Arab J Geosci (2017) 10:435
https://doi.org/10.1007/s12517-017-3225-4

ORIGINAL PAPER

# In situ gamma ray measurements for deciphering of radioactivity level in Sarıhan pluton area of northeastern Turkey

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Received: 13 January 2016 / Accepted: 28 September 2017


**Abstract** The present work utilizes in situ gamma ray spectrometric measurement data to map the surface geology of Sarıhan Granitoid and its surrounding area. The study area comprises three different lithological units, namely, Hozbirikyayla Formation (limestone and sandy limestones), Sarıhan Granitoid (consist of quartz monzodiorite, granodiorite and quartz diorite) and the Ophiolitic olistostromal melange (andesite, basalt, sandstone, gravelly sandstone). When lithological units are assessed according to the radioactivity characteristics, natural radionuclide contents ($^{40}$K and radionuclides from $^{238}$U and $^{232}$Th series) of Hozbirikyayla limestones and ophiolitic melange rocks are lower than the Sarıhan pluton. The U, Th and K radionuclide contents were found to be 0.8–5.4 ppm, 10.1–33.6 ppm and 1.29–4.41% in the Sarıhan plutonic area and 0.9–5.3 ppm, 1.1–20.3 ppm and 0.04–2.71% in Horzbirikyayla formation, respectively. The element concentrations of $^{238}$U, $^{232}$Th and $^{40}$K of the Ophiolitic melange are 1.1–4.5 ppm, 1.6–25.3 ppm and 0.09–3.63%, respectively. Radioelement ratio maps are created for the studied area, because the parameters of radioelement ratios, eU/eTh, eU/K and eTh/K, reflect the radioactive characters of the rock and soil. The Hozbirikyayla Formation is characterized by the highest value of eU/eTh and lowest value of eTh/K. While the lowest eU/eTh and eU/K ratios were observed in the Sarıhan Granodiorite, the highest value of eU/K and eTh/K were obtained in the Ophiolitic olistostromal melange. By comparing these maps with the geology, it was found that the radioelement concentrations are in good agreement with the geological properties of the region. In addition to this, the radiation hazard parameters were evaluated to assess the radiation hazard for people living in this area. It has also been found that there is no significant radiologic hazard for humans and the environment in and around studied area.

**Keywords** In situ gamma ray measurements · Natural radioactivity · Sarıhan Granodiorite · Radioelement ratios · Radiation hazard indices

## Introduction

Natural background radiation and the related to external exposure owing to gamma radiation connect fundamentally with the geological and geographical conditions and appear at different levels in the soil and rocks of each zone in the world (UNSCEAR 1988, 2000). The levels of environmental gamma radiation are associated with the geological compound of each lithologically divided region and to the content in $^{232}$Th, $^{238}$U and $^{40}$K of the rock from which the soils originate in each area (UNSCEAR 2000; Tzortzis and Tsertos 2004; Xinwei and Xiaolon 2008; Abd El-mageed et al. 2011).

Most of the studies related to lithologic differentiation and petrogenic surveys involve analysis of the natural radionuclides such as $^{40}$K, $^{238}$U and $^{232}$Th beside the accessory minerals. Amount of natural radionuclides in rocks may inform a knowledge related to geodynamics and tectonic evolution of an area. Natural radionuclides (uranium (U), potassium (K) and thorium (Th)) concentrated in the acidic intrusive rocks

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Published online: 07 October 2017

are higher than radioelement concentrations of metamorphic and sedimentary rocks (Birch 1954). In terms of natural radioactivity, although the abundance of natural radioelements (uranium, thorium and potassium) in the oceanic crust and the mantle is very low, the contents of these elements in granitic rocks are very high. According to geologists, the cause of this case is the fractional crystallization of magma and partial melting (El-Taher et al. 2007; Canbaz et al. 2010).

Radiometric survey (in situ gamma ray measurements) is one of the geophysical techniques often used and a useful tool in geological mapping to delineate possible geological boundaries of plutonic outcrops.

The natural radioactivity level and lithological discrimination-related studies have mainly been carried out using gamma ray spectrometry by various authors (Altundas 2016; Assran 2012; Pourimani et al. 2014; Gaafar and Aboelkhair 2014; Dżaluk et al. 2014; Youssef and Elkhodary 2013; Ali et al. 2012; Alharbi et al. 2011; Papadopoulos et al. 2010; Uyanık and Akkurt 2009; Bieda and Lizurek 2008; Lundin and Bastani 2007; Chan et al. 2007; Merdanoğlu and Altınsoy 2006; Aydın et al. 2006; Yanga et al. 2005; Abd El-Naby and Saleh 2003; Pagel 1982).

Tzortzis et al. (2003) measured natural gamma radiation of the rock units in Cyprus by using gamma ray spectrometry. It was seen that radionuclide concentrations of ophiolitic complex were lower than sedimentary origin rocks. Abu-Deif et al. (2007) carried out a gamma ray spectrometric survey on some of the mineralized granite areas. The obtained data were statistically treated in order to outline the radio-lithological features of the various rock units in the prospect area. The original uranium content and uranium migration rate were calculated in order to identify the migration trends in the granite and its alteration products.

A comprehensive in situ investigation was carried out in the granite region using a portable detector for the detection of the radioelement concentration of $^{40}K$, $^{238}U$ and $^{232}Th$ on 210 intrusive granite outcrops by Puccini et al. (2013). The median abundances of potassium, uranium and thorium on the Variscan granite were found to be higher than the average values of the continental crust. Alnour et al. (2012) determined the concentration of natural radioelement of granitic rocks and their potential radiologic impacts by using gamma ray spectrometry method. The results of survey revealed that the activity concentrations of granitic rocks change owing to the difference of the kind of granitic rock in the study area.

In the current study, Sarıhan Granodiorite and its vicinity were selected because it has calc-alkaline composition and is characterized by a calc-alkalin granodiorite-series (these rocks have high silica rates). These rocks have higher dose rate and radionuclide contents. $K_2O$ and $SiO_2$ contents of the rocks forming adakitic Sarıhan Granodiorite are 2.16–2.76% and 61.16–65.29% (Eyüboğlu et al. 2011). According to its silica content, Sarıhan Granodiorite is composed of rocks having a transitional composition between felsic and mafic magma (intermediate magma, Si 53–65%).

These rocks, composed of Silica (Si) rich felsic magma, contain significant amounts of sodium (Na), potassium (K), and aluminum (Al), and small amount of Calcium (Ca) and Magnesium (Mg). Besides, the intrusive was surrounded by the late Jurassic–early Cretaceous Hozbirikyayla limestone and the mid-Cretaceous Ophiolitic olistostromal melange. Using gamma-ray spectrometry as a mapping tool requires an understanding of radioelements distribution in a studied area.

The analysis of spatial variability of radionuclides is an important technique in many geological and environmental studies to determine their spatial dependence and to carry out a spatial interpretation of in-situ measurements and map possible boundaries of geological features in the studied area.

The main purpose of the study is to measure radionuclide concentrations of naturally occurred $^{40}K$, $^{238}U$ and $^{232}Th$ in Sarıhan pluton and its surrounding formation located in the Eastern Pontides, Turkey using the 512-channel (NaI) gamma-ray spectrometer and to map radionuclide variations in different geological units. According to these variations, possible boundaries between sedimentary terrain and outcrops of Sarıhan pluton have been delineated. Moreover, using obtained data, it is also aimed to calculate both radiological hazard parameters and the radioelements ratios (eU/eTh, eU/K and eTh/K) which reflect the radioactive characters of the rock and soil. Apart from these, all the calculated parameters are compared with the worldwide acceptable values in order to evaluate the possible radiological risks for people living in and around this area.

## Geological background

The Maastrichtian aged (Aslan 1998, 2005) Sarıhan Granodiorite is located in the southern zone of the eastern Pontide orogenic belt, NE Turkey (Fig. 1). This granodiorite was laid out into the pre-Permo-Carboniferous Pulur Massif which is mainly composed of medium grade metamorphic rocks (green schist, micaschist, para-amphibolite schist, meta-andesite, metapelite, ortho-amphibolite, gneiss, marble and quartzite) (Aslan 2006), the Liassic Hamurkesen Formation beginnings with the Dikmetaş conglomerate and continues upward into volcano-sedimentary rocks, and the Malm-Lower Cretaceous Hozbirikyayla Formation involving in limestone and sandy limestones (Aslan 2005).

An ellipsoidal shaped, forming an elongated double lobe massif (Aydın et al. 2007), Sarıhan Granodiorite outcropped on the studied area covers an area of circa 40 $km^2$, and primarily composed of quartz monzodiorite, granodiorite and lesser quartz diorite (Fig. 2). This plutonic outcrop contains volcanic and silicified limestone xenoliths and dioritic mafic

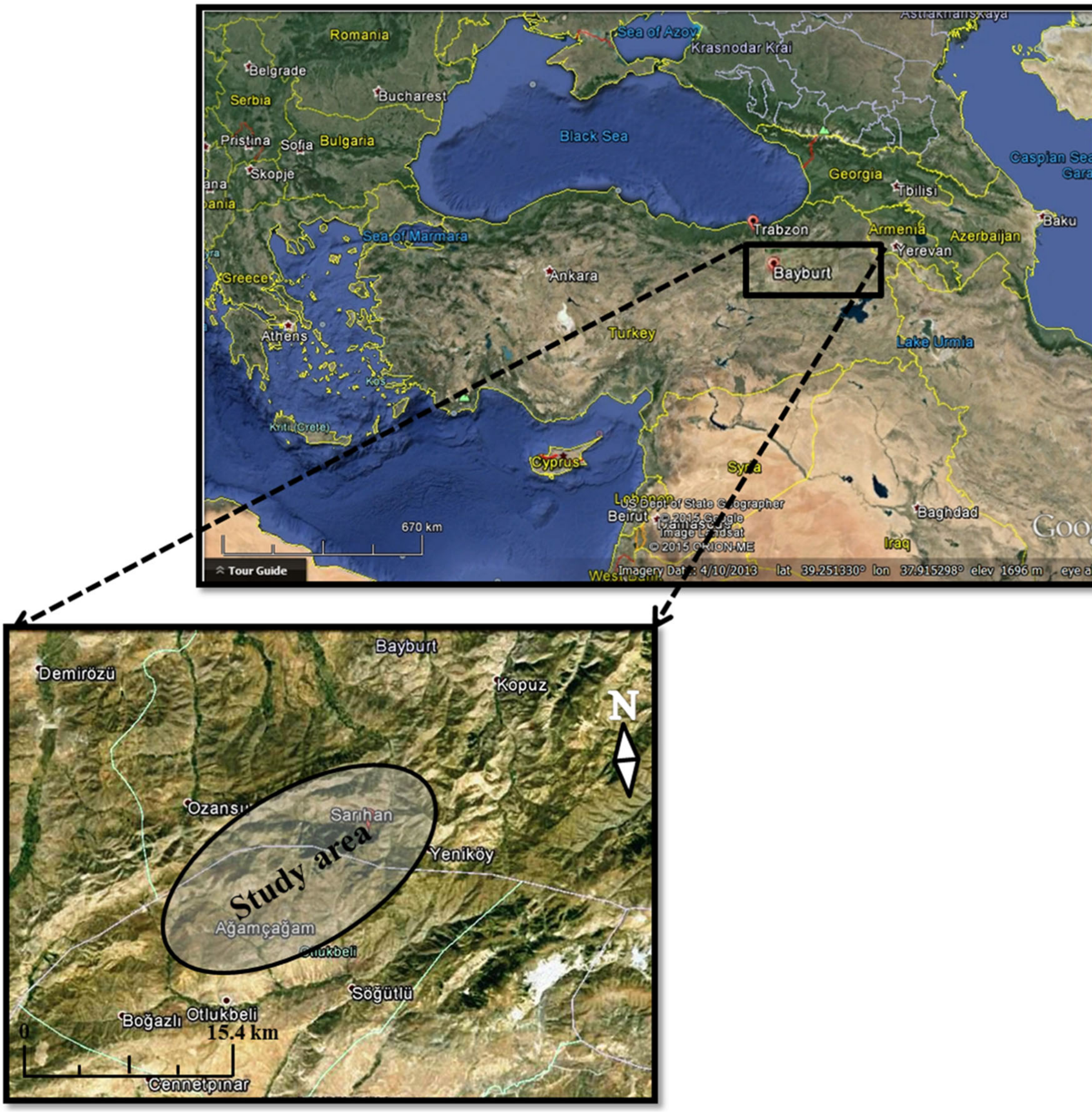


**Fig. 1** Location map of the studied area in the southern zone of the eastern Pontides, NE Turkey

microgranular enclaves. Plutonic rocks exist in this area display medium-grained, poikilitic, monzonitic, anti-rapakivi and sometimes myrmekitic textures, and contain 43–64% plagioclase, 6–18% orthoclase, 10–29% quartz, 5–20% hornblende, 1–85% biotite, and 1–6% opaque oxides, accessory amounts of apatite, titanite and zircon, and secondary phases of calcite, chlorite and sericite (Aslan 2005).

Some textures may suggest mafic magma injections (magma mixing) due mainly to temperature, pressure and compositional fluctuations in the magma chamber, whereas the existence of mafic microgranular enclaves implies that magma-mingling processes (physical mixing), mechanically dominated mixing processes of different melts, were the key process in the evolution of the pluton (Fig. 3).

This pluton has 65–67% $SiO_2$, 1.4–3.1% MgO, 4.1–5.5% $Na_2O$ and <1 $K_2O/Na_2O$. Generally, the pluton is I-type (derived from source rocks of igneous composition that have not gone through the surface weathering process, or from crystal fractionation of magmas), metaluminous and has characteristics of cafemic-group granodiorites, suggesting a hybrid source derived by mixing of sialic and mantle sources. The pluton has calc-alkaline composition and is characterized by a calc-alkaline granodiorite-series trend (Aslan 2005).

## Data and method

### In-situ Radioactivity Content Measurements

Gamma-ray spectrometry (GRS) method is a useful tool for surveying of radiation sources, determination of natural radioelement concentrations (K, eU, eTh), geophysical mapping,

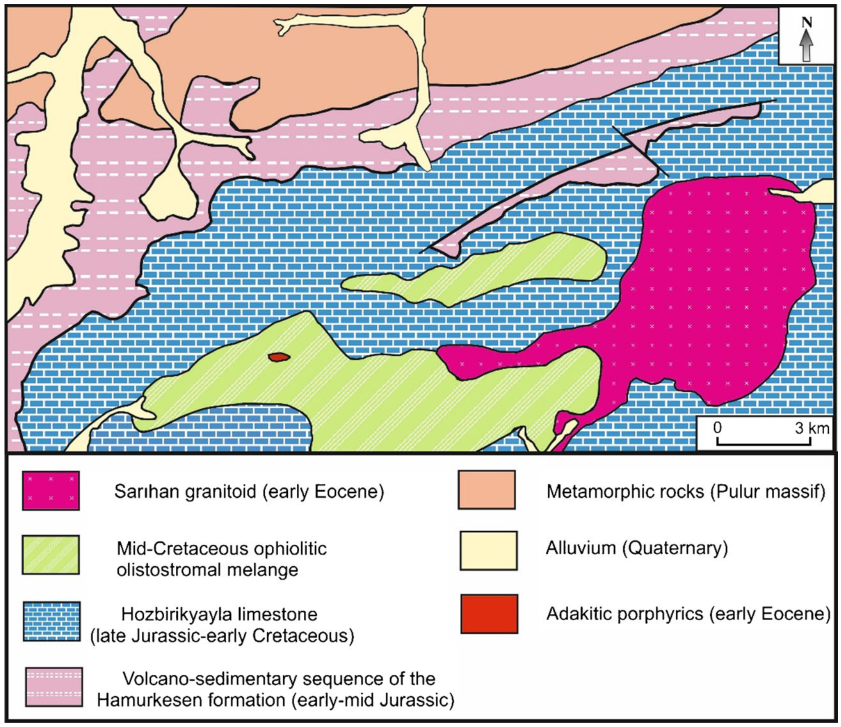


**Fig. 2** Geological map of the study area (modified from Eyüboğlu et al. 2011)

geological studies, mine prospecting, and health care. GRS method is a direct measurement technique in determining of the surface distribution of the naturally occurring radioelements. Since the concentrations of natural radioelement vary between different rock types, the determined radionuclide concentrations can be credibly used to map and discriminate the various lithologies (IAEA 1974). The field procedure for GRS measurements are directly linked to the goal of the search and the geological or environmental problem being researched (IAEA 1989).

GRS used in the current study to typically record 512 channels of knowledge in the energy range 0–3.0 MeV. Each channel has energy within a 5877 keV range. The instrument can record the full gamma ray spectrum as well as sum channels over broad energy windows for estimation of K, U and Th concentrations. The factory calibration is done on high-volume standards. Calibration constants are stored in the instrument memory. Several thousands of field measurements or several hundreds of full energy spectrum can be recorded in the instrument memory. The energy windows (Fig. 4) were set at 1380–1530 keV for $^{40}$K, 1690–1840 keV for $^{238}$U and 2460–2760 keV for $^{232}$Th, respectively (GF Instruments 2009).

The prompt quantitative in-situ analysis of the main three natural radioelements was carried out with the help of the portable multichannel gamma-ray spectrometer produced by GF Instrument. The eU (ppm), eTh (ppm) and K (%) elemental concentrations totally on 267 points (Of these, 224 were measured on outcropping rocks and 43 were measured in


**Fig. 3** Mafic microgránular enclave and aplite dike in the Sarıhan Granodiorite

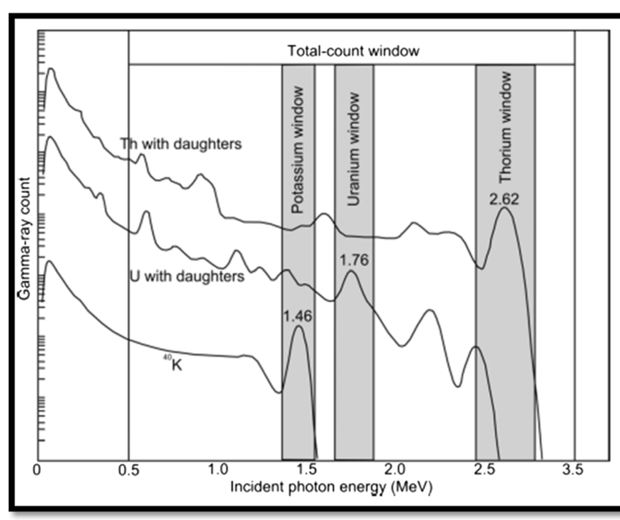


**Fig. 4** Typical counts of different energies produced by scattering of photons produced by the decay of thorium and uranium with daughters, and Potassium (adapted from Løvborg et al. 1979)

soil.). In and around Sarıhan Granodiorite were investigated by performing 5 min in-situ measurements each by placing the portable detector on the ground in this survey (Fig. 5).

The coordinates of the measurement points were obtained by using the hand GPS that its approximate error is ±3 m. All measurements were carefully taken to ensure the reliability of our data. The portable detector was placed on rock and soils where there is no vegetation. There was no measurement in rainy weathers. In this study, the amounts of K, eU and eTh were measured as percent and ppm, respectively.

After the raw data collected in the field, it is then processed using appropriate methods. The processing of the raw gamma-ray field data, Potassium, Uranium and Thorium (Th) concentration maps and environmental gamma dose distribution maps were created. Using these maps, natural radioactive elements and minerals and their lithological dependence on other minerals, geological features and their formation boundaries can easily be determined and investigated. According to IAEA (1989), conversion factors from concentration unit to activity concentration unit in Bq/kg for $^{40}$K, $^{238}$U and $^{232}$Th are 313 Bq/kg, 12.35 Bq/kg and 4.06 Bq/kg, respectively. In brief, measured radionuclide concentrations were converted to the main activity concentration unit (Bq/kg) or the geological and environmental radioactivity measurements using mentioned above appropriate conversion factors.

After the activity concentrations of radionuclides determined, hazard parameters for all points were estimated. In addition to these parameters, radionuclide ratios of (eTh/K, eU/eTh and eU/K) were determined for the studied area. Finally, radionuclide ratios and the concentrations of radionuclide were plotted and interpreted to represent the radiological character of the studied region, in detail. Consequently, contour maps of environmental gamma dose, radioelement ratios,

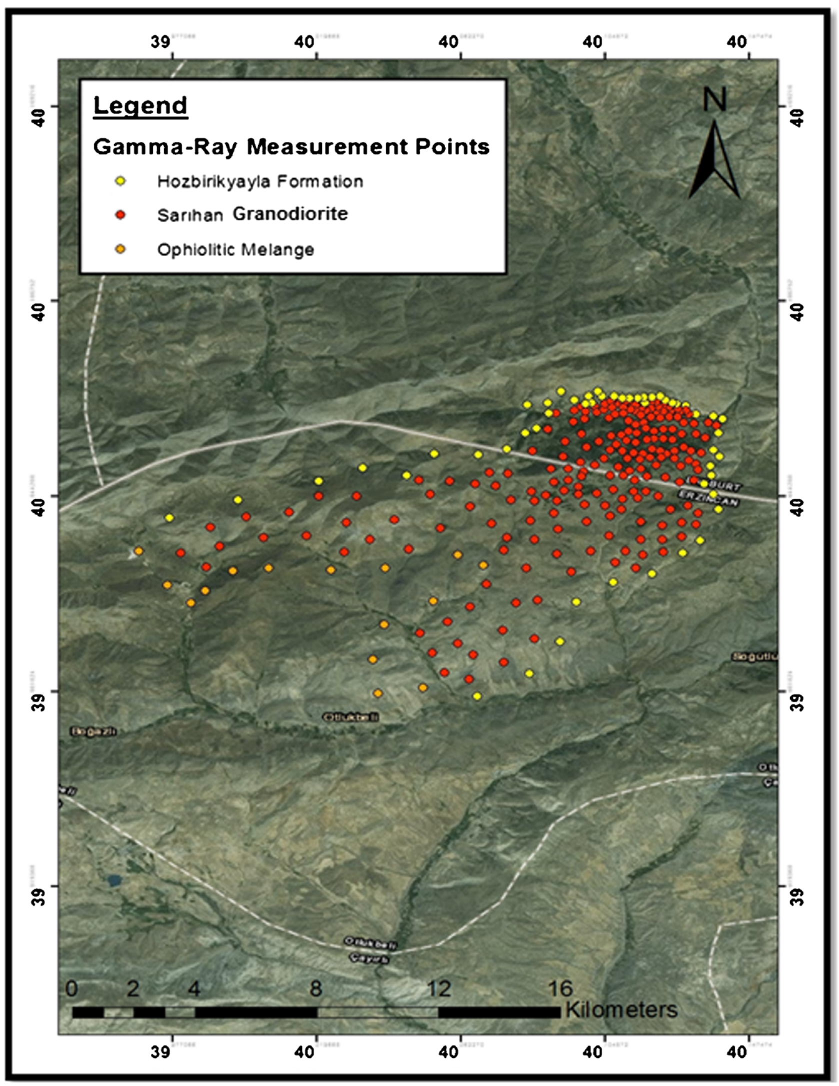


**Fig. 5** In-situ Gamma-ray measurement points in the studied area

eTh(ppm), eU(ppm) and K(%) obtained by using the software SURFER through the Kriging gridding method.

### Estimated radiological hazard parameters

The contribution of natural radioelements to the Absorbed Dose Rate in the air (D) depends on the radioelement concentrations in the soil and rocks. The largest portion of the gamma radiation originates from terrestrial radioelements. There is a direct connection between terrestrial gamma radiation and radioelement contents in soil and rocks (Beck et al. 1972).

If the radionuclide activity in the soil is known, then its exposure dose rate in air at 1 m above the ground can be calculated using the formula proposed by UNSCEAR (1988).

$$D = 0.462C_U + 0.604C_{Th} + 0.0417C_K \quad (1)$$

The activity concentrations of $^{238}U$, $^{232}Th$ and $^{40}K$ (Becquerel per kilogram) are $C_U$, $C_{Th}$ and $C_K$, respectively, and D is in nanogray per hour.

The distribution of $^{238}U$, $^{232}Th$ and $^{40}K$ in granite is not uniform. Uniformity with respect to the exposure to radiation has been defined in terms of $Ra_{eq}$ in $Bqkg^{-1}$ to compare the specific activity of materials containing different amounts of $^{238}U$, $^{232}Th$ and $^{40}K$. It is calculated through the following relation suggested by Beretka and Matthew (1985):

$$Ra_{eq} = C_U + 1.43C_{Th} + 0.077C_K \quad (2)$$

where $C_U$, $C_{Th}$ and $C_K$ are the activity concentration of $^{238}U$, $^{232}Th$ and $^{40}K$ in $Bqkg^{-1}$ respectively.

In the UNSCEAR (1993, 2000), the committee used 0.7 $SvGy^{-1}$ for the conversion coefficient from absorbed dose in air to effective dose received by adults, and 0.2 for the outdoor occupancy factor. Effective dose rate in units of mSv per year is calculated by the following formula (UNSCEAR 2000; Tzortzis et al. 2003):

$$\textit{Effective dose rate}\left(\mu Svyr^{-1}\right) = \textit{Dose rate}\left(nGyh^{-1}\right) \times 8760h \times 0.2 \times 0.7 \times 10^{-3} \quad (3)$$

The external hazard index is an evaluation of the hazard of the natural gamma radiation. The prime objective of this index is to limit the radiation dose to the admissible permissible dose equivalent limit of $1mSvy^{-1}$. The external hazard index should be below the unity. The external hazard index due to the emitted gamma rays of the samples is calculated according to the following relation (Huda 2011).

$$H_{ex} = \frac{C_U}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad (4)$$

where $C_U$, $C_{Th}$ and $C_K$ are the activity concentration of $^{238}U$, $^{232}Th$ and $^{40}K$ in $Bqkg^{-1}$ respectively.

Gamma-ray spectrometry ratios (eTh/K, eU/eTh and eU/K).

The natural radionuclide ratios of (eTh/K, eU/eTh and eU/K) are less influenced some factors such as percentage of outcrop, inversion trapping of radon, different absorbers (soil moisture and vegetation) and surface geometry. For this reason, these ratios are especially useful in interpretation of the in-situ gamma measurements since they are frequently more indicative of lithological units or geological-geochemical environments. The eU/K and eU/ eTh ratios diagnostically describe the uranium rich zones (Darnley 1973; Boyle 1982).

The low eTh/K ratio can easily detect the alteration zone. Because Thorium, as an immobile radioelement, indicates primary 'pre-alteration' ingredients, Thorium levels permit easy fields distinction of different granitic units mistakenly mapped as on type. While spectrometry cannot directly locate the base and precious metals, it can detect the K alteration associated with an epithermal system and can assist in mapping at both regional and local scales.

According to Clark et al. (1966), the eU/eTh ratio in granitic rocks equals approximately 0.33. This ratio depends mainly on the mobile elements (i.e., uranium). Therefore, this ratio is essential for uranium exploration, because it determines the uranium enrichment areas. The eU/eTh ratio for uranium enrichment in granitic rocks is higher than 0.33, while leaching out of uranium have lower values than 0.3.

The examination of the high regions of the eU, eU/K and eU/eTh demonstrates uranium enrichment on the Thorium and Potassium radioelements. The most promising uranium variations as economic potential should have a high equivalent uranium (eU) content depending on eU/K and eU/eTh values (Saunders and Potts 1976). These uranium-enriched offer the best prospect for uranium, due to the fact that their high contents of U with regard to K and Th are significant identifier elements in the description of potential U areas (IAEA 1989).

## In-situ gamma-ray spectrometric data interpretations

In-situ gamma-ray spectrometry measurement is one of very helpful geophysical methods in the mapping of surface geology, which based mainly on the superficial variations of the natural radioactive elements, such as potassium ($^{40}K$), Uranium ($^{238}U$) and Thorium ($^{232}Th$), measurably, and significantly varying with the lithology.

In-situ measurements of the natural radioelement concentration and environmental gamma dose radiation level in and around Sarıhan Granodiorite were performed at the 267

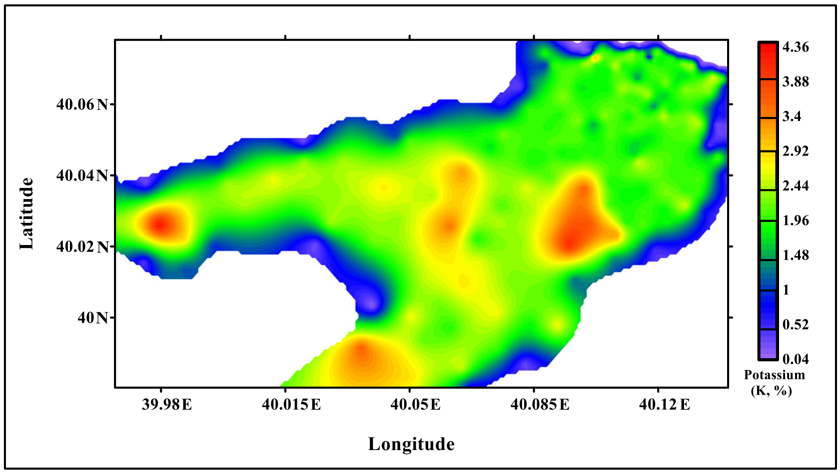


**Fig. 6** K (Potassium percentage) concentration map of the studied area

different points. All of these points were selected to fully reflect the geological units (Sarıhan Granodiorite, Hozbirikyayla limestone and Ophiolitic olistostromal melange) in the studied area. In-situ gamma-ray measurements were presented as contour maps showing the environmental gamma dose, radioelements ($^{40}$K, $^{238}$U and $^{232}$Th), and their geochemical ratios (eU/eTh, eU/K and eTh/K). All these maps were compared with geologic map of the area to determine, easily, the variations which are important in the geochemical prospecting. The qualitative interpretation of the in-situ gamma-ray data consists basically in correlation between the recorded measurements and the surface distribution of rock units. The analysis results show that the variations in the natural radionuclide concentrations reflect the radiological differences between the geological units in the area.

### Potassium concentration map of studied area

From the potassium concentration map (Fig. 6), it is clearly seen that sharp changes in potassium concentration ($^{40}$K) are measured in the studied area. The lowest concentration of $^{40}$K was observed in the Hozbirikyayla Formation which, consist of limestone, sandy limestones, and Ophiolitic olistostromal melange containing andesite, basalt, sandstone, and gravelly sandstone.

The Sarıhan Granodiorite has the medium and higher K element concentration in the area and it varies between 1.29% and 4.41%. Rock-forming minerals, where potassium is chemically combined in the mineral structure; typical examples are the potassium feldspars (orthoclase, microcline), mica (biotite) (Aslan 1998).

Since the plutonic rock contains 6–18% orthoclase and 1–85% biotite (Aslan 2005), it is considered that high concentration areas are associated with soil and rocks containing these minerals. The different rock types in the study area can be distinguished using their mean potassium concentrations, which is 0.718% for Hozbirikyayla Formation, 1.84% for Ophiolitic melange and 2.13% for Sarıhan Granodiorite.

### Equivalent Uranium (eU) map of studied area

As can be inferred from Fig. 7, the equivalent uranium (eU) concentration varies across the different soil and rock types. As the result of field measurements, uranium concentration

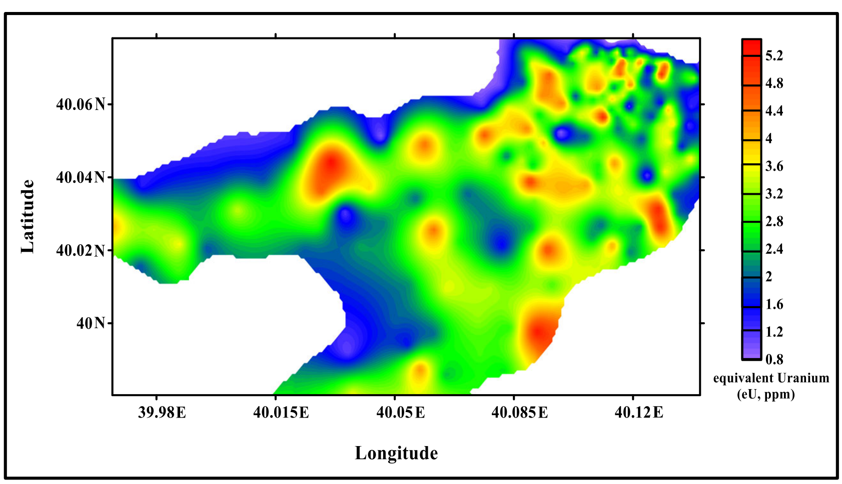


**Fig. 7** eU (equivalent uranium, ppm) concentration map of the studied area

ranges between 0.8 ppm and 5.4 ppm with a mean concentration of 2.74 ppm for all the studied area.

The highest elemental concentration was calculated from locations where there are Sarıhan Granodiorite outcrops, and the lowest concentration was obtained from the limestone and sandy limestone locations and at some point in the melange zone. It is suspected that lower values measured in the studied area are caused by precipitation of eU minerals within organic materials existing in rock and soils or transportation of these minerals into the deeps via surface water.

Uranium is a mobile element, dissolves under suitable conditions, and migrates from the environment. Therefore, it has an important role for the distribution of the radioactivity in an area. The northeastern part of the study area is represented by higher radioactivity values than the southwestern parts. It is considered that the uranium element may be located at the north of the studied area and transported from the south to north. In addition, the high values of uranium radionuclide concentration are associated with some minerals (Plagioclase, Orthoclase, Microcline, Biotite, Apatite) located inside the granite. This conclusion is supported with the rock analyses performed by Aslan (1998). The average concentration value of $^{238}$U in Hozbirikyayla Formation is 1.85 ppm, 2.56 ppm in Ophiolitic melange, and 2.97 ppm in Sarıhan Granodiorite.

## Equivalent Thorium (eTh) concentration map of studied area

Surveyed area possesses also a wide range of eTh content varying from 1.1 ppm to 33.6 ppm, with an average value of about 13.65 ppm (Fig. 8). The highest concentration of equivalent Thorium (33.6 ppm) was recorded in the Sarıhan Granodiorite (consist of quartz monzodiorite, granodiorite and quartzdiorite) while the lowest concentration values were found in the Hozbirikyayla Formation (1.1 ppm) and Ophiolitic olistostromal melange (1.6 ppm).

The average value of Thorium with respect to the geological units in and around of plutonic rock is 4.47 ppm in limestone and sandy limestones, 12.23 ppm in Ophiolitic mélange and 16.15 ppm in Sarıhan Granodiorite. Thorium is generally associated with acid (and intermediate) rocks. It is very stable and cannot dissolve in a solution like uranium.

The measured value for Hozbirikyayla Formation and Ophiolitic melange in the studied area is significantly lower than the plutonic rocks because it is strongly weathered. As can be inferred from Fig. 8, there is a sharp variation between with the plutonic rock and Hozbirikyayla Formation (limestone and sandy limestone). As a result of alteration, Thorium is deposited in the rocks and this process may be caused by an increase in the amount of thorium. On the other hand, magmatic rocks having higher radioactivity are mainly associated with the existence of accessory uranium and thorium bearing minerals. Granitic rocks mainly composed of coarse grains of quartz, K-feldspar, plagioclase and mafic minerals like biotite and amphibole. In addition, there are other common accessory minerals in granites, namely zircon, sphene, apatite and allanite.

## The outdoor gamma dose rate map of the studied area

The outdoor gamma dose rates in and around Sarıhan Granodiorite due to the combined activities of these eU and eTh elements series and K were also measured. Gamma dose rate values range from 8.3 to 160.7 nGy/h with an average of 73.63 nGy/h for all areas. The measured gamma dose distribution is shown in Fig. 9.

As can be seen from Fig. 9, the maximum gamma dose value (160.7nGy/h) was recorded in the Sarıhan Granodiorite (consist of quartz monzodiorite, granodiorite and quartz diorite) while the minimum values were found in

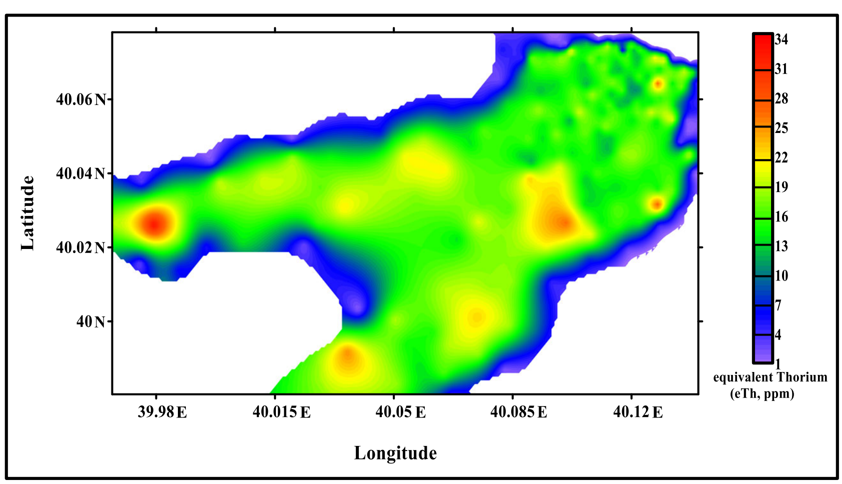


**Fig. 8** eTh (equivalent thorium, ppm) concentration map of the studied area

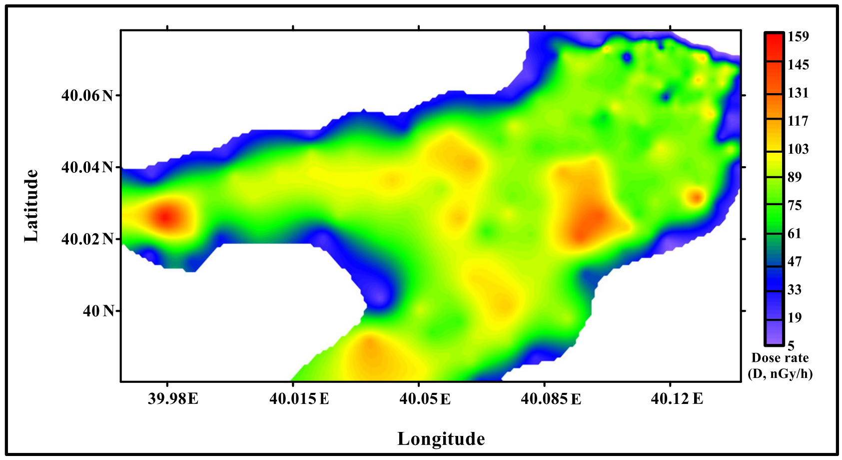


**Fig. 9** The outdoor gamma dose rate map of the studied area

the Hozbirikyayla Formation (8.3 nGy/h) and Ophiolitic melange (14.7 nGy/h). According to the geological units, the average dose rate is 30.8 nGy/h in the Hozbirikyayla limestone, 69.06 nGy/h in melange, and 85.11 nGy/h in the Sarıhan Granodiorite.

## eTh/K ratio map of the studied area

As it was mentioned above, eTh/K ratio was calculated for all rock and soil samples. This ratio varies in the range from 2.0 to 17.77 for all studied areas. Different levels of eTh/K ratio have seen in the ratio map belong to the study area (Fig. 10). The first one which represents minimum values of eTh/K ratio is related to the Hozbirikyayla Formation (limestone and sandy limestones) and this ratio varies between 2 and 4.

The second level represents an intermediate eTh/K ratio and it coincides with plutonic rocks (consist of quartz monzodiorite, granodiorite and quartz diorite), and also characterized by high Potassium content. eTh/K ratio is in the range of 7 and 11.

The last level has a high eTh/K ratio ranges between 12 and 17.77 which is associated with an Ophiolitic melange in the southwestern part of the plutonic rock. In Sarıhan Granodiorite average eTh/K ratio equals 7.56, in limestone 7.23, and in Ophiolitic melange 6.66, respectively.

## eU/eTh ratio map of the studied area

The eU/eTh ratio values range between 0.043 and 1.2 with an average value of about 0.26 for all the investigated area. This ratio is important for uranium exploration because it determines the uranium-enriched areas. The eU/eTh ratio map (Fig. 11) shows that the granodiorite are clearly discriminated from the Hozbirikyayla Formation and Ophiolitic melange by their lowest levels of eU/eTh. The highest eU/eTh ratios (0.8–1.2) are mainly obtained in limestone and sandy limestone which locate in the southeastern part of the granodiorite.

These high valued areas may have been formed due to the presence of solutions highly enriched with U, which has higher mobilization than Th. The average eU/eTh ratios of

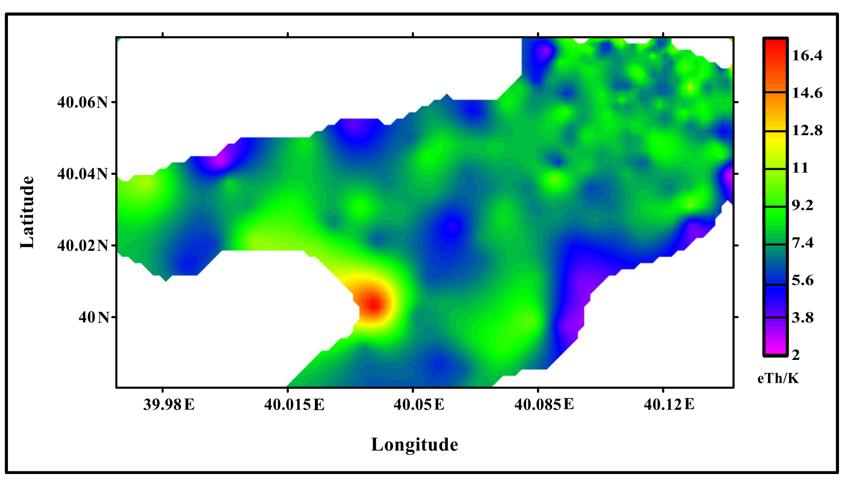


**Fig. 10** eTh/K ratio map of the studied area

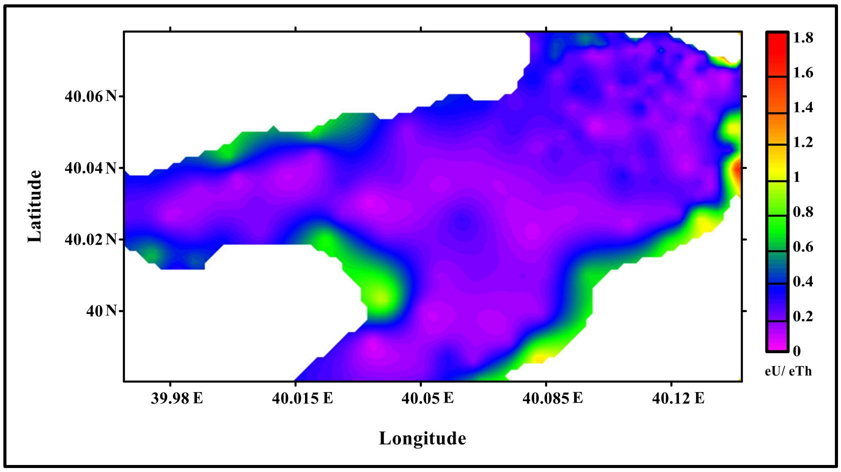


**Fig. 11** eU/eTh ratio map of the studied area

Sarıhan Granodiorite, Hozbirikyayla Formation and Ophiolitic melange are 0.18, 0.52 and 0.3, respectively.

## eU/K ratio map of the studied area

The eU/K ratio map shown in Fig. 12 implies a contrast in eU/K ratio content between the different lithological units. The highest value of the eU/ K ratio (>6) reflects the distribution of the basalt, sandstone, gravelly sandstone rocks in the southwest of the plutonic body. Whereas Sarıhan Granodiorite (consist of quartz monzodiorite, granodiorite and quartz diorite) has a low eU/K ratio (ranges between 0.42–3), the limestone and sandy limestones which surround Sarıhan Granodiorite from NW to SE has an intermediate eU/K ratio (3–6).

## Comparison of all in-situ gamma-ray data with global studies

Figures 7 and 8 show specific activity of $^{238}$U and $^{232}$Th in samples. From the results it can be understood that the specific activity of $^{232}$Th increases regularly toward the more acidic rocks while the increasing of $^{238}$U activity is slight and irregular. Therefore, in this work no strong correlation between $^{238}$U and $^{232}$Th concentrations was observed. The relative enrichment of Thorium in the plutonic rocks may be explained on the basis of oxidation and loss of uranium from magmas during the later stages of their crystallization. Hence, $^{232}$Th elemental and activity concentrations of granite rocks of this work are generally higher than $^{238}$U concentrations.

The concentrations of uranium, thorium and potassium, measured in this study, were compared with those of similar investigations carried out by several researchers in some of the world countries (Table 1). The results of Mattsson et al. (2003) show that the element concentration of uranium, thorium and potassium for granite is higher than those of obtaining in this study. In limestones, the mean values of uranium, thorium and potassium in Isparta, Turkey (Uyanık and Akkurt, 2009) are slightly less than the values in the

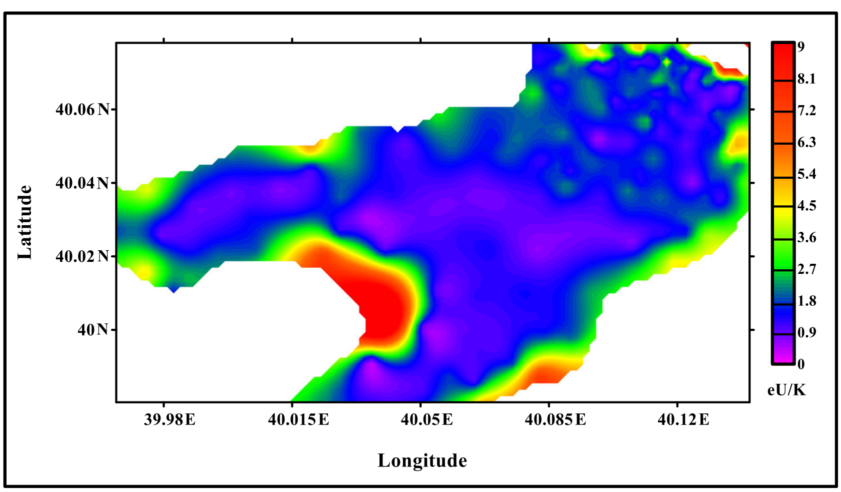


**Fig. 12** eU/K ratio map of the studied area

**Table 1** Comparison of mean natural radionuclide concentrations obtained in this study with those obtained from similar investigations

| Type of rock | Mean concentration | | | Reference |
|---|---|---|---|---|
| | U (ppm) | Th (ppm) | K (%) | |
| Granite to quartz monzodiorite, generally porphyritic | 4.4 | 18.3 | 3.6 | Mattsson et al.(2003) |
| Granite, fine to medium grained (red aplite dayk) | 6.1 | 48.9 | 5.6 | Mattsson et al.(2003) |
| Quartz monzodiorite to granodiorite | 4.8 | 11.2 | 3.3 | Mattsson et al.(2003) |
| Corravillers granite | 7.1 | 23.6 | | Pagel (1982) |
| Quartz monzonite + quartz monzodiorite + granite | 3.3 | 16.0 | 3.6 | Ilbeyli et al. (2004) |
| Granodiorite (boulder batholith) | 3.4 | 11.0 | 2.8 | Tilling and Gottfried (1969) |
| Limestone | 4.5 | 11.0 | 0.5 | Uyanık and Akkurt (2009) |
| Quartzdiorite | 2.0 | 4.0 | 1.6 | İbrahim and Ali (2003) |
| Granite (Oliverian Pluton) | 5.7 | 19.3 | – | Lyons (1964) |
| Granodiorite | 2.2 | 14.6 | – | Lyons (1964) |
| Quartzdiorite | 2.0 | 7.6 | – | Lyons (1964) |
| Melange | 1.29 | 13.00 | 1.25 | Tzortzis et al. (2003) |
| Biotite-muscovite granite | 6.2 | 4.6 | 4.7 | El-Arabi et al. (2007) |
| Granite, Turkey | 24.8 | 61 | 4.2 | Örgün et al. (2005) |
| Granite, South Africa | 6.5 | 21.6 | 4.15 | Cermak et al.(1982) |
| Granodiorite (eastern desert, Egypt) | 3.7 | 10.3 | 3.6 | Abbady (2004) |
| Granodiorite | 2.1 | 8.3 | 2.3 | Dortman (1976) |
| Alkali basalt | 0.99 | 4.6 | 0.61 | Atlas (1985), Schlumberger (1982) |
| Andesite | 1.2 | 4.0 | 1.7 | Dobrynin et al. (2004) |
| Limestone | 2.0 | 1.5 | 0.3 | Rybach (1976) |
| Sandstone | 0.5 | 1.7 | 1.1 | Atlas (1985) |
| Sarıhan Granodiorite(quartz monzodiorite, granodiorite and quartz diorite) | 2.98 | 16.15 | 2.14 | Present study |
| Hozbirikyayla Formation (limestone and sandy limestones) | 1.85 | 4.47 | 0.72 | Present study |
| Ophiolitic olistostromal melange (andesite, basalt, sandstone, gravelly sandstone) | 2.56 | 12.23 | 1.84 | Present study |

present work and concentrations of these elements in melange (Tzortzis et al. 2003) is lower than the values found in the present work.

In UNSCEAR (2000), it is reported that median values of uranium (35 Bq/kg), thorium (30 Bq/kg), potassium (400 Bq/kg) activities, and gamma dose rates (60 nGy/h). In the present study, while the calculated mean $^{232}$Th, $^{40}$K activities, and gamma dose rate value were found to be higher than the values to be given in UNSCEAR (2000), the median value of $^{238}$U was a little lower from this value. Table 2 shows the

**Table 2** Minimum, maximum and average values for the radionuclide activity concentrations, the gamma radiation hazard indices and radioelement ratios in and around Sarıhan Granodiorite

| | $^{40}$K (Bq/kg) | $^{232}$Th (Bq/kg) | $^{238}$U (Bq/kg) | $D_{measured}$ (nGy/h) | $D_{absorbed}$ (nGy/h) | Ra(eq) (Bq/kg) | Hex | $AEDE_{out.env}$ (mSv/y) | eTh/K | eU/eTh | eU/K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Min. | 12.52 | 4.46 | 9.88 | 8.3 | 7.78 | 31.22 | 0.084 | 0.017 | 2 | 0.04 | 0.30 |
| Max. | 1380.3 | 136.41 | 66.69 | 160.7 | 158.78 | 342.11 | 0.924 | 0.195 | 17.77 | 1.2 | 9.09 |
| Average | 576.77 | 55.45 | 33.79 | 73.63 | 73.15 | 157.50 | 0.425 | 0.090 | 7.9 | 0.26 | 1.85 |

minimum, maximum and mean values of the $^{238}U$, $^{232}Th$, $^{40}K$ activity concentrations, $D_{absorbed}$, $Ra_{eq}$, $H_{ex}$, $AEDE_{out.\ env.}$ And radioelement ratios of the study area.

The average $Ra_{eq}$ results for all measurement points are presented in Table 2. The calculated $Ra_{eq}$ ranged from 31.22 to 342.11 Bq/kg, which are lower than recommended maximum value of UNSCEAR (2000) (370 Bq/kg) except in Sarıhan Granodiorite, Ophiolitic melange and Hozbirikyayla formation which computed mean values 182.02, 147.05 and 66.19 Bq/kg, respectively. In this work, the highest $Ra_{eq}$ activity was found in Sarıhan Granodiorite. This sample contains K-rich minerals of biotite and high amount of orthoclase and also accessory minerals of zircon, apatite and epidote that contribute to the level of radioactivity of the sample. The Ophiolitic melange was displayed the lowest Radium equivalent activity among all the geological units with 31.21 Bq/kg.

The estimated absorbed dose rate in the air varies from 7.78 to 158.78 nGy/h with an average value of 73.15 nGy/h. According to the UNSCEAR (2000), the corresponding worldwide average value of the absorbed dose rate is 60nGy/h. The calculated mean absorbed dose rate in the air for Sarıhan Granodiorite, Ophiolitic melange and Hozbirikyayla formation are 84.47, 68.65 and 30.93 nGy/h, respectively. This reveals that the absorbed dose rates in the air for plutonic rock and sandstones except Hozbirikyayla formation are higher than the worldwide average value.

The relative contributions of natural radionuclides to dose rate in air outdoor were calculated from the concentrations of nuclides of $^{232}Th$ and $^{238}U$ series, and of $^{40}K$. Measured radionuclide concentrations were converted to the main dose rate unit (nGy/h) using an appropriate conversion factor given in Gamma Surveyor User Guide (2009) (13.078 for 1% K, 5.675 for 1 ppm eU and 2.494 for 1 ppm eTh).

Fig. 13 shows the measured relative contribution to the total dose rate outdoors for the different geological units indicated. For Sarıhan Granodiorite, the relative contribution to dose due to $^{232}Th$ is 47%, followed by a lower contribution due to $^{40}K$ and $^{238}U$ (33% and 20%, respectively). The contribution of the three radionuclides to the total gamma dose in melange is in decreasing manner (36% $^{232}Th$, 34% $^{238}U$ and 30% $^{40}K$). For sedimentary rocks, dose contribution of $^{232}Th$, $^{238}U$ and $^{40}K$ were obtained as 36%, 34% and 30%, respectively.

The obtained min, max and average values for the effective dose equivalent are given in Table 2. The corresponding effective dose for the outdoor environment ranges from 0.017 to 0.195 mSv with a mean value of 0.090 while its acceptable value is approximately 2.4 $mSvy^{-1}$ (IAEA 2003). The obtained values for all geological formations (granodiorite, limestone and sandstone) are lower than the average value given in the literature. The results have indicated that Sarıhan Granodiorite and its surrounding area can be considered as an area with normal radiation level.

The calculated external hazard index values for studying area vary between 0.084 and 0.923, with a mean value of 0.425. The value of $H_{ex}$ should be below the unity, implies that there is no radiation risk in studied region.

Whereas the minimum and maximum values of $H_{ex}$ for Ophiolitic melange and Hozbirikyayla formation are less than unity, the maximum value of $H_{ex}$ close to the limit values given in the literature ($H_{ex} \leq 1$).The calculated radiological hazard parameters are less than limit values, which means it is safe for human and other living creatures to carry out their activities in the area.

## Results and discussions

In this field study, in-situ gamma-ray spectrometry maps showed different values over the surveyed area, which reflect

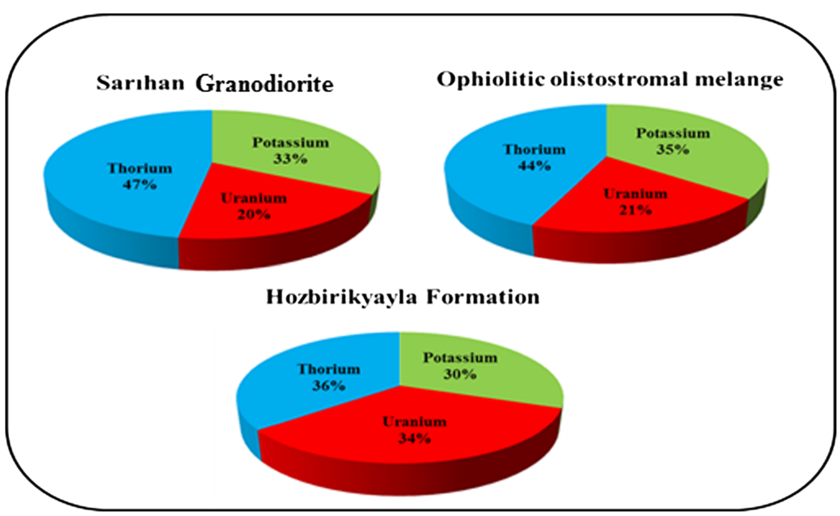


**Fig. 13** The relative contribution of $^{40}K$, $^{238}U$ and $^{232}Th$ to the total absorbed gamma dose rate in air

contrasting radioelement contents for the outcropped various rock units. While the highest radioelement concentrations were observed in the middle part of the study area which mainly associated with Sarıhan Granodiorite Granodiorite (consist of quartz monzodiorite, granodiorite, quartz diorite), lowest values were obtained in the Hozbirikyayla formation (limestone and sandy limestones) and Ophiolitic melange that surrounds Sarıhan Granodiorite from NW to SE.

The areas on the contour maps showing higher dose rate and radionuclide contents are associated with the plutonic areas containing K feldspar and high amount of $SiO_2$ rich quartz.U, Th, and K are the most unstable elements in the geochemical cycle.

Therefore, the quantities of these elements generally increase in the final stage of magmatic processes, such as differentiation, fractional crystallization, partial melting, etc., which lead to an increase $SiO_2$ and alkali quantity in the rocks. Thus, these elements are enriched in acidic rocks (Wilson 1989; Rollinson 1993). Generally, the increase in U content along with the increasing quantities of $SiO_2$ and alkali in the rocks is much more significant than the increase in Th quantity (Örgün et al. 2005; Örgün et al. 2007; Yılmaz et al. 2010). Therefore, the rock types and soils in which it works have showed different radioactivity values. When the radioelements ratios which reflect the radioactive characters of the rock and soil are analyzed and it is seen that the maximum eU/K and eU/eTh ratios are related to limestone and sandy limestones and the minimum ones are measured on the granodiorite. Ophiolitic olistostromal melange has the highest eTh/K value and the lowest values are observed in the Hozbirikyayla Formation.

In UNSCEAR (2000), it is reported that median values of uranium (35 Bq/kg), thorium (30 Bq/kg), potassium (400 Bq/kg) activities, and gamma dose rates (60 nGy/h). In this study, while the calculated mean $^{232}$Th, $^{40}$K activities, and gamma dose rate value were found to be higher than the values to be given in UNSCEAR (2000), the median value of $^{238}$U was a little lower from this value.

## Conclusions

The radiological hazard indices were calculated to determine radiological impact on living things of background radioactivity level in the study area. The average of total absorbed dose rate and annual effective dose are consistent with the values reported in the UNSCEAR (2000), and the external hazard index for all points is lower than unity. These radiation hazard parameters are used to determine what levels of radiation are safe or dangerous for human and environment. Gamma rays are the most dangerous form of ionizing radiation. These extremely high energy photons can travel through most forms of matter because they have no mass.

If a person is exposed to gamma rays, they pass through one's entire body, affecting all of tissues from the skin to the marrow of bones. This causes widespread, systemic damage in the human body (Grabianowski 2011). The human population has lived in some parts of the study area and the level of radiation in this area is not a problem for people. The measurement results are comparable with other global radioactivity measurements and it is concluded that radionuclide levels in the region are not harmful for human health and the environment.

It is finally concluded that in-situ gamma-ray spectrometry measurements, using a portable NaI(Tl) detector, carried out in this study are quickly applicable, and acceptably an inexpensive field investigation method, and it is suitable to obtain the data required for imaging of the radiometric variations and surface geological features of the plutonic areas.

The radiometric maps obtained based mainly on conveniently designed measurement points are properly significant to describe the surficial heterogeneities displayed by that geological system, even in the presence of poorly contrasting geological features and of small variations of radionuclide concentration values. Thus, these types of maps could pioneer to more comprehensive and further in-situ and ex-situ studies concerning the radiometric, geologic, petrologic and geochemical characterization of a given area.

**Acknowledgments** We would bluntly like to express our gratitude to the reviewers and the editor of the Journal, for their helpful criticism and detailed discussions and suggestions that improved the text. Grateful thanks are offered to the provider of financial support for the research presented here: Karadeniz Technical University Scientific Research Project (Project no: BTAP-9588). The authors also would like to thank undergraduate students; İnci Gökçelik, Metin Yılmaz and Ufuk Çoban for assisting during field work.

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