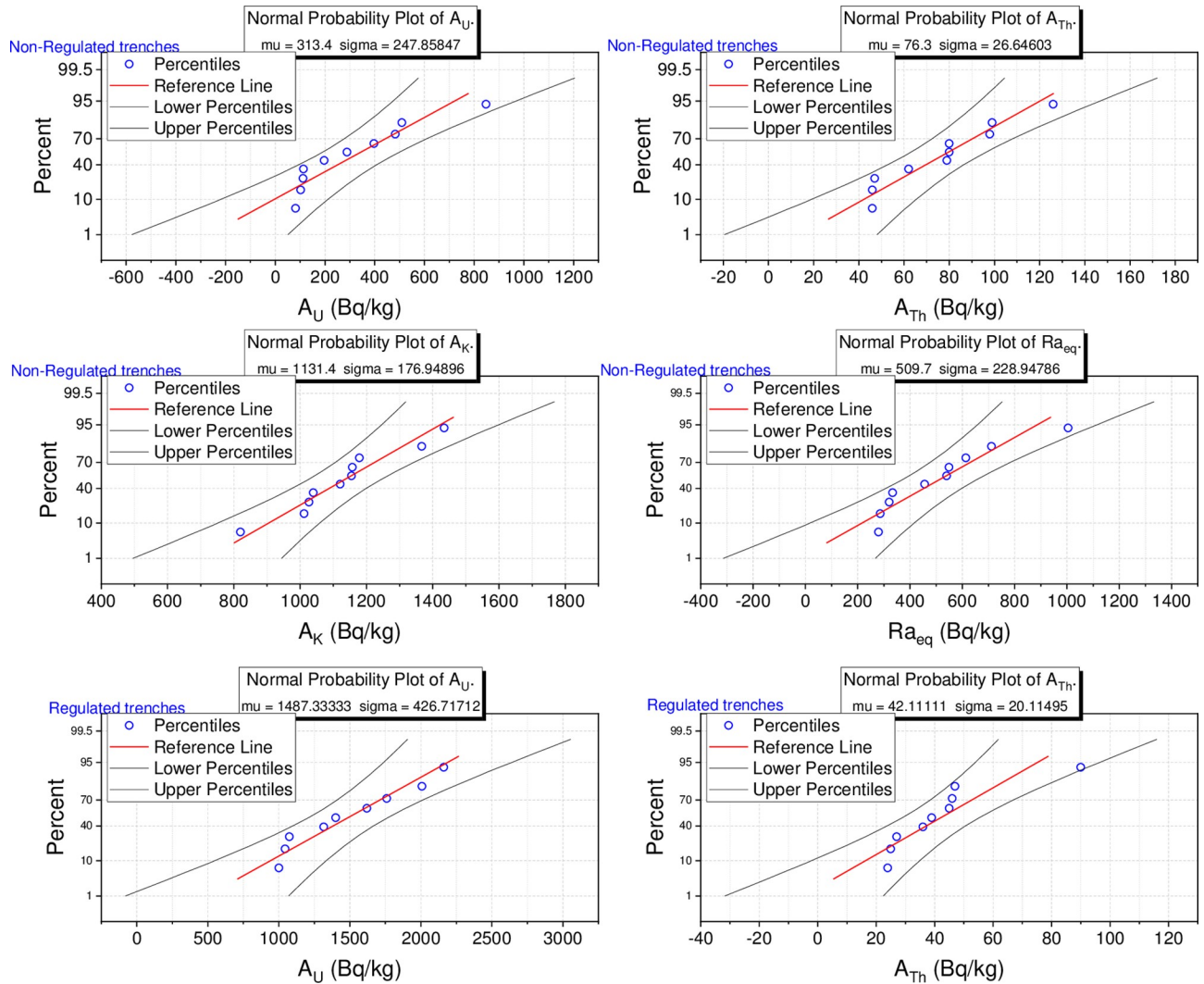


Fig 3. The normal probability of ^{238}U , ^{232}Th , and ^{40}K activity concentrations for the studied non-regulated and regulated trenches.

<https://doi.org/10.1371/journal.pone.0249329.g003>

prospecting trenches, the range of Ra_{eq} values are 1146–2282 Bq kg^{-1} with a mean of 1634 Bq kg^{-1} . The mean values of Ra_{eq} in all of the prospecting trenches these are above the recommended value of 370 Bq kg^{-1} [31], graphically represented in Fig 4. The higher Ra_{eq} belong to granite rocks, rich in potassium together with content of uranium, thorium, and their decay products [35, 36].

In regard to the estimated occupational absorbed dose rates in air (nGy h^{-1}), in the non-regulated and regulated prospecting trenches respectively, these range from 131 to 446 nGy h^{-1} with a mean of 241 nGy h^{-1} , and from 505 to 982 nGy h^{-1} with a mean of 709 nGy h^{-1} . In all of the prospecting trenches these absorbed dose rates are above the recommended value of 59 nGy h^{-1} [1].

The occupational radiation exposure inside the prospecting trenches occurs via two different pathways: external exposure from gamma-rays and internal exposure due to the inhalation of radon and thoron gases and their decay products, attached to atmospheric dust. Present study focuses on the external gamma exposure to workers in the prospecting trenches, with the annual effective dose estimated based on a working period of 2000 h over one year. Fig 5

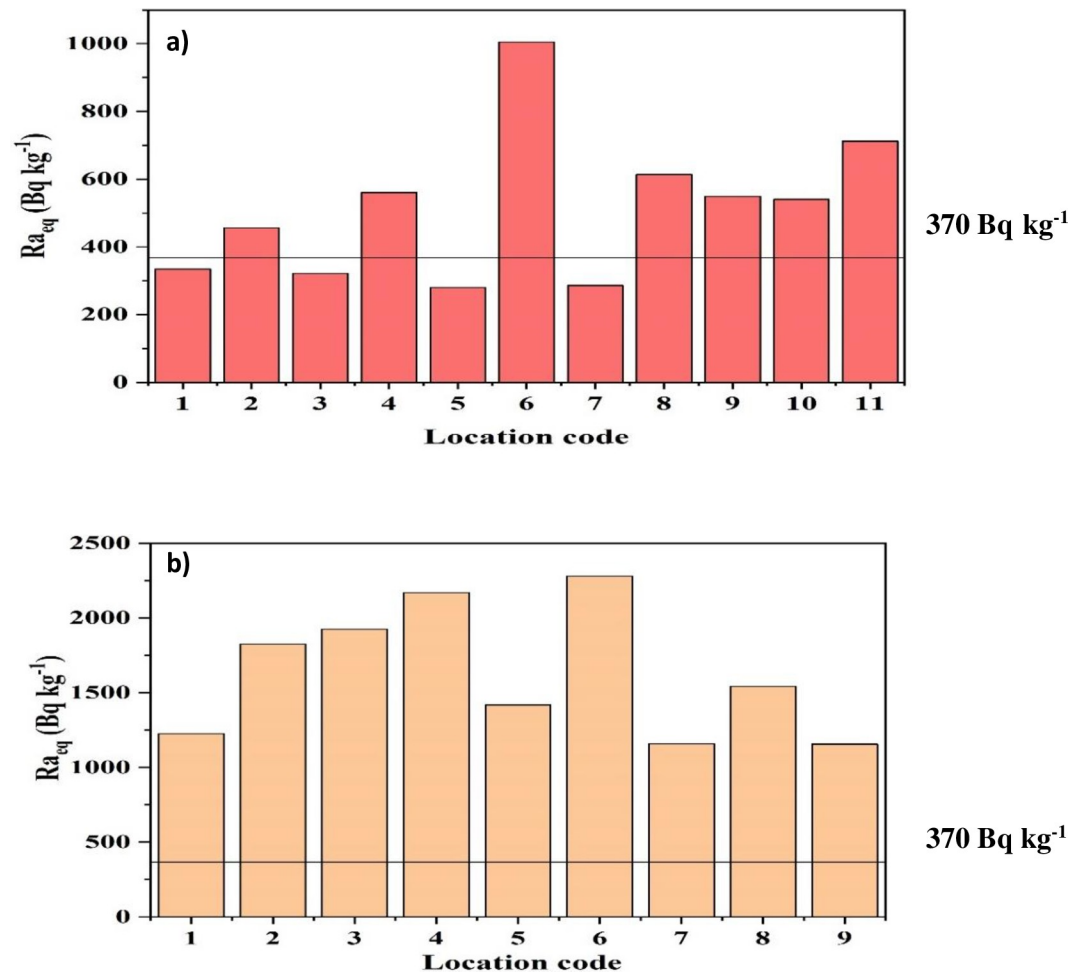


Fig 4. Radium equivalent activity in: (a) non-regulated (a) and; (b) regulated trenches.

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shows the average annual effective dose (AED) for non-regulated and regulated trenches in the Seila area, with respective values of 0.48 (range 0.27–0.89) mSv y⁻¹ and 1.4 (range 1.01–1.97) mSv y⁻¹. The occupational AED for regulated trenches exceeds the recommended safe level limit of 1 mSv y⁻¹ for members of the public, although it is very much lower than the occupational maximum limit of 20 mSv y⁻¹, as mentioned in respect of prospecting trenches [37]. The observed annual effective dose in the trenches showed no significant radiation dose from gamma radiation. Nevertheless, people who live in this area or use the residues as building materials may be exposed to elevated levels of radiation dose.

The ²³²Th/²³⁸U ratios for non-regulated and regulated trenches in the Seila area are shown in Fig 5, comparison being made with the world average value of 3.94 [38]. The ²³²Th/²³⁸U ratio for non-regulated trenches ranges between 0.054 and 0.975, with a mean of 0.495. The range for regulated trenches is 0.018 to 0.055, with a mean value of 0.03. These values are below the worldwide average value [39–41], point to the Seila trenches media being igneous zircon [42], containing high uranium-content granitic rocks. Related to variations in stream sediments in terms of geochemical properties, the weather conditions may have affected this ratio. It is worth mentioning that the trenches are located on the high mountains and hills, which surrounded the Seila area. The weather in this area is characterized by rainy in the

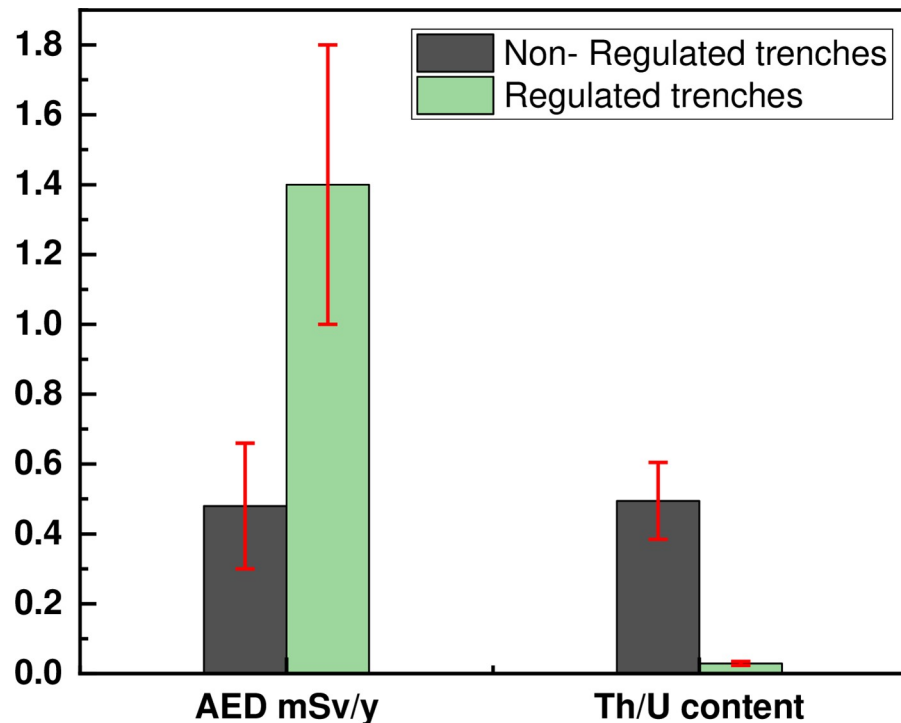


Fig 5. The average AED (in mSv/y) and the Th/U ratio.

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winter season, therefore the leaching processes could be happened and there is a high possibility that the stream sediments may contributed in various ratios.

The statistical analysis was performed using Pearson correlation for the results in non-regulated and regulated trenches and presented in Tables 2 and 3. Table 2 shows that A_U has a strong negative correlation with A_{Th} and A_K and a weak negative correlation with the Th/U ratio. A_{Th} has a positive correlation with the Th/U ratio. A_K has a negative correlation with A_{Th} and a positive correlation with A_U . This is due to the relatively high activity of ^{238}U and ^{40}K .

Table 3 shows that A_K has a negative correlation with all other parameters due to the relatively high activity concentration of ^{238}U , greater than 1 kBq kg^{-1} and more elevated than the activity of ^{40}K itself. A_{Th} has a positive correlation with all other parameters except for A_K . A_U has a strong negative correlation with A_K and the Th/U ratio but a weak positive correlation with A_{Th} . In both non-regulated and regulated trenches, A_U has a strong correlation with the

Table 2. Pearson correlation for non-regulated trenches.

	A_U	A_{Th}	A_K	Ra_{eq}	D_{air}	AED	Th/U
A_U	1	-	-	-	-	-	-
A_{Th}	-0.35	1	-	-	-	-	-
A_K	-0.33	-0.36	1	-	-	-	-
Ra_{eq}	0.90	-0.41	0.070	1	-	-	-
D_{air}	0.834	-0.44	0.21	0.98	1	-	-
AED	0.84	-0.45	0.21	0.98	0.99	1	-
Th/U	-0.87	0.38	0.34	-0.75	-0.68	-0.68	1

<https://doi.org/10.1371/journal.pone.0249329.t002>

Table 3. Pearson correlation for regulated trenches.

	A_U	A_{Th}	A_K	R_{aeq}	D_{air}	AED	Th/U
A_U	1	-	-	-	-	-	-
A_{Th}	0.29	1	-	-	-	-	-
A_K	-0.15	-0.14	1	-	-	-	-
R_{aeq}	0.99	0.34	-0.12	1	-	-	-
D_{air}	0.99	0.35	-0.11	0.99	1	-	-
AED	0.99	0.35	-0.10	0.99	0.99	1	-
Th/U	-0.25	0.82	-0.046	-0.20	-0.19	-0.19	1

<https://doi.org/10.1371/journal.pone.0249329.t003>

radiological hazard indices (R_{aeq} , D_{air} , and AED), approaching unity. This is due to the activity of ^{238}U , in all trenches being greater than the recommended limit.

5. Conclusions

The Seila region in Egypt is considered as a potential area for exploration of heavy minerals, therefore the prospecting trenches were drilled following some geological and radioactive studies. Present study forms an interest of measuring the concentrations of terrestrial radionuclides in some non-regulated and regulated trenches in this area. The mean activity concentrations of ^{238}U , ^{232}Th , and ^{40}K are found to be 313.4, 76.3 and 1131.4 Bq kg⁻¹ respectively in non-regulated trenches, and 1487, 42, and 1112 Bq kg⁻¹ respectively in the regulated trenches. In the regulated trenches, with the exception of thorium, the values are greater than that of the worldwide mean data. The estimated radiological indices and concomitant dose show that the workers in the prospecting trenches receive a much lower annual effective dose than the maximum occupational limit of 20 mSv/y, but in regulated trenches the values are above the safe limit of 1 mSv/y for the general population. In order to avoid any unnecessary radiation exposure, measured data suggests the need for control in use of any trench materials/residues for construction of dwellings. The measured concentrations of ^{238}U clearly support the viability of heavy mineral (uranium) extraction for practical applications within the nuclear fuel cycle.

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Writing – review & editing: Mayeen Uddin Khandaker, D. A. Bradley.

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