



Mineral chemistry and radiological characteristics of syenogranite bearing rare metals mineralization: environmental implications for radiation safety

Ahmed E. Abdel Gawad · Elena G. Panova · Mohamed M. Ghoneim · Turki Kh. Faraj · Mohamed Y. Hanfi

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Abstract The investigated syenogranite is predominantly enriched in rare metals mineralization. Thorite contains rare earth elements (REEs), and monazite has low Th- concentrations, while Th and Y are found in zircon crystals. These may be attributed to the effect of hydrothermal alteration. Fe_2O_3 and MnO are identified in the studied columbite, with a significant concentration of Fe_2O_3 indicating ferrocolumbite. REE minerals are prominently included in

the investigated syenogranite including (i) REE fluorocarbonates and fluoride (synchysite and fluorite); (ii) REE phosphates (monazite and xenotime). The total rare earth elements (TREE_2O_3) exhibit significant variability in their concentrations, particularly in monazite, synchysite, xenotime, fergusonite and columbite with average values of 64.16, 56.05, 22.58, 14.19 and 11.63 wt%. Ce is the most prevalent REEs in the analyzed monazite and synchysite, with average concentrations 32.27 and 25.57 wt%, respectively. This study also evaluates the radiological hazards and statistical relationships of radionuclides ^{238}U , ^{232}Th and ^{40}K in syenogranite samples collected from a specific geological area. Gamma-ray spectrometry revealed that the activity concentrations of ^{238}U , ^{232}Th and ^{40}K exhibited mean values of 153 ± 37 , 171 ± 35 , and 1390 ± 252 Bq kg^{-1} , respectively. The calculated radiological hazard indices, including radium equivalent content (Ra_{eq}), external and internal hazard indices (H_{ex} and H_{in}), absorbed dose rate (ADR), annual effective doses (E_{out} and E_{in}), and excess lifetime cancer risk (ELCR), generally exceeded international safety limits, suggesting potential health risks in the study area. Statistical analyses, including Kolmogorov–Smirnov tests, confirmed the normal distribution of radionuclide concentrations, while multivariate methods such as Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) provided insights into the relationships among variables. These results highlight the significance of recognizing the mineralogical and radiological characteristics

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A. E. Abdel Gawad (✉) · M. M. Ghoneim · M. Y. Hanfi (✉)
Nuclear Materials Authority, P.O. Box 530, Maadi, Cairo, Egypt
e-mail: gawadnma@gmail.com

M. Y. Hanfi
e-mail: mokhamed.khanfi@urfu.ru

E. G. Panova
Department of Geochemistry, Saint Petersburg State University, Saint Petersburg 199034, Russia

T. K. Faraj
Department of Soil Science, College of Food and Agricultural Sciences, King Saud University, Riyadh, Saudi Arabia

M. Y. Hanfi
Department of Life Safety, Institute of Fundamental Education, Ural Federal University, St. Mira, 19, Yekaterinburg 620002, Russia

of syenogranite, underscoring their relevance in geological research and ensuring its safe use in construction and various other applications.

Keywords Environment · Syenogranite · Rare metals mineralization · Radiological hazards · Statistical analysis

Introduction

Natural radioactivity is a fundamental characteristic of the Earth's crust, with specific isotopes occurring in varying amounts depending on the geological formation. Radionuclides such as uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K) are key contributors to background radiation. Their activity levels and distribution are influenced by the mineralogical makeup and geological history of rocks. The presence of these naturally occurring radionuclides raises concerns about their potential risks to human health and the environment, especially with prolonged exposure, driving considerable research into their concentrations across various rock types (Aberikae et al., 2023; Anjos et al., 2005; Yalcin et al., 2020).

Granites, one of the most prevalent rocks in the Earth's crust, are recognized for their elevated levels of natural radioactivity. This is attributed to the higher concentrations of ^{238}U , ^{232}Th and ^{40}K present in their composition. These radionuclides are generally linked to radioactive minerals such as uraninite, brannerite, pitchblende, coffinite, thorite, thorianite, uranothorite, monazite, and zircon, which are frequently embedded in minerals such as feldspars, biotite, and quartz (Abdel Gawad et al., 2024; Khattab et al., 2017).

Investigating the distribution of radionuclides in granite is especially vital in regions where the rock is extensively used for construction purposes. The radiation emitted from these rocks can elevate indoor exposure levels, emphasizing the need for detailed assessments of their radiological properties. This focus has made granite a critical subject for geological research and radiation safety evaluations, highlighting the collaborative efforts of geological and radiation protection agencies (Abbasi, 2013; Asaduzaman et al., 2015).

Rare metals encompass high field strength elements (HFSE) such as Zr, Nb, Ta, and W; large

elements such as Sn and Cs; the rare earth elements (Ce–Lu) and Y; as well as small and low valence elements such as Li and Be. These elements are significant strategic metals with economic importance in high-tech industry, hybrid electric vehicles, electronics, catalysts, generators in wind turbines, metal alloys, automobile industries, and for the transition to sustainable energy sources (Gunn, 2014; Linnen 2005; Linnen et al., 2012). Consequently, these elements are enriched in silicate melts during partial melting of low degree as well as fractional crystallization. They predominantly exist in the upper continental crust. Furthermore, the rare metals are distinguished by their capacity to perform chemical complexes particularly with Cl and F, which are mobile during magmatic and hydrothermal processes (Abdel Gawad, et al., 2022a; Ballouard et al., 2020; Hanfi et al., 2024; Harlaux et al., 2017; Salvi and Williams-Jones 2005; Timofeev et al., 2017). These metals are typically linked to carbonatites, mylonite, albite granite, peralkaline to peraluminous granite, syenite, nepheline syenite, ash flow tuffs, and pegmatites (Abdel Gawad et al., 2025a; Abd El-Naby & Dawood, 2024; Alekseev & Alekseev, 2023; Ali et al., 2021; Černý & Ercit, 1985). The rare metals granite is extensively found in Egypt's Eastern Desert (ED), attracting significant interest from economic geologists due to its strategic economic value. Moreover, the most granites in the ANS are influenced by post-magmatic processes, including silicification, albitization, chloritization, sericitization, and kaolinitization. The hydrothermal alteration and metasomatic processes may have played crucial role in the formation of rare metals mineralization (Abdalla et al., 1998; Abdel Gawad et al., 2025b; Sami et al., 2017; Skublov et al., 2021).

The Nikeiba region is of significant interest to numerous researchers due to its prominent rare metal deposits, situated in the South Eastern Desert (SED) in Egypt (Abdel Gawad et al., 2021; Ali et al., 2018; Eliwa et al., 2018; Hanfi et al., 2022). This is a case study from the SED of Egypt, chosen from the ANS (Fig. 1a, b). The primary objective of this study is to conduct microchemical analyses of rare metals mineralization from the syenogranite at Nikeiba. Furthermore, the aim of this work is to investigate the radiological characteristics of syenogranite samples, focusing on the activity concentrations of naturally occurring radionuclides ^{238}U , ^{232}Th and ^{40}K . The

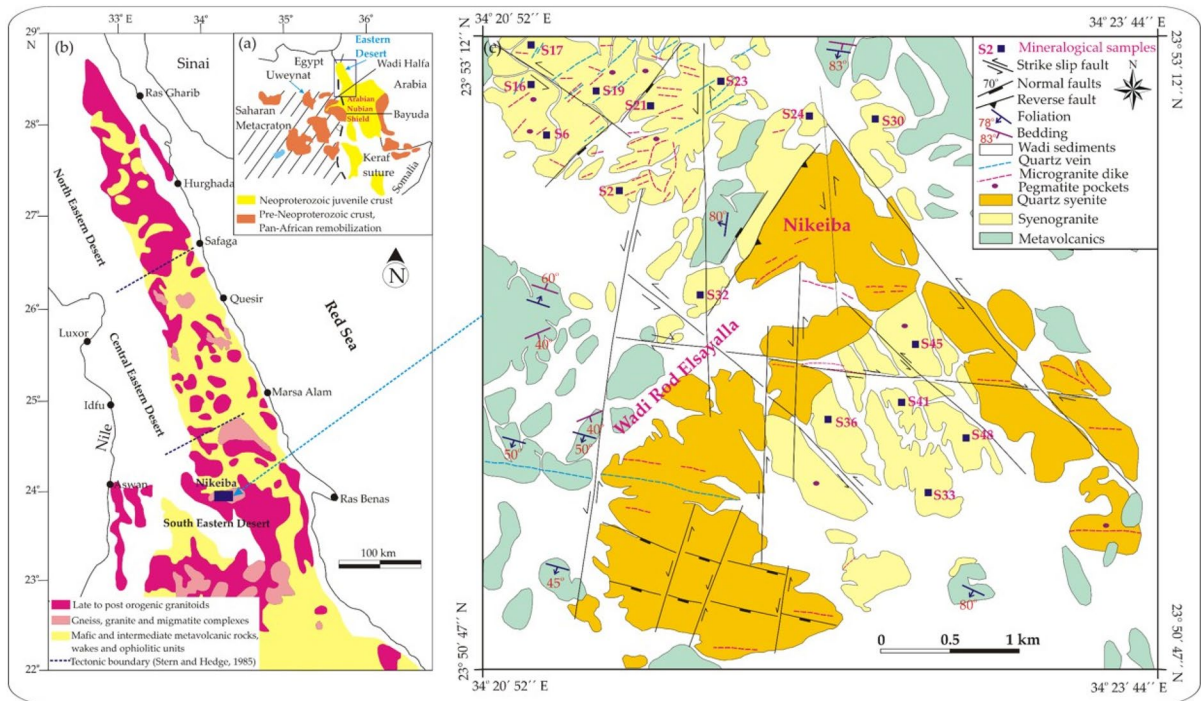


Fig. 1 **a** Geologic map showing the Arabian Nubian Shield (ANS); **b** Geologic map showing the Neoproterozoic the basement complex in the ED of Egypt (Liégeois & Stern, 2010); **c** Detailed geologic map of Nikeiba, SED of Egypt (Abdel Gawad et al., 2022b)

study seeks to evaluate the radiological hazards associated with these radionuclides by calculating relevant indices such as radium equivalent activity (Ra_{eq}), external and internal hazard indices (H_{ex} and H_{in}), and annual effective dose rates. Furthermore, statistical techniques, including Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), are employed to analyze the relationships between radionuclides and their environmental and geological implications. This comprehensive approach aims to provide insights into the safe utilization of syenogranite in construction and its broader environmental impact.

Geologic setting

The investigated Nikeiba area revealed the basement complex consisting of metavolcanics, syenogranite and quartz syenite as well as pegmatites (Figs. 1c and 2a–d). They were dissected by microgranite dikes and quartz veins, exhibiting E–W, NE, NNW and NW trends (Fig. 1c).

Metavolcanics exhibit a stratified, thick sequence of lava flows characterized by colors ranging from black, dark gray, buff to reddish brown, with a fine-grained, and significant foliation (Fig. 2a). They vary in composition from metabasalt, meta-andesite, metadacite and metarhyolite. They are interbanded with pyroclastics including ash tuffs and lithic lapilli tuffs. These rocks were intruded by syenogranite and quartz syenite exhibiting distinctly sharp intrusive contacts (Fig. 2b). Syenogranite has low to moderate relief, with reddish pink to buff colors, medium-to coarse-grained, and distinguished by cavernous weathering and boulder appetences (Fig. 2c). It is extensively fractured, jointed and exfoliated. Syenogranite is mostly consisted of K-feldspar, quartz, plagioclase and biotite. It was intruded metavolcanics with distinctly sharp intrusive contacts (Fig. 2b). Quartz syenite is distinguished by its higher elevated rock type in the study area (Fig. 2d). This rock exhibits a color range from dark gray to pale pink, possesses a medium to coarse grain, massive, and displays boulder-like characteristics. It is extensively

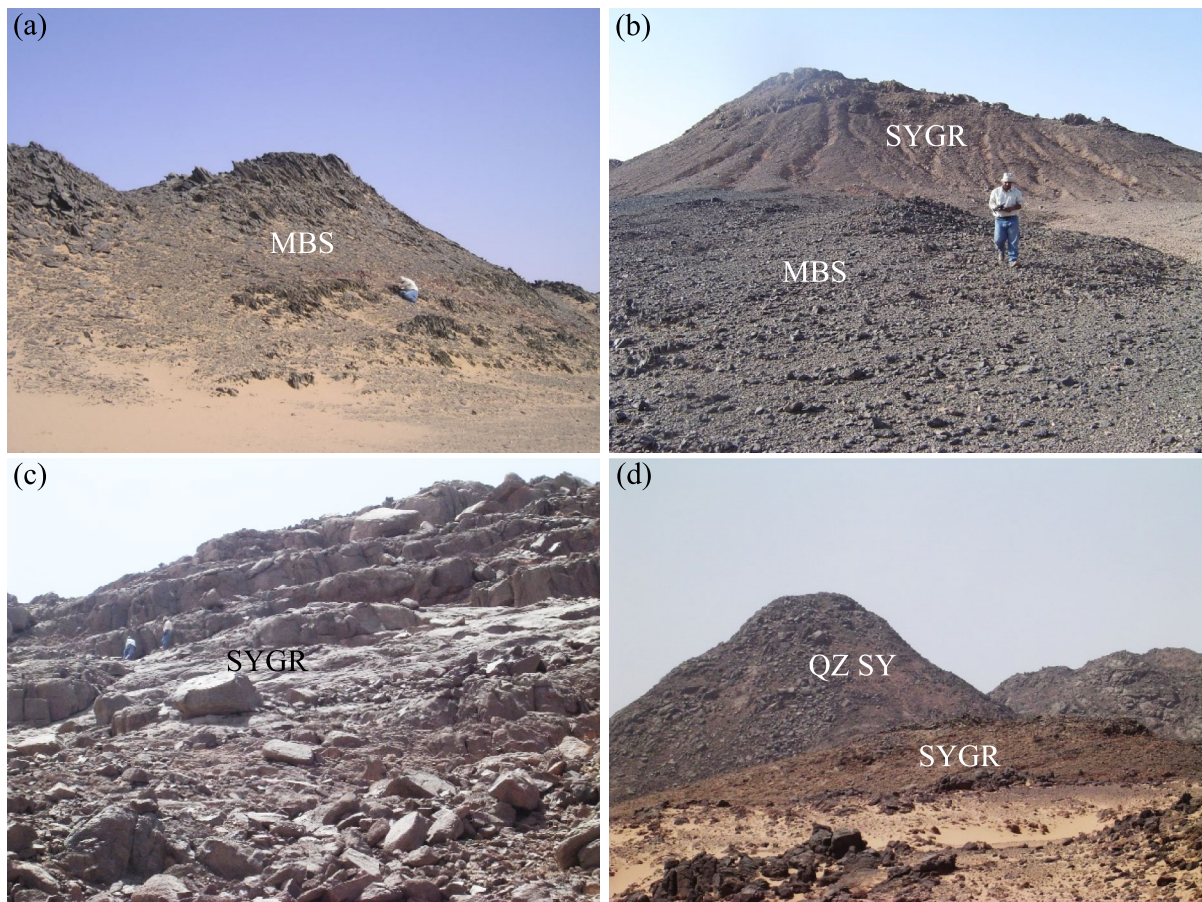


Fig. 2 **a** Highly foliated metabasalt (MBS); **b** Syenogranite (SYGR) was intruded metabasalt (MBS); **c** Boulder appearances of syenogranite (SYGR); **d** Quartz syenite (QZ SY)

shows high elevation, and was intruded the syenogranite (SYGR) at Nikeiba, SED of Egypt

weathered, altered, fractured, jointed and exfoliated. It is mostly consisted of quartz, K-feldspars, biotite, amphibole, and plagioclase. It was intruded the syenogranite with distinct intrusive contacts (Fig. 2d). Pegmatite pockets are irregular bodies, characterized by very coarse-grains, buff to reddish brown colors, and predominantly found within syenogranite. They exhibited strips in their appearances. Microgranite dikes were dissected granites in the investigated region. They exhibit colors ranging from reddish brown to buff, possess a fine grain, and display E–W, NE, NNW and NW trends with almost vertical dips. Quartz veins have been intersected the basement rocks, exhibiting E–W, NE and NW trends with almost vertical dips.

Petrography of syenogranite

It possesses an equigranular and hypidiomorphic texture, exhibiting medium to coarse grain with a color range from buff to reddish pink. Microscopically, syenogranite is composed essentially of K-feldspar, quartz, plagioclase and biotite. Zircon, allanite, apatite, fluorite, iron oxides and opaques are accessory minerals, while chlorite, sericite and epidote are alteration products. K-feldspar is predominantly represented by orthoclase-perthites, and occurs as anhedral to subhedral prismatic crystals showing simple twinning. It exhibits flame, patchy and string perthitic intergrowths. Quartz occurs as interstitial subhedral to anhedral crystals. The presence of undulose and wavy extinction suggests that the syenogranite may have



Fig. 3 Photomicrographs showing the petrographical characteristics of syenogranite at Nikeiba, SED of Egypt. **a** Cracked crystals of antiperthite filled with iron oxides; **b** Plagioclase stained with iron oxides, and associated with zircon; **c** Zircon enclosed in quartz and stained with iron oxides; **d** Twisting of

biotite flakes enclose zircon crystals; **e** Ferric biotite showing kinked flame structure; **f** Zoned allanite crystal associated with zircon and biotite. Abbreviations: Plg, plagioclase; Qz, quartz; Pth, perthite; Bt, biotite; Zrn, zircon; All, allanite; Fe-ox, iron oxides; Op, opaques

undergone significant deformation events (Fig. 3a). Small anhedral crystals occur poikilitically occur in perthite, plagioclase and biotite. Plagioclase of oligoclase composition (An_{16}) occurs as euhedral to subhedral tabular crystals. It exhibits the simple, percline and lamellar twinning. It is significantly sericitized especially in the inner core. Biotite occurs as subhedral flakes, which are commonly altered to chlorite and stained with iron oxides along cleavage planes and outer rims. It exhibits criteria for deformation as wavy extinction and kinked flame structure (Fig. 3b). It is significantly corroded by K-feldspar and quartz along the outer periphery (Fig. 3c). Zircon occurs as subhedral to euhedral minute prismatic crystals, identified as microinclusions within feldspars, quartz and Biotite (Fig. 3b, c, d, f). It is usually cloudy and rimmed with iron oxides. Some crystals are partially to completely metamictized, and surrounded by thin pleochroic halos. Allanite is found in the periphery of biotite crystal as burned brown, zoned crystal, exhibiting idiomorphic prismatic and slight pleochorism (Fig. 3f). Apatite is found as fine-needles, and enclosed in quartz, feldspars and biotite. Opaque minerals manifest as small, irregular aggregates or as minute microinclusions in feldspars, quartz and biotite. Fluorite is identified as anhedral crystals and is typically enclosed in quartz and feldspars.

Material and methods

Mineralogical investigation

Fifteen polished sections have been prepared for the identification of micro-chemical analyses of rare metals (Th, U, Zr, Nb, Ta, Y and REE) bearing-mineralization from the investigated syenogranite. The current study was conducted using a scanning electron microscope equipped with the Pegasus 4000 (EDAX, Mahwah, NJ, USA). Micro-analyses were conducted utilizing an Electron Probe Microanalysis (EPMA) system fitted with a CAMECA SX 100 (Madison, WI, USA). The diameter of the electron beam utilized for spot examination on the surface is 1–2 μm . Additional conventional settings are a 15 kV acceleration potential, a 15 nA beam current, and counting times of 10 s for the peak and 5 s for the background. The microprobe technique frequently incorporates an automated wavelength dispersive

spectrometer (WDS) alongside an energy dispersive spectrometer (EDS). Albite for Al ($K\alpha$), olivine for Mg ($K\alpha$), orthoclase for Si ($K\alpha$), wollastonite for Ca ($K\alpha$), monazite for Yb ($L\alpha$), and hematite for Fe ($K\alpha$) are the most natural standards employed in this study. Conversely, the synthetic standard compounds include UO_2 , ThO_2 , ZrO_2 , PbCrO_4 , CePO_4 , NdPO_4 , SmPO_4 , GdTiGe , DyRu_2Ge_2 , and YPO_4 , which are deemed the most appropriate standards for quantifying U ($M\beta$), Th ($M\alpha$), Zr ($L\alpha$), Pb ($M\alpha$), Ce ($L\alpha$), Nd ($L\alpha$), Sm ($L\alpha$), Gd ($L\alpha$), Dy ($L\alpha$), and Y ($L\alpha$), respectively. The standard of fluorite has been employed for measuring F ($K\alpha$).

Sampling preparations for gamma spectroscopy

Syenogranite samples were systematically collected from various locations, ensuring coverage their distribution in the investigated Nikeiba plutons. A total of 50 samples, each weighing approximately 1–2 kg, were gathered using clean, non-contaminating tools. The collected samples were labeled and transported to the laboratory for processing. In the laboratory, the samples were washed thoroughly with distilled water to remove surface contaminants such as dust and organic material. The clean samples were then dried in an oven at a temperature of 110 $^{\circ}\text{C}$ for 24 h to eliminate moisture. After drying, the samples were crushed using a jaw crusher and ground into a fine powder with a particle size of less than 200 mesh (75 μm) using an agate mortar and pestle to ensure uniformity. Approximately 200 g of each powdered sample was packed into plastic cylindrical containers. The containers were sealed hermetically and left for at least 4 weeks to allow secular equilibrium between the parent radionuclides (^{238}U , and ^{232}Th) and their progenies.

Radioactive analysis

The prepared samples were then analyzed using High-Purity Germanium (HPGe) detectors, which provide high resolution and efficiency for identifying and quantifying the specific radionuclides (e.g., ^{238}U , ^{232}Th , and ^{40}K) present in the syenogranite. The HPGe spectrometry data were subsequently used to assess the radiological impact of the investigated syenogranite. The activity concentrations of radionuclides in the syenogranite samples were measured

using High-Purity Germanium (HPGe) gamma-ray spectrometry. HPGe detectors are renowned for their high resolution and ability to accurately distinguish between closely spaced gamma peaks. After preparing the samples, the Nuclear Materials Authority at Cairo Egypt (NMA) conducted a survey using gamma ray spectrometric measurements High-Purity Germanium (HPGe). A relative efficiency greater than 40% was achieved with the (HPGe) coaxial detector (Canberra GC4018) used for measurements. The detector was interfaced with the Canberra DSA-1000 digital multichannel analyzer (MCA) and the Genie 2000 software (Canberra Industries, USA) was used to acquire and process the spectra. To limit uncertainty and ensure good counting statistics, each sample was counted for 86,400 s (24 h). Energy and efficiency calibration for gamma spectrometry was set using range certified material reference standards

(CRM), such as IAEA RGU-1, IAEA RGTh-1, and IAEA RGK-1 and the calibrated radioactive sources ^{137}Cs (661 keV) and ^{60}Co (1173 and 1332 keV) to determine the full width at half maximum (FWHM) of the calibration peaks. The same geometry and count times for all of the standards and unknowns were used for each standard. The generated efficiency calibration curve for the HPGe detector, plotted with error bars representing $\pm 5\%$ uncertainty for each efficiency value, and confirming the reliability of the system (Fig. 4).

The detector's energy resolution was assessed through the Full Width at Half Maximum (FWHM) of calibration peaks, which typically range from 1.33 keV at 122 keV (cobalt-57), 2.0 keV at 661 keV (cesium-137), and 2.5 keV at 1332 keV (cobalt-60). These FWHM values ensure precise identification of gamma peaks in the spectra, which is essential for

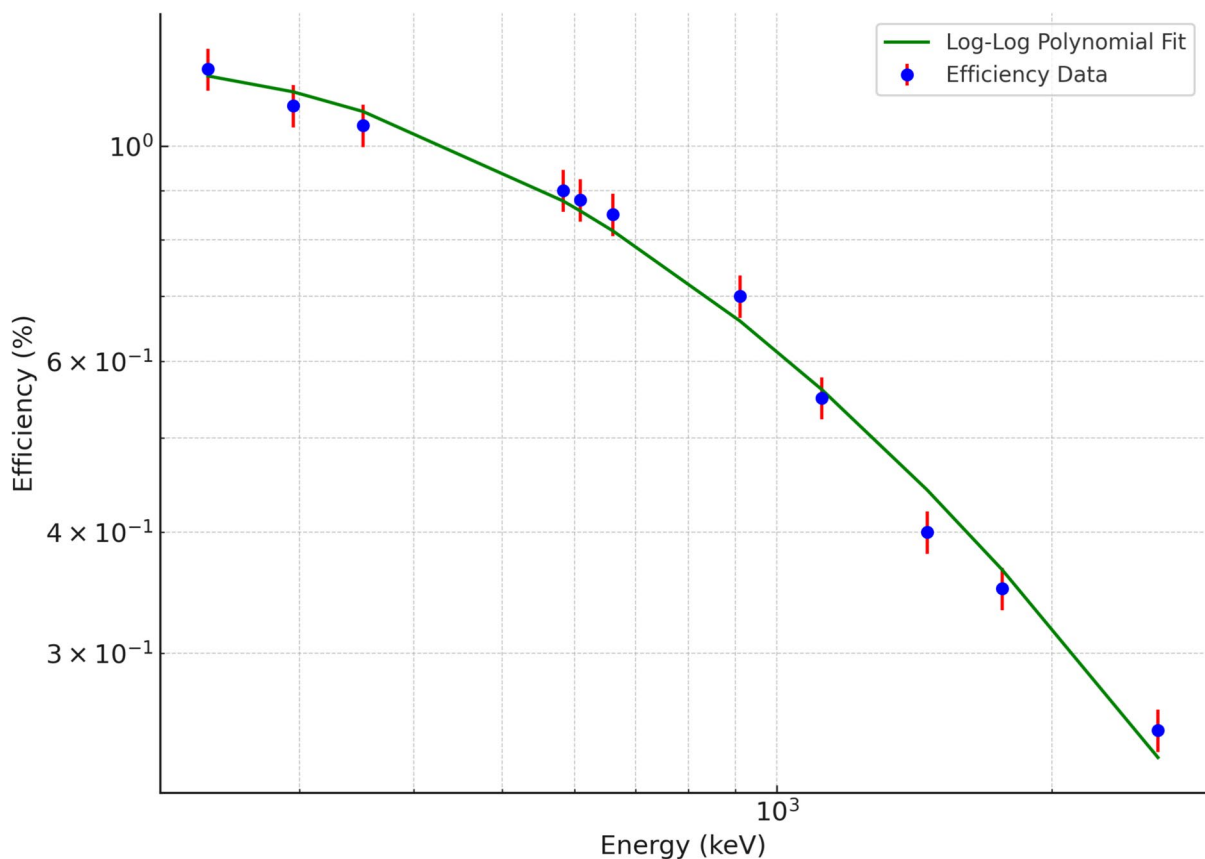


Fig. 4 Efficiency calibration curve of the HPGe detector used in the analysis. The plot has the relative efficiency (%) plotted as a function of gamma-ray energy (keV) on a log–log

scale. The blue circles are the experimental data points plotted with $\pm 5\%$ error bars and the green curve is the polynomial fit to the data

distinguishing the specific gamma energies emitted by uranium-238 (U-238), thorium-232 (Th-232), and potassium-40 (K-40). For the analysis, the primary gamma energies associated with the decay chains of U-238 include 295 keV and 352 keV (lead-214) and 609 keV, 1120 keV, and 1764 keV (bismuth-214). The Th-232 series was analyzed using gamma energies of 238 keV (lead-212), 338 keV (actinium-228), 583 keV, 911 keV (actinium-228), and 2614 keV (thallium-208). The characteristic gamma energy of K-40 was detected at 1460 keV. These energy peaks were used to calculate the activity concentrations of the radionuclides present in the granite samples (Abedin et al., 2019; Asaduzzaman et al., 2015). The activity concentration of each radionuclide in the syenogranite samples was calculated using the following equation (Abedin et al., 2019):

$$A(\text{Bq/kg}) = \frac{C}{\varepsilon \cdot P\gamma \cdot m} \quad (1)$$

where A is the activity concentration in Bq kg^{-1} , C is the net count rate under the gamma peak (counts per second), ε is the detector efficiency at the specified gamma energy, $P\gamma$ is the gamma emission probability for the radionuclide and m is the mass of the sample in kg. This equation provides a direct calculation of the radionuclides concentration based on the gamma-ray spectrometric data. The Minimum Detectable Activity (MDA) represents the lowest radionuclide concentration that the HPGe detector can reliably measure. The MDA is calculated using the equation (Abedin et al., 2019):

$$\text{MDA} = \frac{2.71 + 4.65\sqrt{B}}{\varepsilon \cdot P\gamma \cdot t \cdot m} \quad (2)$$

where B is the background count rate in counts per second, t is the counting time in seconds and ε , $P\gamma$ and m are defined as before. In this study, we identified the MDA was found to be about $1.5\text{--}3 \text{ Bq kg}^{-1}$ for U-238 and Th-232, and $10\text{--}15 \text{ Bq kg}^{-1}$ for K-40. These values are in line with previous studies that determined MDAs using HPGe detectors for environmental and geological samples. The obtained MDAs presumably indicate optimal measurement conditions such as an adequate sample mass, long counting times, high detector efficiency, and low background levels.

Moreover, MDA values are contingent on the type of matrix, the detector setup and the conditions of the measurement, and our values reported reflect the solid geological context of our study. MDAs are likely to vary according to the specific specifications of the detector, energies of gamma-rays that were analyzed, and likewise the specific experimental setup. Moreover, the uncertainties in the measurements are expressed in terms of the standard deviation ($\pm 2\sigma$), where σ is calculated as $\sigma = \sqrt{\frac{N_s}{T_s} + \frac{N_b}{T_b}}$, (Abedin et al., 2019) with N_s and T_s representing the sample counts and measurement time, and N_b and T_b representing the background counts and measurement time, respectively. The overall uncertainty in activity concentration measurement was determined by summing and propagating the associated errors from counting statistics (counting time), background subtraction, efficiency calibration, and standard. The combined relative uncertainty on measured radionuclide activities is generally within $\pm 5\text{--}10\%$ depending on the radionuclide energy and a similarly matrix nature (Abedin et al., 2019). Calculating various radiation-related quantities involves applying specific formulas and considerations based on radiation measurements and exposure scenarios.

Radium Equivalent Content (R_{eq}): R_{eq} is a measure used to assess the potential radiation hazard from different radioactive isotopes present in a sample or material. R_{eq} is typically calculated using the activity concentrations (in Bq kg^{-1}) of different radionuclides (Eq. 3). R_{eq} is an essential measure for evaluating radiation safety, helping to ensure that the annual effective dose for the public is kept within safe limits. By keeping R_{eq} values below 370 Bq kg^{-1} , we can maintain the annual effective dose under 1 mSv , thereby minimizing health risks associated with radiation exposure (Shuaibu et al., 2017).

$$R_{\text{eq}} = A_{\text{U}} + 1.43 A_{\text{Th}} + 0.077 A_{\text{K}} \quad (3)$$

where A_{U} , A_{Th} , A_{K} are the activity concentrations (in Bq kg^{-1}) of uranium-238, thorium-232, and potassium-40, respectively.

The external radiation index (H_{ex}) is used to assess the potential radiological hazard posed by the external gamma radiation from the sample. It is based on the activity concentrations of ^{238}U , ^{232}Th , and ^{40}K in the sample. The formula (4) for the external radiation index is (Akbar Abbasi, 2022; Kolo et al., 2019):

$$H_{ex} = \frac{A_U}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (4)$$

The constants (185, 259, and 4810) are derived from the corresponding conversion factors based on the gamma radiation dose rates for these radionuclides. Threshold value: If $H_{ex} \leq 1$, the material is generally considered safe for use in construction. If $H_{ex} > 1$, the material may pose a higher radiation hazard and should be used cautiously.

The internal radiation index H_{in} is related to the radiation risk from inhalation of radon and its progeny, which are produced from the decay of ^{238}U , ^{232}Th , and ^{40}K . It is calculated using the following formula (5) (Sivakumar et al., 2014; Taalab et al., 2024):

$$H_{in} = \frac{A_U}{259} + \frac{A_{Th}}{237059} + \frac{A_K}{4810} \quad (5)$$

Threshold value: If H_{ex} and $H_{in} \leq 1$, the material is generally considered safe for use in construction. If H_{ex} and $H_{in} > 1$, the material may pose a higher radiation hazard and should be used cautiously.

Representative gamma level index (I_γ) index applied to identify the safe level of the investigated materials includes the radionuclide. The following relation (6) utilized to compute I_γ values (Devanesan et al., 2020):

$$I_\gamma = \frac{A_U}{150} + \frac{A_{Th}}{100} + \frac{A_K}{1500} \leq 1 \quad (6)$$

Absorbed Dose Rate (ADR): ADR is the rate at which energy from ionizing radiation is deposited per unit mass of tissue (in Gy/h or mGy/h). Absorbed dose rate can be estimated using the following formula (7), considering the activity concentrations and dose conversion factors (Abdel Gawad et al., 2024; Baykara et al., 2011; Abdel-Razek et al., 2016):

$$ADR = \sum A_i \times D_i \times \gamma_i \quad (7)$$

where A_i is the activity concentration of each radionuclide (in Bq kg⁻¹), D_i is the dose conversion coefficient for each radionuclide (in nGy h⁻¹ Bq⁻¹ kg), where D_U , D_{Th} and D_K are 0.430, 0.666 and 0.042 nGy h⁻¹ Bq⁻¹ kg, respectively, γ_i is the gamma-ray energy fraction emitted per decay of the radionuclide.

Annual Effective Dose (AED): AED represents the radiation dose received by an individual over one year, accounting for the type of radiation and tissue sensitivity (in mSv). AED can be calculated as (Eq. 8) (Abbasi, 2022; Guillén et al., 2014):

$$AED \left(\frac{\text{mSv}}{\text{y}} \right) = \sum \left(D_{air} \left(\frac{\text{nGy}}{\text{h}} \right) \times 0.7 \left(\frac{\text{Sv}}{\text{Gy}} \right) \times \text{occupancy factor} \right) \times 8760 \text{h} \times 10^{-6} \quad (8)$$

where the occupancy factor accounts for occupancy time in case outdoor is 0.2 and indoor 0.8.

Annual Gonadal Dose Equivalent (AGDE): AGDE assesses the radiation dose specifically to the gonads (testes or ovaries) due to external radiation exposure (in mSv). AGDE can be estimated as follow (Eq. 9) (Sivakumar et al., 2018):

$$AGDE (\mu\text{Sv y}^{-1}) = 3.09A_{(238\text{U})} + 4.18AA_{(232\text{Th})} + 0.314A_{(40\text{K})} \quad (9)$$

Excess Lifetime Cancer Risk (ELCR): ELCR estimates the probability of developing cancer over a lifetime due to exposure to ionizing radiation. ELCR is calculated using the following formula (Eq. 10), based on the AED and cancer risk coefficients (Qureshi et al., 2014):

$$ELCR(\text{mSv/y}) = AED_{out} \times DL \times RF \quad (10)$$

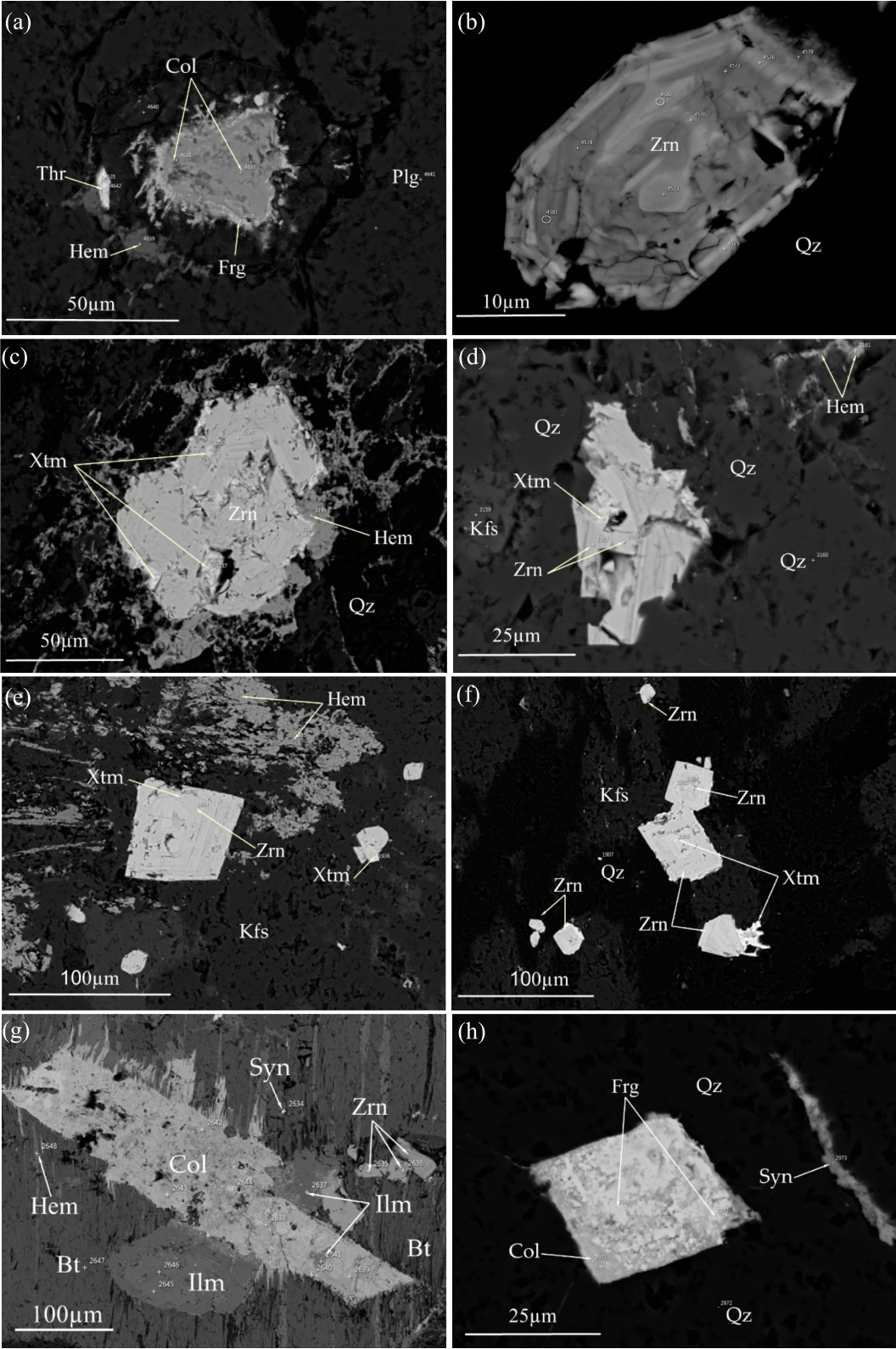
If locals were continuously exposed to gamma rays from quartz, both indoors and outdoors, there is a significant likelihood of carcinogenic effects over time. The excess lifetime cancer risk (ELCR) is calculated to assess this risk, using the ICRP's cancer risk factor of $RF=0.05 \text{ Sv}^{-1}$ and the outdoor annual effective dose (AED_{out}) over a $DL=70$ -year lifetime.

Results and discussion

Mineralogical characterization

Radioactive minerals

Thorite occurs as fine-grained, anhedral, bright microinclusions enclosed in zircon. It is predominantly enclosed in feldspars and quartz (Fig. 5a). According to the analyzed EPMA data, thorite



◀**Fig. 5** Back-scattered images of Th-, Zr-, Nb-, Ta-bearing mineralization from syenogranite at Nikeiba, SED of Egypt. **a** Fine-grained of thorite associated with columbite and fergusonite; **b** Faint zoned zircon enclosing microinclusions of zircon and opaques; **c–f** Xenotime enclosed as microinclusions in zircon and others occurred along zircon rims; **g** Large elongated columbite crystal encountered with synchysite and zircon; **h** Rhombic crystal showing overgrowth of columbite and fergusonite. Abbreviations: Thr, thorite; Zrn, zircon; Col, columbite; Frg, fergusonite; Syn, synchysite; Xtm, xenotime; Kfs, K-feldspar; Plg, plagioclase; Qz, quartz; Bt, biotite; Ilm, ilmenite; Hem, hematite

mostly consists of ThO_2 , which ranges from 53.81 to 59.67 wt%, and SiO_2 from 16.72 to 19.04 wt%. Thorite contains a high concentration of uranium, with UO_2 ranging from 1.48 to 6.89 wt%. Y_2O_3 and ZrO_2 are presented in the analyzed thorite crystals, with concentrations reached up to 6.56 and 3.26 wt%, respectively. This may suggest the substitution of Th by Y and Zr. REEs have been recorded in thorite, specifically Ce_2O_3 , Gd_2O_3 , Dy_2O_3 , Er_2O_3 , and Yb_2O_3 with concentrations of 0.36, 0.41, 1.53, 1.14 and 1.43 wt%, respectively. Al_2O_3 , P_2O_5 , CaO, and Fe_2O_3 are identified as minor elements in the studied thorite (Table 1). The total analyses of thorite crystals around 90 wt% (Table 1), which may be ascribed to hydration processes and/or significant metamictization (Abd El-Naby, 2009; Abdel Gawad, 2022). The chemical formula for the investigated thorite has been determined as follows: $(\text{Th}_{0.67}\text{Y}_{0.11}\text{Ca}_{0.09}\text{P}_{0.07}\text{Fe}_{0.06}\text{Ce}_{0.02}\text{Gd}_{0.01}\text{Dy}_{0.02}\text{Er}_{0.02}\text{Yb}_{0.02}\text{U}_{0.03}\text{Si}_{0.93})\text{O}_4$.

Zircon

It occurs as prismatic, euhedral, with certain crystals exhibiting significant cracking owing to deformation. It encloses xenotime, fine zircon, and opaque minerals, with some crystals reached up to 100 μm (Fig. 5b–f). Xenotime and hematite have been occurred along the rims of zircon crystal (Figs. 5c–f). It is primarily enclosed in quartz, feldspars and biotite, and is almost coincided with thorite, columbite, monazite, xenotime, hematite, and ilmenite from the investigated syenogranite. According to EPMA data, zircon mostly consists of ZrO_2 , which ranges from 58.94 to 61.84 wt%, SiO_2 from 28.94 to 33.71 wt%, and HfO_2 from 0.89 to 2.45 wt%. The radioactive elements ThO_2 and UO_2 are represented with averages 1.09 and 1.06 wt%, respectively. Y_2O_3 and Yb_2O_3 are well recorded and reached up 1.81

and 3.11 wt%, respectively. Additional elements such as Al_2O_3 , CaO, MnO, and Fe_2O_3 have been reported in low concentrations, with average values of 0.83, 1.27, 0.26, and 1.06 wt%, respectively (Table 2). The average chemical formula of the analyzed zircon crystals can be represented as follows: $(\text{Zr}_{0.92}\text{Hf}_{0.01}\text{Ca}_{0.04}\text{Fe}_{0.03}\text{Y}_{0.02}\text{Yb}_{0.01}\text{Th}_{0.01}\text{U}_{0.01})(\text{Si}_{0.97}\text{O}_4)$.

EPMA data of the analyzed zircons from the syenogranite are situated inside the hydrothermal or metasomatic domains, as well as adjacent to the magmatic domain, as illustrated in the binary diagram of ZrO_2 versus HfO_2 and the ternary diagram of Zr–Hf–(U + Th + Y + HREE) (Figs. 6, 7) (Abdalla et al., 2008; Kempe 1997; Wedepohl, 1969).

Nb–Ta-rich minerals

Syenogranite is enriched in rare metals, particularly those bearing Nb and Ta minerals. They are comprising columbite and fergusonite.

Columbite It manifests as fine- to medium-grained, anhedral crystals, exhibiting elongated to subrounded crystals and significant corrosion along along their peripheries (Fig. 5a, g, h). Some columbite crystals occur as fine-grained along fluorite rims, and predominantly encapsulated within feldspars, quartz and biotite. It is associated with fergusonite, thorite, zircon, ilmenite, rutile, and hematite. Large columbite crystals are enclosed fine-grained fergusonite and ilmenite (Fig. 5g, h). EPMA data indicate that columbite crystals mostly consist of Nb_2O_5 , ranging from 53.59 to 71.84 wt%, Fe_2O_3 from 8.48 to 20.33 wt%, Ta_2O_5 from 1.66 to 8.04 wt%, and TiO_2 from 1.13 to 7.47 wt%. Y_2O_3 exhibited a wide range of concentrations, ranging from 0.88 to 10.09 wt%. MnO is recorded as minor constituent, with a range from 0.57 to 3.63 wt%. REEs (Ce_2O_3 – Er_2O_3) are well recorded in some columbite crystals (Table 3), and Ce_2O_3 , Nd_2O_3 , Sm_2O_3 , Gd_2O_3 , Dy_2O_3 and Er_2O_3 are reached up to 0.95, 1.48, 1.86, 3.26, 6.67 and 3.44 wt%, respectively.

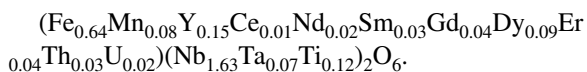
EPMA analyses indicate a significant enrichment of Fe_2O_3 compared to MnO (Table 3), whereas the Ta/(Ta + Nb) ratio ranges from 0.02–0.03, and Mn/(Mn + Fe) ratio ranges from 0.02–0.05. This indicates a standard composition of ferrocolumbite, as seen in the quadrilateral diagram (Černý & Ercit, 1985) (Fig. 8).

Table 1 Representative EPMA of thorite (oxides in wt%) from syenogranite at Nikeiba, SED of Egypt

S. No./oxides	S30	S2	S33	S2	S2	S16	S23
ThO ₂	53.81	58.15	54.42	59.67	59.01	55.21	55.05
SiO ₂	17.37	18.55	16.72	17.33	18.65	17.73	19.04
UO ₂	4.62	2.03	6.89	2.93	1.54	1.48	1.51
Y ₂ O ₃	4.86	5.56	3.21	4.47	4.87	3.47	3.11
Ce ₂ O ₃	n.d	n.d	0.31	n.d	n.d	0.36	0.34
Gd ₂ O ₃	n.d	n.d	0.34	n.d	n.d	0.41	0.38
Dy ₂ O ₃	n.d	n.d	0.98	n.d	n.d	1.17	1.53
Er ₂ O ₃	n.d	n.d	1.09	n.d	n.d	1.14	1.10
Yb ₂ O ₃	n.d	n.d	1.12	n.d	n.d	1.09	1.43
P ₂ O ₅	2.04	1.26	1.97	1.05	1.44	1.85	1.25
CaO	1.57	1.61	1.74	1.81	1.62	1.86	1.52
Fe ₂ O ₃	2.04	1.66	1.07	1.49	0.76	2.13	2.12
Al ₂ O ₃	0.87	0.93	0.74	0.49	0.81	0.89	0.85
ZrO ₂	3.26	1.12	1.23	1.41	1.72	2.65	1.55
Total	90.44	90.87	91.83	90.65	90.42	91.44	90.78
Cations	Calculated chemical formulae based on 4 oxygen atoms (apfu)						
Th	0.63	0.68	0.66	0.73	0.69	0.64	0.64
Si	0.89	0.95	0.89	0.93	0.96	0.90	0.97
U	0.05	0.02	0.08	0.03	0.02	0.02	0.02
Y	0.13	0.15	0.09	0.13	0.13	0.09	0.08
Ce			0.01			0.01	0.01
Gd			0.01			0.01	0.01
Dy			0.02			0.02	0.03
Er			0.02			0.02	0.02
Yb			0.02			0.02	0.02
P	0.09	0.05	0.09	0.05	0.06	0.08	0.05
Ca	0.09	0.09	0.10	0.10	0.09	0.10	0.08
Fe	0.08	0.06	0.04	0.06	0.03	0.08	0.08
Al	0.05	0.06	0.05	0.03	0.05	0.05	0.05
Zr	0.08	0.03	0.03	0.04	0.04	0.07	0.04
ΣCations	2.09	2.10	2.09	2.09	2.08	2.11	2.10

n.d. (not determined)

The radioactive elements ThO₂ and UO₂ attained concentrations of 5.01 and 2.03 wt%, respectively, in the analyzed ferrocolumbite crystals. The average chemical formula of columbite is presented as follows:



Fergusonite It occurs as fine microinclusions (white grains) and is poikilitically enclosed in large fluorite crystals, with additional occurrences at the peripheries of columbite crystals (Fig. 5a, h). The analyzed EPMA data indicate that fergusonite mostly consists of Nb₂O₅, ranging from 46.68 to 48.74 wt%,

and Y₂O₃ ranging from 28.91 to 32.41 wt%. The TREE₂O₃ (Ce₂O₃–Yb₂O₃) in fergusonite exhibits significantly elevated concentrations, ranging from 12.25 to 17.4 wt%. The radioactive elements, notably thorium and uranium, are prominently featured, with concentrations reaching 2.1 wt% for ThO₂ and 2.33 for UO₂. Substantial amounts of TiO₂, CaO, Fe₂O₃ and SiO₂ are recorded as mentioned in Table 4. The chemical formula of fergusonite has been identified as A³⁺B⁵⁺O₄, where A-site predominantly occupied by REE and Y, while the B-site is filled by Nb, Ta and Ti. Alternative cations may occupy in the A-site. The chemical formulae of fergusonite is provided as

Table 2 Representative EPMA of zircon (oxides in wt%) from syenogranite at Nikeiba, SED of Egypt

S. No./oxides	S41	S30	S17	S48	S6	S36	S19	S24	S2	S24
SiO ₂	28.94	29.73	32.13	31.89	30.83	32.01	33.71	32.13	31.19	31.01
ZrO ₂	60.03	59.57	61.84	58.94	59.78	60.75	61.03	60.88	59.32	61.79
HfO ₂	0.89	2.45	1.52	1.25	0.91	1.14	1.66	1.52	1.61	1.14
CaO	1.75	1.04	1.61	1.55	1.61	0.53	0.83	1.71	1.55	0.53
MnO	0.27	0.24	0.29	0.18	0.23	0.23	0.33	0.23	0.27	0.32
Fe ₂ O ₃	0.71	1.44	0.79	1.62	1.52	0.97	0.24	0.79	1.62	0.87
Y ₂ O ₃	1.81	1.52	0.79	0.72	1.42	1.21	0.86	0.91	0.72	1.21
Yb ₂ O ₃	3.11	1.91	0.17	0.68	0.39	0.55	0.26	0.17	0.58	0.55
Al ₂ O ₃	1.13	0.75	0.23	1.23	1.42	0.72	0.69	0.23	1.23	0.71
ThO ₂	0.88	0.83	0.12	1.09	0.83	0.91	0.04	0.92	1.06	0.89
UO ₂	0.48	0.52	0.51	0.85	1.06	0.98	0.35	0.51	0.85	0.98
Total	100	100	100	100	100	100	100	100	100	100
Cations	Calculated based on 4 oxygen atom per formula unit (apfu) for zircon									
Si	0.92	0.94	0.99	0.98	0.96	0.99	1.03	0.99	0.97	0.97
Zr	0.93	0.92	0.93	0.89	0.91	0.92	0.91	0.92	0.9	0.94
Hf	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Ca	0.06	0.04	0.05	0.05	0.05	0.02	0.03	0.06	0.05	0.02
Mn	0.01	0.01	0.01	0	0.01	0.01	0.01	0.01	0.01	0.01
Fe	0.02	0.03	0.02	0.04	0.04	0.02	0.01	0.02	0.04	0.02
Y	0.03	0.03	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.02
Yb	0.03	0.02	0	0.01	0	0.01	0	0	0.01	0.01
Al	0.04	0.03	0.01	0.04	0.05	0.03	0.02	0.01	0.05	0.03
Th	0.01	0.01	0	0.01	0.01	0.01	0	0.01	0.01	0.01
U	0	0	0	0.01	0.01	0.01	0	0	0.01	0.01
ΣCations	2.06	2.05	2.04	2.05	2.06	2.03	2.03	2.04	2.05	2.03

follows: $(Y_{0.71}Ce_{0.01}Nd_{0.02}Sm_{0.02}Gd_{0.03}Dy_{0.06}Er_{0.04}Yb_{0.02}Fe_{0.04}Ca_{0.02}U_{0.02}Th_{0.01})(Nb_{0.94}Ti_{0.03})O_4$.

REE minerals

The investigated syenogranite reveals the presence of two categories of rare earth element (REE) minerals: (i) REE fluorocarbonates and fluoride (synchysite and fluorite); (ii) REE phosphates (monazite and xenotime), (Figs. 5, 9 and Tables 5, 6, 7).

REE fluorocarbonates and fluoride *Synchysite* is a rare earth element fluorocarbonate mineral that manifests as fine-grained to large independent crystals, as well as radial, fibers, acicular, and flattened tabular forms. It is enclosed in quartz, K-feldspar, and along periphery of biotite crystals. It is effectively displayed as bright radial and/or acicular aggregates, associated with zircon, columbite and xenotime (Figs. 5g, h, 9b–d). The analyzed synchysite exhibits a higher

concentration of LREEs, which can vary significantly as indicated in Table 5; specifically, Ce_2O_3 is the most prevalent LREEs, with average 25.57 wt%, followed by Nd_2O_3 with average 11.78 wt%, and then La_2O_3 , Sm_2O_3 and Pr_2O_3 with averages of 11.59, 2.74 and 2.7 wt%, respectively. Gd_2O_3 is recorded as only HREE in the analyzed synchysite crystals, with average concentration of 1.68 wt%. CaO is regarded as a crucial component of synchysite, ranging from 14.11 to 16.87 wt%, with average of 15.34 wt%. ThO_2 , Y_2O_3 , and SiO_2 are exhibited in lower concentrations, with averages of 1.1, 1.92 and 0.23 wt%, respectively. The chemical formula for synchysite has been accurately determined based on the foundational formula $CaCe(CO_3)_2F$ (Ni et al., 1995), as follows:

$Ca_{0.85}(Ce_{0.48}La_{0.22}Nd_{0.22}Pr_{0.05}Sm_{0.05}Gd_{0.03}Y_{0.05})(CO_3)_2F_{1.03}$. Consequently, Ce is the most predominated LREEs in the investigated synchysite as indicated by the calculated apfu as mentioned in Table 5, suggesting synchysite-(Ce).

Fig. 6 Binary diagram showing ZrO_2 versus HfO_2 diagram of the analyzed zircon crystals from syenogranite at Nikeiba, SED of Egypt. Trends are reported as mentioned from (Kempe 1997), while the box is referring to granitic rocks according to (Wedepohl, 1969)

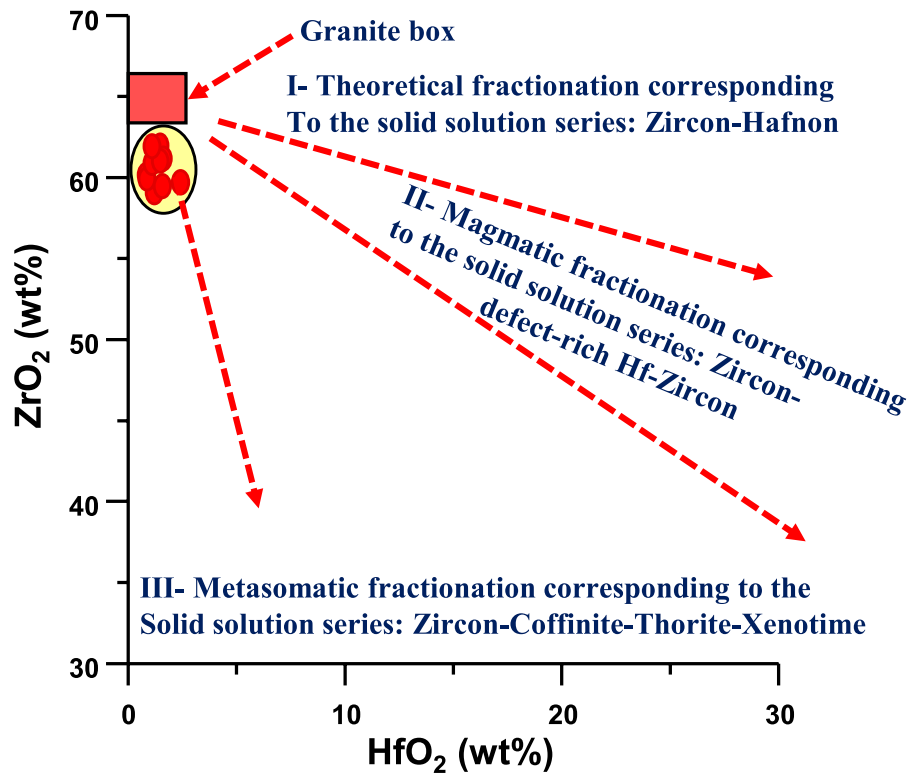


Fig. 7 Zr-Hf-(Y, HREE, U, Th) ternary diagram showing the geochemical composition of the analyzed zircon crystals from syenogranite, Nikeiba, SED, Egypt. Solid lines refer to the trends of magmatic and hydrothermal zircon (Kempe 1997 and Abdalla et al. 2008)

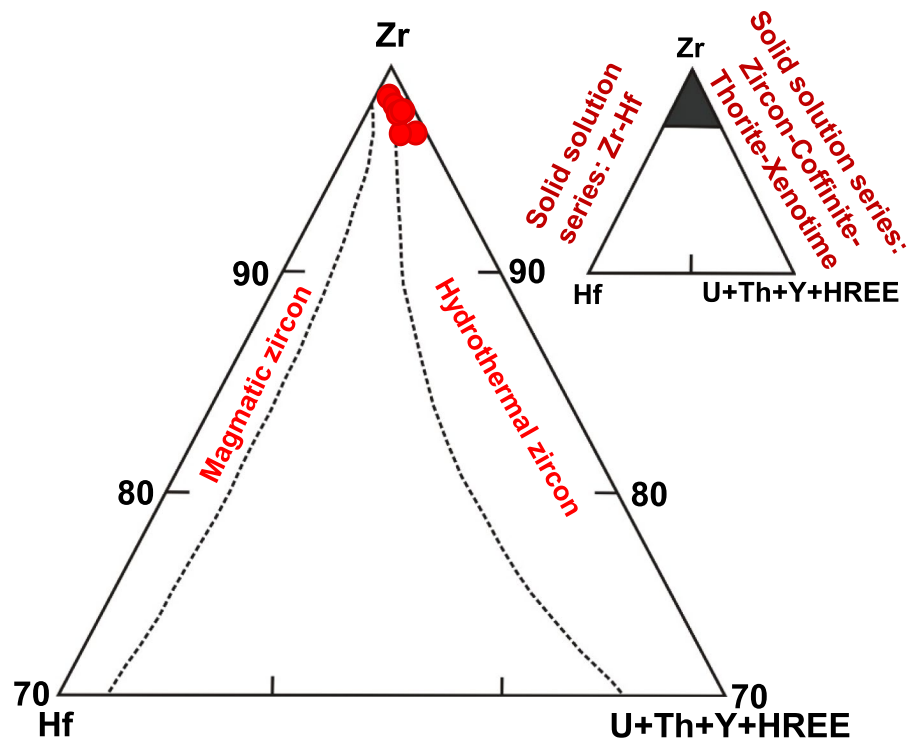


Table 3 Representative EPMA of columbite (oxides in wt%) from syenogranite at Nikeiba, SED of Egypt

S. No./oxides	S21	S17	S23	S6	S6	S33	S2	S2	S48	S33
Nb ₂ O ₅	71.28	70.25	69.63	71.84	71.13	55.83	55.64	55.58	53.59	54.54
Ta ₂ O ₅	2.54	8.04	7.54	3.69	1.66	3.65	3.89	3.92	3.71	5.08
TiO ₂	1.38	1.13	1.15	2.27	1.33	6.34	2.19	2.22	7.47	2.52
Fe ₂ O ₃	20.33	16.56	16.8	16.03	18.32	13.31	8.48	10.44	13.54	15.53
MnO	3.59	2.79	3.63	1.13	2.68	0.62	0.71	0.57	0.73	0.65
Y ₂ O ₃	0.88	1.23	1.25	2.54	2.74	5.59	10.09	9.36	7.07	7.62
Ce ₂ O ₃	n.d	n.d	n.d	n.d	n.d	0.95	0.83	0.52	0.49	0.42
Nd ₂ O ₃	n.d	n.d	n.d	n.d	n.d	0.36	0.76	1.48	0.29	0.98
Sm ₂ O ₃	n.d	n.d	n.d	n.d	n.d	0.94	1.79	1.86	0.67	1.06
Gd ₂ O ₃	n.d	n.d	n.d	n.d	n.d	1.3	3.07	3.26	0.95	1.51
Dy ₂ O ₃	n.d	n.d	n.d	n.d	n.d	3.55	6.51	6.67	4.02	2.92
Er ₂ O ₃	n.d	n.d	n.d	n.d	n.d	1.83	3.44	2.71	1.44	1.57
ThO ₂	n.d	n.d	n.d	1.54	1.16	3.70	1.35	0.67	5.01	4.22
UO ₂	n.d	n.d	n.d	0.96	0.98	2.03	1.25	0.74	1.02	1.38
Total	100	100	100	100	100	100	100	100	100	100
ΣTREE ₂ O ₃						8.93	16.4	16.5	7.86	8.46
Cations	Calculated chemical formulae based on 6 oxygen atoms (apfu)									
Nb	1.74	1.75	1.74	1.78	1.76	1.48	1.57	1.55	1.42	1.48
Ta	0.04	0.12	0.11	0.06	0.02	0.06	0.07	0.07	0.06	0.08
Ti	0.06	0.05	0.05	0.09	0.05	0.28	0.1	0.1	0.33	0.11
Fe	0.83	0.69	0.7	0.66	0.75	0.59	0.4	0.48	0.6	0.70
Mn	0.16	0.13	0.17	0.05	0.12	0.03	0.04	0.03	0.04	0.03
Y	0.03	0.04	0.04	0.07	0.08	0.17	0.33	0.31	0.22	0.24
Ce						0.02	0.02	0.01	0.01	0.01
Nd						0.01	0.02	0.03	0.01	0.02
Sm						0.02	0.04	0.04	0.01	0.02
Gd						0.03	0.06	0.07	0.02	0.03
Dy						0.07	0.13	0.13	0.08	0.06
Er						0.03	0.07	0.05	0.03	0.03
Th				0.02	0.01	0.05	0.02	0.01	0.07	0.06
U				0.01	0.01	0.03	0.02	0.01	0.01	0.02
ΣCations	2.85	2.78	2.81	2.75	2.82	2.86	2.88	2.89	2.89	2.90
Ta/(Ta + Nb)	0.022	0.064	0.059	0.033	0.011	0.039	0.043	0.043	0.041	0.051
Mn/(Mn + Fe)	0.162	0.159	0.195	0.070	0.138	0.048	0.091	0.059	0.063	0.041

n.d. (not determined)

Fluorite (CaF₂) manifests as subhedral to anhedral crystals and is predominantly associated with synchysite, zircon, columbite, and fergusonite crystals (Fig. 9a). It is enclosed in K-feldspar and quartz crystals. The EPMA data reveal that fluorite consists of F 48.22 and Ca 51.78 wt%.

REE phosphates Monazite manifests as anhedral crystals, exhibiting fine-grained, and is consistently predominated in plagioclase and quartz crystals (Fig. 9e, f). EPMA data indicate that monazite is

composed of P₂O₅ ranging from 29.88 to 31.83 wt%, together with a notable enrichment of LREEs (La₂O₃–Gd₂O₃) concentrations ranging from 62.85 to 65.86 wt% (Table 7). Ce₂O₃ exhibits higher concentrations in analyzed monazite crystals compared to other LREEs with average 32.27 wt%, followed by La₂O₃, then Nd₂O₃, Pr₂O₃ and Sm₂O₃ with average concentrations 14.13, 10.54, 3.58 and 2.26 wt%, respectively. Gd₂O₃ is recorded exclusively as heavy rare earth elements (HREEs) in monazite, with an average concentration of 1.41 wt%. Radioactive ele-

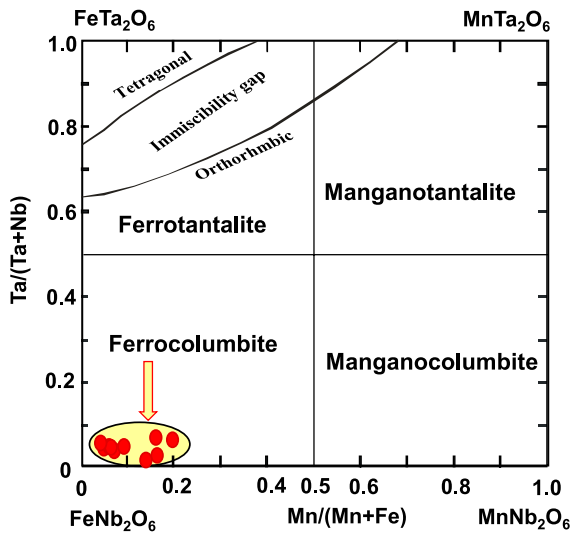
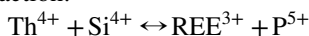


Fig. 8 Quadrilateral diagram showing the geochemical composition of the analyzed columbite crystals according to (Černý & Ercit, 1985) from the syenogranite, Nikeiba, SED of Egypt

ments consisting of ThO_2 and UO_2 were recorded, and achieving concentrations of 3.05 and 0.71 wt%, respectively. SiO_2 is identified as minor constituent, with average 1.33 wt%.

The average chemical formulae of monazite crystals is provided as follows: $\{(\text{Ce}_{0.45}\text{La}_{0.20}\text{Nd}_{0.14}\text{Pr}_{0.05}\text{Sm}_{0.03}\text{Gd}_{0.02}\text{Th}_{0.03}\text{U}_{0.01})(\text{P}_{0.99}\text{Si}_{0.05})\text{O}_4\}$. Consequently, It is important to note that Ce is the most predominated REEs as (0.45 apfu) indicating a typical monazite-Ce (Table 6). The analyzed monazite crystals exhibit a notable resemblance in their geochemical composition, characterized by lower thorium concentrations as recorded by Abdel Gawad (2021) and Watt (1995). The lowest thorium may be attributed to hydrothermal alteration, while the geochemical substitutions could have occurred by the following reaction:



Xenotime occurs as anhedral, fine-grained, with some overgrowing along zircon rims and others present as microinclusions in zircon (Fig. 5c–f). It is enclosed in feldspars, quartz, and zircon, with certain grains located at the periphery of biotite (Fig. 9d). The analyzed EPMA data reveal that xenotime mostly consists of Y_2O_3 , P_2O_5 and $\Sigma\text{HREE}_2\text{O}_3$ (Gd_2O_3 – Lu_2O_3) with averages 41.78, 32.12 and 22.58 wt%, respectively. UO_2 and ThO_2 are well

recorded with averages 1.42 and 0.65 wt%, respectively. SiO_2 , CaO and Fe_2O_3 are identified as minor constituents (Table 7), exhibiting lower concentrations with average values of 0.38, 0.58 and 0.49 wt%, respectively. The average chemical formula of the calculated xenotime crystals are reported as following: $(\text{Y}_{0.77}\text{Ca}_{0.02}\text{Fe}_{0.01}\text{U}_{0.01}\text{Th}_{0.01}\text{Gd}_{0.03}\text{Dy}_{0.08}\text{Ho}_{0.02}\text{Er}_{0.05}\text{Tm}_{0.02}\text{Yb}_{0.04}\text{Lu}_{0.02})(\text{P}_{0.95})\text{O}_4$.

Other accessory minerals

Barite (BaSO_4) manifests as fine- to large crystals, anhedral, massive, and fibrous varieties (Fig. 9g). It is consistently enclosed in feldspars and quartz. EPMA data indicate that barite consists of BaO ranging from 50.1 to 65.48 wt%, SO_3 from 35.16 and 36.41 wt%, and SrO from 2.58 and 11.95 wt%. Fe_2O_3 and CaO are recorded at lower concentrations and reached up to 1.13 and 1.79 wt%, respectively.

Rutile (TiO_2) is regarded as the most prevalent accessory mineral. It manifests as subhedral to euhedral, fine-grained, and is associated with others (Fig. 9h). The EMPA data indicate that rutile mostly consists of TiO_2 , ranging from 91.81 to 94.78 wt%, Fe_2O_3 from 1.32 to 3.35 wt%, and Nb_2O_5 from 2.85 to 5.87 wt%, signifying a rutile-rich Nb-content.

Ilmenite (FeTiO_3) is found along the edges of columbite and/or as gray microinclusions within large columbite crystals (Fig. 5g). It is consistently linked with columbite, zircon, and synchysite crystals. According to EMPA analyses, ilmenite is composed of TiO_2 , ranging from 44.84 to 48.43 wt%, Fe_2O_3 from 50.12 to 52.23 wt%, Nb_2O_5 2.13 to 5.62 and MnO from 0.65 to 1.17 wt%.

Radioactive ratios

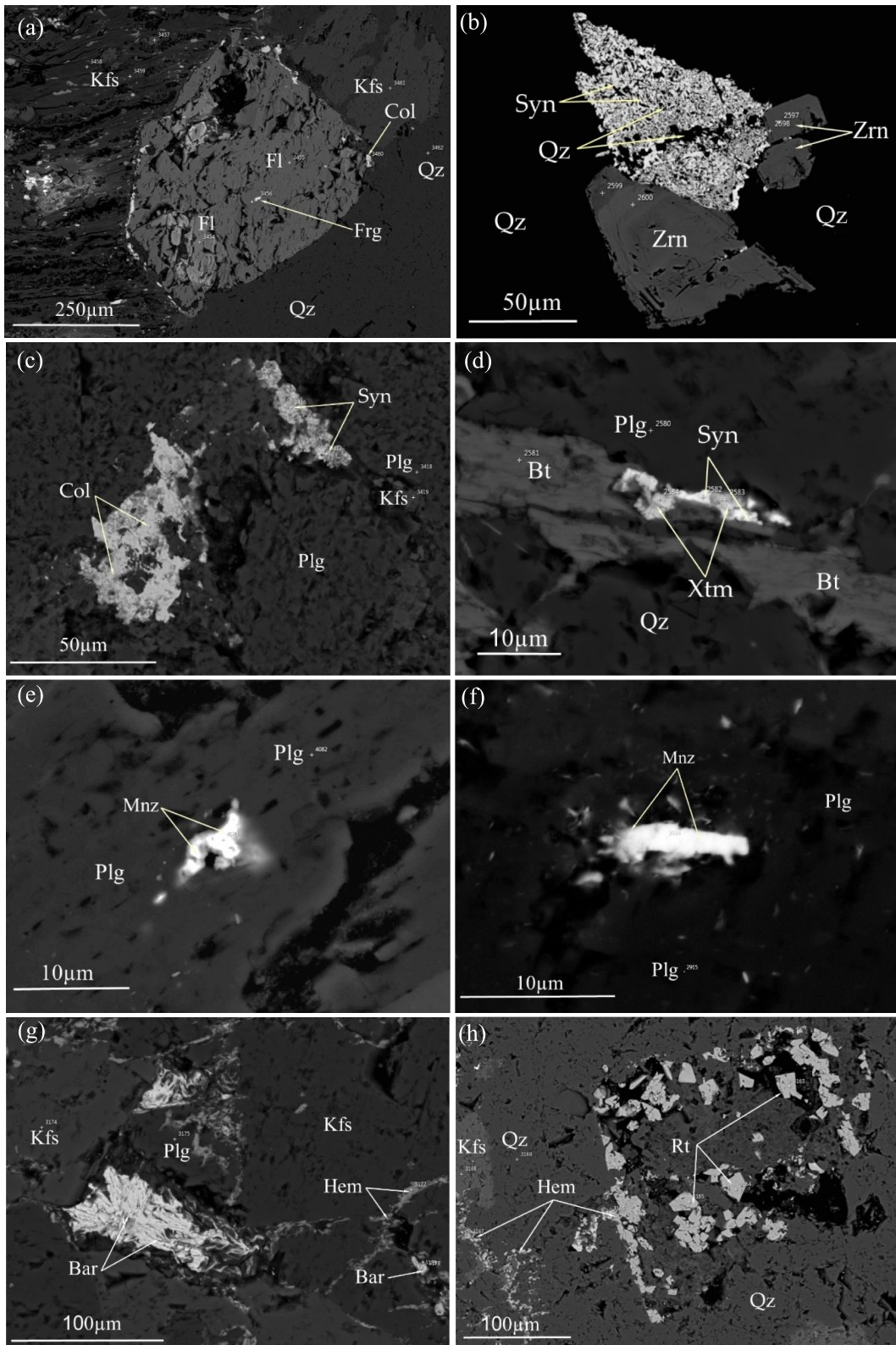
Figure 10 analyzes the relationships between eU, eTh, K, and their ratios in syenogranite samples, highlighting the mineralogical features and processes controlling radionuclide distribution. Figure 10a reveals the very low $R^2=0.04$ value indicates a negligible correlation between eTh and eU. This weak association suggests that thorium and uranium are distributed independently within the syenogranite. Thorium is typically immobile in most geochemical conditions, while uranium is more susceptible to mobilization under oxidizing conditions. Both U and Th are coincided with the magmatic-rich minerals such as (e.g.,

Table 4 Representative EPMA of fergusonite (oxides in wt%) from syenogranite at Nikeiba, SED of Egypt

S. No./oxides	S48	S23	S17	S2	S17	S17
Y ₂ O ₃	30.66	31.88	31.57	28.91	32.41	30.92
Nb ₂ O ₅	46.68	48.76	48.91	47.15	48.40	47.42
Ce ₂ O ₃	0.32	0.35	0.93	0.87	0.49	0.40
Nd ₂ O ₃	1.21	1.32	0.92	2.89	0.58	0.57
Sm ₂ O ₃	1.12	1.28	1.83	1.89	1.75	1.72
Gd ₂ O ₃	1.52	1.74	2.32	3.28	2.52	2.24
Dy ₂ O ₃	4.84	3.31	3.40	4.30	4.82	5.07
Er ₂ O ₃	3.61	2.23	2.32	2.66	2.40	2.09
Yb ₂ O ₃	2.80	2.02	1.53	1.51	1.04	1.12
TiO ₂	0.97	0.92	0.52	0.65	0.46	2.31
CaO	0.66	0.32	0.42	0.35	0.69	0.54
Fe ₂ O ₃	1.23	1.75	1.54	1.11	0.53	1.44
ThO ₂	1.37	1.47	1.19	2.10	1.44	1.45
UO ₂	1.43	1.36	1.77	2.33	1.65	1.21
SiO ₂	1.58	1.29	0.83	0.97	0.82	1.50
Total	100	100	100	100	100	100
$\sum \text{TREE}_2\text{O}_3$	15.42	12.25	13.25	17.40	13.60	13.21
Cations	Calculated chemical formulae based on 4 oxygen atoms (apfu)					
Y	0.70	0.72	0.72	0.67	0.75	0.70
Nb	0.91	0.94	0.95	0.93	0.95	0.91
Ce	0.01	0.01	0.01	0.01	0.01	0.01
Nd	0.02	0.02	0.01	0.05	0.01	0.01
Sm	0.02	0.02	0.03	0.03	0.03	0.03
Gd	0.02	0.02	0.03	0.05	0.04	0.03
Dy	0.07	0.05	0.05	0.06	0.07	0.07
Er	0.05	0.03	0.03	0.04	0.03	0.03
Yb	0.04	0.03	0.02	0.02	0.01	0.01
Ti	0.03	0.03	0.02	0.02	0.01	0.07
Ca	0.03	0.01	0.02	0.02	0.03	0.02
Fe	0.04	0.06	0.05	0.04	0.02	0.05
Th	0.01	0.01	0.01	0.02	0.01	0.01
U	0.01	0.01	0.02	0.02	0.02	0.01
Si	0.07	0.05	0.04	0.04	0.04	0.06
$\sum \text{Cations}$	2.03	2.01	2.01	2.02	2.02	2.02

uraniothorite, thorite and zircon). This may result from the heterogeneity of the granite's mineralogical composition or secondary processes such as uranium leaching and remobilization. Figure 10b provides the moderate inverse correlation which suggests that eU increases, the eTh/eU ratio decreases. This trend is consistent with uranium enrichment or mobilization processes. The decreasing eTh/eU ratio could be due to uranium's solubility in oxidizing conditions, leading to its leaching and subsequent redistribution within the syenogranite. This behavior contrasts with

thorium's immobility, which causes it to remain relatively constant. Zones with lower eTh/eU ratios may represent areas where uranium has been enriched through secondary processes, such as fluid interaction or hydrothermal activity, as suggested in the "Leached-U" zone identified in other plots. Moreover, Fig. 10c illustrates that weak to moderate positive correlation indicates higher eTh concentrations are loosely coincided with higher eTh/eU ratios, eTh/eU vs. eTh ($R^2=0.24$). This relationship suggests that areas with abundant thorium reflect the immobility



◀**Fig. 9** Back-scattered images of REEs-bearing mineralization associated with other accessory minerals from syenogranite, Nikeiba, SSEd of Egypt. **a** Large crystal of fluorite encloses fergusonite and columbite along periphery; **b** Radial or acicular shape of synchysite occurs along peripheries of zircon crystals; **c** Associations of anhedral crystals of columbite and synchysite enclosed in feldspars; **d** Fine-grained of xenotime and synchysite occurring along periphery of biotite; **e, f** fine-grained of monazite enclosed in plagioclase; **g** Barite shows fibrous enclosed in feldspars; **h** Fine-grained of rutile associated with hematite. Abbreviations: Col, columbite; Frg, fergusonite; Zrn, zircon; Syn, synchysite; Xtm, xenotime; Mnz, monazite; Fl, fluorite; Kfs, K-feldspar; Ab, albite; Qz, quartz; Bt, biotite; Bar, barite; Rt, rutile; Hem, hematite

of thorium-rich minerals and their persistence during geological processes such as hydrothermal alteration. The eTh/eU ratio may serve as a proxy for identifying thorium-enriched zones in the syenogranite, which are often unaffected by uranium mobilization. This pattern highlights the geochemical stability of thorium compared to uranium. The near-zero R^2 value in Fig. 10d reflects no meaningful correlation between potassium and uranium concentrations, K (%) vs. eU ($R^2 = 9.8 \times 10^{-4}$). Potassium, typically found in minerals like K-feldspar, biotite, muscovite and clay minerals, does not appear to have a direct geochemical or mineralogical link to uranium. This independence suggests that uranium distribution is controlled by distinct processes, such as its association with accessory minerals or its mobilization during hydrothermal alterations. The lack of correlation supports the idea that potassium content remains unaffected by the factors influencing uranium variability. In Fig. 10e, the weak correlation between potassium and thorium concentrations K (%) vs. eTh ($R^2 = 0.14$) suggests minimal association. Thorium-rich minerals, such as thorite, monazite and zircon, are not strongly tied to potassium-bearing minerals like feldspars, mica and clay minerals. The slightly positive trend may arise from specific geological settings where these minerals coexist but remain independent in their geochemical behavior. The weak correlation highlights that potassium and thorium are distributed by separate mineralogical and geochemical processes. Meanwhile, the non-linear distribution in Fig. 10f reveals distinct groupings along the eTh/eU axis, corresponding to two major zones; Fixed Zone includes samples with high eTh/eU ratios reflect thorium enrichment and its immobility during geochemical processes. These zones likely represent primary granite compositions

where thorium remains unaltered. In addition to Leached-U zone contains samples with low eTh/eU ratios suggest areas where uranium has been selectively leached, possibly due to fluid-rock interactions under oxidizing conditions. The vertical spread in eTh/K indicates variations in thorium and potassium ratios, driven by differences in mineralogy or alteration. This plot underscores the role of geochemical processes, such as weathering and uranium mobilization, in shaping radionuclide distributions within the syenogranite.

Radionuclides in syenogranite

The activity concentrations of radionuclides ^{238}U , ^{232}Th and ^{40}K for each syenogranite sample are presented in Table S1. Moreover, the statistical parameters from Table 8 provide additional context for interpreting the radionuclide data. By analyzing the mean, standard deviation (SD), range (Min–Max), skewness, kurtosis, and coefficient of variation (CV), it can be better figure out the variability and geochemical behavior of ^{238}U , ^{232}Th and ^{40}K in the syenogranite samples. U-238 in the syenogranite samples exhibits a mean concentration of $153 \pm 37 \text{ Bq kg}^{-1}$, with the highest variability ($\text{CV} = 24\%$) among the radionuclides studied. Its concentration ranges from 68 to 232 Bq kg^{-1} , reflecting significant heterogeneity due to uranium's mobility under oxidizing conditions. The nearly symmetrical distribution (skewness = -0.03) suggests that the variations are not driven by extreme outliers but rather by geochemical processes such as leaching and enrichment. This is further supported by Fig. 10f, which shows weak correlations with other radionuclides and highlight uranium redistribution in "Leached-U" zones. These findings emphasize uranium's sensitivity to alteration processes in the syenogranite. Th-232 shows a mean concentration of $171 \pm 35 \text{ Bq kg}^{-1}$, with lower variability ($\text{CV} = 20\%$) compared to U-238, reflecting its geochemical immobility. Its concentration range ($102\text{--}222 \text{ Bq kg}^{-1}$) is narrower, and the slightly left-skewed distribution (skewness = -1.38) suggests a uniform presence in the granite. Thorium's stability is attributed to its association with minerals like thorite, monazite and zircon. Figure 10f confirm that thorium maintains consistent distribution patterns, particularly in the "Fixed Zone," further highlighting its immobility and reliability as

Table 5 Representative EPMA of synchysite (oxides in wt%) from syenogranite at Nikeiba, SED of Egypt

S. No./oxides	S2	S24	S41	S2	S41	S21	S21	S48
ThO ₂	0.82	0.94	0.99	1.43	1.34	0.85	1.27	1.12
La ₂ O ₃	13.48	13.31	12.37	10.57	10.14	11.83	10.92	10.06
Ce ₂ O ₃	25.96	25.94	25.2	26.72	26.06	24.7	24.96	24.98
Pr ₂ O ₃	2.64	2.71	1.91	2.54	2.51	2.69	2.87	3.71
Nd ₂ O ₃	11.21	10.71	11.55	13.18	11.17	11.12	12.72	12.6
Sm ₂ O ₃	2.65	2.71	1.89	2.85	2.75	2.84	3.12	3.07
Gd ₂ O ₃	1.68	1.57	1.64	1.61	1.58	1.76	1.81	1.79
Y ₂ O ₃	1.17	2.24	2.16	1.54	2.11	2.61	2.17	1.36
CaO	14.85	15.58	15.11	15.08	14.11	15.69	15.45	16.87
F	5.83	5.65	5.48	5.52	5.08	5.56	5.32	5.76
SiO ₂	0.19	0.24	0.21	0.22	0.23	0.29	0.24	0.19
Total	80.48	81.6	78.51	81.26	77.08	79.94	80.85	81.51
ΣTREE ₂ O ₃	57.62	56.95	54.56	57.47	54.21	54.94	56.4	56.21
Cations	Calculated chemical formulae (apfu)							
Th	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01
La	0.26	0.25	0.24	0.20	0.20	0.22	0.21	0.19
Ce	0.49	0.48	0.48	0.50	0.52	0.46	0.47	0.46
Pr	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.07
Nd	0.21	0.19	0.22	0.24	0.22	0.20	0.23	0.23
Sm	0.05	0.05	0.03	0.05	0.05	0.05	0.06	0.05
Gd	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Y	0.03	0.06	0.06	0.04	0.06	0.07	0.06	0.04
Ca	0.82	0.84	0.85	0.83	0.82	0.86	0.85	0.91
Si	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Sum	1.95	1.97	1.97	1.97	1.98	1.98	1.98	1.99
F	1.08	1.03	1.04	1.02	0.99	1.03	0.99	1.04

Calculated chemical formulae (apfu): number of ions could be based on one fluorine (apfu) on the basis of (CO₃)₂F

an indicator of primary granite composition. K-40 has the highest mean concentration (1390 ± 252 Bq kg⁻¹) but the lowest variability (CV = 18%), indicating relatively uniform distribution with localized enrichment in potassium-rich minerals like K-feldspar, mica and clay minerals. Its range (1033–2410 Bq kg⁻¹) includes significant outliers, as indicated by the right-skewed distribution (skewness = 1.58) and high kurtosis (4.33). While Fig. 10d, e reveal weak correlations between K-40 and other radionuclides, the data suggest that potassium's distribution is largely independent of uranium and thorium, controlled instead by its host mineralogy. This enrichment in select samples reflects specific geological processes influencing potassium concentration. The mean values of ²³⁸U, ²³²Th and ⁴⁰K concentrations are 5, 4 and 3 times higher than the worldwide average of 33, 45 and 412 Bq kg⁻¹, respectively (UNSCEAR, 2010). In Table 8, the standard deviation (SD) values for ²³⁸U,

²³²Th and ⁴⁰K are lower than their respective mean values, which indicates that the data for each radionuclide is relatively clustered around the mean with no extreme dispersion. This implies that the concentrations of these radionuclides within the syenogranite samples are relatively consistent, despite some variability. Therefore, the higher detection of radioactive levels than those of accepted global averages could have been attributed to the recorded rare metals mineralization such thorite, zircon, monazite, columbite and fergusonite in the investigated syenogranite.

The analysis of the histograms and distribution parameters in Fig. 11a–c reveals that U-238 and Th-232 exhibit more uniform and symmetric distributions, indicating a relatively homogeneous geological environment. In contrast, K-40 shows greater variability, possibly influenced by localized enrichment of potassium-rich minerals.

Table 6 Representative EPMA of monazite (oxides in wt%) from syenogranite at Nikeiba, SED of Egypt

S. No./oxides	S17	S45	S45	S19	S19	S41
P ₂ O ₅	29.88	31.52	31.83	30.17	30.42	29.98
Fe ₂ O ₃	0.76	0.69	0.57	0.58	0.65	0.61
La ₂ O ₃	13.96	13.36	15.18	13.54	14.41	14.31
Ce ₂ O ₃	32.53	32.31	32.51	32.63	31.67	31.94
Pr ₂ O ₃	3.49	3.64	3.33	3.41	3.81	3.77
Nd ₂ O ₃	11.73	10.48	9.02	10.8	10.54	10.65
Sm ₂ O ₃	2.53	2.41	1.46	2.36	2.34	2.43
Gd ₂ O ₃	1.62	1.46	1.35	1.38	1.29	1.33
ThO ₂	1.87	2.28	2.78	2.94	3.05	2.97
UO ₂	0.54	0.48	0.58	0.71	0.64	0.56
SiO ₂	1.09	1.37	1.39	1.48	1.18	1.45
Total	100	100	100	100	100	100
ΣTREE ₂ O ₃	65.86	63.66	62.85	64.12	64.06	64.43
Cations	Calculated chemical formulae based on 4 oxygen atoms (apfu)					
P	0.98	1.01	1.01	0.98	0.99	0.98
Fe	0.02	0.02	0.02	0.02	0.02	0.02
La	0.20	0.19	0.21	0.19	0.2	0.20
Ce	0.46	0.45	0.45	0.46	0.45	0.45
Pr	0.05	0.05	0.05	0.05	0.05	0.05
Nd	0.16	0.14	0.12	0.15	0.14	0.15
Sm	0.03	0.03	0.02	0.03	0.03	0.03
Gd	0.02	0.02	0.02	0.02	0.02	0.02
Th	0.02	0.02	0.02	0.03	0.03	0.03
U	0.005	0.004	0.005	0.006	0.005	0.005
Si	0.04	0.05	0.05	0.06	0.05	0.06
ΣCations	1.99	1.97	1.97	1.98	1.98	1.99

The Shapiro–Wilk test used normality to analyze the distribution patterns of the three radiometric concentrations (²³⁸U, ²³²Th and ⁴⁰K) in the syenogranite samples. The Shapiro–Wilk test results are summarized in Table 9. The activity concentrations of U-238 with a *p*-value of 0.67 and Shapiro–Wilk statistic of 0.98 showed no evidence of deviation (*p* > 0.05). Therefore, the distribution of U-238 activity concentrations in the syenogranite samples can be considered roughly normal. Distribution of Th-232 and K-40 behaved much more anomalously. Th-232 and K-40 had Shapiro–Wilk values of 0.92 (*p* = 0.0036) and 0.89 (*p* = 0.0002). Both radionuclides have *p*-values < 0.05, therefore, the null hypothesis of normality was rejected and concentrations of activities were not normally distributed. The non-normality could include various factors from differing weathering levels, different geochemistry of the radionuclides in the study area, concentration from local enrichment

processes (e.g., hydrothermal alteration), or heterogeneous distributions of mineral. While the non-normal distributions for Th-232 and K-40, suggest that uranium, which shows a recorded normal distribution, is perhaps more homogeneously distributed within the syenogranite because it is hosted in or associated with accessory minerals that are homogeneously distributed (e.g., zircon and thorite). The deviations from normality on the other hand may be due to the concentration of potassium and thorium into specific mineral phases or alteration zones.

Table 10 illustrates that the analysis of syenogranite samples from the Nikeiba region found the mean activity concentrations of the natural radionuclides to be 153 ± 37 Bq/kg for U-238, 171 ± 35 Bq/kg for Th-232, and 1390 ± 252 Bq/kg for K-40; these were all substantially higher when compared to most previous studies of granitic rocks all over the world. For instance, Anjos et al. (2005), studying Brazilian

Table 7 Representative EPMA of xenotime (oxides in wt%) from syenogranite at Nikeiba, SED of Egypt

S. No./oxides	S32	S48	S48	S2	S32	S32	S6	S30	S6	S30
Y ₂ O ₃	43.42	42.5	40.01	40.49	41.73	41.95	42.26	41.19	41.78	42.49
Gd ₂ O ₃	1.53	2.94	4.15	3.67	1.99	1.54	1.75	1.88	2.22	1.87
Dy ₂ O ₃	6.37	6.61	8.51	6.93	7.88	7.88	6.34	6.52	6.94	7.19
Ho ₂ O ₃	1.29	1.31	1.51	1.32	1.57	1.42	1.47	1.33	1.29	1.27
Er ₂ O ₃	4.64	4.73	4.64	5.11	4.86	4.95	4.31	4.52	4.63	4.48
Tm ₂ O ₃	2.41	1.96	1.46	1.74	1.54	1.86	1.48	1.51	1.42	1.49
Yb ₂ O ₃	3.25	4.16	4.91	5.37	2.11	2.77	3.20	3.51	3.54	2.98
Lu ₂ O ₃	2.33	2.28	1.51	1.43	1.82	1.41	2.59	1.39	1.58	1.43
P ₂ O ₅	31.53	30.39	30.29	30.45	32.7	32.78	33.35	34.6	32.12	32.95
CaO	0.91	0.82	0.39	0.41	0.92	0.42	0.43	0.46	0.43	0.63
Fe ₂ O ₃	0.29	0.33	0.27	0.41	0.38	0.58	0.36	0.32	0.83	1.16
ThO ₂	0.58	0.71	0.64	0.81	0.73	0.68	0.67	0.49	0.58	0.61
UO ₂	1.11	0.98	1.32	1.37	1.29	1.47	1.44	1.97	2.22	1.01
SiO ₂	0.34	0.28	0.39	0.49	0.48	0.29	0.35	0.31	0.42	0.44
Total	100	100	100	100	100	100	100	100	100	100
ΣHREE ₂ O ₃	21.82	23.99	26.69	25.57	21.77	21.83	21.14	20.66	21.62	20.71
Cations	Calculated chemical formulae based on 4 oxygen atoms (apfu)									
Y	0.81	0.81	0.77	0.77	0.76	0.77	0.77	0.74	0.77	0.77
Gd	0.02	0.04	0.05	0.04	0.02	0.02	0.02	0.02	0.03	0.021
Dy	0.07	0.08	0.1	0.08	0.09	0.09	0.07	0.07	0.08	0.08
Ho	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
Er	0.05	0.05	0.05	0.06	0.05	0.05	0.05	0.05	0.05	0.05
Tm	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Yb	0.03	0.05	0.05	0.06	0.02	0.03	0.03	0.04	0.04	0.03
Lu	0.02	0.02	0.02	0.02	0.02	0.01	0.03	0.01	0.02	0.01
P	0.93	0.92	0.92	0.92	0.95	0.96	0.97	0.99	0.95	0.95
Ca	0.03	0.03	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02
Fe	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.03
Th	0	0.01	0.01	0.01	0.01	0.01	0.01	0	0	0
U	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
Si	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.02
ΣCations	2.03	2.08	2.06	2.06	2.03	2.04	2.04	2.00	2.04	2.02

granites, concluded the averages of the radioactivity levels of U-238 averaged 58 Bq kg⁻¹, 84 Bq kg⁻¹ of Th-232, and K-40 levels averaged 1270 Bq kg⁻¹. El-Taher et al. (2007) discussed that Egyptian granites were found to have K-40 activity levels ranging from 800 to 1100 Bq kg⁻¹, Th-232 A activity in the range of 60 to 140 Bq kg⁻¹, and U-238 activity in the range of 50–120 Bq kg⁻¹. The reason for the high values in this study can be determined by the mineralogy, specifically the high levels of radioactive accessory phases in the syenogranite including thorite, monazite and zircon.

Radiological hazards assessment

Table 11 presents the results for radiological hazard indices, reveal critical insights into the radiological safety and exposure risks associated with the syenogranite samples. These indices— Ra_{eq} , H_{in} , H_{ex} , I_{γ} , ADR, E (outdoor and indoor), AGDE, and ELCR—are used to assess both immediate and long-term health risks from natural radioactivity. The radium equivalent activity (Ra_{eq}) values range from 336 to 654 Bq kg⁻¹, with a mean of 504 Bq kg⁻¹. Ra_{eq} is a consolidated index combining the activity contributions of ²³⁸U, ²³²Th and ⁴⁰K, ensuring compliance

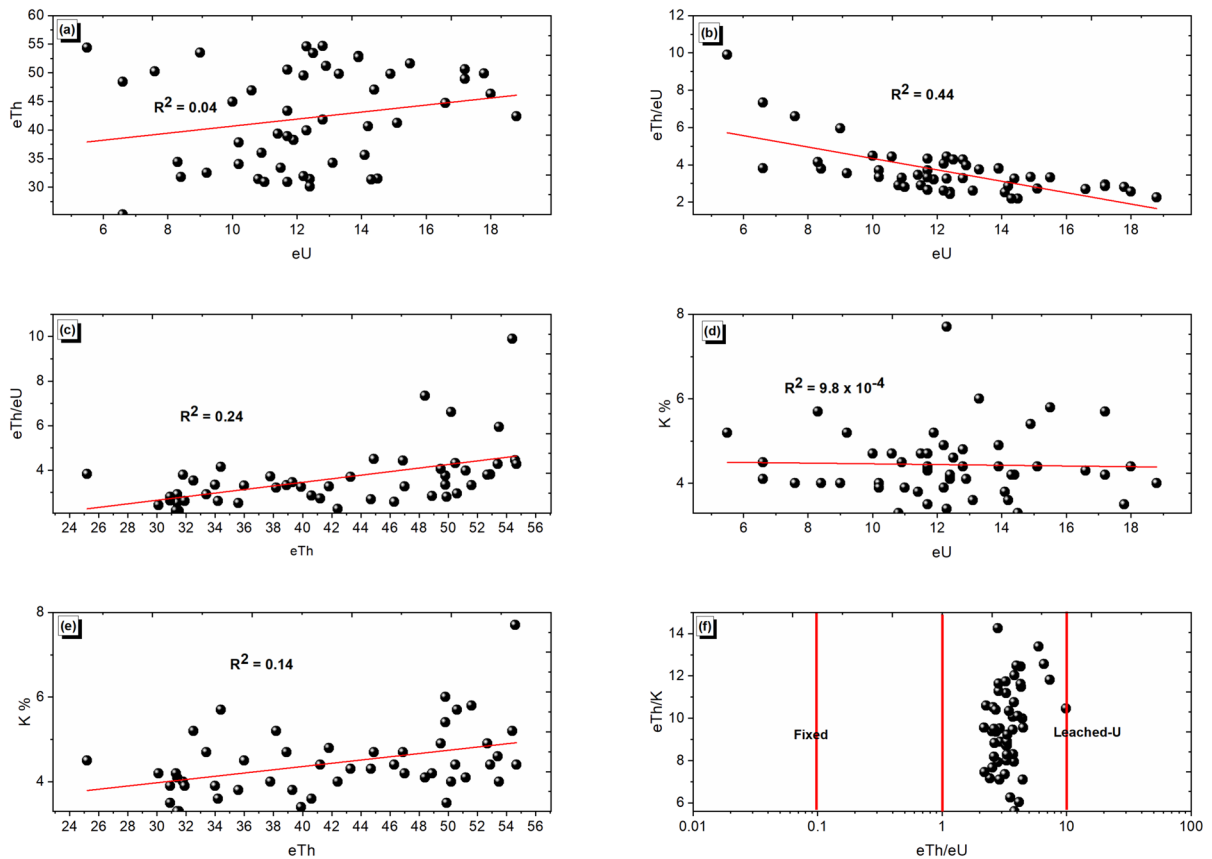


Fig. 10 a eU vs eTh., b eU vs. eTh/eU, c eTh vs. eTh/eU d eU vs K%, e eTh vs K% and f eTh/eU vs eTh/K% for syenogranite of studied area

Table 8 Descriptive statistics of studied syenogranite samples in the investigated area

	N	Mean	SD	Min	Max	Skewness	Kurtosis	CV, %
U-238	50	153	37	68	232	− 0.03	0.05	24
Th-232	50	171	35	102	222	− 0.11	− 1.38	20
K-40	50	1390	252	1033	2410	1.58	4.33	18

with radiation safety standards. The average Ra_{eq} exceeds the recommended safe limit of 370 Bq kg^{-1} (Qureshi et al., 2014) for building materials, indicating that the syenogranite samples may pose potential radiological hazards, particularly if used in construction. Samples with higher Ra_{eq} , such as S2 (654 Bq kg^{-1}) and S11 (644 Bq kg^{-1}), reflect elevated concentrations of all radionuclides, necessitating caution in their application.

Table 10 show that the internal (H_{in}) and external (H_{ex}) hazard indices average 1.77 and 1.36, respectively, with maximum values of 2.31 (H_{in}) and 1.77

(H_{ex}). Both indices exceed the safety threshold of 1 in many samples (Fig. 12), signaling potential risks from inhalation of radon (H_{in}) and external gamma radiation exposure (H_{ex}). Similarly, the gamma activity index (I_γ), which measures gamma dose hazard, shows an average of 1.83, with some samples exceeding 2.42, further highlighting potential radiological concerns. These elevated values indicate that prolonged exposure to these granites could increase radiological risks.

The absorbed gamma dose rate (ADR) varies between 157 and 303 nGy/h, with an average

Fig. 11 Frequency distribution of **a** ^{238}U , **b** ^{232}Th , and **c** ^{40}K activity concentrations of the syenogranite of the studied area

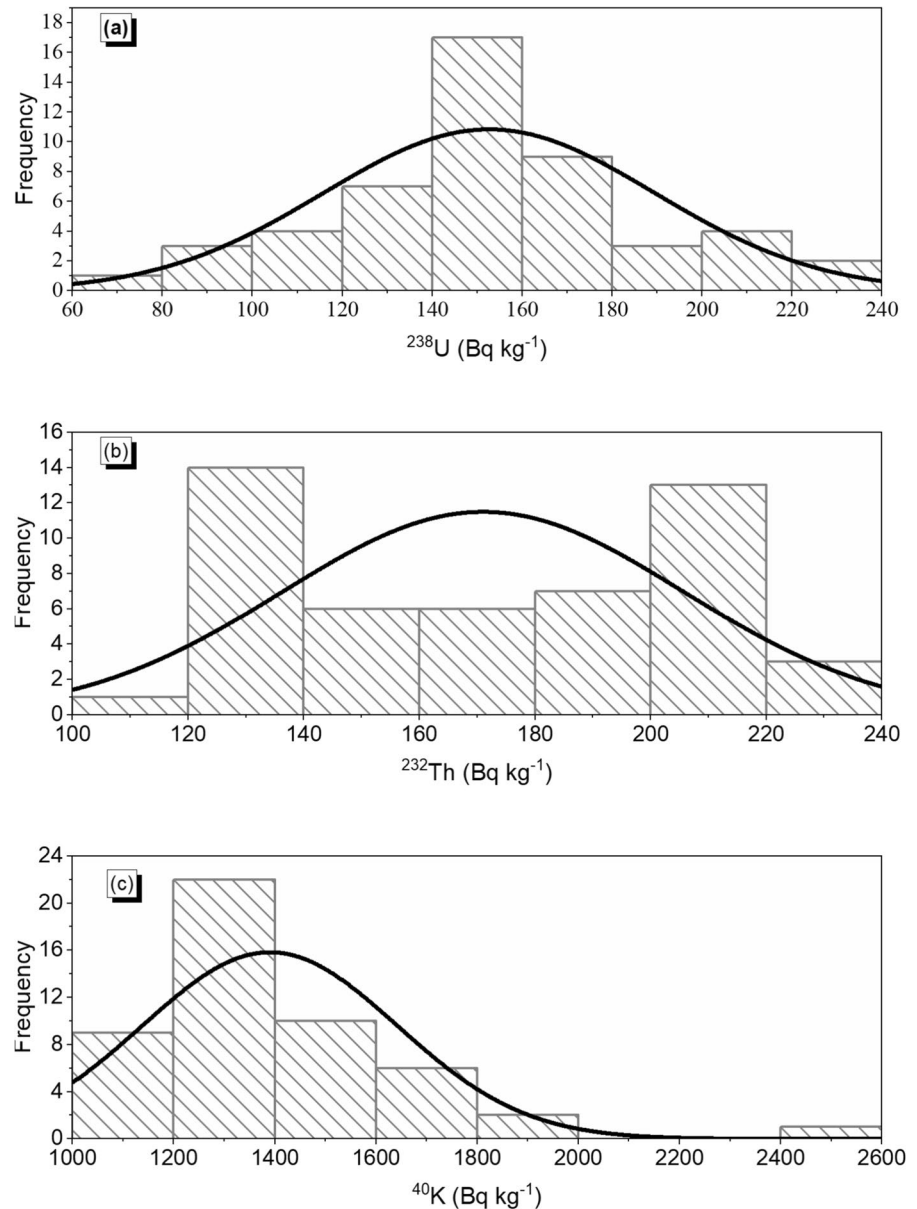


Table 9 Results of Shapiro–Wilk test normality tests

	DF	Statistic	<i>p</i> -value
U-238	50	0.98	0.67
Th-232	50	0.92	0.0036
K-40	50	0.89	0.0002

of 231 nGy/h. This is significantly higher than the worldwide average of 59 nGy/h for natural background radiation (UNSCEAR, 2000). Consequently,

the annual effective dose rates (E_{out} and E_{in}) also exceed global averages, with outdoor doses ranging from 0.19 to 0.37 mSv/y with a mean 0.28 mSv/y and indoor doses ranging from 0.77 to 1.49 mSv/y (mean of 1.13 mSv/y). The outdoor and indoor doses are particularly concerning, as they surpass the safety reference level of 0.07 and 0.41 mSv/y, respectively (UNSCEAR, 2000), emphasizing the need for restricted indoor usage of these granite materials. Table 10 show that also the annual gonadal dose equivalent (AGDE) values range between 1.12 and

Table 10 Comparison of activity concentrations (Bq/kg) of natural radionuclides in the present study and previous studies

Study/Location	U-238 (Bq/kg)	Th-232 (Bq/kg)	K-40 (Bq/kg)	References
Present study (Nikeiba, Egypt)	153 ± 37	171 ± 35	1390 ± 252	This study
UNSCEAR Global average	33	45	412	UNSCEAR (2010))
Brazilian granites (Rio de Janeiro)	58	84	1270	Anjos et al. (2005))
Egyptian granites (Eastern Desert)	50–120	60–140	800–1100	El-Taher et al. (2007))
Turkish granites	61.2	63.1	982	Baykara et al. (2011))
Cyprus granites	44.3	70.5	980	Tzortzis and Tsertos (2004))

2.15 mSv, with a mean of 1.62 mSv, which higher than the reported limit of 0.3 mSv (Tuo et al., 2020). AGDE quantifies the impact of gamma radiation on reproductive organs, and the observed values are indicative of significant radiological risks. Furthermore, the excess lifetime cancer risk (ELCR), which reflects long-term carcinogenic potential, averages 0.0010 (range: 0.0007–0.0013), surpassing the recommended safety threshold of 0.00029 (Qureshi et al., 2014). These elevated ELCR values signify potential public health concerns, especially with prolonged exposure.

Multivariate statistical analysis

The Pearson correlation analysis in Table 12 exhibits the distinct contributions of ^{238}U , ^{232}Th , and ^{40}K to radiological hazard indices. ^{238}U shows strong correlations with internal hazard indices (H_{in} , $r=0.82$) and moderate correlations with other radiological parameters, indicating its significant role in internal exposure risks. ^{232}Th demonstrates strong positive correlations with key hazard indices, such as Ra_{eq} ($r=0.87$) and ELCR ($r=0.85$), making it a primary contributor to both external and long-term health risks. ^{40}K exhibits weaker correlations, emphasizing its secondary role, though it contributes notably to external gamma dose rates. The weak correlation between ^{238}U and ^{40}K suggests distinct geochemical behaviors. Overall, ^{232}Th and ^{238}U are the dominant radionuclides influencing radiological hazards.

The provided Fig. 13 includes two key visualizations: a dendrogram from hierarchical cluster analysis and a principal component analysis (PCA). Hierarchical Cluster Analysis (HCA) in Fig. 13a, performed using Ward's method and Pearson correlation, effectively groups variables based on their similarities and relationships. Ward's method minimizes the

variance within each cluster, ensuring that the variables grouped together are highly homogeneous. Pearson correlation, on the other hand, assesses the linear relationships between variables, which provides insight into how closely they vary together. In the resulting dendrogram, two main clusters emerge. The first cluster groups variables such as radiological hazard indices (H_{in}), activity concentrations (U-238, Th-232), and risk parameters (Ra_{eq} , I_{γ} , and AGDE). These variables share strong interrelationships, as they collectively reflect the radiological risks posed by the radionuclides. The second cluster isolates K-40 and ELCR, reflecting their unique contributions to radiation exposure and risk. K-40, being a naturally abundant isotope, shows weaker correlation with indices dominated by U-238 and Th-232, while ELCR highlights the carcinogenic risk independently. Overall, this approach effectively delineates radiological variables into meaningful clusters based on their statistical relationships and hazard significance.

Using the Varimax rotation method in PCA in Fig. 13b helps to enhance the interpretability of the components by maximizing the variance of squared loadings for each factor, making the relationships between variables and factors more distinct. In this analysis, Factor 1 (84.67% of the total variance) predominantly represents the contributions of radiological hazard and exposure indices, including H_{in} , H_{ex} , Ra_{eq} , I_{γ} , AGDE, E_{in} , and E_{out} . These variables cluster together under Factor 1, suggesting that they are strongly correlated and collectively reflect the radiological risk levels in the samples studied. The significant loading of radionuclides U-238 and Th-232 within this factor further underscores their influence on these indices. Factor 2 (10.44% of the variance) isolates ELCR, highlighting its specific focus on long-term carcinogenic risk, independent of the immediate hazard measures captured by Factor 1. Additionally,

Table 11 Radium equivalent activity (Ra_{eq}) and radiological hazards parameters in the syenogranite samples in the studied area

Samples	Ra_{eq} (Bq kg ⁻¹)	H_{in}	H_{ex}	$I\gamma$	ADR (nG/h)	E_{out} (mSv)	E_{in} (mSv)	AGDE (mSv)	ELCR
S1	472	1.75	1.28	1.70	217	0.27	1.06	1.52	0.0009
S2	654	2.18	1.77	2.42	303	0.37	1.49	2.15	0.0013
S3	385	1.32	1.04	1.41	177	0.22	0.87	1.25	0.0008
S4	336	1.13	0.91	1.25	157	0.19	0.77	1.12	0.0007
S5	452	1.58	1.22	1.65	208	0.26	1.02	1.47	0.0009
S6	552	1.97	1.49	1.99	251	0.31	1.23	1.76	0.0011
S7	585	2.04	1.58	2.11	265	0.33	1.30	1.86	0.0011
S8	441	1.68	1.19	1.58	202	0.25	0.99	1.41	0.0009
S9	482	1.55	1.30	1.75	218	0.27	1.07	1.54	0.0009
S10	442	1.53	1.19	1.60	202	0.25	0.99	1.42	0.0009
S11	644	2.31	1.74	2.33	295	0.36	1.45	2.08	0.0013
S12	395	1.43	1.07	1.43	181	0.22	0.89	1.27	0.0008
S13	461	1.47	1.25	1.68	209	0.26	1.03	1.48	0.0009
S14	575	2.18	1.55	2.05	263	0.32	1.29	1.83	0.0011
S15	417	1.47	1.13	1.52	192	0.24	0.94	1.35	0.0008
S16	509	1.56	1.37	1.87	232	0.28	1.14	1.64	0.001
S17	500	1.74	1.35	1.81	228	0.28	1.12	1.60	0.001
S18	494	1.73	1.33	1.81	228	0.28	1.12	1.61	0.001
S19	598	2.06	1.62	2.18	275	0.34	1.35	1.94	0.0012
S20	434	1.59	1.17	1.58	200	0.25	0.98	1.41	0.0009
S21	594	2.20	1.60	2.11	269	0.33	1.32	1.87	0.0012
S22	429	1.57	1.16	1.56	198	0.24	0.97	1.40	0.0009
S23	518	1.70	1.40	1.87	234	0.29	1.15	1.64	0.001
S24	597	2.21	1.61	2.14	273	0.33	1.34	1.91	0.0012
S25	498	1.82	1.34	1.78	227	0.28	1.11	1.58	0.001
S26	428	1.46	1.15	1.58	199	0.24	0.98	1.41	0.0009
S27	598	2.19	1.61	2.14	272	0.33	1.33	1.90	0.0012
S28	516	1.75	1.39	1.88	236	0.29	1.16	1.66	0.001
S29	532	1.94	1.44	1.92	244	0.30	1.20	1.71	0.001
S30	582	2.00	1.57	2.10	264	0.32	1.29	1.85	0.0011
S31	449	1.60	1.21	1.64	208	0.25	1.02	1.47	0.0009
S32	544	1.86	1.47	1.97	247	0.30	1.21	1.74	0.0011
S33	575	1.97	1.55	2.08	261	0.32	1.28	1.84	0.0011
S34	516	1.82	1.39	1.88	237	0.29	1.16	1.67	0.001
S35	484	1.70	1.31	1.76	222	0.27	1.09	1.57	0.001
S36	596	2.07	1.61	2.15	271	0.33	1.33	1.91	0.0012
S37	497	1.68	1.34	1.81	227	0.28	1.12	1.61	0.001
S38	408	1.49	1.10	1.47	187	0.23	0.92	1.31	0.0008
S39	556	1.91	1.50	2.02	254	0.31	1.25	1.79	0.0011
S40	447	1.64	1.21	1.61	205	0.25	1.00	1.43	0.0009
S41	555	1.93	1.50	2.00	252	0.31	1.24	1.76	0.0011
S42	409	1.47	1.11	1.49	189	0.23	0.93	1.33	0.0008
S43	440	1.46	1.19	1.63	205	0.25	1.00	1.46	0.0009
S44	568	2.09	1.53	2.04	260	0.32	1.27	1.81	0.0011
S45	631	2.22	1.70	2.29	289	0.35	1.42	2.04	0.0012
S46	465	1.67	1.26	1.67	212	0.26	1.04	1.48	0.0009

Table 11 (continued)

Samples	Ra _{eq} (Bq kg ⁻¹)	H _{in}	H _{ex}	I _γ	ADR (nG/h)	E _{out} (mSv)	E _{in} (mSv)	AGDE (mSv)	ELCR
S47	430	1.57	1.16	1.56	198	0.24	0.97	1.39	0.0008
S48	603	2.13	1.63	2.19	276	0.34	1.36	1.94	0.0012
S49	461	1.62	1.24	1.66	210	0.26	1.03	1.48	0.0009
S50	460	1.72	1.24	1.66	212	0.26	1.04	1.49	0.0009
Mean	504	1.77	1.36	1.83	231	0.28	1.13	1.62	0.0010
SD	76	0.28	0.20	0.27	34	0.04	0.17	0.24	0.0001
Min	336	1.13	0.91	1.25	157	0.19	0.77	1.12	0.0007
Max	654	2.31	1.77	2.42	303	0.37	1.49	2.15	0.0013

Fig. 12 Internal (H_{in}), external (H_{ex}) hazard indices and representative gamma level index (I_γ) in the syenogranite samples in the studied area

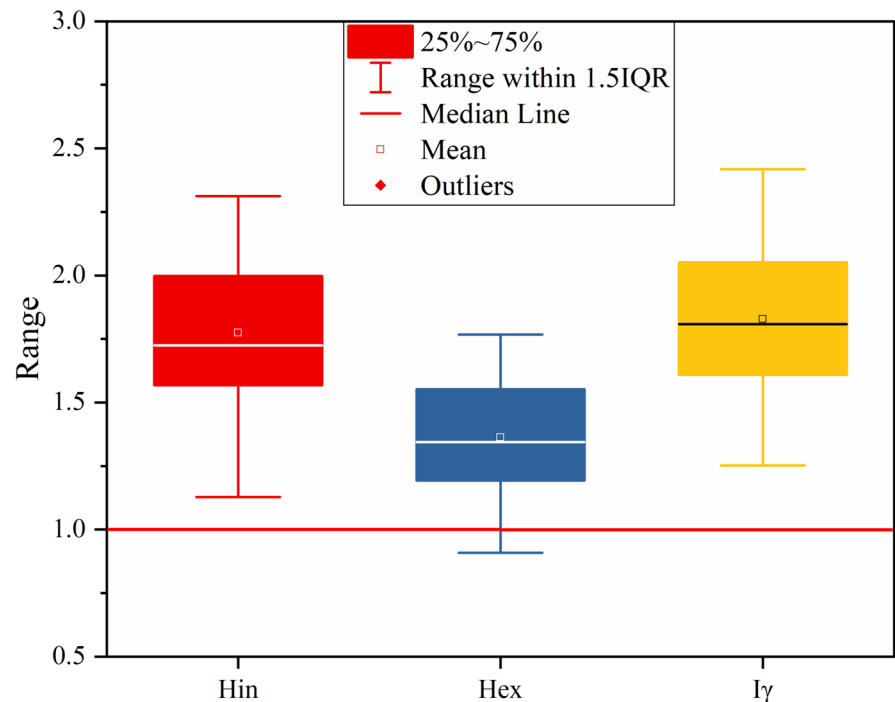


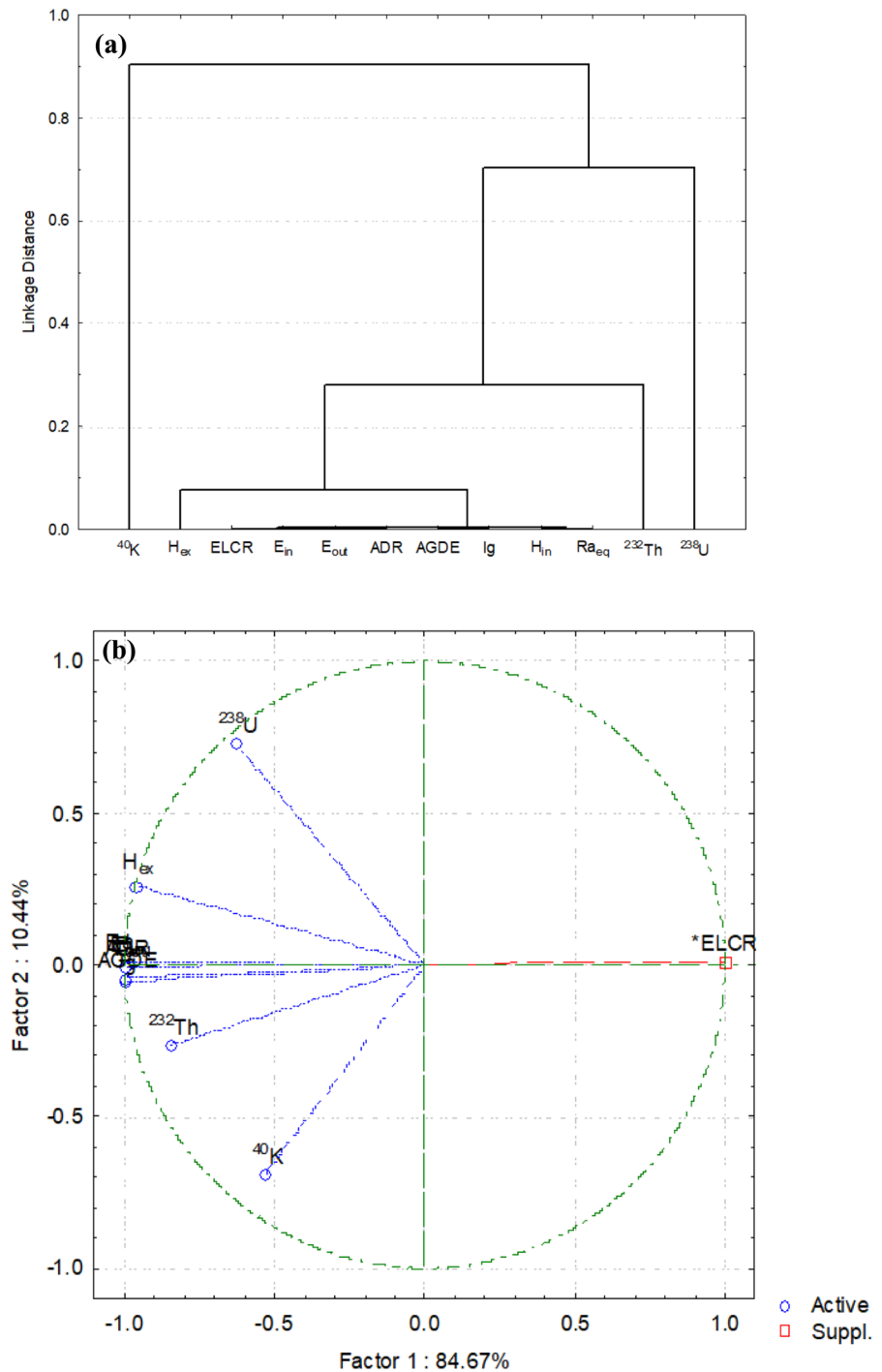
Table 12 Pearson correlation between natural radionuclides and the radiological hazard coefficients of syenogranite samples in the studied area

	U-238	Th-232	K-40	Ra _{eq}	H _{in}	H _{ex}	I _γ	ADR	E _{out}	E _{in}	AGDE	ELCR
U-238	1.00	0.21	− 0.03	0.62	0.82	0.62	0.58	0.62	0.62	0.62	0.60	0.62
Th-232	−	1.00	0.41	0.87	0.71	0.87	0.87	0.85	0.85	0.85	0.85	0.85
K-40	−	−	1.00	0.51	0.36	0.51	0.56	0.54	0.54	0.54	0.57	0.54

K-40 appears distinctly aligned, reflecting its unique radiological behavior and contribution compared to U-238 and Th-232. This differentiation suggests that while K-40 contributes to overall radiation exposure,

its impact is less correlated with hazard indices and exposure parameters compared to the other radionuclides. The Varimax rotation effectively separates

Fig. 13 **a** The clustering analysis of the radiological parameters and **b** Principal component analysis (PC1 and PC2) for radiological data at studied area



these factors, allowing a clearer interpretation of the underlying radiological dynamics in the dataset.

Conclusion

The investigated syenogranite microscopically is composed essentially of K-feldspar, quartz,

plagioclase and biotite, while chlorite, sericite and epidote are alteration products. Zircon, allanite, apatite, fluorite, iron oxides and opaques are accessory minerals. Syenogranite shows a diverse array of Th-, U-, Zr-, Nb-, and REE-mineralization. Thorite and monazite are considered radioactive mineral. ThO₂ and UO₂ are well presented in zircon, columbite and fergusonite. Columbite and fergusonite are main source of Nb-rich minerals, and having a considerable amounts of HREEs. Synchysite and monazite are considered as main resources of LREEs in the investigated syenogranite with averages 56.05 and 64.16 wt%, whereas xenotime and fergusonite are a good resources for HREE and Y, with averages 22.58 and 14.19 wt%. This study highlights the radiological significance of naturally occurring radionuclides ²³⁸U, ²³²Th and ⁴⁰K in syenogranite samples, revealing elevated levels that exceed international safety thresholds in many cases with a mean concentration of 153 ± 37, 171 ± 35, and 1390 ± 252 Bq kg⁻¹, respectively. The higher concentrations in the syenogranite are attributed to the recorded rare metals mineralization such thorite, monazite, zircon, columbite and fergusonite. The calculated radiological hazard indices confirm potential health risks associated with external and internal exposure, particularly in areas with high radionuclide concentrations. Multivariate statistical analyses provided valuable insights, with PCA demonstrating the dominant contributions of ²³⁸U and ²³²Th to radiological hazards and HCA grouping variables into distinct clusters based on their statistical relationships. The integration of radiological assessment with advanced statistical tools enhances our understanding of the environmental behavior and health implications of radionuclides, emphasizing the need for regular monitoring and mitigation strategies in regions with high natural radioactivity.

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Y. Hanfi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing.

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Declarations

Conflict of interest The authors declare no competing interests.

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