Airborne gamma-ray spectrometric data, covering Gabal Umm Hammad area, near Quseir City, in the Eastern Desert of Egypt, has been utilized to identify the uranium migration path, and U, Th and K-favorability indices. The following of the uranium migration technique enabled estimation of the amount of migrated uranium, in and out of the rock units. Investigation of the Taref Formation, Nakhil Formation, Tarawan Formation and Dawi Formation shows large negative amount of uranium migration, indicating that uranium leaching is outward from the geologic body toward surrounding rock units. Moreover, calculation of the U, Th and K-favorability indices has been carried out for the various rock units to locate the rocks having the highest radioelement potentialities. The rock units that possess relatively major probability of uranium potentiality include Mutiq Group, weakly deformed granitic rocks, and Trachyte plugs and sheets. Meanwhile, the rock units with major potential of Th-index are Taref Formation, Quseir Formation and Dawi Formation. The rock units with major potential of K-index are Dokhan volcanic and Mutiq group.

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1. Introduction

Utilization of gamma-ray spectrometric method, as a tool of geophysical prospecting, is based mainly on mapping the surface anomalies induced by the decay products of the natural radioactive series of $^{238}\text{U}$ and $^{232}\text{Th}$, as well as the natural isotope $^{40}\text{K}$. The anomalous values of concentrations of these three radioactive elements can be used to map the mineralized zones in the uraniferous deposits (Hiodo et al., 1999). The method constitutes an important element for explanation of the geologic units (Dickson and Scoot, 1997) and, eventually, for the identification of structures, that bound lithologic units. Gamma-ray spectrometric signatures of rocks can be used to delineate the lithologies and structures (Darnely and Grasty, 1973).

Application of the airborne gamma-ray spectrometric data has been intensively used by many scientists (Dodd et al., 1974; Abdel Nabi, 1990; Abdelaziz et al., 2003; El-Kattan et al., 2007, Youssef and Elkhodary, 2013, Abdel Rahman, 2014; Khalil et al., 2015). The area under investigation is located in the central part of the Eastern Desert (Fig. 1) and lies between longitudes $33^\circ50'42.20''$ and $34^\circ21'09.48''$ East, and latitudes $25^\circ54'13.03''$ and $26^\circ15'27.47''$ North.

Different rock units such as Calc alkaline of weakly deformed granitic rock, Mutiq Group and Dawi Formation are the key rock bodies for uranium exploration and are widely exposed all over the different parts in the study area. The economic importance of these rock units is attributed to the host of the different mineral resources, such as uranium mineralization.
and NW-SE, into which the Cretaceous–Eocene series were involved during the Late Eocene and Oligocene times. Beadnell (1924) enumerated several anticlines encountered in the post-Eocene strata in the area between El Quseir and wadi Ranga. Jabal Duwi is shown by Hume (1907) to terminate at about ten kilometers southwest of El Quseir, where the Eocene and Cretaceous rocks abut against the schists along a nearly north–south fault.

3. Methodology and data acquisition

In 1982, the MPGAP project (cooperation between the Egyptian General Petroleum Corporation (EGPC), the Egyptian Geological Survey and Mining Authority (EGSMA) and (Aero-Service Division, Western Geophysical Company of America) performed an airborne magnetic and spectral gamma-ray survey over a huge part of the Eastern Desert, with a small part in the Central Western Desert of Egypt; in order to provide data to assist in identifying and evaluating minerals, petroleum and groundwater resources of the region (Aero-Service, 1984). The traverse lines took N45°E direction, with spacing of 1.5 km approximately. The tie lines were perpendicular to the traverse lines (took N135° direction) and spaced with about 10 km. The average ground speed of the aircraft ranged from 222 to 314 km/h, with a mean terrain clearance of 120 m. High-sensitivity 256-channel (12 KeV/channel) gamma-ray spectrometer system was used in the spectrometric measurements. There were two groups of detectors: a) Primary detectors (downward looking): Three detector packages, each one is composed of four crystals of high-resolution sodium iodide, thallium-activated (NaI “Tl”) for measuring the terrestrial gamma radiation; the total volume of the primary detectors is 3072 cubic inches (50.341 liters). b) Secondary detectors (upward looking): comprise two crystals of sodium iodide thallium-activated (NaI “Tl”) of a total volume of 512 cubic inches (8.39 liters) for measuring the atmospheric radon.

Each detecting package was enclosed in a thermally stabilized container to assure the system spectral stability (Aero-Service, 1984) and the recorded aero-spectrometric data then passed through several corrections (scattering effects, background effects, atmospheric effects, altitude correction… etc.) and produced as contoured sheets (Abdelrahman, 2014). The present study area is located in Sheet no. 61, that has been digitized, using Didger Software to obtain the XYZ data file, that comprises Total Count, Potassium, Uranium and Thorium to be used in various processing techniques.

4. Data analysis and Interpretation

The analysis of the γ-ray spectrometric data of the study area contains:

1. The T.C colored map (Fig. 3) and a set of radioelements (eU, eTh and K) colored contour maps (Figs. 4–6), as well as the radioelements composite image map (Fig. 7) K, eU and eTh are plotted and contoured by GeoSoft Program (2015).
2. Separation of the radioelements over each lithologic unit.
3. Determination of the characteristic statistics of these units, such as arithmetic mean (X), standard deviation (ơ), as well as checking the normality of distribution of all measurements, using the coefficient of variation (CV percent).
4. Application of uranium migration technique to the different rock units of the study area.

Calculation of the U, Th and K-favourability indices, that have been carried out for the various rock units.

Fig. 1. Location map of the study area.

2. Geologic setting

The regional rock units and the observed structures investigated in the study area are shown in Fig. 2. The lithology of the study area could be divided as follow (Conoco, 1987; EGSMA, 1992; EMRA, 2009; Badawy, 2008): (A) Late Proterozoic rocks, comprise Mu’tiq Group (highly metamorphic schist, fine grained serecite, medium grained quartz of feldspatic and orthogneissess of alkali magma), Ophiolite Group (serpentine, metagabbrro, undifferentiated metavolcanics, basic metavolcanics, intermediate to acid metavolcanics, metapyroclastics and metamorphosed shelf sediments), Hammamat clastics (non-metamorphosed conglomerate, greywackes, sandstone and siltstone), weakly deformed granitic rocks, alkaline undeformed granitic rocks, Dokhan volcanic (non-metamorphosed volcanics) and Post Hammamat units (effusive felsite, felsite porphyry and quartz porphyry, and overlain by a series of trachyte plugs and sheets). (B) Cretaceous rocks, comprise the following, from the older to younger; Taref Sandstone, Quseir Formation (varicolored shale, siltstone and flaggy sandstone) and Duwi Formation (three phosphate horizons ranging in thickness between 30 and 100 m, and separated by beds of marls, shale and Oyster limestone with flint). (C) Cenozoic rocks, from bottom to top, as follow; Tarawan Formation (marl and marly limestones), Thebes Formation (fossiliferous limestone), Nakhil Formation (very coarse brecciated beds and fine-grained lacustrine deposits), Ranga Formation (conglomerate is embedded in a red brown sandy matrix), Umhum Mahara Formation (sandy limestone and gypsiferous fossiliferous limestone), Abu Dabbab Formation (evaporate (gypsum) deposits), Umm Gheig Formation (hard dolomite), Shagra Formation (sandstone, bioclastics and some siliicals) and Quaternary deposits.

Structurally; the investigated area was subjected to different tectonic movements, giving rise to some complex structures. It is dissected by various types of faults and folds. Investigation of the tectonic movements, giving rise to some complex structures. It is revealed two main directions of major faults; they are: NW-SE, which is the most widespread one, that is adhered to the main direction of the Red Sea graben (known as the Red Sea or East African faulting), while the second direction corresponds with the Gulf of Aqaba direction (known as the Aulatic faults) (Said, 1962). The dominant folds are trending NNW-SSE.
4.1. Qualitative interpretation

4.1.1. Total count map

Investigation of the total count map (Fig. 3) shows that, it can be divided into three distinct levels. The first low radiometric concentration level is less than 30 $\mu$R/h and recorded at the eastern, northeastern and some dispersed spots in the central parts of the area, that is covered by intermediate to acidic metavolcanics, Thebes Formation, Nakhil Formation, Um Mahara and Ranga Formations, Um Gheig and Abu Dabbab Formations, Shagara Formation, and some locations belonging to Quaternary sediments, that lie at the northern parts. The second level ranges from 30 to 40 $\mu$R/h and recorded mainly over metasediments and Hammamat clastics at the southern and dispersed spots in the central parts of the area. The third level is more than 40 $\mu$R/h and recorded over the Alkaline undeformed granitic rock, Calc alkaline of weakly deformed granitic rocks, Mu’tiq Group, Taref Formation, Dawi Formation, Quseir Formation, Tarawan Formation, and some locations belonging to Quaternary sediments at the northern, southeastern, southwestern and western parts of the study area.

4.1.2. Radioelements maps

In the eU contour map (Fig. 4), three uranium concentration levels could be distinguished according to their uranium contents. The first level has concentration values less than 3.5 ppm and associated with the intermediate to acidic metavolcanics, metasediments, Um Gheig and Abu Dabbab Formations, Shagara Formation, at the eastern, northeastern and some dispersed locations in the central parts of the area, in addition to these locations of Quaternary sediments, which overlook the Red Sea coast. The second level ranges from 3.5 to 6 ppm and recorded over the Hammamat clastics at the southern parts and small spots at the central part belonging to the metasediments in the study area. The third level possesses relatively high concentrations up to 6 ppm and is related mainly to the Mu’tiq Group in the western parts, as well as the Calc alkaline of weakly deformed granitic rocks in the southeastern portions of the area and some locations belonging to the Taref Formation, Quseir Formation, Dawi Formation, Tarawan Formation, Thebes Formation and Nakhil Formation, that lie at the northern parts. The increasing of eU values over the Quaternary sediments,
which lie at the northern, southeastern and southwestern parts of the study area relative to the Calc alkaline of weakly deformed granitic rocks refer to possible leaching and migration from the granitic rocks to the Quaternary sediments. This phenomena is due to the fact that; unlike thorium and potassium, the uranium is active and easily mobilizes and migrates under the action of oxygen from underground water and atmosphere during its evolution, while thorium is relatively stable in the oxidation zone and stay in place, as a result of breaking the original U-Th state (Benzing Uranium Institute, 1977).

The equivalent Thorium contour map (Fig. 3) shows that, there are three levels of thorium concentrations. The first low level has eTh values less than 5 ppm. It is noticed that, these low concentrations are equivalent to Thebes Formation, Um Gheig and Abu Dabbab Formations, Shagara Formation and Quaternary sediments in the eastern, northeastern and some localities at the central part of the study area. The second intermediate level (from 5 to 7 ppm) corresponds to intermediate to acidic metavolcanics in the northeastern central parts. The third relatively high level of more than 7 ppm, is mainly related to the Mu'tiq Group, Calc alkaline

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Fig. 3. Fill colored contour map of Total Count (T.C) in μR/

Fig. 4. Fill colored contour map of equivalent Uranium (eU) in ppm.
of weakly deformed granitic rocks, Alkaline undeformed granitic rocks and Taref Formation at the western, southeastern, southwestern and the northern portions of the study area.

The potassium contour map (Fig. 6) reflects three levels of concentrations. The lowest one (less than 1.5%) is represented in the central parts, which limited to the intermediate to acidic metavolcanics and Thebes Formation and at the northeastern parts, which belong to Umm Mahara and Ranga Formations, Um Gheig and Abu Dabbab Formations, Shagara Formation and Quaternary sediments. The values ranging from 1.5 to 2.5% are classified as intermediate values of the second level, which are represented by Hammamat clastics and metasediments at the southern parts of the study area. The third level is relatively of high zone, with more than 2.5% and mainly concentrated at the western side of the area, that is related to Mu'tiq Group, southeastern, western and northern parts, which associated with the Calc alkaline of weakly deformed granitic rocks, southwestern parts of the investigated area and belonged to the Alkaline undeformed granitic rocks, Taref, Quseir and Dawi Formations at the northern parts of the study area.

4.1.3. Radioelements Composite Image

Different rock types have different characteristic concentrations of the radioelements, potassium, uranium and thorium. Therefore, the concentrations calculated from gamma-ray spectrometric data...
can be used to identify the zones of consistent lithology and contacts between constraining lithologies. The three radioelements composite image map (Fig. 7) of the study area shows the variations occurring in the three radioelements concentrations, which mainly reflect lithologic variations. This map is three-elements display of equivalent uranium (ppm), equivalent thorium (ppm) and potassium (%). The color index at each corner of the triangular legend (K in red, eU in blue and eTh in green) indicates 100% concentration of the indicated radioelements. The eU, eTh and K image emphasize the radioelements and high light areas, where the particular radioelement has relatively higher concentrations. The observed radioelement zones show a fairly close spatial correlation with the geologically mapped lithologies.

It was noticed that, the higher light zones are clearly correlated with the Mu’tiq Group at the western side of the study area, southeastern and northern parts, associating the Calc alkaline of weakly deformed granitic rocks and southwestern parts of the investigated area, which belonged to Alkaline non-deformed granitic rocks. Meanwhile, the low eU, eTh and K concentrations (black area in Fig. 7) show scattered spots correlated with the intermediate to acidic matavolcanics and metasediments at the central and southwestern parts, in addition to Quaternary sediments, which lie at the northeastern side of the study area. The blue color, which is indicative of eU concentration and commonly associated with Dawi Formation at the northern and southeastern parts and is also associated with Thebes Formation at the northern parts of the area. The interference between the different color zones may be attributed to lithologic mining and distribution in the area.

4.2. Quantitative Interpretation

The quantitative interpretation depends principally upon the fact that, the absolute and relative concentrations of the radioelements (K, eU and eTh) vary measurably and significantly with lithology (Darnley and Ford, 1989). The quantitative treatment of the spectrometric data in the present study is discussed in a statistical framework. The collected spectrometric data (T.C, eU, eTh and K) are in the form of digital grids. Standard statistics were applied to the raw data to compute means, minima, maxima, standard deviations and coefficient of variability (CV%) technique for each variable (Table 1). The statistical analysis was applied on the four variables (T.C, eU, eTh, K of each rock unit, according to the detailed geologic map of the study area. Table 2 summarize the statistical results of the four variables, as well as the three ratios over the rock units in the area under investigation.

For a certain variable value in the study area, if the (CV%) is less than 100%, the variables tend to exhibit normal distribution, according to the following Eq. (1):

\[
CV\% = \left( \frac{\sigma}{X} \right) \times 100
\]

where \(\sigma\) is the standard deviation and \(X\) is the arithmetic mean.

4.3. Uranium migration

Uranium and thorium are usually accompanied together in the geologic unit formation, due to the similarity in their ionic radii. \(U^{4+}\) is easily oxidized and migrates during crustal evolution, while

Table 1

| Variables | Minimum | Maximum | X     | \(\sigma\) | CV (%) |
|-----------|---------|---------|-------|-----------|--------|
| T.C (µR/h)| 2       | 140     | 47.5  | 26.02     | 54.8   |
| eU (ppm) | 0.53    | 25.5    | 5.6   | 3.2       | 57.4   |
| eTh (ppm) | 0.5    | 40.3    | 8.7   | 5.9       | 67.4   |
| K (%)     | 0.17    | 8       | 2.6   | 1.6       | 61     |

Explanation: T.C = Total count in µR/h, eU = equivalent Uranium in (pppm), eTh = equivalent Thorium in (ppm), K = potassium in (%), µR/h = Microroentgen per hour, ppm = Part of radioactive material per million pares of rock, % = Percent, X = arithmetic mean, \(\sigma\) = Standard Deviation and CV (%) = Coefficient of Variability.
Table 2
Statistical analysis of (Tc, eU, eTh and K) variables in the different rock units in the study area.

| Age          | Rock unit                            | Radioelements | No. | Min  | Max  | X    | CV (%) |
|--------------|--------------------------------------|---------------|-----|------|------|------|--------|
| Cenozoic     | Quternary Sediments                  | Tc (µR/h)     | 2116| 2    | 130  | 42.3 | 22.8  | 54     |
|              |                                      | eU (ppm)      | 2116| 0.66 | 17.1 | 5.04 | 2.7   | 54.1   |
|              |                                      | eTh (ppm)     | 2116| 0.5  | 31.03| 7.6  | 4.54  | 59.9   |
|              |                                      | K (%)         | 2116| 0.18 | 6.9  | 2.2  | 1.47  | 67.3   |
| Shagara      | Formation                            | Tc (µR/h)     | 25  | 2    | 16   | 11.5 | 4.17  | 36.2   |
|              |                                      | eU (ppm)      | 25  | 0.98 | 3.23 | 2.26 | 0.53  | 23.6   |
|              |                                      | eTh (ppm)     | 25  | 1.2  | 2.78 | 1.92 | 0.31  | 16.2   |
| Um Gheigh    | and Abu Dabbab Formation             | Tc (µR/h)     | 166 | 4    | 50   | 18.1 | 9.78  | 54.1   |
|              |                                      | eU (ppm)      | 166 | 0.65 | 8.24 | 2.67 | 1.63  | 60.9   |
|              |                                      | eTh (ppm)     | 166 | 0.79 | 8.39 | 2.45 | 1.67  | 64.5   |
| Um Mahara    | and Ranga Formation                  | Tc (µR/h)     | 170 | 6    | 94   | 35.1 | 18.6  | 53     |
|              |                                      | eU (ppm)      | 170 | 0.68 | 11.8 | 5.05 | 3.23  | 64     |
|              |                                      | eTh (ppm)     | 170 | 1.4  | 20.01| 5.85 | 3.25  | 55.5   |
| Nakhil       | Formation                            | Tc (µR/h)     | 167 | 0.24 | 5.65 | 1.69 | 1.22  | 72     |
| Thebes       | Formation                            | Tc (µR/h)     | 614 | 6    | 110  | 35.1 | 18.6  | 53     |
|              |                                      | eU (ppm)      | 614 | 0.68 | 18.8 | 6.97 | 2.25  | 32.3   |
|              |                                      | eTh (ppm)     | 614 | 1.2  | 20.01| 5.85 | 3.25  | 55.5   |
| Tarawan      | Formation                            | Tc (µR/h)     | 219 | 12   | 94   | 36.9 | 15.9  | 51.1   |
|              |                                      | eU (ppm)      | 219 | 1    | 16.4 | 7.01 | 2.84  | 40.6   |
|              |                                      | eTh (ppm)     | 219 | 1.77 | 14.99| 4.77 | 3.18  | 66.6   |
| Mesozoic     | Dawi Formation                       | Tc (µR/h)     | 484 | 8    | 80   | 38.5 | 14.42 | 37.4   |
|              |                                      | eU (ppm)      | 484 | 1.8  | 18.7 | 8.6  | 3.58  | 41.5   |
|              |                                      | eTh (ppm)     | 484 | 1.32 | 12.4 | 4.68 | 2.52  | 53.8   |
| Quseir       | Formation                            | Tc (µR/h)     | 296 | 6    | 70   | 39.1 | 15.4  | 39.2   |
|              |                                      | eU (ppm)      | 296 | 1.1  | 25.5 | 11   | 5.12  | 46.5   |
|              |                                      | eTh (ppm)     | 296 | 1.5  | 8.32 | 3.84 | 1.5   | 39.1   |
| Taref        | Formation                            | Tc (µR/h)     | 210 | 26   | 94   | 39.1 | 15.4  | 39.2   |
|              |                                      | eU (ppm)      | 210 | 2.82 | 9    | 6.43 | 1.53  | 23.8   |
|              |                                      | eTh (ppm)     | 210 | 2.26 | 20.35| 10.95| 3.86  | 35.3   |
| Precambrian  | Trachyte plugs and sheets            | Tc (µR/h)     | 132 | 24   | 130  | 68.8 | 28.8  | 41.8   |
|              |                                      | eU (ppm)      | 132 | 2.2  | 10.9 | 5.74 | 1.93  | 33.7   |
|              |                                      | eTh (ppm)     | 132 | 5.5  | 35.7 | 16.4 | 8.4   | 51.2   |
| Post Hammamat| Formation                            | Tc (µR/h)     | 210 | 20   | 94   | 58.02| 16.54 | 28.5   |
|              |                                      | eU (ppm)      | 210 | 2.82 | 9    | 6.43 | 1.53  | 23.8   |
|              |                                      | eTh (ppm)     | 210 | 2.26 | 20.35| 10.95| 3.86  | 35.3   |
| Dokhan Volcanic| Formation                         | Tc (µR/h)     | 197 | 4    | 90   | 51.9 | 17.4  | 33.5   |
|              |                                      | eU (ppm)      | 197 | 0.74 | 19.9 | 8.01 | 3.59  | 44.7   |
|              |                                      | eTh (ppm)     | 197 | 0.89 | 16.7 | 8.35 | 3.25  | 38     |
| Alkaline undeformed granitic rock | Tc (µR/h)     | 855 | 18   | 114  | 56.6 | 18.35 | 32.4   |
|              |                                      | eU (ppm)      | 855 | 1.64 | 22.9 | 9.9  | 4.61  | 46.6   |
|              |                                      | eTh (ppm)     | 855 | 1.52 | 17.3 | 6.1  | 3.5   | 56.8   |
| Calc alkaline weakly deformed granitic rock| Tc (µR/h)     | 855 | 0.22 | 5.9  | 2.24 | 1.15  | 51.6   |
|              |                                      | eU (ppm)      | 855 | 1.64 | 22.9 | 9.9  | 4.61  | 46.6   |
|              |                                      | eTh (ppm)     | 855 | 1.52 | 17.3 | 6.1  | 3.5   | 56.8   |
| Gabbroic Rocks| Formation                            | Tc (µR/h)     | 1225| 14   | 140  | 73.84| 34.93 | 47.3   |
|              |                                      | eU (ppm)      | 1225| 1.09 | 16.4 | 6.04 | 2.52  | 41.7   |
|              |                                      | eTh (ppm)     | 1225| 2.4  | 40.3 | 16.31| 9.97  | 61.1   |
| Hammamat clastics| Formation                      | Tc (µR/h)     | 619 | 14   | 94   | 45.9 | 14.2  | 30.8   |
|              |                                      | eU (ppm)      | 619 | 1.5  | 9.1  | 5.04 | 1.32  | 26.2   |
|              |                                      | eTh (ppm)     | 619 | 2.6  | 24.01| 9.4  | 3.42  | 36.3   |
| Metasediments| Formation                            | Tc (µR/h)     | 2692| 6    | 120  | 36.6 | 16.8  | 46.1   |
|              |                                      | eU (ppm)      | 2692| 0.53 | 21.4 | 4.21 | 3.04  | 72.1   |
|              |                                      | eTh (ppm)     | 2692| 1.5  | 27.6 | 6.65 | 3.03  | 45.6   |
|              |                                      | K (%)         | 2692| 0.32 | 6.65 | 1.99 | 0.91  | 45.7   |
Table 2 (continued)

| Age                  | Rock unit                                      | Radioelements | No. | Min  | Max  | X    | σ   | CV (%) |
|----------------------|------------------------------------------------|---------------|-----|------|------|------|-----|--------|
| Intermediate to acidic metavolcanic | Tc (μR/h)                                      | 2131          | 8   | 130  | 37.4 | 15.5 | 41.4 |
|                      | eU (ppm)                                       | 2131          | 0.8 | 17.9 | 4.02 | 1.95 | 48.4 |
|                      | eTh (ppm)                                      | 2131          | 1.65| 33.7 | 7.1  | 2.9  | 40.8 |
|                      | K (%)                                          | 2131          | 0.3 | 6.1  | 2.13 | 0.84 | 39.7 |
| Basic metavolcanics  | Tc (μR/h)                                      | 86            | 12  | 58   | 36.9 | 13.96| 37.9 |
|                      | eU (ppm)                                       | 86            | 0.77| 6.2  | 3.36 | 1.26 | 37.4 |
|                      | eTh (ppm)                                      | 86            | 2.6 | 12.4 | 7.62 | 2.88 | 37.8 |
|                      | K (%)                                          | 86            | 0.58| 3.54 | 2.22 | 0.87 | 39.1 |
| Metavolcanic undifferentiated | Tc (μR/h)                                      | 69            | 26  | 94   | 59.9 | 18.67| 31.1 |
|                      | eU (ppm)                                       | 69            | 2.26| 8.46 | 4.52 | 1.36 | 30.2 |
|                      | eTh (ppm)                                      | 69            | 6.6 | 11.3 | 5.44 | 2.26 | 19.6 |
|                      | K (%)                                          | 69            | 0.95| 5.4  | 3.33 | 1.19 | 35.8 |
| Metagabbro           | Tc (μR/h)                                      | 27            | 12  | 22   | 15.48| 2.25 | 14.5 |
|                      | eU (ppm)                                       | 27            | 1.67| 3.04 | 2.18 | 0.42 | 19.2 |
|                      | eTh (ppm)                                      | 27            | 3.92| 4.04 | 3.99 | 0.02 | 0.5  |
|                      | K (%)                                          | 27            | 0.54| 1.17 | 0.79 | 0.14 | 18.8 |
| Serpentinite         | Tc (μR/h)                                      | 316           | 4   | 100  | 28.2 | 16.3 | 57.8 |
|                      | eU (ppm)                                       | 316           | 0.81| 8.53 | 3.46 | 1.66 | 48   |
|                      | eTh (ppm)                                      | 316           | 1.05| 22.2 | 5.88 | 3.51 | 59.8 |
|                      | K (%)                                          | 316           | 0.19| 5.6  | 1.52 | 0.89 | 58.7 |
| Mu’tiq group         | Tc (μR/h)                                      | 734           | 58  | 130  | 98.37| 14.73| 14.9 |
|                      | eU (ppm)                                       | 734           | 4.3 | 14.5 | 9.28 | 1.84 | 19.9 |
|                      | eTh (ppm)                                      | 734           | 9.7 | 27.3 | 18.7 | 3.43 | 18.3 |
|                      | K (%)                                          | 734           | 3.41| 7.02 | 5.75 | 0.61 | 10.7 |

On the other hand, the variations in uranium and thorium ratios reflect the extent of U migration in or out of this environment. The migration rate of uranium could be calculated according to Eqs. (2)-(4). According to the NMA Internal Scientific Report (1999), the uranium migration value (Um) for a certain rock unit can be obtained by subtracting the original uranium content (U0) from the present measured uranium content (Up) as shown through the following steps:

A. The paleo-uranium background (i.e. original uranium content U0) can be calculated, using the equation:

\[ U_0 = e\text{Th} + (e\text{U} - e\text{Th}) \]

where e\text{Th} is the average e\text{Th} content (in ppm) in a certain geologic unit and e\text{U} - e\text{Th} is the average regional e\text{U}/e\text{Th} ratio for different geologic units.

B. The amount of mobilized uranium (i.e. amount of uranium migration, Um), can be calculated, using the equation:

\[ Um = Up - U0 \]

where Up is the average uranium content in a certain geologic unit.

Table 3

Results of uranium migration estimations the different rock units of the study area.

| Age            | Rock units                  | Up      | U0      | Um     | (P) %   |
|----------------|-----------------------------|---------|---------|--------|---------|
| Cenozoic       | Quaternary Sediments        | 5.04    | 6.2     | -1.16  | -23     |
|                | Shagara Formation           | 2.26    | 2.28    | -0.02  | -0.9    |
|                | Um Gheigh and Abu Dabbab Formation | 2.67    | 3.21    | -0.54  | -20.2   |
|                | Um Mahara and Ranga Formation | 5.05    | 5.8     | -0.75  | -14.8   |
|                | Nakhil Formation            | 6.97    | 9.9     | -2.93  | -42.04  |
|                | Thebes Formation            | 7.43    | 9.64    | -2.21  | -29.7   |
|                | Tarawan Formation           | 7.01    | 9.81    | -2.8   | -39.9   |
| Meso-Occ       | Dawi Formation              | 8.6     | 10.97   | -2.4   | -27.9   |
|                | Quseir Formation            | 11      | 11.4    | -0.4   | -3.6    |
|                | Taref Formation             | 9.9     | 13.1    | -3.2   | -32.3   |
| Precambrian    | Trachyte plugs and sheets   | 5.74    | 6.6     | -0.86  | -14.9   |
|                | Post Hamamat                | 6.43    | 7.2     | -0.77  | -11.9   |
|                | Dokhan Volcanic             | 8.01    | 9.95    | -1.94  | -24.2   |
|                | Alkaline undeformed granitic rock | 5.13    | 5.6    | -0.47  | -9.2    |
|                | Calc alkaline weakly deformed granitic rock | 6.04    | 7.3    | -1.26  | -20.9   |
|                | Gabbroic Rocks              | 3.415   | 3.411   | 0.004  | 0.11    |
|                | Hamamat clastics            | 5.04    | 5.4     | -0.36  | -7.1    |
|                | Metasediments               | 4.21    | 4.6     | -0.39  | -8.3    |
|                | Intermediate to acidic metavolcanic | 4.02    | 4.3    | -0.28  | -6.9    |
|                | Basic metavolcanics         | 3.36    | 3.45    | -0.09  | -2.7    |
|                | Metavolcanic undifferentiated | 4.529   | 4.520   | 0.009  | 0.2     |
|                | Metagabbro                  | 2.18    | 2.178   | 0.002  | 0.1     |
|                | Serpentinite                | 3.46    | 3.84    | -0.38  | -10.9   |
|                | Mu’un group                 | 9.28    | 9.4     | -0.12  | -1.3    |

Explanation: Up = Present Uranium content in ppm, U0 = Original Uranium content in ppm, Um = Migrated Uranium in ppm and (P) % = Uranium migration rate.
A positive \( U_m \) value means inward uranium migration (mobility), whereas a negative value of \( U_m \) indicates an outward uranium migration.

C- The mobilized uranium migration rate (\( P \)) can be calculated, using the equation:

\[
P = \frac{U_m}{U_p} \times 100
\]

There are two statuses of (\( U_m \)) values; the first is if \( U_m > 0 \), it reflects that uranium migration is into the geologic body, the second is if \( U_m < 0 \), it reflects that, uranium migration is out of the geologic body. Accordingly, a careful examination of the statistical results of application of the uranium migration (Table 3), for different rock units reflect negative amount of uranium migration, except for the Gabbroic rocks, Metavolcanic non-differentiated and Metagabbro reflects positive values.

This means that, their uranium leachings is outward from the geologic body, except for the Gabbroic rocks, Metavolcanic undifferentiated and Metagabbro is into the geologic body. The more negative amount of outward uranium migration are recorded in the Taref Formation, Nakhil Formation, Tarawan Formation and Dawi Formation, with uranium migration (\( U_m \)) of about \(-3.2\), \(-2.93\), \(-2.8\) and \(-2.4\) ppm, respectively. Their uranium migration rates (\( U_m/U_p \times 100 \)) attain about 32.3, 42.02, 39.9 and 27.9 respectively (Table 3), which indicates strong tendency to represent a potential source for uranium mineralization in the studied area. On the other hand, Gabbroic rocks, Metavolcanic undifferentiated and Metagabbro, have positive values with uranium migration (\( U_m \)) values of about 0.004, 0.009 and 0.002 ppm, respectively and migration rate of 0.1, 0.2 and 0.1, respectively.
4.4. Uranium favorability index of the rock units

Saunders and Potts (1978) attempted to determine a general “uranium favorability index” by plotting the histograms of various possible indices, such as the $eU/eTh$ ratio for about 30 different areas, where the existing mines and occurrences were known to be favorable. They concluded that the median values of aerial gamma-ray spectrometer parameters for the geologic map units could be used as a guide to identify the uraniferous provinces, reasoning that the crustal abundance of uranium is high. They further reasoned that, the geochemical processes must have concentrated a part of the uranium in deposits. Removal of uranium from average rocks and separating it from thorium and potassium, result in low $eU/eTh$ and median $eU/K$ values. Based on the observation that high mean uranium content indicates that there is sufficient uranium for possible geochemical concentrating processes to work and that low mean $eU/eTh$ and $eU/K$ values indicate the occurrence of these processes, they derived the index $U2$ for uranium, as follows:

\[
U2 = \frac{MeU}{MeU/M} \left( \frac{MeU/M \cdot K}{MeU} \right)
\]

where $M$ denotes the mean value of any radioactive element. It is to be noted that, a high value of $U2$ indicates a high potential of uranium. Then, the two other indices for thorium and potassium can also be calculated as follows: The first equation is called the
three-elemental effective ($F$) parameter that is proposed by Efimove, 1978, as shown:

$$F = \text{Th}2 = \frac{(M \text{eU} + M \text{K})}{M \text{eTh}}$$

(6)

The second equation is called the corroboration Factor ($C$), introduced by Ammar et al. (1999) as shown:

$$C = \frac{K2 = \frac{(M \text{eU} + M \text{eTh})}{M \text{K}}}$$

(7)

These equations were proposed to identify all the zones of possible primary enrichment within the country rocks by searching, as rapidly as possible, for the probable major locations of radionuclides enrichment in the area under study. Calculations of these three indices have been carried out to locate the rocks having the highest radionuclide potentialities. A high index indicates high potential for radioactive elements. Accordingly, these areas will be considered as promising exploration targets for radioactive mineral deposits. Table 4 and the histograms in (Figs. 8–10) show the vertical bar charts of the radionuclides favorability indices for the different radiometric lithologic units forming the study area.

The rock units, that possess relatively major probability of uranium potentiality, include the Mu’tiq Group, Calc alkaline of weakly deformed granitic rock and the Trachyte plugs and sheets. Meanwhile, the rock units with major potential of Th-index are associated with The Taref Formation, Quseir Formation and Dawi Formation. The rock units with major potential K-index belong to the Dokhan volcanic and Mu’tiq Group and virtually most of the rock units.

5. Conclusions

The application of the uranium migration technique showed that, each rock unit within the area reflects negative amount of uranium migration, except the Gabroic rocks, while the Metavolcanic undifferentiated and Metagabbro reflect positive values. This means that, their uranium leaching is outward from the geologic body, except for the Gabroic rocks, Metavolcanic undifferentiated and Metagabbro where leaching is into the geologic body. High negative amount of uranium migration is associated with the Tariq Formation, Nakhil Formation, Tarawan Formation and Dawi Formation. Meanwhile, Uranium favorability indices calculated for the different lithologic units in the study area indicate that the Mu’tiq group, Calc alkaline of weakly deformed granitic rocks and Trachyte plugs and sheets reflect relatively high probability of uranium potentiality, while the rock units with major potential Th-index belong to the Taref Formation, Quseir Formation and Dawi Formation. On the other hand, The Dokhan volcanics and Mu’tiq Group explained the major potential rock units of K-index.

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