Acta Geochim (2024) 43:507–519
https://doi.org/10.1007/s11631-023-00670-2

ORIGINAL ARTICLE

Thorium anomaly on the lunar surface and its indicative meaning

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Received: 20 June 2023 / Revised: 10 December 2023 / Accepted: 21 December 2023 / Published online: 27 February 2024

Abstract The Moon has been divided into three terranes: Procellarum KREEP Terrane (PKT), Feldspathic Highland Terrane (FHT), and South Pole-Aitken Terrane (SPAT), using globally measured Th and FeO. Many lunar evolution models have predicted that a lunar magma ocean will produce a residual layer enriched in incompatible elements such as K, REE, and P (i.e., KREEP) in the late age of crystallization; and that the distribution of thorium can be used as a proxy for determining the global distribution of KREEP. The thorium distribution in these three terranes is inhomogeneous. The highest concentration of thorium is in PKT, the medium concentration of thorium is in SPAT, and almost none in FHT. Then what is the specific distribution in each of the terrane and what enlightenment can it tell us? Here we present and describe the detailed thorium distribution in PKT, SPAT, and FHT and provide some information for the origin of asymmetries on the lunar surface.

Keywords Procellarum KREEP Terrane (PKT) · Feldspathic Highland Terrane (FHT) · South Pole-Aitken Terrane (SPAT) · KREEP · Thorium abundance

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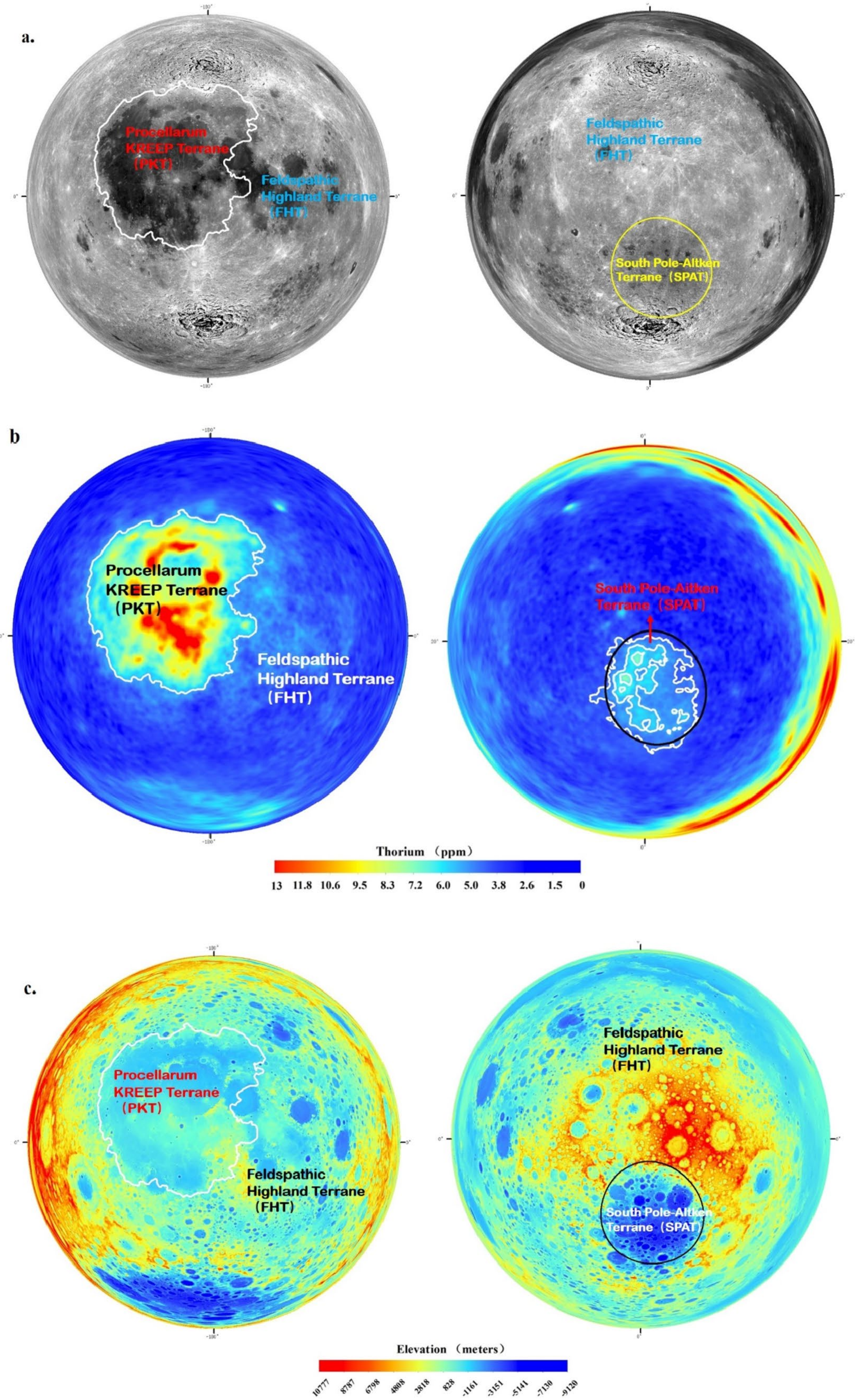
1 Introduction

Many models of early lunar evolution have predicted that there exists an outermost molten layer consisting of a thick magma ocean around the Moon. As the lunar magma ocean crystallizes, those dense minerals sink to form the mantle, and light minerals floated to the surface to form the lunar crust. The last materials to crystallize are rich in Th, K, and many other incompatible elements, which are abundant in a lunar substance called KREEP [potassium (K), rare earth elements (REE), and phosphorus (P)]. According to the most widely accepted models, KREEP is located between the lunar crust and mantle (Warren and Wasson 1979; Warren 1985; Shearer et al. 2006). Based on the results from Lunar Prospector (LP), some workers (Jolliff et al. 2000; Haskin et al. 1996) have proposed that the surficial distribution of Th, which has been measured on a global scale (Lawrence et al. 1998, 2000, 2007; Feldman et al. 2002; Wang et al. 2016; Chen et al. 2016), can be used as a proxy for determining the global distribution of KREEP.

Jolliff et al. (2000) provided an important interpretive framework by subdividing the lunar surface into three major "terranes" using global Th and FeO (Lucey et al. 1998a, b) distributions and extrapolating the near-surface remote sensing measurements to the lunar crust underlying the surface: Procellarum KREEP Terrane (PKT), Feldspathic Highland Terrane (FHT) and South Pole-Aitken Terrane (SPAT). The FHT, which constitutes 65% of the lunar surface, was interpreted to represent the upper part of the primary lunar crust, dating to magma ocean solidification. The thorium abundance data in FHT is very low (< 2 ppm). The SPAT is located at the south pole of the lunar farside, constituting about 19% of the Moon's surface. SPAT is mainly made up of the SPA basin and its adjacent ejecta according to Jolliff et al. (2000), which is predicted to represent more


a.
Procellarum
KREEP Terrane
(PKT)
Feldspathic
Highland Terrane
(FHT)
Feldspathic
Highland Terrane
(FHT)
South Pole-Aitken
Terrane (SPAT)
b
Procellarum
KREEP Terrane
(PKT)
Feldspathic
Highland Terrane
(FHT)
South Pole-Aitken
Terrane (SPAT)
Thorium (ppm)
13 11.8 10.6 9.5 8.3 7.2 6.0 5.0 3.8 2.6 1.5 0
c.
Procellarum
KREEP Terrane
(PKT)
Feldspathic
Highland Terrane
(FHT)
Feldspathic
Highland Terrane
(FHT)
South Pole-Aitken
Terrane (SPAT)
Elevation (meters)
10777 8787 6798 4808 2818 828 -1161 -3151 -5141 -7130 -9120

◂**Fig. 1** The lunar surface is divided into the lunar three terranes. **a** CE-1 global lunar image map form CE-1 CCD stereo camera DOM-120 m lunar image data. **b** Global thorium abundance from LP gamma-ray spectrometer (Lawrence et al. 2002) overlain on LOLA hill-shade map (Smith et al. 2010). Both (**a**) and (**b**) show the three terranes on the lunar surface, outlined according to Jolliffe et al. (2000). South pole-Aitken Terrane (SPAT) is marked with a white solid line (2 ppm thorium value), Procellarum KREEP Terrane (PKT) boundary (white line) is denoted by thorium value of 3 ppm contour (Jolliff et al. 2000) and Feldspathic Highland Terrane (FHT) is tabled by white texts. Maps are plotted in Lambert azimuth area Projection

mafic lower crustal and perhaps mantle material exposed by the huge oblique South Pole–Aitken basin impact that occurred early in lunar history (Garrick-Bethell and Zuber 2009; Potter et al. 2012) that removed the upper anorthositic crust and redistributed it northward into the surrounding FHT. There is some medium Th concentration in SPAT compared to FHT (~4 ppm). The PKT, comprising 16% of the lunar surface, is located on the near side of the Moon. There is obviously very high thorium concentration in PKT (the highest Th value can reach 13 ppm). It seems that the lunar farside generally lacks the high nearside abundances of Th and other KREEP-like elements (Warren and Kallemeyn 1998; Zhu et al. 2019a, b). In Jolliff et al. (2000)'s conclusion, they thought that some 40% of Th in the lunar crust may have concentrated in the Procellarum-Imbrium region, which accounts for only 10% of the total lunar crust volume. Apparently, such high concentration of Th and other heat-producing elements in PKT has profound effects on the subsequent thermal and geological evolution of the Moon, leading to "a fundamentally different thermal and igneous evolution within this region compared to other parts of the lunar crust" (Jolliff et al. 2000), as explored further by Elardo et al. (2020), Shearer et al. (2006) and others.

Because of the high abundance of KREEP materials in Procellarum-Imbrium region, PKT has been considered to explain several asymmetries observed on the lunar surface: (1) the largely resurfaced area in PKT with mare basaltic lava flow (about 60% of the mare basalts by area) and the emplacement of all "young" mare basalts (< 3 Ga in age), on account of a possible thicker KREEP-rich residual liquid layer beneath the PKT (Wieczorek et al. 2000). (2) The lack of distinctive large-scale topographic variations due to viscous relaxation caused by the high geothermal heat flux in the PKT (Laneuville et al. 2013; Grimm, 2013). The low magnetic field intensities within the interior portion of the PKT, due to the high temperature caused by the enriched heat-producing elements in PKT region which delaying the time that magnetic mineral closing temperatures are reached (Wieczorek 2018; Laneuville et al. 2018).

Then some questions about the nature of the PKT will be raised: what is the structure beneath the PKT? And most importantly, what is the mechanism to cause the

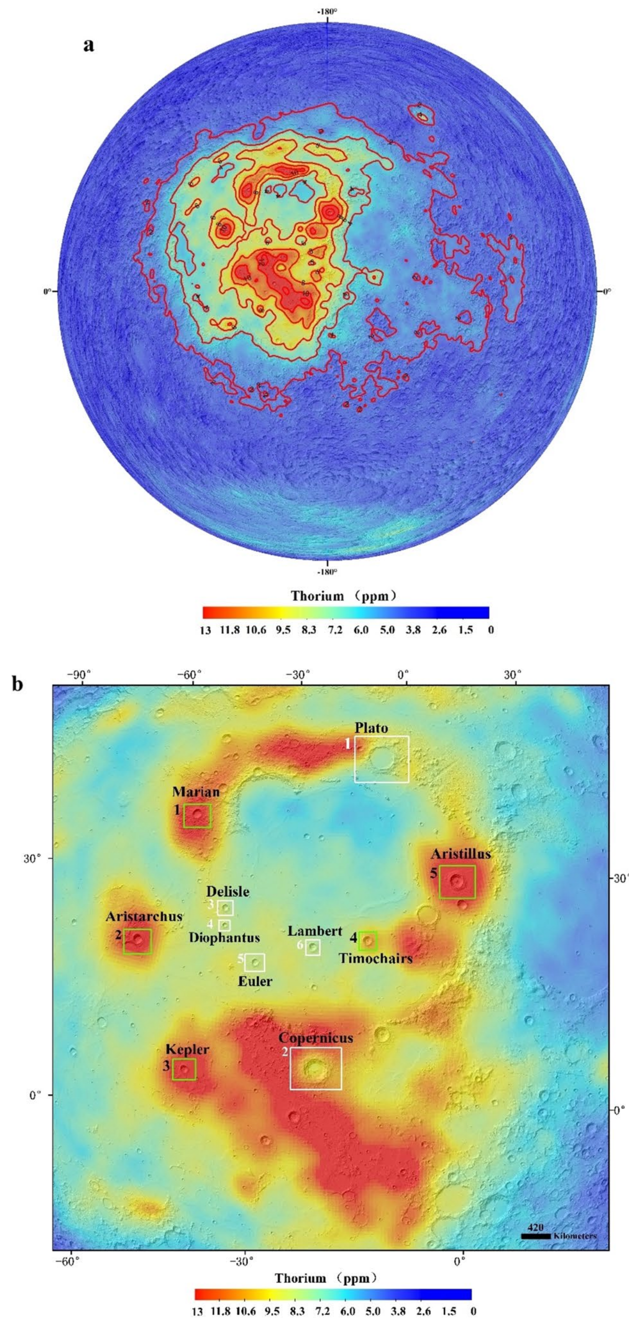


Fig. 2 Thorium distribution in PKT and Imbrium region. **a** Thorium abundance in the Procellarum region from LP-gamma-ray spectrometer overlain the LOLA hillshade map. Red lines represent the thorium contour with the thorium value on it. This map is plotted in Lambert azimuth area Projection. **b** The thorium distribution in the Imbrium region (Zhang et al. 2023)

concentration of KREEP in the Procellarum-Imbrium region? But, the lateral and vertical extent and distribution of this "KREEP" layer is currently a matter of debate. There are several mechanisms have been proposed to explain the asymmetric distribution of KREEP materials, including: (1) inhomogeneous differentiation of the magma ocean. The thinner crustal thickness on the nearside would cause a thicker magma ocean to this hemisphere, concentrating more KREEP in PKT (Warren and Wasson, 1979; Lope and Werner 2002). (2) Asymmetric development of a long-wavelength (degree-1) convection instability of the ilmenite-bearing mineral residual formed during the late-stage magma ocean crystallization (Zhong et al. 2000; Parmentier et al. 2002). (3) the ancient and large SPA impact disturbed the lunar mantle beneath this impact region and promoted the migration of KREEP towards its antipode region—PKT (Schultz and Crawford 2011; Jones and Evans 2019; Jones et al. 2020; Zhang et al. 2022). (4) Procellarum basin is the oldest lunar basin, which may cause the accumulation of KREEP-enriched residual liquid on the nearside, in contrast, lunar farside lacks these Th and other KREEPy elements (Zhu et al. 2019a, b).

In this study, we will present and describe the Th distribution on the lunar surface and provide more detailed Th distribution characteristics in PKT, SPAT, and FHT to explain the mechanism of the lunar surface inhomogeneities.

2 Data and background

For this study, we mainly use a synthesis of data from remoting sensing, geomorphology mapping and contrastive analysis to present the Th distribution on the lunar surface. So, we are using the following data: Th abundance data are taken from LP mission (Lawrence et al. 1998, 2002, 2003), which is available in the Planetary Data System Geoscience Node (https://pds-geosciences.wustl.edu/missions/lunarp/reduced_special.html, accessed on 16 December 2018). We then merged this Th map with an altimetric shaded relief map and lunar global image map from CE-1 CCD stereo camera DOM-120 m lunar image data.

In this study, we use Th value of 3 ppm as the PKT boundary and ring structure from Garrick-Bethell and Zuber (2009)'s study to describe the SPA basin (Fig. 1). Here the reason that we use 3 ppm as the PKT boundary is that this contour of 3 ppm is correlated with the region of flat terrain in PKT, and close to the Th value that Jolliff et al. (2000) use to define the PKT (3.5 ppm). There are obvious high-Th abundance locations in the PKT, but almost none in FHT, and only medium Th concentrations in parts of SPAT (Fig. 1b).

Fig. 3 Units with thorium anomaly in PKT and thorium value. **a** Enlarge the map of thorium distribution of craters and Apollo 14 landing site in PKT. This map shows the high-thorium anomaly units: Marian, Aristillus, Timochairs, Aristarchus and Apollo 14 landing site; the low-thorium anomaly crater: Copernicus. **b** The thorium value of craters and the Apollo 14 landing site is shown in **a**.

3 Thorium distribution on the lunar surface

3.1 Thorium abundance in the procellarum KREEP terrane (PKT)

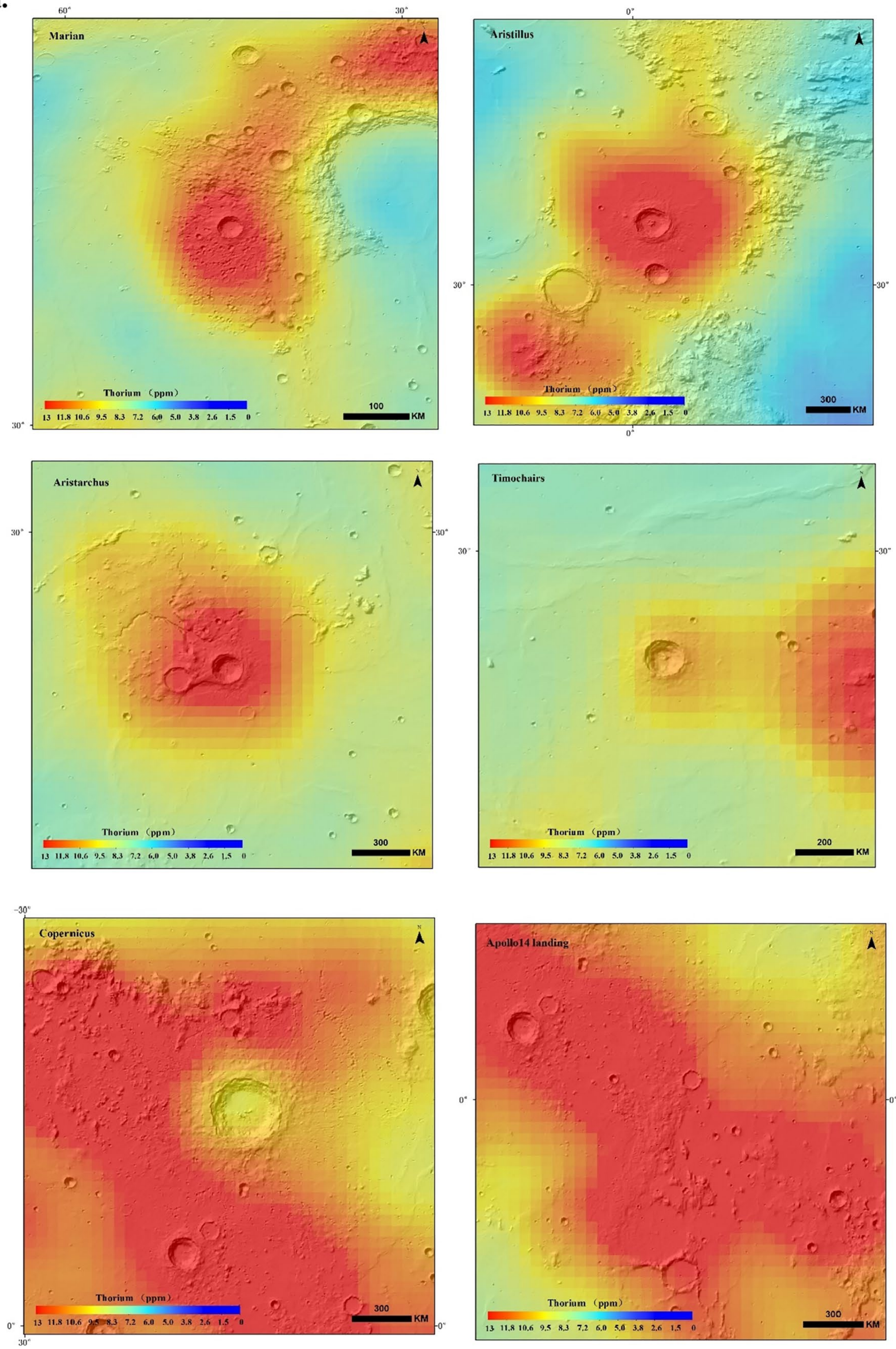
The PKT occupies most of the lunar nearside, showing a dark image, depression in topography, and very flat terrain (Fig. 1). The second large impact basin—Imbrium basin is located in its northeast part. The compositional data tell us that large-scale mare basalts are exposed in this region and there exists very high elevated thorium abundance.

The thorium concentration map shows that not all areas in PKT are high in thorium value. There is a higher concentration of thorium in the inner parts of PKT, and a relatively lower abundance of thorium when it is towards the rim of PKT (Fig. 2a). In PKT, the average thorium value is about 5 ppm and the highest concentration of thorium can reach about 12 ppm, which may also be the highest thorium value on the global lunar surface. Within the PKT, the high abundance of thorium is mainly related to the highland/non-mare region, whereas most of the relatively low concentration of thorium is located in the mare region. The highland region with high-thorium value in PKT is thought to be the rim and ejecta from the Imbrium basin, which is also called Fra Mauro Formation (FMF) (about 8–12 ppm in Th). These high-thorium ejecta are mainly distributed in the south of the Imbrium basin. Besides, some impact craters surrounding the Imbrium basin also show very high thorium abundance (about 8–12 ppm in Th): Marian, Aristarchus, Kepler, Timochairs, and Aristillus (Figs. 2b, 3). There are also some larger impact craters located in the highland region that do not appear to show elevated thorium abundance (crater Copernicus and Plato). Other low-thorium concentrations in PKT are associated with the mare region and some small impact craters (about 4–6 ppm in Th). Although, these mare units are relatively low in thorium value in PKT, but are absolutely higher than the FHT.

3.2 Thorium abundance in the South Pole-Aitken Basin Terrane (SPAT)

The South Pole-Aitken basin is thought to be the oldest and largest impact basin identified on the Moon by far with a diameter of 2400 km (Garrick-Bethell and Zuber 2009) and a depth of 12 km (Spudis 1993). Because the

a.


60°
30°
Marian
Thorium (ppm)
13 11.8 10.6 9.5 8.3 7.2 6.0 5.0 3.8 2.6 1.5 0
100
KM
0°
Aristillus
Thorium (ppm)
13 11.8 10.6 9.5 8.3 7.2 6.0 5.0 3.8 2.6 1.5 0
300
KM
Aristarchus
Thorium (ppm)
13 11.8 10.6 9.5 8.3 7.2 6.0 5.0 3.8 2.6 1.5 0
300
KM
Timochairs
Thorium (ppm)
13 11.8 10.6 9.5 8.3 7.2 6.0 5.0 3.8 2.6 1.5 0
200
KM
-30°
Copernicus
Thorium (ppm)
13 11.8 10.6 9.5 8.3 7.2 6.0 5.0 3.8 2.6 1.5 0
300
KM
Apollo14 landing
Thorium (ppm)
13 11.8 10.6 9.5 8.3 7.2 6.0 5.0 3.8 2.6 1.5 0
300
KM

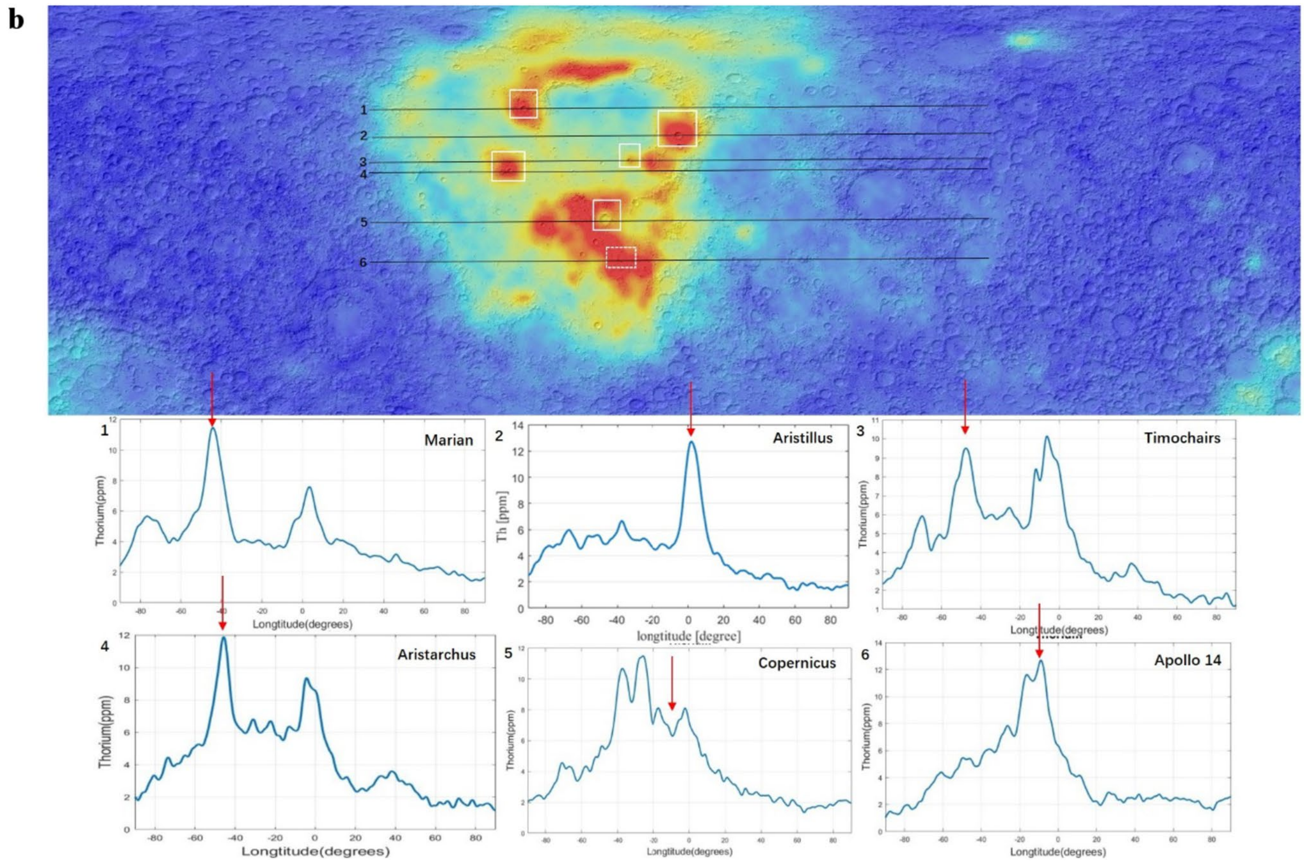


Fig. 3 (continued)

extent of the SPA basin is so large that it has been thought to have excavated the lower crust even the mantle materials (Pieters et al. 1997; Lucey et at. 1998a, 1998b; Melosh et al. 2017; Uemoto et al. 2017; Moriarty et al. 2021a, b). The topography data and lunar crustal thickness of SPA show that this basin presents an elliptical structure (Fig. 4), which is believed to be formed by an oblique impact (Garrick-Bethell and Zuber 2009). Other compositional data from Lunar Prospector and Clementine mission also show the distinct content in SPA (like FeO and Thorium). All these data suggest that the SPA basin region is very different from its surrounding areas, and it is better to separate the SPA basin region from the farside as an individual unit.

The overall thorium distribution in SPAT is also inhomogeneous, showing a slightly elevated thorium abundance than the surrounding areas (about 2–4 ppm in Th), especially the northwest of the SPA basin (Fig. 5). However, its thorium value is still much lower than the PKT. The thorium abundance within SPAT seems can be divided into two parts: The relatively low abundance of thorium through the whole SPA basin and the moderately elevated thorium abundance the in local area. The average concentration of the relatively low abundance thorium region is about 2–3 ppm, distributed throughout the basin. The region with moderately elevated thorium abundance is situated in the west part of the SPA basin. The highest thorium abundance is located at two craters in the northwest of the SPA basin: Birkeland (30°S, 174°E) and Oresme V (41°S, 165°E), which are mainly associated with the SPA basin rim (Fig. 5b, c).

3.3 Thorium distribution in the Feldspathic Highland Terrane (FHT)

The FHT is dominated by highlands on the lunar farside. The FHT is the most extensive terrane on the lunar surface, occupying approximately 60% of the lunar surface area. The most distinctive characteristic of FHT is its high albedo, widespread cratering, thickest crustal thickness, and elevated topography (Fig. 6). Also, from the lunar compositional

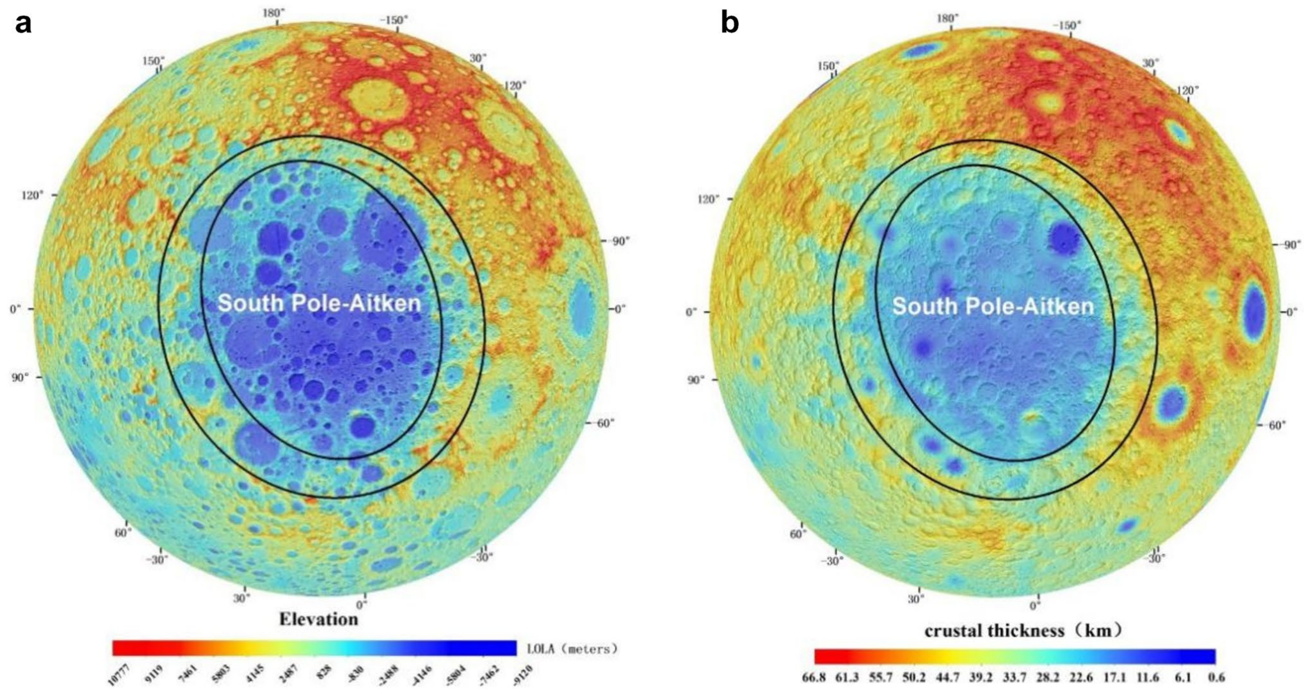


Fig. 4 The South Pole-Aitken (SPA) basin with ring structure. **a** The elevation map from LOLA (Smith and Zuber 2010). The black ellipses represent the two-ring structures of SPA (Garrick-Bethell and Zuber 2009). **b** The crustal thickness of the SPA region from GRAIL (Zuber et al. 2013; Wieczorek et al. 2013) with two ring structures

data, the inner part of FHT shows anorthositic feature with the thickest crustal thickness (Fig. 6c), and the rest of FHT is more mafic than the inner region. Due to the thick crustal thickness and the elevated topography, many of the FHT is thought to have been covered by the ejecta from many large impact basins and these ejecta may be from the deep crustal or mantle (Ryder and Wood 1977; Spudis 1993; Ryder et al. 1997). The most obvious difference between the FHT and the PKT is the emergence of mare basalt. There is almost no mare basaltic lava flow distributed in the FHT, while most of the PKT is covered by the mare basalts.

The bulk concentration of thorium in FHT is extremely low (< 2 ppm in Th), compared with SPAT and PKT (Fig. 7). However, there is an exception—Compton-Belkovich region in the northeast part of the FHT, shows a very high thorium abundance (about 9 ppm in Th) (Fig. 7a). The Compton-Belkovich region (centered at 61.6°N, 99.5°E) is close to Humboldtianum, locating at between the Belkovich and Compton (Fig. 7b). This separated high-thorium region in FHT does not correspond to cratering, hinting that some other geologic process may have occurred in this region (like ejecta from the nearby impact craters or basins, the ejecta from Imbrium basin on the nearside or indigenous origin). Jolliff et al. (2011) excluded the possibility of ejecta origin and considered that this Compton-Belkovich thorium anomaly is related to an exposure of an alkali-intrusive/extrusive volcanism from the local subsurface based on the image data, topographic data, and spectral data. A recent study shows that there exists a large granitic batholith underlain this area (Siegler et al. 2023). Besides, there is a Dewar crater, northwest of the SPA, which also shows a slightly elevated Th concentration (Fig. 7a, c), which is thought that maybe thorium-rich mafic impact-melt breccias (Lawrence et al. 2003).

4 Discussion

The evident inhomogeneity of thorium concentration on the lunar surface implies that these three terranes are not only different in the lunar surface expression but also own distinguishing substructure deep in the crust or mantle, and may have experienced different geologic processes.

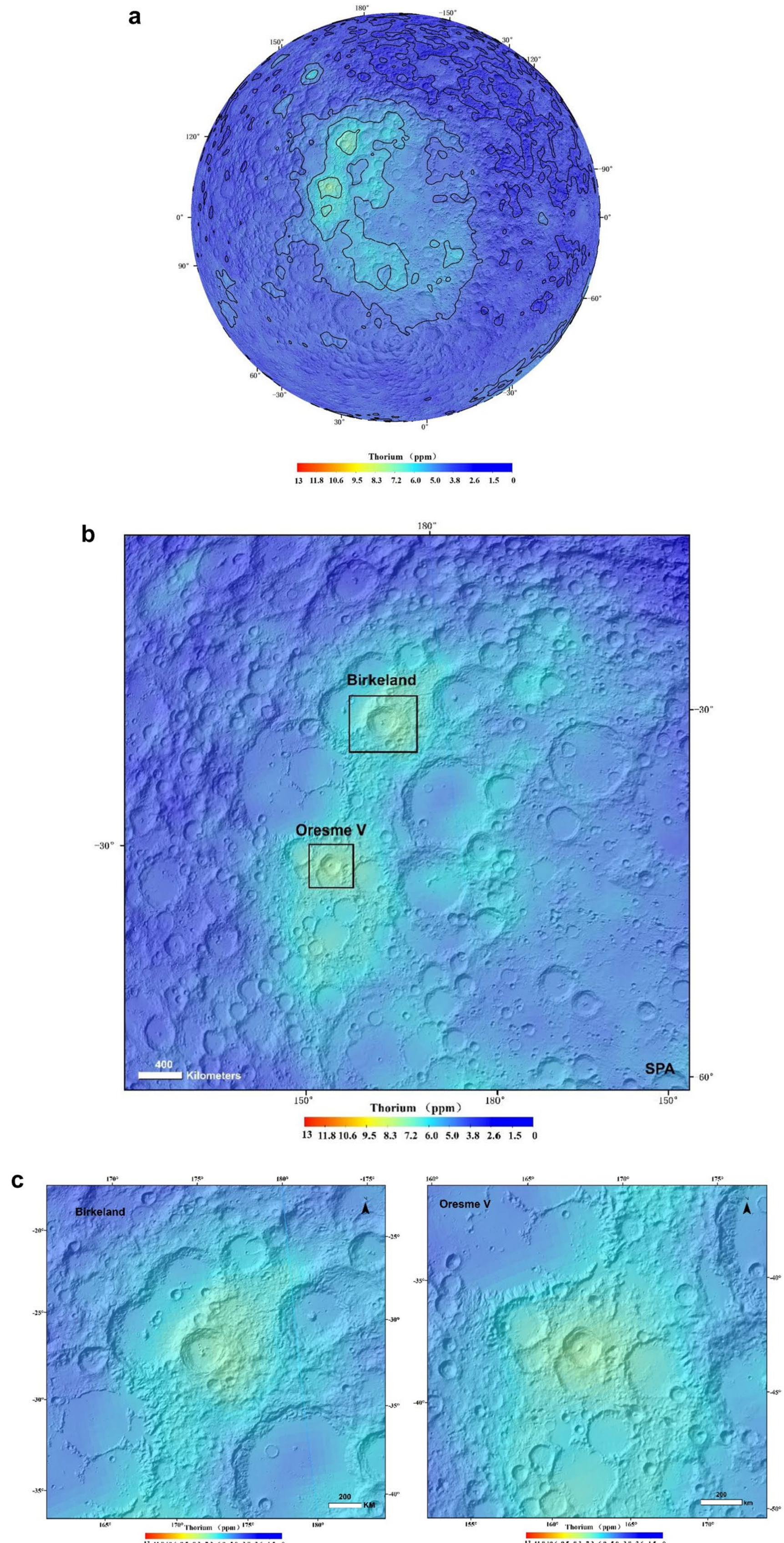


Fig. 5 Thorium distribution in SPAT. **a** The overall distribution of thorium in SPAT, the black line is the thorium contour. **b** The southwest region of SPAT with a moderately elevated thorium abundance. **c** The thorium distribution of the highest thorium value locations: crater Birkeland and Oresme V

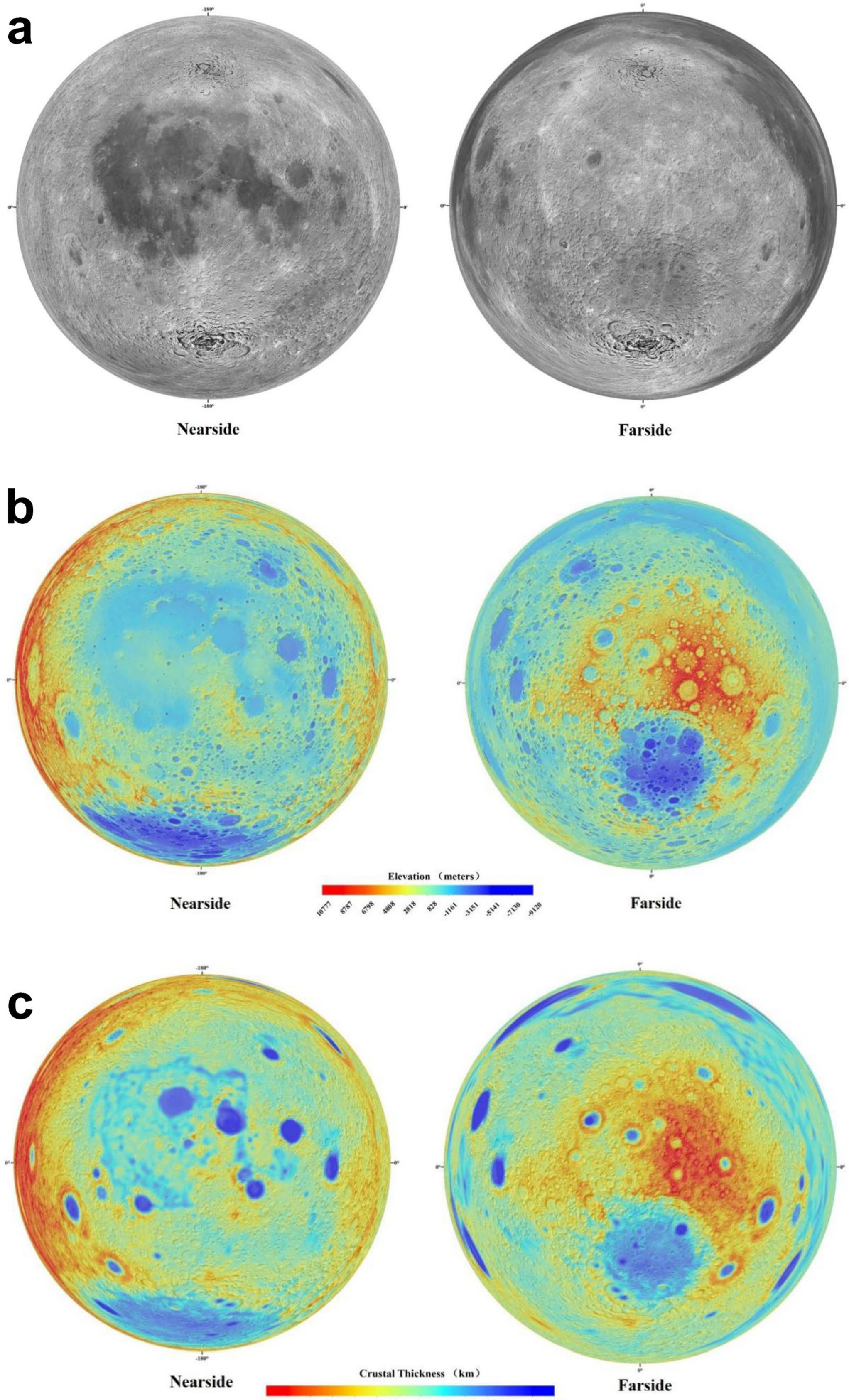
The PKT presents the highest abundance of thorium and inhomogeneous thorium distribution feature, exerting a profound effect on the lunar thermal evolution. Despite many models have been put forward, their origin is remaining debated. (1) The precondition of the lunar magma ocean inhomogeneous differentiation model is that the thickness of the lunar crust is already asymmetric between the nearside and the farside during the crystallization of magma. In this model, the thinner crust thickness on the nearside will lead to a thicker magma beneath this region, which means more KREEP concentration is here. However, this model could not explain what caused the crustal thickness asymmetry. (2) The degree-1 convection model suggests that because of the long-wavelength gravitational instability, the ilmenite-rich cumulates (IC), which is denser than the underlying mantle, will sink into the deep interior. Because IC is rich in heat producing elements, the thermal expansion due to the radioactive heating will give IC buoyancy, which causes the IC to upwell again. These asymmetries occur during the downwelling or upwelling (Zhong et al. 2000; Parmentier et al. 2002). However, the upwelling model requires an at least 250 km-radius lunar core, which is smaller than the most lunar core model proposed so far. The downwelling model needs a smaller viscosity than the underlying mantle, which is a big problem. (3) The SPA impact model thought that the energy caused by SPA impact can generate a high-temperature anomaly beneath this region which trigger the mantle convection. This convection can migrate the KREEP material to concentrate in the antipodal region of SPA. This model uses numerical modeling to simulate an SPA-scale impact and relevant mantle convection (Arkani-Hamed and Pentecost 2001; Jones et al. 2019, 2020, 2022; Zhang et al. 2022). In this model, they got the results that these KREEP materials dose concentrated in the antipodal region of impact and also deep in the mantle, but there are very little remain at the impact area. This distribution is not exactly consistent with observations where high abundance Th in PKT, medium value Th in SPAT and almost none in FHT. (4) The ancient Procellarum basin model gives us another view of the influence of huge impact (Zhu et al. 2019b). This model also uses the numerical modeling method to simulate an Procellarum basin on the nearside, and this giant basin can explain the differences in crustal thickness, elevation and composition between the nearside and the farside. But because of the ancient age of the possible Procellarum basin and high heat-producing elements in this region, the huge basin structure cannot be reserved. Therefore, whether there is an Procellarum basin is still to be verified. Since the most common geological structure on the Moon is impact crater, and the first two models above have obvious unexplained problems and contradictions, we thought that the thorium anomaly in PKT is very likely to be caused by large impact events, like SPA impact or Procellarum basin. But this formation mechanism deserves further discussion.

For the SPAT, the high-Th is closely related to the two impact craters (Birkeland and Oresme V). Combined with the previous work, the consistency of the SPA ring structure and local Th anomaly contour in our work shows that its medium thorium abundance is more likely from the local excavation by SPA impact event, rather than the ejecta from the Imbrium or Serenitatis on the nearside (Hakin et al. 1996, 1998; Wieczorek and Zuber 2001). This slightly elevated thorium concentration combined with the huge SPA impact event proves that SPA impact may has excavated the lower crustal even the mantle materials, since KREEP materials are thought to be between the lunar crust and mantle (Warren et al.1979; Shearer et al. 2006). Then some young craters impact the inner SPA later, may penetrating the SPA impact melt and excavating some Th-rich material.

Based on the global Th distribution on the lunar surface above, we found that most of the Th anomalies are related to impact events. In PKT, whether high Th anomalies or low value is located at some craters and its ejecta, like Aristarchus, Marian. In SPA, the two craters—Birkeland and Oresme V show high-Th features. As for FHT, the slightly high-Th feature is located at Dewar crater, though the Compton-Belkovich region is not an impact area. Therefore, the superficial distribution of Th may be closely related to the impact events.

5 Conclusion

1. There are obvious high-Th abundance locations in the PKT, but almost none in FHT, and only medium Th concentrations in parts of SPAT.
2. The thorium distribution in PKT is inhomogeneous. Most high thorium is related to the highlands/nonmare (FMF) and impact craters. The relatively low-thorium abundance is associated with the mare region in PKT.
3. Farside SPAT, mainly refers to the SPA basin region and parts of its ejecta, shows a relatively high Th value which is thought to be of indigenous origin.


a
Nearside
Farside
b
Elevation (meters)
10777 8787 6798 4808 2818 828 -1161 -3151 -5141 -7130 -9120
Nearside
Farside
c
Crustal Thickness (km)
66.8 61.7 56.6 51.5 46.4 41.3 36.2 31.1 26.1 20.9 15.9 10.88 5.7 0.59
Nearside
Farside

◂**Fig. 6** The image, elevation, and crustal thickness of the nearside (the left column) and the farside (the right column) of the Moon. **a** The image from CE-1 CCD stereo camera DOM-120 m lunar image data, which shows the dark nearside and bright farside. **b** The elevation from LOLA, showing the depression in PKT and elevated topography in FHT. **c** The crustal thickness derived from GRAIL (Zuber et al. 2013; Wieczorek et al. 2013). The FHT presents a very thick crust. Maps are plotted in Lambert azimuth area Projection

4. The thorium abundance is very low in FHT, except Comton-Belkovich region, which has a high thorium value of 9 ppm, is thought to be unusual non-basaltic volcanism, and a light elevated Th value impact crater—Dewar crater, which may be mafic impact-melt breccias.
5. Most of these Th anomalies on the lunar surface are closely related to impact events.

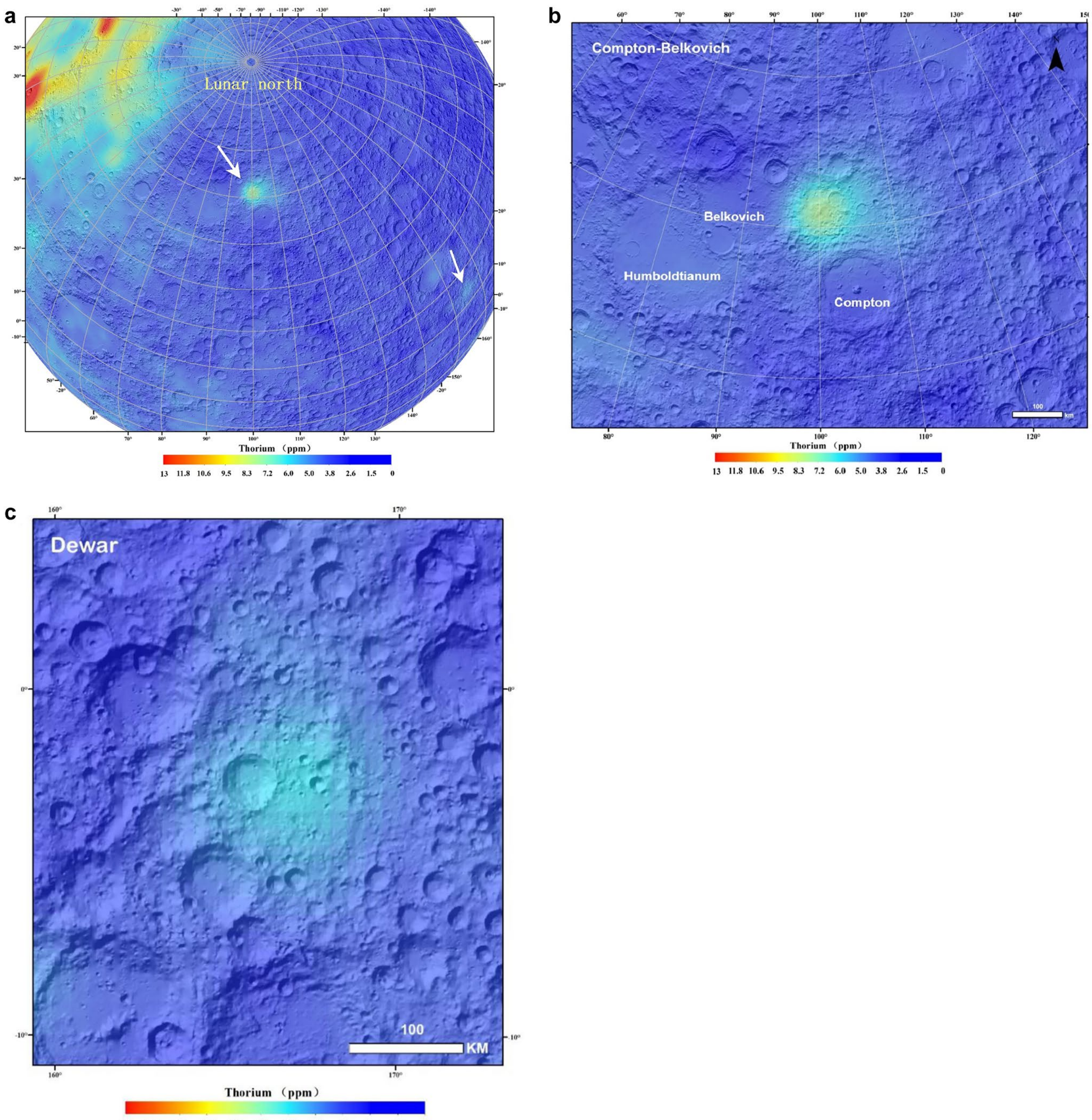


Fig. 7 The thorium distribution of FHT on the lunar farside. **a** The thorium abundance on the farside, the white arrow points out the Compton-Belkovich region. **b** The enlarged map of the Compton-Belkovich region. **c** The enlarged the map of Dewar crater

Acknowledgements This work was supported by National Key Research and Development Program of China (Grant No. 2022YFF0503100), and the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDB 41000000). We thank the constructive advice of Professor James Head from Brown University.

Author contributions JZ designed the study and drafted the manuscript. All authors participated in discussion and revision of the manuscript.

Data availability All the data used in this manuscript are from open database.

Declarations

Conflict of interest We declare no conflict of interest in this study.

Ethical approval The authors declare that we follow all the Ethics rules, including those listed in the Acta Geochimica web site.

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