



# Geological constraints on the distribution of naturally occurring uranium and thorium in soils of southwestern Spain

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## Abstract

Naturally occurring uranium (U) and thorium (Th) concentrations in soils of southwestern Spain were explored to assess their spatial variability, establish regional geochemical baselines, and identify anomalies. A total of 505 soil and 95 bedrock samples were collected from distinct geological domains across the Iberian Massif, Betic Cordillera, and Guadalquivir Basin. Total U and Th concentrations (size fraction < 2 mm) were determined by ICP-OES, with median values of 2.30 mg kg<sup>-1</sup> for U and 8.80 mg kg<sup>-1</sup> for Th in topsoil, slightly exceeding those in subsoil and bedrock. Parent rock lithology was found to be the primary factor controlling U and Th concentrations in soils. The highest contents were observed in Cambisols developed on granitic rocks over the Central Iberian Zone and the Ossa-Morena Zone of the Iberian Massif. Geochemical baselines were established, with upper limits of 18.0 mg kg<sup>-1</sup> for Th and 4.7 mg kg<sup>-1</sup> for U in topsoil, and 16.1 mg kg<sup>-1</sup> for Th and 4.2 mg kg<sup>-1</sup> for U in subsoil. Anomalies exceeding these threshold values were mainly observed in samples from monzogranites of the Los Pedroches batholith and tonalites of the Santa Olalla stock. Statistical analysis revealed strong correlations between Th and light rare earth elements, suggesting that Th is primarily hosted by monazite. The variability in U and Th concentrations could have environmental monitoring implications, as elevated levels may influence radiation exposure. Future work should integrate high-resolution mapping, mineralogical analysis, and radiological assessments to refine anomaly detection and evaluate potential risks.

**Keywords** Geochemical baseline · Anomaly detection · Lithological control · Radioactive elements · Southwestern Spain soils

## EsCondicionantes geológicos en la distribución del uranio y torio presentes de forma natural en los suelos del suroeste de España

### Resumen

Este estudio analizó las concentraciones naturales de uranio (U) y torio (Th) en los suelos del suroeste de España para evaluar su variabilidad espacial, establecer los valores de fondo regional e identificar anomalías geoquímicas. Se tomaron 505 muestras de suelo y 95 de roca madre en distintos dominios geológicos del Macizo Ibérico, Cordillera Bética y Cuenca del Guadalquivir. Las concentraciones totales de U y Th se determinaron por ICP-OES en la fracción granulométrica < 2 mm. Las concentraciones medianas de U y Th en la capa superficial del suelo (2.30 mg kg<sup>-1</sup> y 8.80 mg kg<sup>-1</sup>, respectivamente) superan significativamente los valores encontrados en el subsuelo y la roca madre. La litología de la roca madre es el principal factor que controla las concentraciones de U y Th en los suelos. Los contenidos más elevados se observaron en

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Cambisoles desarrollados sobre rocas graníticas en la Zona Centro-Ibérica y en la Zona Ossa-Morena del Macizo Ibérico. Los valores límites superiores establecidos para el fondo regional son: 18.0 mg kg<sup>-1</sup> para Th y 4.7 mg kg<sup>-1</sup> para U en capa superficial, y 16.1 mg kg<sup>-1</sup> para Th y 4.2 mg kg<sup>-1</sup> para U en el subsuelo. Las anomalías que excedieron estos valores de referencia se registraron en monzogranitos del batolito de Los Pedroches y tonalitas del stock de Santa Olalla. El análisis estadístico reveló fuertes correlaciones entre Th y los elementos de tierras raras ligeros, lo que sugiere que el Th reside principalmente en la monacita. La variabilidad en las concentraciones de U y Th podría tener implicaciones ambientales, ya que los niveles elevados pueden influir en la exposición a la radiación. Por ello, se recomienda realizar investigaciones que incluyan una cartografía geoquímica de mayor resolución, análisis mineralógicos y análisis radiológicos para refinar la detección de anomalías y evaluar riesgos potenciales.

**Palabras clave** Valor de fondo regional · Detección de anomalías · Control litológico · Elementos radiactivos · Suelos del suroeste de España

## 1 Introduction

Uranium (U) and thorium (Th) are the most abundant actinides in the Earth's upper continental crust, with average concentrations of 2.6 mg kg<sup>-1</sup> (Hu & Gao, 2008) and 10.5 mg kg<sup>-1</sup> (Rudnick & Gao, 2003), respectively. Their concentrations vary significantly with lithology, being more enriched in felsic igneous rocks than in mafic and ultramafic rocks. These lithophile elements are primarily hosted in accessory minerals commonly found in granitic rocks, such as zircon, apatite, titanite, allanite, monazite, and xenotime (Bea, 1996). Sedimentary rocks display even greater variability in U and Th contents, with the highest values typically found in argillaceous lithologies, notably black shales (Ketris & Yudovich, 2009).

Over geological timescales, erosion and weathering processes gradually release U and Th into soils, contributing to the natural radiation background. Globally, mean soil concentrations range from 0.79 to 11 mg kg<sup>-1</sup> for U and 3.4 to 10.5 mg kg<sup>-1</sup> for Th (Kabata-Pendias & Pendias, 2001). The mobility of U in soils is largely controlled by its oxidation state. Hexavalent uranium (U[VI]), typically in the form of uranyl ion (UO<sub>2</sub><sup>2+</sup>), is highly soluble and mobile, while tetravalent uranium (U[IV]) is less soluble and tends to form solid compounds, thus limiting its mobility. In oxidizing, low-organic soils, U behaves similarly to soluble cations like Ca, Mg, K, and Na, becoming easily leached and redistributed. In contrast, Th has extremely low solubility under most environmental conditions due to the high positive charge of Th<sup>4+</sup> ions and the chemical stability of its host minerals, which hampers its bioavailability and uptake by plants (Dunn, 2011).

Both U and Th are radioactive elements with long half-lives (4.5 billion years for <sup>238</sup>U and 14 billion years for <sup>232</sup>Th). Their decay chains produce a series of intermediate radionuclides that emit ionizing radiation at various energy levels, posing potential health risks (UNSCEAR, 2020). In Spain, for instance, it has been estimated that

the average dose of ionizing radiation from terrestrial radionuclides contributes to approximately 13% of the overall background radiation exposure (CSN, 2010). Because the radioactive decay of U releases radon, a radiotoxic and highly mobile gas, accurate soil U measurements are critical for determining radon sources.

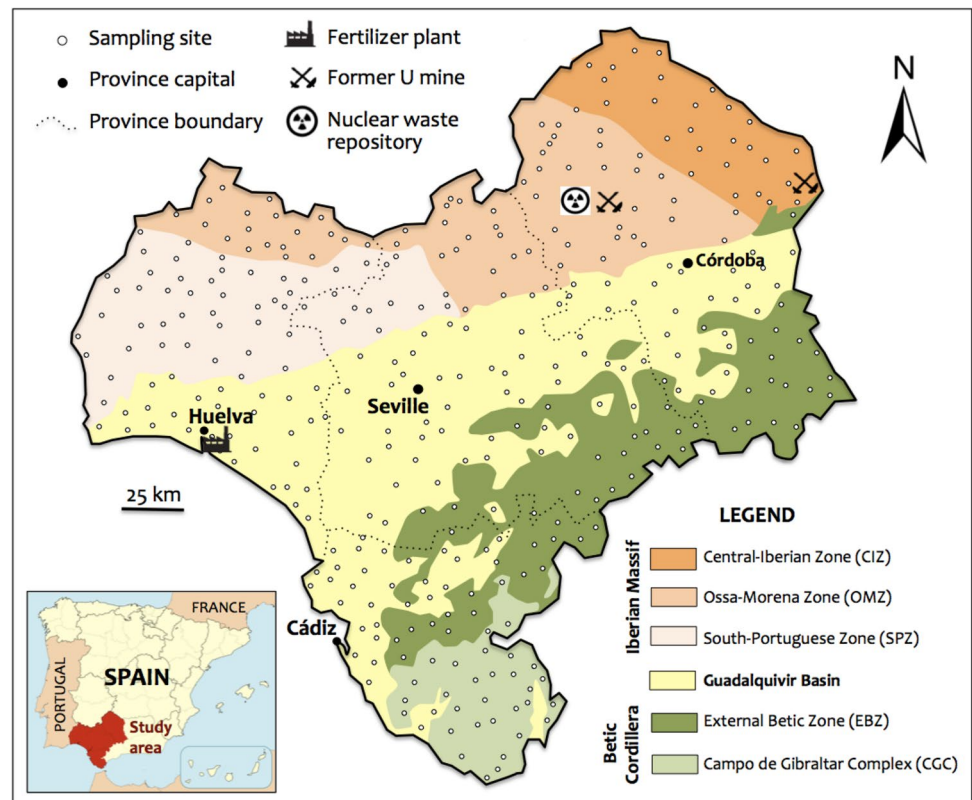
Although naturally occurring radionuclides generally pose minimal threat to human health and the environment at typical concentrations (Elles & Lee, 2002), areas with elevated levels present potential hazards (Lima et al., 2005). The accumulation of U in upper soil horizons raises concerns about plant uptake and subsequent food chain contamination (Anke et al., 2009), especially considering its chemical toxicity and carcinogenic properties.

To accurately identify lithogenic geochemical anomalies and assess soil contamination from anthropogenic sources (e.g. legacy uranium mining, phosphate fertilizers, nuclear fuel cycle), it is important to establish a robust geochemical baseline for U and Th (Naftz & Walton-Day, 2016). In this context, we adopt the definition of baseline as described by Salminen and Gregorauskiene (2000), referring to the actual content of U and Th in the soil environment, encompassing both geogenic content (background) and anthropogenic contributions at the time of sampling.

An understanding of U and Th distribution and concentrations in soils is essential for various applications. In mineral exploration, U and Th composition can help identify potential ore deposits. In environmental geochemistry these radioelements are crucial for assessing radiological risks stemming from human activities and natural processes (Ielsch et al., 2017). Moreover, geochemical baseline data are important for supporting environmental legislation and evaluating near-surface environmental conditions (Demetriades et al., 2022).

This study aimed to determine the total concentrations of U and Th in soils of southwestern Spain to advance our understanding of soil geochemical variation and constrain the influence of parent rock and geological setting. The

**Fig. 1** Simplified geological map (after IGME, 2004) of the survey area showing the spatial distribution of the sampling sites (open circles) and the locations of former mines of U, plant fertilizer and nuclear waste repository



specific objectives were to: (1) analyze the spatial distribution patterns of U and Th within the survey area; (2) establish their regional baseline concentrations; and (3) define threshold values for detecting anomalies.

## 2 Geological setting

The study covers an area of about 45,400 km<sup>2</sup> in south-western Spain, encompassing the Andalusian provinces of Huelva, Seville, Cádiz, and Córdoba. This region experiences a Mediterranean climate (Csa—Köppen classification), characterized by hot, dry summers and mild, wet winters. The area has a complex geological history, with a diverse array of lithologies, including igneous, metamorphic, and sedimentary rocks of varying ages and chemical compositions. It is divided into three major geological units (Julivert et al., 1980): Iberian Massif, Betic Cordillera, and Guadalquivir Basin (Fig. 1).

The Iberian Massif is composed of Paleozoic sedimentary formations that were deformed and metamorphosed during the Variscan orogeny (Simancas, 2019), followed by extensive granitoid intrusions. Within the study area, this continental basement is further subdivided into three distinct tectonostratigraphic zones: Central-Iberian Zone (CIZ), Ossa-Morena Zone (OMZ), and South-Portuguese Zone (SPZ).

The CIZ is distinguished by the Los Pedroches batholith, an igneous alignment dominated by granodioritic rocks with smaller monzogranitic plutons intruded into low-grade metamorphic rocks of Late Precambrian to Carboniferous age (Donaire et al., 1999). This elongated magmatic body hosts numerous hydrothermal vein deposits, historically mined for valuable metals (Locutura et al., 1990). Cambisols, Leptosols, Regosols, and Arenosols are the most widespread reference soil groups (WRB, 2022) in this zone.

The OMZ features a complex stratigraphic sequence that includes Precambrian formations as well as Paleozoic sedimentary and volcanic units. It hosts abundant ore deposits, including volcanic-hosted massive sulfides (VHMS), sedimentary-exhalative deposits, orthomagmatic ores, hydrothermal veins, and skarns, which reflect a long history of magmatic and tectonic activity (Tornos et al., 2004). Cambisols and Leptosols are the predominant soil types.

The SPZ is best known for the Iberian Pyrite Belt (IPB), a globally significant metallogenic province containing the world's largest concentration of VHMS deposits. The IPB consists of three main lithostratigraphic units, dated as Devonian and Carboniferous (Schermerhorn, 1971): the Phyllite-Quartzite Group, the Volcanic Sedimentary Complex, which hosts the VHMS deposits, and the Culm Group, a thick sequence of turbidites. In its eastern portions, the IPB is intruded by the Seville Sierra Norte batholith (De la

Rosa, 1992). This zone is also characterized by a widespread distribution of Leptosols and Cambisols.

South of the Iberian Massif lies the Betic Cordillera, a geologically intricate mountain chain formed during the Alpine orogeny (Vergés & Kullberg, 2019). Within the study area, the Betic chain comprises two main units: the External Betic Zone (EBZ) and the flysch deposits of the Campo de Gibraltar Complex (CGC).

The EBZ is composed of Mesozoic and Tertiary sedimentary successions, which represent the sedimentary cover of the Iberian Massif (Vera, 2004). These successions include: (a) Triassic deposits, dominated by red-bed detrital sediments and evaporites; (b) Jurassic sequences, characterized by marine carbonates, such as dolostones and limestones; and (c) Cretaceous marly limestones. The most common reference soil groups in the EBZ are Calcisols and Cambisols.

The CGC is a series of tectonic units located along the boundary between the internal and external zones of the Betic orogen. It primarily consists of turbiditic siliciclastic formations, ranging in age from the Cretaceous to the Early Miocene (Pendón, 1978). This flysch complex records significant tectono-sedimentary processes related to the convergence of the African and Iberian plates. Regosols and Cambisols are prevalent in this area.

The Guadalquivir Basin (GB) is a foreland basin situated between the Iberian Massif (northern passive margin) and the Betic Cordillera (southern active margin). This elongated Neogene-Quaternary basin reflects a dynamic interplay between subsidence and sedimentation during and after the Alpine orogeny (Braga & Proença, 2019). The sedimentary infill comprises five westward-younging depositional sequences (Sierra et al., 1996), including autochthonous siliciclastic and carbonate sediments that unconformably overlie the Iberian Massif, and allochthonous units, mainly olistostrome deposits derived from the southern active margin. The dominant soil types in the GB are Calcisols, Vertisols, Arenosols, and Fluvisols.

### 3 Material and methods

A stratified random sampling methodology was adopted to account for the geodiversity of the region, with stratification based on underlying bedrock type, as lithology is the primary soil-forming factor influencing local soil geochemistry (Fernández-Caliani et al., 2020; Galán et al., 2008). A total of 505 soil samples (304 topsoil and 201 subsoil) and 95 parent rock samples were collected from 304 sites that showed no apparent signs of anthropogenic contamination (Fig. 1) at a sampling density of 1 site per 150 km<sup>2</sup>. The sample site coordinates were recorded using a Garmin GPS unit.

Soil samples were taken using an Edelman hand auger at two depth intervals: 0–20 cm (topsoil) and 20–40 cm

(subsoil). Bedrock samples were obtained from locations where exposed rock was visible within the upper 50 cm of the soil profile. At each sampling point, composite soil samples were prepared by bulking material from four soil pits collected radially around the central sampling point at every depth interval.

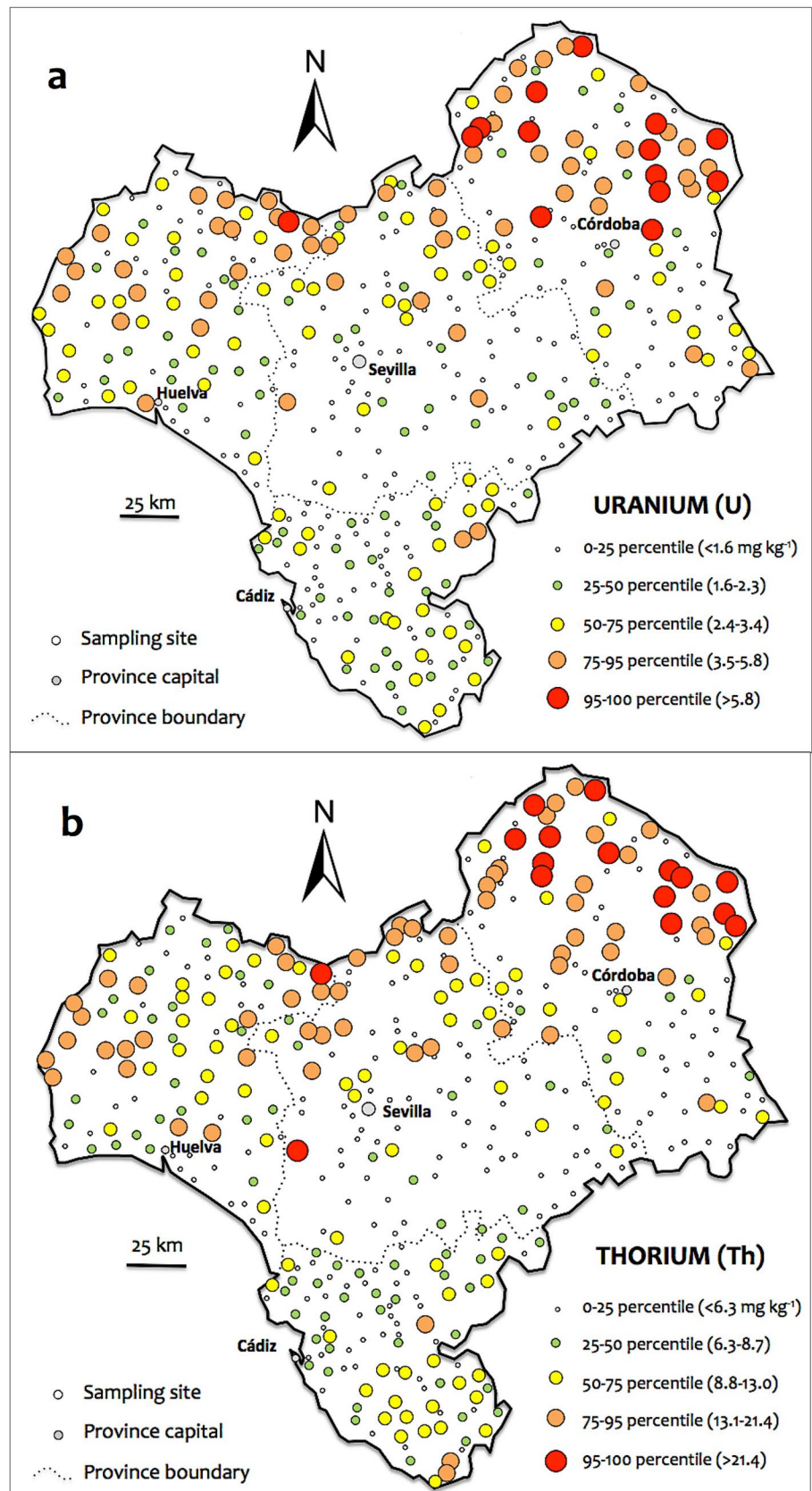
The soil samples were air-dried, disaggregated with a wooden hammer and roller, sieved to < 2 mm, homogenized and split into several sub-samples. A subsample of the sieved soil was further manually ground in an agate mortar with a pestle and pulverized to < 63 µm grain size. For the bedrock samples, larger fragments were hammered to reduce their size, followed by pulverization in an agate mill, and homogenization prior to chemical analysis.

The U and Th content was determined at ACTLABS (Ancaster, Ontario, Canada), an ISO/IEC 17025 accredited laboratory. Samples were fully dissolved using a vigorous multi-acid attack (HF-HClO<sub>4</sub>-HNO<sub>3</sub>-HCl) at 260 °C. Total U and Th concentrations were measured using inductively coupled plasma-optical emission spectrometry (ICP-OES). Detection limits were 0.2 mg kg<sup>-1</sup> for Th and 0.5 mg kg<sup>-1</sup> for U. Quality control procedures by ACTLABS included reagent blanks, duplicate samples, and certified reference materials (DMMAS-14, DMMAS-18) to test reproducibility and accuracy. The relative standard deviations (RSD) from certified concentrations typically remained below 10%, and analytical precision consistently was better than 5% RSD.

Statistical evaluation of compositional data involved descriptive statistics, including Spearman's rank correlation analysis, and outlier detection methods. For statistical purposes, all values below detection limits were replaced with half the detection limit values, a commonly used approach in geochemistry and environmental chemistry when dealing with left-censored data (Henne et al., 2024; Singh & Nocerino, 2002). Given the considerable variability typically observed in element concentrations, the median was chosen as the central tendency measure for establishing the baseline, owing to its robustness against outliers. The upper limit of baseline variation was determined by adding twice the median absolute deviation (MAD) to the median (Me), as described by the formula: Me + 2MAD. This approach minimizes the influence of extreme values (Reimann & De Caritat, 2017; Reimann et al., 2005).

Outlier detection was performed using the Tukey's fences method (ISO, 2018). This quartile-based technique identifies data points deviating significantly from the dataset. The upper inner fence (UIF), referred to as the upper whisker in a Tukey boxplot, was calculated as follows: UIF = Q<sub>3</sub> + 1.5 × IQR, where Q<sub>3</sub> is the third quartile (75th percentile), and IQR is the interquartile range (the difference between the 75 and 25th percentiles). The UIF is acknowledged as the threshold separating baseline values and mild anomalies (Carranza, 2009; Reimann et al.,

**Fig. 2** Percentile rank maps showing the spatial distribution of uranium (a) and thorium (b) concentrations in surface soils (0–20 cm) across the study area. Each dot represents a sampling location, with color indicating the percentile ranges of elemental concentrations ( $\text{mg kg}^{-1}$ )



**Table 1** Basic statistics of U and Th concentrations in topsoil, subsoil, and bedrock samples

Element (mg kg <sup>-1</sup> )	Uranium	Thorium
<b>Topsoil (n = 304)</b>		
Range	<0.5–14.3	<0.2–44.9
Mean	2.64	10.24
Std. deviation	1.70	6.22
Median	2.30	8.80
Kurtosis	7.51	6.28
Skewness	1.79	1.96
Th/U ratio (median):	3.87	
<b>Subsoil (n = 201)</b>		
Range	<0.5–15.5	<0.2–54.4
Mean	2.60	10.67
Std. deviation	1.99	8.12
Median	2.10	8.40
Kurtosis	9.64	7.92
Skewness	2.41	2.53
Th/U ratio (median):	4.07	
<b>Bedrock (n = 95)</b>		
Range	<0.5–11.2	<0.2–276
Mean	2.77	13.05
Std. deviation	1.82	28.22
Median	2.90	10.60
Kurtosis	3.43	1.87
Skewness	1.02	0.80
Th/U ratio (median):	4.01	
<b>Reference values (median)</b>		
Western European soils <sup>a</sup>		
Topsoil (n = 843)	2.00	7.24
Subsoil (n = 790)	2.03	7.63
Spanish soils <sup>b</sup>		
Topsoil (n = 13,505)	2.9	13.4
Subsoil (n = 7,682)	2.8	14.0
European agricultural soils <sup>c</sup>		
Ap horizon (n = 2,108)	0.80	2.89

Reference values are given for comparison

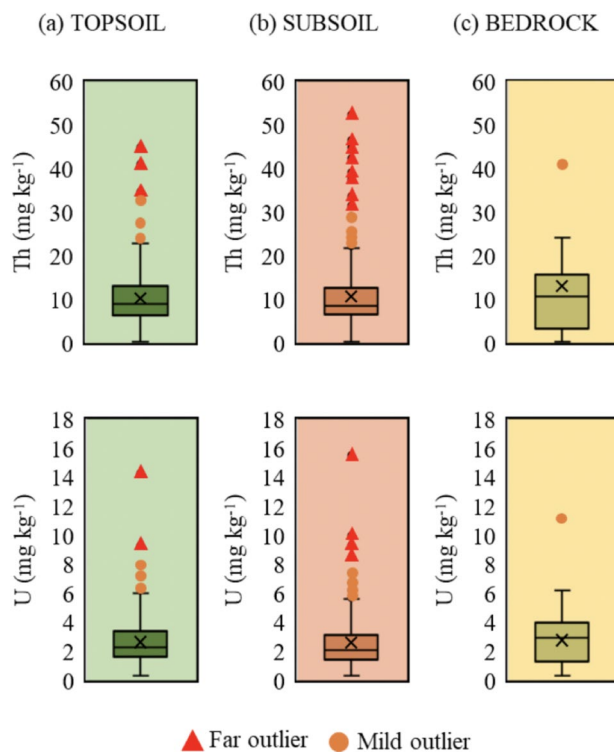
<sup>a</sup><2 mm fraction, total, ICP-MS. FOREGS database (Salminen, 2005)

<sup>b</sup><2 mm fraction, total, ICP-MS. Geochemical Atlas of Spain (Locutura et al., 2012)

<sup>c</sup><2 mm fraction, aqua regia extraction, ICP-OES (Negrel et al., 2018)

2005). Values exceeding the upper outer fence (UOF), lying more than three times the IQR above the third quartile ( $UOF = Q3 + 3.0 \times IQR$ ), were classified as far outliers, indicative of extreme anomalies. Tukey outlier definition was used to identify areas of potential interest for further investigations.

To ensure the validity of the statistical analysis, Levene's test in R was first applied to assess the homogeneity of variances, indicating significant heterogeneity of variances



**Fig. 3** Box-and-whisker diagram illustrating the distribution of U and Th concentrations in (a) topsoil, (b) subsoil, and (c) bedrock samples. The box represents the interquartile range (IQR), encompassing 50% of the data. The line within the box indicates the median, and the whiskers extend to 1.5 times the IQR. Outliers are depicted as points beyond the whiskers

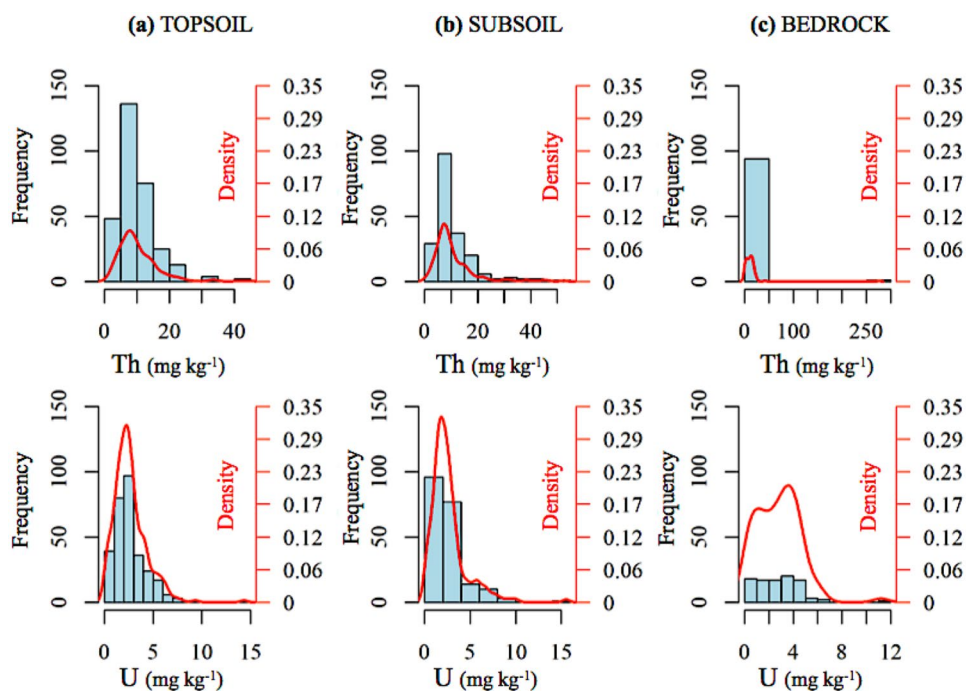
( $p < 0.05$ ). Welch's ANOVA, which is robust to this issue, identified significant differences between lithologies and geological domains ( $p < 0.05$ ). A post hoc Tukey's HSD test then determined specific pairs with significant differences.

## 4 Results

The spatial distribution of U and Th concentrations in surface soils (0–20 cm) is shown in Fig. 2. The percentile rank maps allows for an immediate and intuitive way to pinpoint areas with lower, average, or higher U and Th concentrations, thereby highlighting potential anomalies and large-scale trends across the region.

Table 1 summarizes the descriptive statistics for U and Th concentrations in topsoil, subsoil, and bedrock samples over the surveyed area, along with the upper limits of their baseline concentrations. For comparative analysis, it also includes the median concentrations of these radioelements in the <2 mm size fraction (total digestion) of topsoil and subsoil samples from western Europe (Salminen, 2005) and Spain (Locutura et al., 2012). Figure 3 presents

**Fig. 4** Frequency histograms and density curves depicting the distribution of U and Th concentrations in (a) topsoil, (b) subsoil, and (c) bedrock samples



box-and-whisker plots depicting the median values within the IQR, the non-outlier range indicated by whiskers, and any outlier values falling outside the expected distribution range. Figure 4 combines histograms and density plots, showing the inhomogeneous nature of the data distribution.

## 5 Discussion

### 5.1 Distribution patterns of U and Th concentrations

The spatial distribution of U and Th concentrations in the study area is highly heterogeneous, varying both laterally and vertically (between soil and bedrock). This heterogeneity, supported by high coefficients of variation ranging from 60 to 76% across all soil datasets, is consistent with the development of residual soils directly over a Th and U-rich bedrock. Soil U concentrations ranged from below the detection limit ( $0.5 \text{ mg kg}^{-1}$ ) to  $15.5 \text{ mg kg}^{-1}$ , while Th varied from below detection ( $0.2 \text{ mg kg}^{-1}$ ) to  $54.5 \text{ mg kg}^{-1}$ . The Th/U ratios at 3.87 in topsoil, 4.07 in subsoil, and 4.01 in bedrock are consistent with the global crustal average ratio of 4.04.

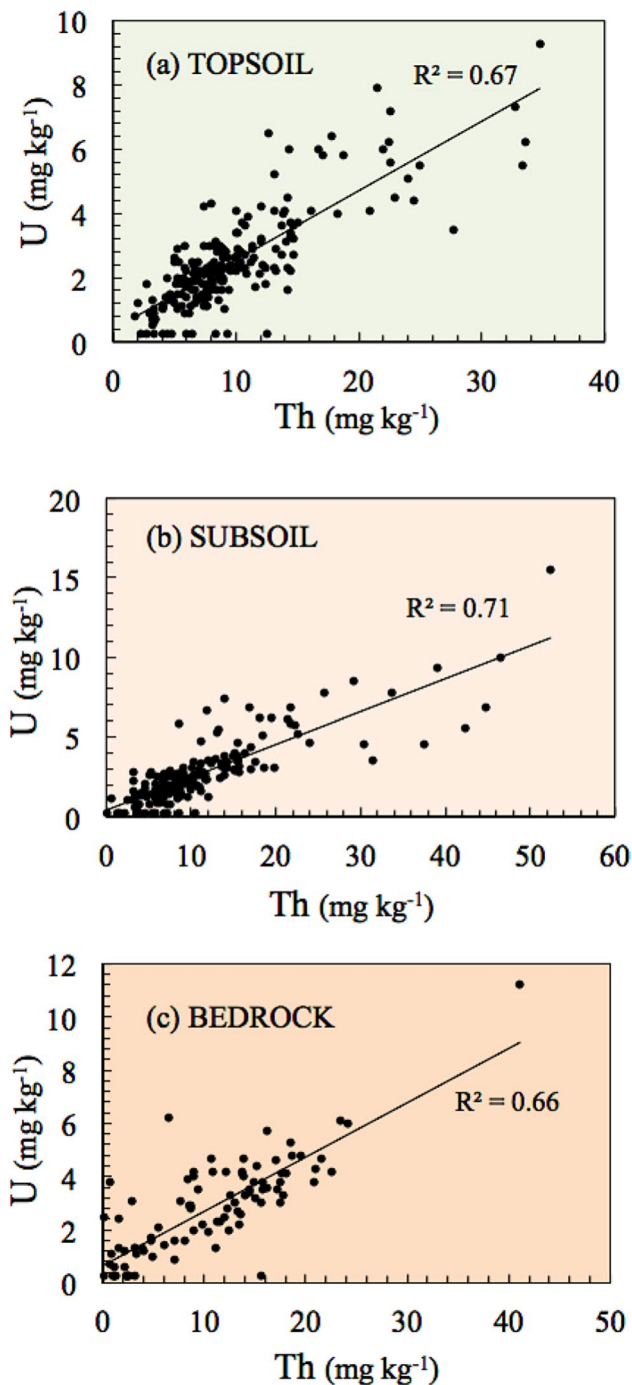
Topsoil samples generally showed slightly higher median concentrations of U ( $2.30 \text{ mg kg}^{-1}$ ) and Th ( $8.80 \text{ mg kg}^{-1}$ ) compared to subsoil samples ( $2.10$  and  $8.40 \text{ mg kg}^{-1}$ , respectively). The distribution of U and Th concentrations displays a right-skewed pattern in both soil layers, reflecting the influence of outliers on the overall data distribution. The

strong positive correlations observed between these elements in topsoil ( $R^2=0.67$ ), subsoil ( $R^2=0.71$ ), and bedrock ( $R^2=0.66$ ) point to a significant association, suggesting common sources or shared geochemical processes controlling their distribution (Fig. 5).

Mean U and Th concentrations in bedrock samples ( $2.77 \text{ mg kg}^{-1}$  and  $13.95 \text{ mg kg}^{-1}$ , respectively) were slightly above the mean crustal abundances (Hu & Gao, 2008; Rudnick & Gao, 2003) and consistently above the median values observed in soil samples ( $2.90 \text{ mg kg}^{-1}$  U and  $10.60 \text{ mg kg}^{-1}$  Th). The results are consistent with residual soils having developed over Th and U-rich bedrock.

Soil U and Th concentrations in the study area are broadly consistent with published median values for western European and Spanish soils, although notable variations in abundance and distribution exist. Both topsoil and subsoil concentrations were slightly elevated in U and Th relative to western European soils (Salminen, 2005) and clearly exceeded those reported for *aqua regia* extracts from agricultural soils of Europe (Négrel et al., 2018), which were  $0.80 \text{ mg kg}^{-1}$  for U and  $2.89 \text{ mg kg}^{-1}$  for Th (Table 1). Assuming the reactive (non-residual) fractions of U and Th in the studied soils are similar to those in European agricultural soils, a substantial portion (72–75%) of the total U and Th could be present in residual forms, tightly bound to weathering-resistant minerals derived from the parent rock.

U and Th levels in the survey area fall below the Spanish soil median values of  $2.9 \text{ mg kg}^{-1}$  U and  $13.4 \text{ mg kg}^{-1}$  Th for topsoil, and  $2.8 \text{ mg kg}^{-1}$  U and  $14 \text{ mg kg}^{-1}$  Th for



**Fig. 5** Bivariate plots showing the relationship between concentrations of U and Th in: (a) topsoil, (b) subsoil, and (c) bedrock

subsoil (Locutura et al., 2012), indicating regional variability in geochemical baselines. By comparison, northwestern Spain (Galicia) has higher mean concentrations, reaching  $12.4 \text{ mg kg}^{-1}$  for U and  $17.7 \text{ mg kg}^{-1}$  for Th (Taboada et al., 2006). Importantly, the baseline U levels are considerably lower than those found in soils impacted by human activities, such as areas surrounding abandoned U mines in Portugal

(e.g.  $337 \text{ mg kg}^{-1}$ , Neiva et al., 2014) and phosphogypsum stacks resulting from phosphate fertilizer production (e.g.  $96.3 \text{ mg kg}^{-1}$ , Fernández-Caliani, 2012).

The topsoil/subsoil concentration ratios for U (1.095) and Th (1.048) are close to 1, suggesting a relatively uniform distribution between soil layers. This consistency is indicative of minimal vertical redistribution and supports the interpretation that the underlying bedrock geology is a major controlling factor on current U and Th concentrations. The slightly higher topsoil/subsoil ratio for U may reflect its greater tendency to accumulate in the topsoil due to various retention mechanisms, such as adsorption onto clay minerals (Bachmaf & Merkel, 2011) and soil organic matter (Lefebvre et al., 2022), as well as co-precipitation with iron oxides (Duff et al., 2002). This observed U distribution pattern is in line with findings from western Spain (Santos-Francés et al., 2018), where increased clay content in upper soil horizons correlates with enhanced U retention.

Conversely, studies in northwestern Spain (Taboada et al., 2006) have documented an opposite trend, with U and Th generally depleted in topsoil and enriched in deeper horizons. This supergene enrichment process involves the leaching of these elements from the surface layer and their subsequent accumulation near the bedrock. This regional discrepancy likely arises from contrasting climatic conditions. The humid climate of northwestern Spain promotes element mobility and redistribution within, or even out of, the soil profile, with development of well-drained and highly leached soils (Macías, 1981).

## 5.2 Influence of geological setting and soil types on the U and Th distribution

Descriptive statistics (Table 2) show significant spatial variability in soil U and Th concentrations across geological domains. This heterogeneous distribution appears to be primarily controlled by parent rock lithology, with soil type playing a secondary but influential role, as it is itself influenced by lithology. Welch's ANOVA confirmed highly significant differences ( $p < 0.0001$ ) in U and Th concentrations across both lithological groups and geological domains. Variability was strongest in topsoil, especially for Th, with similar trends in subsoil and bedrock, reinforcing the influence of lithology and geological setting on element distribution.

The CIZ exhibited the highest median concentrations of Th and U in the study area, with soil profile concentrations of  $22.6 \text{ mg kg}^{-1}$  and  $5.6 \text{ mg kg}^{-1}$ , respectively, and corresponding bedrock concentrations of  $14.5 \text{ mg kg}^{-1}$  and  $3.8 \text{ mg kg}^{-1}$ . Among soil types, Cambisols and Arenosols developed on granitic rocks display the highest Th concentrations. However, U levels remained well below the  $29.8 \text{ mg kg}^{-1}$  background value reported for natural soils on granitic terrains elsewhere in the CIZ, such as Salamanca

**Table 2** Basic statistics of Th and U concentrations in topsoil, subsoil, and bedrock samples grouped by geological setting

Sample	Topsoil		Subsoil		Bedrock	
	Th	U	Th	U	Th	U
Central-Iberian zone (CIZ)						
Sample size	21	21	15	15	5	5
Range	3.1–41.1	1.6–14.3	9.4–52.4	2.3–15.5	1.3–41.1	<0.5–11.2
Mean	20.78	5.34	27.45	6.35	17.62	4.70
Std. Deviation	9.00	2.89	13.11	3.49	14.51	4.00
Median	20.3	5.1	22.6	5.6	14.5	3.8
Th/U (median):	3.67		4.10		4.14	
Ossa-Morena zone (OMZ)						
Sample size	60	60	27	27	36	36
Range	<0.2–44.9	<0.5–6.6	1.2–44.8	<0.5–7.8	<0.2–276	<0.5–6.2
Mean	12.67	3.53	14.65	4.00	17.89	3.00
Std. Deviation	7.85	1.80	9.96	2.12	44.73	1.65
Median	12.15	3.60	13.4	3.8	11.75	3.15
Th/U (median):	3.44		3.74		3.76	
South-Portuguese zone (SPZ)						
Sample size	50	50	17	17	35	35
Range	2.5–19.0	<0.5–5.6	6.7–17.1	<0.5–4.4	2.3–24.1	<0.5–6.0
Mean	11.12	2.66	11.38	2.51	12.35	2.97
Std. Deviation	4.09	1.44	3.87	1.04	5.77	1.55
Median	11.45	2.85	10.1	2.6	13.5	3.0
Th/U (median):	4.13		4.50		4.29	
Guadalquivir basin (GB)						
Sample size	104	104	81	81	11	11
Range	1.7–24.9	<0.5–5.5	1.4–31.5	<0.5–5.8	0.8–8.9	<0.5–2.4
Mean	7.72	1.94	7.83	1.90	4.44	1.29
Std. Deviation	3.58	0.88	3.94	1.00	3.11	0.61
Median	7.55	1.95	7.2	1.9	4.9	1.3
Th/U (median):	3.77		3.95		4.29	
External betic zone (EBZ)						
Sample size	38	38	31	31	8	8
Range	3.2–18.9	<0.5–4.2	0.5–24.0	<0.5–7.4	0.2–15.8	<0.5–3.8
Mean	7.05	2.06	6.73	1.82	3.33	1.73
Std. Deviation	3.16	1.06	4.59	1.06	5.31	1.41
Median	6.6	2.1	5.9	1.5	0.9	1.4
Th/U (median):	3.77		3.86		1.91	
Campo de Gibraltar complex (CGC)						
Sample size	31	31	30	30	0	0
Range	5.3–14.7	<0.5–3.4	4.1–17.6	1.2–3.5		
Mean	9.15	2.11	10.02	2.24		
Std. Deviation	2.38	0.7	3.23	0.69		
Median	9.1	2.2	9.65	2.2		
Th/U (median):	4.25		4.23			

province, western Spain (Santos-Francés, 2018). Lower median concentrations were found in Leptosols and Regosols, with U ranging from 5.0 to 5.5 mg kg<sup>-1</sup> and Th from 17.5 to 21.5 mg kg<sup>-1</sup>. These concentration patterns highlight the influence of parent rock lithology. The decline in the Th/U ratio from 4.14 in bedrock to 3.67 in topsoil suggests

U enrichment in surface layers, probably due to weathering-driven mobilization and subsequent retention. In contrast, similar ratios in bedrock and subsoil (4.10–4.14) suggest minimal redistribution in deeper layers.

In the OMZ, soil samples showed median Th concentrations of 12.2–13.4 mg kg<sup>-1</sup> and U concentrations of

3.6–3.8 mg kg<sup>-1</sup>, slightly exceeding bedrock values (Th: 11.8 mg kg<sup>-1</sup>; U: 3.2 mg kg<sup>-1</sup>). Interestingly, tonalitic rocks of the Santa Olalla stock (Romeo et al., 2006) exhibited exceptional Th enrichment (276 mg kg<sup>-1</sup>). The most widespread soil groups (Cambisols and Leptosols) showed comparable U (3.3–4.0 mg kg<sup>-1</sup>) and Th (12.0–12.4 mg kg<sup>-1</sup>) concentrations. However, soils derived from felsic magmatic rocks were more enriched in U (4.3 mg kg<sup>-1</sup>) and Th (17.3 mg kg<sup>-1</sup>) than those formed on mafic (1.8 and 6.1 mg kg<sup>-1</sup>) and calcareous rocks (2.8 and 8.0 mg kg<sup>-1</sup>). The presence of old U mines and mineral occurrences (locations shown in Fig. 1) linked to granitic rocks (Calvo et al., 1991; García-Cortés, 2011) emphasize the localized U enrichment in this zone. The relatively low Th/U ratios observed in the OMZ, compared to other zones, indicates a slightly higher proportion of U relative to Th. This U enrichment is most pronounced in the surface layer, where the Th/U ratio (3.44) is lower than in the bedrock (3.76).

Soils in the SPZ contain lower median Th (10.1–11.5 mg kg<sup>-1</sup>) and U (2.6–2.9 mg kg<sup>-1</sup>) concentrations compared to the CIZ and OMZ. Bedrock concentrations were slightly higher (Th: 13.5 mg kg<sup>-1</sup>; U: 3.0 mg kg<sup>-1</sup>), suggesting soil depletion via leaching under the acidic and oxidizing conditions prevalent in this zone (Fernández-Caliani et al., 2009). The SPZ displays the highest Th/U ratios among all zones, with values reaching up to 4.50 in the subsoil. This finding indicates substantial U loss, likely resulting from preferential leaching. Leptosols developed on fine-grained metasediments contained the highest U (3.16 mg kg<sup>-1</sup>) and Th (12.6 mg kg<sup>-1</sup>) levels. Conversely, Cambisols and Luvisols on mafic rocks showed the lowest concentrations (U: 0.74 mg kg<sup>-1</sup>; Th: 5.56 mg kg<sup>-1</sup>). A similar trend, indicative of lithological control, has been observed in residual soils of the Iberian Pyrite Belt (Martín-Méndez et al., 2023).

The GB soils developed over sedimentary substrates (clays, silts, and marls) had lower U and Th concentrations than the crystalline terrains of the Iberian Massif (CIZ, OMZ, and SPZ), with median Th at 7.2–7.6 mg kg<sup>-1</sup> and U at 1.90–1.95 mg kg<sup>-1</sup>. Bedrock values were similarly low (Th: 4.9 mg kg<sup>-1</sup>; U: 1.3 mg kg<sup>-1</sup>) attributed to dilution by less mineralized sediments or low-U and Th soil parent lithologies. Vertisols and Fluvisols on detrital sediments

showed relatively higher U (1.8–2.2 mg kg<sup>-1</sup>) and Th (8.0–8.8 mg kg<sup>-1</sup>) levels, whereas Calcisols on marly and calcareous sediments had lower values (U: 1.9 mg kg<sup>-1</sup>; Th: 6.9 mg kg<sup>-1</sup>). Regosols and Arenosols exhibited the lowest median contents (U: 1.5–1.7 mg kg<sup>-1</sup>; Th: 5.0 mg kg<sup>-1</sup>). The increasing Th/U ratio from topsoil (3.77) to bedrock (4.29) reflects U retention in the upper soil layer coupled with limited Th redistribution.

The EBZ soils displayed the lowest median Th concentrations in the study area (0.9 mg kg<sup>-1</sup> in bedrock and 7.2–7.6 mg kg<sup>-1</sup> in the solum), suggesting limited Th geoavailability in the parent material. This is supported by the strikingly low Th/U ratio (1.91) in the bedrock compared to the soil layers (3.77–3.86). Relatively low U concentrations were also observed, consistent with findings from FOREGS soil samples collected over Mesozoic rocks in the Alpine terrain of southern Spain (Salminen, 2005). Topsoil U content (2.1 mg kg<sup>-1</sup>) exceeded subsoil (1.5 mg kg<sup>-1</sup>) and bedrock (1.4 mg kg<sup>-1</sup>) levels, potentially due to external inputs (e.g. phosphate fertilizer application). Calcisols derived from carbonate rocks had the lowest median U (1.4 mg kg<sup>-1</sup>) and Th (5.9 mg kg<sup>-1</sup>) concentrations, matching the typically low U and Th content reported for these rock types (Guagliardi et al., 2020). Cambisols and Leptosols exhibited slightly higher median values, with U ranging from 2.9 to 3.1 mg kg<sup>-1</sup> and Th from 8.5 to 10.9 mg kg<sup>-1</sup>.

In the CGC, median solum Th concentrations were moderate, at 9.1 mg kg<sup>-1</sup> in topsoil and 9.7 mg kg<sup>-1</sup> in subsoil, while U concentrations remained relatively constant at 2.2 mg kg<sup>-1</sup> in both layers. The consistently high Th/U ratio observed across layers suggests minimal element mobility within the soil profile, likely due to stabilization by resistant minerals or adsorption onto soil particles, thus preventing significant leaching or redistribution. While CGC values fall within the low-to-moderate range compared to other zones (CIZ, OMZ, and SPZ), they exceeded those observed in the GB and EBZ, which have parent materials poorer in U and Th. Most CGC soils occur over sandstone substrate, with U and Th concentrations ranging from 1.6–2.4 mg kg<sup>-1</sup> and 6.4–10.8 mg kg<sup>-1</sup>, respectively, with Regosols and Luvisols showing the highest values.

This dataset from southwestern Spain aligns with observations from other European regions (Plant et al., 2003),

**Table 3** Spearman's correlation coefficients of thorium (Th) and uranium (U) with hafnium (Hf) and selected rare earth elements (La, Ce, Nd, Sm, Eu, Yb, Lu)

Element		Hf	La	Ce	Nd	Sm	Eu	Yb	Lu
Topsoil	Th	0.64	0.89	0.89	0.83	0.80	0.67	0.70	0.70
	U	0.57	0.76	0.74	0.74	0.68	0.59	0.63	0.62
Subsoil	Th	0.64	0.93	0.92	0.88	0.84	0.74	0.74	0.73
	U	0.60	0.79	0.80	0.78	0.78	0.69	0.73	0.73
Bedrock	Th	0.72	0.82	0.88	0.82	0.77	0.60	0.75	0.74
	U	0.68	0.69	0.71	0.68	0.66	0.52	0.60	0.59

where felsic basement rocks are linked to elevated U and Th levels, while sedimentary basins tend to display lower concentrations (Ielsch et al., 2017). In the study area, the highest concentrations (up to 15.5 mg kg<sup>-1</sup> U and 52.4 mg kg<sup>-1</sup> Th) occur in terrains of the Variscan orogen dominated by felsic lithologies, such as the CIZ and the OMZ, where late- and post-orogenic granites were emplaced. In contrast, the overlying sedimentary cover (GB zone) displays lower values, generally below 2 mg kg<sup>-1</sup> for U.

### 5.3 Statistical correlations of U and Th with Hf and REEs in soil profiles

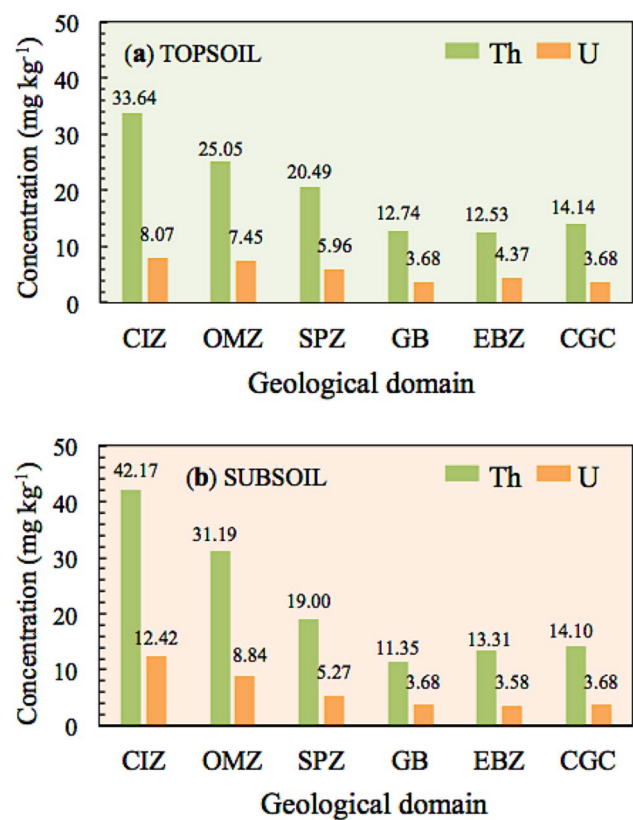
Table 3 displays Spearman correlation coefficients between U and Th concentrations measured in this study and hafnium (Hf) and selected rare earth elements (REEs), previously reported by Fernández-Caliani et al. (2020) for the same sample set, size fraction (< 2 mm), and analytical method (total digestion, ICP-OES). Statistical analysis indicated significant ( $p < 0.05$ ) geochemical relationships among these elements, providing insights into the factors controlling the distribution of U and Th within the soil profiles.

Strong positive correlations were observed between Th and the REEs, particularly the light REEs (LREEs) such as La, Ce, Nd, and Sm, in both the solum ( $\rho = 0.80\text{--}0.93$ ) and underlying parent rock ( $\rho = 0.77\text{--}0.88$ ). This suggests that Th concentrations are largely controlled by LREE-bearing accessory phases, likely monazite [(Ce, La, Nd, Th) PO<sub>4</sub>], a LREEs phosphate that can incorporate appreciable amounts of Th into its crystal structure (Bea, 1996; Galán et al., 2007).

A good correlation between Hf and Th in the bedrock ( $\rho = 0.72$ ) may indicate the presence of zircon (ZrSiO<sub>4</sub>), a Hf-bearing mineral (Bea, 1996) that often occurs together with monazite in felsic igneous rocks. It is therefore reasonable to infer that much of the Th in soils overlying granite substrates is hosted within monazite, with a lesser contribution from zircon, both inherited from the parent rock. These weathering-resistant minerals remain largely unaltered during pedogenesis, leading to their residual concentration in soil profiles.

Unlike Th, U showed weaker correlations with REEs in bedrock ( $\rho = 0.52\text{--}0.71$ ), suggesting its association with different phases or control by distinct geochemical processes. Because uraninite (UO<sub>2</sub>) is a common primary U-bearing mineral in the granitic rocks of the survey area (Calvo et al., 1991; García-Cortés, 2011), it could be the main host for U, rather than REE-bearing phases. In topsoil, moderate positive correlations between U and REEs ( $\rho = 0.59\text{--}0.76$ ) suggest some degree of association during soil development, although the association is weaker than that observed for Th.

These patterns indicate contrasting geochemical behaviors: Th, Hf, and REEs remained relatively immobile during



**Fig. 6** Geochemical baselines of Th and U in (a) topsoil and (b) subsoil for each geological domain (CIZ: Central-Iberian Zone. OMZ: Ossa-Morena Zone. SPZ: South-Portuguese Zone. GB: Guadalquivir Basin. EBZ: External Betic Zone. CGC: Campo de Gibraltar Complex)

weathering and pedogenesis due to their association with geochemically stable minerals, while U exhibits greater mobility attributed to its higher solubility in oxidative surface environments. The breakdown of reactive primary minerals in granitic rocks (e.g. uraninite, apatite) likely contributes to U mobilization.

These findings corroborate previous research on weathering profiles and residual soils (e.g. Fernández-Caliani & Cantano, 2010; Martín-Méndez et al., 2023; Panahi et al., 2000), reinforcing the use of Th, Hf, and REEs as reliable tracers of source rock composition. Conversely, the mobility of U underscores its geochemical reactivity, especially in oxidizing soil environments, where mineral dissolution can release sorbed or co-precipitated U(VI), driving its redistribution (Skierszkan et al., 2020).

### 5.4 Soil geochemical baseline and anomalous concentrations

Regional geochemical baselines reflecting the natural variability of U and Th were determined for both topsoil and subsoil. In topsoil, baseline concentrations reached

**Table 4** Threshold values for mild and extreme anomalies and number of samples exceeding the thresholds

Element (mg kg <sup>-1</sup> )	95th percentile	98th percentile	Mild outliers (UIF)	Number of mild anomalies	Far outliers (UOF)	Number of extreme anomalies
Topsoil						
Th	21.41	27.53	23.30	6	33.50	3
U	5.80	6.49	6.10	9	8.80	2
Subsoil						
Th	25.70	31.10	21.40	8	30.40	8
U	6.70	7.80	5.65	13	8.20	4
Bedrock						
Th	21.83	26.14	33.62	1	51.85	1
U	5.42	6.11	8.05	1	12.10	0

Outliers according to Tukey's inner fence criteria

UIF upper inner fence, UOF upper outer fence

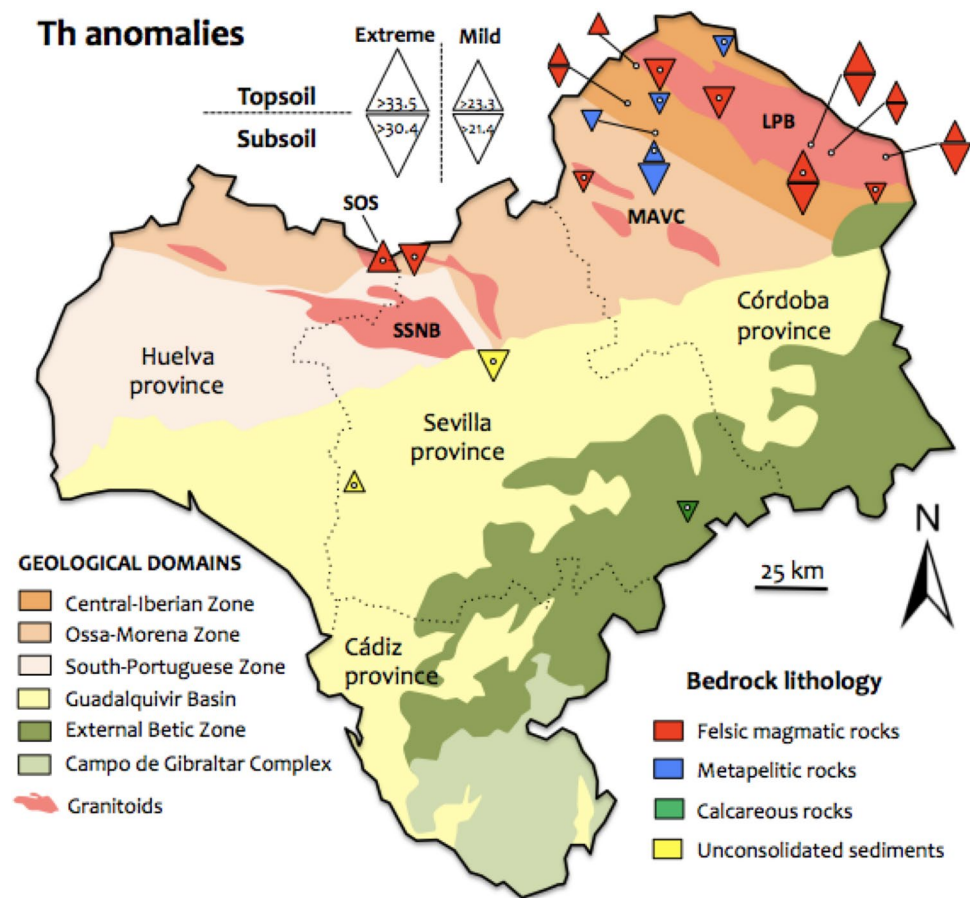
18.0 mg kg<sup>-1</sup> for Th and 4.7 mg kg<sup>-1</sup> for U. In subsoil, corresponding values were slightly lower, with 16.1 mg kg<sup>-1</sup> for Th and 4.2 mg kg<sup>-1</sup> for U.

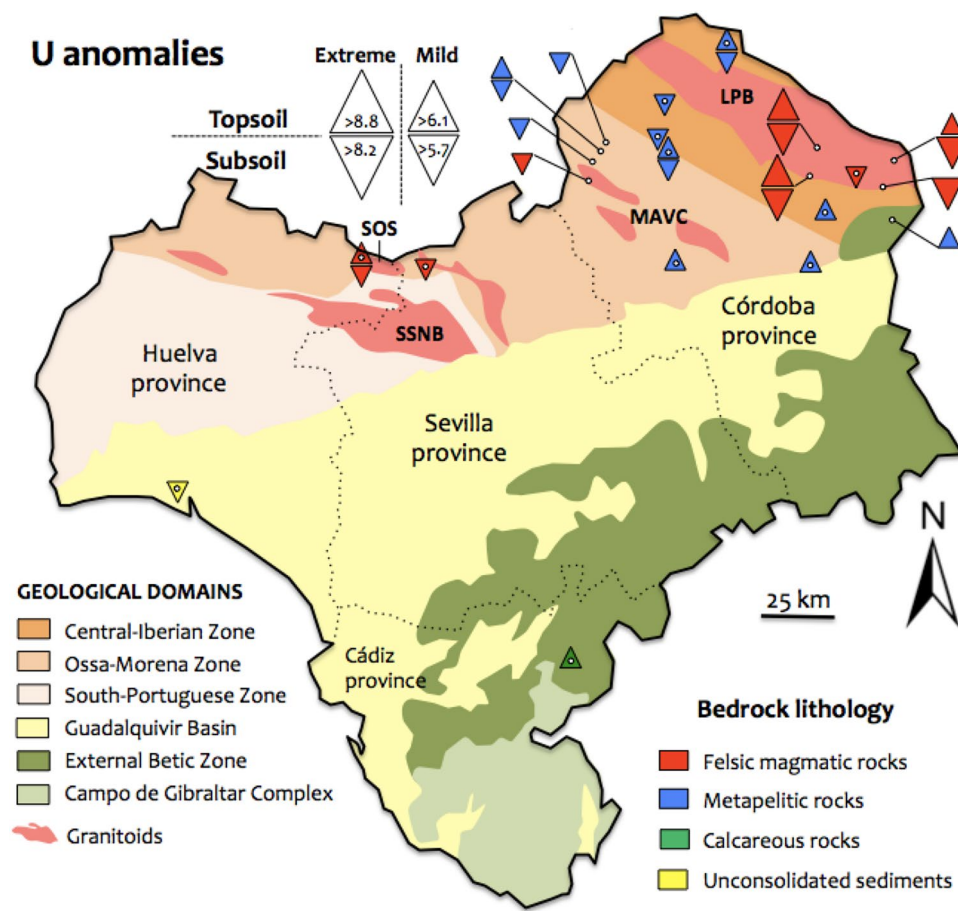
Given the strong influence of parent rock lithology on U and Th concentrations, as shown in the results above, baseline levels were specifically determined for each geological domain (Fig. 6). These baselines indicate the variability of the radioelements across different geological settings and

may also serve as benchmarks for environmental monitoring and risk assessment.

The highest baseline values for Th and U, in both subsoil and topsoil, occur over the crystalline basement rocks of the Iberian Massif. The CIZ and OMZ domains, characterized by extensive granitic intrusions, exhibited the highest upper limit baselines, while the SPZ, with a mixture of metamorphic and volcano-sedimentary rocks, showed intermediate

**Fig. 7** Geochemical anomaly mapping of thorium (Th) in topsoil and subsoil. Threshold values for mild and extreme anomalies in mg kg<sup>-1</sup>. Extreme anomalies are shown with a large symbol. LPB Los Pedroches Batholith, MACV Magmatic Alignment Villaviciosa de Córdoba-La Coronada, SSNB Sevilla Sierra Norte Batholith, SOS Santa Olalla Stock





**Fig. 8** Geochemical anomaly mapping of uranium (U) in topsoil and subsoil. Threshold values for mild and extreme anomalies in  $\text{mg kg}^{-1}$ . Extreme anomalies are shown with a large symbol. *LPB* Los Pedroches Batholith, *MAVC* Magmatic Alignment Villaviciosa de Córdoba-La Coronada, *SSNB* Sevilla Sierra Norte Batholith, *SOS* Santa Olalla Stock

concentrations. Conversely, the GB and EBZ, which are dominated by sedimentary rocks, displayed the lowest baseline levels, although these values still exceeded the western European median concentrations reported by Salminen (2005) for topsoil ( $U = 2.00 \text{ mg kg}^{-1}$ ;  $Th = 7.24 \text{ mg kg}^{-1}$ ) and subsoil ( $U = 2.03 \text{ mg kg}^{-1}$ ;  $Th = 7.63 \text{ mg kg}^{-1}$ ). This supports that bedrock type is the primary factor influencing the observed variations in baseline concentrations.

Deviations from the established baseline values may indicate potential anthropogenic or natural influences on regional soil geochemistry. To separate anomalous U and Th concentrations from background levels, threshold values were determined using Tukey's fences (Table 4), with mild anomalies defined by the upper inner fence (UIF) and extreme anomalies by the upper outer fence (UOF).

A comparison of Th and U concentrations with the established threshold values revealed that most soil samples remain within the expected baseline range, with only occasional exceedances in specific locations. These outliers suggest localized natural enrichment driven by factors such

as mineral occurrences and soil forming processes, although some may also result from anthropogenic inputs.

In topsoil, six mild Th anomalies exceeded  $23.3 \text{ mg kg}^{-1}$ , and three extreme Th anomalies exceeded  $33.5 \text{ mg kg}^{-1}$ , while nine mild U anomalies exceeded  $6.1 \text{ mg kg}^{-1}$ , and two extreme U anomalies surpassed  $8.8 \text{ mg kg}^{-1}$ . Subsoil samples showed eight mild Th anomalies above  $21.4 \text{ mg kg}^{-1}$  and eight extreme Th anomalies above  $30.4 \text{ mg kg}^{-1}$ , as well as thirteen mild U anomalies exceeding  $5.65 \text{ mg kg}^{-1}$ , and four extreme U anomalies surpassing  $8.2 \text{ mg kg}^{-1}$ . In bedrock, one mild and one extreme Th anomaly were detected above  $33.62$  and  $51.85 \text{ mg kg}^{-1}$ , respectively, along with a single mild U anomaly above  $8.05 \text{ mg kg}^{-1}$ .

Anomalies were more frequently observed in Cambisols (43%) and Leptosols (30%). Interestingly, a mildly elevated U concentration of  $5.8 \text{ mg kg}^{-1}$  was measured in the salt marsh soils (Solonchaks) of the Huelva estuary. This mild anomaly is likely anthropogenic and potentially related to nearby phosphogypsum stacks, which are known to cause localized radioactive effects on adjacent salt marshes

(Bolívar et al., 1995). Overall, the spatial distribution pattern of mild and extreme anomalies clearly reflects the strong influence of local geology on soil geochemistry (Fig. 7 and Fig. 8). The true extent of Th and U anomalies shown on the maps is likely underestimated due to the relatively low sampling density.

An exploratory analysis of geochemical anomalies within the geological domains reveals a strong association between the highest U and Th concentrations, including potential hotspots, and granitic lithologies. The spatial distribution of these anomalies is influenced by the occurrence of tectono-magmatic alignments within the Iberian Massif, such as the Los Pedroches batholith and smaller intrusive bodies of the Villaviciosa de Córdoba-La Coronada belt in the CIZ, and the Santa Olalla stock in the OMZ. The most extreme anomalous concentrations occur in soils over the southern portion of the Los Pedroches batholith, where monzogranites are the dominant host rocks for known mineral occurrences.

These findings reinforce the dominant control of parent rock lithology on the distribution and abundance of U and Th in the soils of western Andalusia, consistent with observations for other trace elements of economic and environmental significance (Fernández-Caliani et al., 2020; Galán et al., 2008; Locutura et al., 2012). Nonetheless, further investigation is needed to clarify the precise origin of these anomalies and to assess their implications for soil quality, environmental health, and potential resource exploration.

### 5.5 Radiological implications

Overall, the relatively low U and Th concentrations observed across most the survey area suggest a generally low radiological risk under typical exposure scenarios. The SPZ, GB, EBZ, and CGC domains have particularly low environmental concern due to limited U enrichment. For context, while generic soil screening levels for U are not as explicitly published in Spain, the US EPA's screening level is set at  $1.6 \text{ mg kg}^{-1}$  for residential soil, based on a  $10^{-6}$  target cancer risk (US EPA, 2024). Abnormally high U concentrations detected in soils overlying granitic terrains within the CIZ and OMZ warrant attention. This is particularly true under environmental conditions that enhance the solubility of U[VI] species and subsequent leaching into groundwater, thereby increasing potential exposure pathways.

In natural soils with high U levels, U-238 and its decay products (U-234, Th-230, Ra-226, Pb-210) are typically in secular equilibrium. The International Atomic Energy Agency sets guidelines for naturally occurring radioactive materials, limiting any decay product to  $1 \text{ Bq g}^{-1}$  (roughly equivalent to 81 ppm of total U). Of particular concern for gamma radiation is Ra-226. Elevated Ra-226 can lead to dangerous levels of Rn-222 gas in buildings constructed on these soils.

Despite the importance of assessing radiation exposure from naturally occurring radionuclides, data on actual radiation levels in the studied soils remain limited. Activity concentrations of radionuclides reported for soils in the western OMZ (López et al., 2007) indicate natural radioactivity levels within the global range of background radiation. An exception was noted in Cambisols developed over tonalitic rocks of the Santa Olalla stock, where a radiological anomaly was identified due to elevated Th-series radionuclides. This anomaly is directly linked to the granitic composition of the soil parent material and the significantly elevated radioelement concentrations found at that location.

## 6 Conclusions and future research

This exploratory study established baseline concentrations of Th and U in soils across the diverse geological settings of southwestern Spain, providing threshold values for anomaly detection and insights into potential sources and factors influencing soil geochemical variation and anomalies.

The data indicated a strong control of parent rock lithology on U and Th distribution and abundance, resulting in significant regional variability. Felsic magmatic rocks, particularly within the CIZ and OMZ, were identified as the principal sources of U and Th enrichment, while sedimentary-dominated zones (GB and EBZ) showed comparatively lower levels, in line with global trends. The strong positive correlations with LREE and Hf suggest that Th is hosted within monazite and zircon crystals inherited from the granitic parent rocks. Indeed, the highest concentrations coincide with monzogranites of the Los Pedroches batholith and tonalites of the Santa Olalla stock. These hotspots may warrant further exploration.

Although the data largely reflect natural geochemical processes, minor deviations in topsoil concentrations may arise from anthropogenic activities, such as phosphate fertilizer production and historical mining operations in certain areas. Pedogenic processes (e.g. weathering, translocation) also play a role in modulating soil enrichment by influencing mobility and accumulation of the radioelements. The increasing Th/U ratio from topsoil to bedrock, coupled with a higher topsoil/subsoil ratio for U, suggests a greater tendency of U to accumulate in the topsoil.

The insights from this study have several environmental implications including the need to assess potential radiological risks associated with elevated concentrations of U and Th, particularly in areas exceeding established upper baseline values ( $4.7 \text{ mg kg}^{-1}$  for U and  $18.0 \text{ mg kg}^{-1}$  for Th in topsoil).

The findings also offer several potential applications. The geochemical baselines and anomaly patterns can serve as a valuable tool for mineral exploration, by delineating prospective areas for U deposits. Furthermore, this knowledge is applicable to land-use planning, enabling informed decisions

regarding development and environmental management in areas with naturally elevated radioactivity.

To fully understand the sources, distribution, and environmental implications of the U and Th anomalies, a multidisciplinary approach integrating geochemistry, mineralogy, hydrology, and radiological sciences is essential. Future research should focus on: 1) high-resolution geochemical mapping to refine anomaly detection and pinpoint source areas with greater precision; 2) mineralogical analysis to characterize host minerals and better understand U and Th retention mechanisms and their potential release under varying environmental conditions; and 3) radiological risk assessment to evaluate potential hazards by examining radiation dose rates, radionuclide migration pathways, and soil-to-plant transfer in hotspot areas.

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**Data availability** The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Declarations

**Conflict of interest** The authors have no competing interests to declare that are relevant to the content of this paper.

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