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# Major lunar crustal terranes: Surface expressions and crust-mantle origins

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**Abstract.** In light of global remotely sensed data, the igneous crust of the Moon can no longer be viewed as a simple, globally stratified cumulus structure, composed of a flotation upper crust of anorthosite underlain by progressively more mafic rocks and a residual-melt (KREEP) sandwich horizon near the base of the lower crust. Instead, global geochemical information derived from Clementine multispectral data and Lunar Prospector gamma-ray data reveals at least three distinct provinces whose geochemistry and petrologic history make them geologically unique: (1) the Procellarum KREEP Terrane (PKT), (2) the Feldspathic Highlands Terrane (FHT), and (3) the South Pole–Aitken Terrane (SPAT). The PKT is a mafic province, coincident with the largely resurfaced area in the Procellarum-Imbrium region whose petrogenesis relates to the early differentiation of the Moon. Here, some 40% of the Th in the Moon's crust is concentrated into a region that constitutes only about 10% of the crustal volume. This concentration of Th (average ~5 ppm), and by implication the other heat producing elements, U and K, led to a fundamentally different thermal and igneous evolution within this region compared to other parts of the lunar crust. Lower-crustal materials within the PKT likely interacted with underlying mantle materials to produce hybrid magmatism, leading to the magnesian suite of lunar rocks and possibly KREEP basalt. Although rare in the Apollo sample collection, widespread mare volcanic rocks having substantial Th enrichment are indicated by the remote data and may reflect further interaction between enriched crustal residues and mantle sources. The FHT is characterized by a central anorthositic region that constitutes the remnant of an anorthositic craton resulting from early lunar differentiation. Basin impacts into this region do not excavate significantly more mafic material, suggesting a thickness of tens of kilometers of anorthositic crust. The feldspathic lunar meteorites may represent samples from the anorthositic central region of the FHT. Ejecta from deep-penetrating basin impacts outside of the central anorthositic region, however, indicate an increasingly mafic composition with depth. The SPAT, a mafic anomaly of great magnitude, may include material of the upper mantle as well as lower crust; thus it is designated a separate terrane. Whether the SPA basin impact simply uncovered lower crust such as we infer for the FHT remains to be determined.

## 1. Introduction and Background

Results from the 1998 Lunar Prospector mission [*Binder*, 1998] and the 1994 Clementine mission [*Nozette et al.*, 1994] are leading to significant new views of the structure and distribution of materials in the crust and upper mantle of the Moon. Multispectral imaging, geochemical mapping, and geophysical constraints indicate that instead of having a grossly layered global stratigraphy, the Moon's crust can better be characterized in terms of at least three or perhaps more major geologic terranes. Each of these terranes, as exposed at the surface, represents a geologic province that has distinctive character laterally and at depth, and each has a distinctive and unique geologic history.

This new view offers a significant refinement to previous models for the compositional asymmetry of the Moon, which has been recognized for many years [*Kaula et al.*, 1972; *Wood*, 1973; *Haines and Metzger*, 1980; *Warren and Wasson*, 1980; *Wasson and Warren*, 1980; *Taylor*, 1982]. The high resolution and compositional definition afforded by the Clementine mission (altimetry, ultraviolet-visible (UVVIS) spectrometry, gravity) have highlighted broad regions such as the South Pole–Aitken basin and the Imbrium-Procellarum resurfaced area as being distinctive both in their compositions and in their topographic expressions. Apollo gamma-ray remote sensing provided hints of the unusual character (Th-rich) of the Imbrium-Procellarum region [*Metzger et al.*, 1973, 1977], as did the east-west dichotomy of lunar samples [e.g., *Warren and Wasson*, 1980; *Shervais and Taylor*, 1986], but it was the Lunar Prospector global coverage gamma-ray data that definitively showed the region to have the form of an extensive oval [*Haskin*, 1998] and to be the only major area of

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Th concentration on the Moon [*Lawrence et al.*, 1998]. Models of lunar crustal structure based on Clementine Doppler tracking and refined by Lunar Prospector are leading to an improved understanding of how the crust responded in different regions to deep basin impacts [e.g., *Zuber et al.*, 1994; *Neumann et al.*, 1996, 1998; *Wieczorek and Phillips*, 1998a, b, 1999b; *Wieczorek et al.*, 1999]. Such geophysical models complement the geochemical evidence for crustal asymmetry and, coupled with results of Apollo geophysical experiments, provide important constraints on the nature of the crust and mantle at depth beneath major lunar surface provinces.

Traditionally, lunar terrains and their materials have been classified as "highland" or "mare" principally on the basis of surface smoothness and albedo. The new geochemical information from Lunar Prospector and Clementine as well as consideration of sample data emphasize the limitations of that approach [*Korotev*, 1999a]. In this paper, we advocate dividing the lunar crust into three major geologic terranes, the Feldspathic Highlands Terrane (FHT), the Procellarum KREEP Terrane (PKT) and the South Pole–Aitken Terrane (SPAT). In this context, KREEP is an acronym for material rich in K, REE, P, and other incompatible trace elements.

In this paper, we use the term "terrane" to mean a group of rock formations that have some specific aspect of geologic history in common and that differ from adjacent groups of rock units. In our use this term connotes a province that has both a continuity of spatial extent and a depth dimension to it. Thus the terranes represent provinces that extend downward to the base of the crust and possibly into the underlying upper mantle. These terranes thus reflect major early lunar differentiation as well as later modification events, including mare volcanism. This particular division of the crust into three terranes is simply a starting point that provides context for some important observations and inferences and is made largely in response to global surface geochemistry as revealed by Lunar Prospector and Clementine data. However, as will be described below, other characteristics correspond well to the geochemical definitions.

Although we focus here on three ancient crustal terranes, more terranes or other divisions could certainly be devised. As we have divided them, we interpret the terranes to have formed early in the Moon's history. In some other scheme, mare basalts could be considered a separate terrane type, and, indeed, in Table 1 we list the mare basalts that occur outside of the PKT and the SPAT separately. However, within the PKT and SPAT, and possibly within the FHT, volcanic flows may be coupled in petrogenetically important ways (e.g., timing, compositions, assimilation, vertical mixing between crust and mantle, and heat production within the mantle) to the nature and origins of the terranes [e.g., *Korotev*, 1999b, this issue; *Wieczorek and Phillips*, 1999a, this issue; *Parmentier and Hess*, 1999; *Wieczorek et al.*, 1999]. Furthermore, the mare basalts formed relatively late in the Moon's crustal evolution, and in all cases they form a veneer over some preexisting crust; thus we consider them to be modifiers of the primary crustal terranes, and it is the latter that we wish to compare.

Other basin impacts besides SPA have had important influences, and perhaps one or some group of basins should also be considered a separate terrane. However, we take these to be modifiers of the primary crustal terranes, and, in fact, by excavating their host terrane, they have revealed its nature at depth. We call out SPA separately because it occurred early, because it was so big, and because it exhibits unusual geochemical and geophysical characteristics. Below, after examining the characteristics of materials exposed within the three major terranes, we will pose a possible scenario for what SPA represents and ask the question of whether it should indeed be considered a separate terrane.

**Table 1.** FeO and Th Concentrations in Crustal Terranes as Exposed at the Lunar Surface

| | FeO, wt % | | Th, ppm | | % of Area |
|---|---|---|---|---|---|
| | Mean | s.d. | Mean | s.d. | (60°S-60°N) |
| FHT-An | 4.2 | 0.5 | 0.8 | 0.3 | 24.8 |
| FHT-O | 5.5 | 1.6 | 1.5 | 0.8 | 34.7 |
| Other mare | 16.2 | 2.3 | 2.2 | 0.7 | 2.8 |
| OM, mixed | 8.8 | 2.3 | 1.6 | 0.8 | 10.2 |
| PKT-nonm | 9.0 | 1.6 | 5.2 | 1.4 | 2.0 |
| PKT-mare | 17.3 | 1.8 | 4.9 | 1.0 | 7.6 |
| PKT-mixed | 10.7 | 2.6 | 4.5 | 2.0 | 6.9 |
| SPAT-inner | 10.1 | 2.1 | 1.9 | 0.4 | 5.3 |
| SPAT-outer | 5.7 | 1.1 | 1.0 | 0.3 | 5.7 |

Abbreviations: FHT, Feldspathic Highlands Terrane (An, anorthositic; O, outer, mainly basin-ejecta covered); PKT, Procellarum KREEP Terrane (nonm, nonmare); SPA, South Pole–Aitken Terrane; "other mare" refers to regions of mare basalt within the FHT-O, for which individual 5° pixels consist entirely of basalt; "OM, mixed" refers to regions surrounding "other mare" where individual pixels contain both mare and nonmare materials.

In this paper, we focus first on compositional definition and comparison of the three major terranes as well as the relationships between terrane compositions and compositions of known lunar materials. Then we discuss the implications of the strongly asymmetric distribution of Th on the thermal evolution and origin of major suites of igneous rocks. It is certainly possible and probably likely that close examination of the high-resolution Lunar Prospector data, especially once information for elements such as Al and Mg becomes available, will lead to improved definition of terranes and delineation of additional, distinctive terranes. However, at present, we limit inferences to those that will likely remain pertinent in light of the higher-resolution data.

## 2. Terrane Definition and Characteristics

To define the boundaries of each terrane as reflected by surface exposure, we use the FeO map derived from Clementine UVVIS data by *Lucey et al.* [1998a] and the Th data from *Lawrence et al.* [1998] calibrated to the Apollo gamma-ray-spectrometer (GRS) data as described by *Gillis et al.* [1999] (Plate 1). Other features, including petrologic, geophysical, and geomorphologic features correspond to these boundaries; these features are discussed below.

The approximate boundaries of the terranes as we envision them are shown on Plate 1. The PKT is defined primarily on the basis of Th concentrations and roughly coincides with the large resurfaced area on the near side where Th concentrations generally exceed 3.5 ppm. We divide the South Pole–Aitken terrane into two parts: an inner region where the topographic expression is greatest and where FeO concentrations generally exceed 8 wt % according to the Clementine data (Plate 1a). The outer part of the SPAT is defined as the extent of the mafic anomaly surrounding the central region to about 5 wt % FeO (Plate 1a) and may correspond to regions of extensive SPA ejecta and degraded rim deposits. The FHT is most prominent on the central-northern far side, especially the central anorthositic region, which we distinguish from other regions where the surface has been modified by volcanic deposits or by basin impacts and their ejecta deposits. Based upon the compositional information we have now, which must be considered preliminary in light of ongoing Lunar Prospector data reduction, we consider the basin-ejecta and basalt-modified surfaces outside of the PKT and SPAT to be part of the FHT.

### 2.1. Feldspathic Highlands Terrane

The most extensive lunar terrane by area and volume is the Feldspathic Highlands Terrane, constituting over 60% of the Moon's surface. This terrane is characterized at the surface by high albedo, extensive cratering, elevated topography, high local relief, and highly feldspathic compositions. This terrane is centered around 40°N, 180°E and includes the bulk of the lunar far side, excluding the SPA basin and ejecta, Mare Moscoviense, and a few other isolated areas of mare basalt.

To further characterize the FHT, we distinguish on the basis of its geochemical signature a highly anorthositic region, which corresponds to the thickest parts of the crust, concentrated mainly in a vast region of the far side (Plate 1). There, the crust appears to be 70 to 90 km thick or more [*Zuber et al.*, 1994; *Wieczorek and Phillips,* 1998a]. The area circled in Plate 1 occupies some 25% of the Moon's surface between 60° north and 60° south. Concentrations of FeO at the surface are low, averaging ~4.2 wt % away from areas that have been mixed at the surface with more mafic ejecta from some of the nearby basins (Table 1, Figure 1; cf. independent estimate by *Korotev* [1999c]). On the basis of Fe-Al correlations among Apollo samples, concentrations of $Al_2O_3$ in this terrane would be correspondingly high, averaging ~29 wt % [cf. *Korotev*, 1999c]. Despite heavy cratering, there are no broad areas within this region that have elevated FeO concentrations, with the main exception of Mare Moscoviense (Plate 1). *Tompkins and Pieters* [1999] showed that the central peaks of large craters within the FHT, which expose materials from as deep as 15 km, are dominantly anorthositic. Even some basins (e.g., Freundlich-Sharanov (18.5°N, 175°E), Hertzsprung (1.5°N, 128.5°W), and Korolev (4.5°S, 157°W)) in this region, which would have penetrated some 25–35 km, apparently did not excavate material that was substantially more mafic. The lack of FeO enrichment indicates that throughout a substantial thickness of megaregolith and extending to the maximum depths sampled by the largest craters and basins, the terrane is very anorthositic, that is, it is dominated by a mixture of materials whose average composition is that of noritic anorthosite, a rock type with 80–90% plagioclase.

In regions away from the central anorthositic region the surface exhibits more mafic material in the form of basin ejecta and in a few patches of mare or cryptomare which obscure the older, presumably feldspathic surface. This part of the FHT, which we take as all parts of the lunar surface that are outside the boundaries of the PKT or SPA, or basin-filling mare, makes up some 40% of the Moon's surface (not including the central, anorthositic region). We refer to these regions as the outer FHT (FHT-O) (Plate 1a). However, to investigate the composition of the crustal (nonmare) parts of the FHT-O, we tabulate FeO and Th concentrations separately for the basin-filling mare basalts (Table 1). Despite the mafic contributions from basin ejecta, these regions are on average feldspathic, with a mean FeO concentration of only ~6 wt % (Table 1, Figure 1). Indeed, some basins, such as Smythii, did not excavate material with greater than ~6 wt % FeO despite penetrations of some 30 km into the crust and exposure of deep-seated material in ring structures [*Gillis and Spudis*, 1999].

It has long been argued that ejecta from the larger basins represent deep crustal, mafic material [e.g., *Ryder and Wood*, 1977; *Spudis*, 1993; *Ryder et al.*, 1997]. Furthermore, using basin-ejecta compositions, *Spudis and Davis* [1986] argued that with increasing basin size, increasingly mafic material was exhumed, indicating a progressively more mafic crust with depth. However, *Korotev* [this issue] questions that relationship, and we suggest that it be reevaluated on a terrane-by-terrane basis. As a working hypothesis, we suggest also

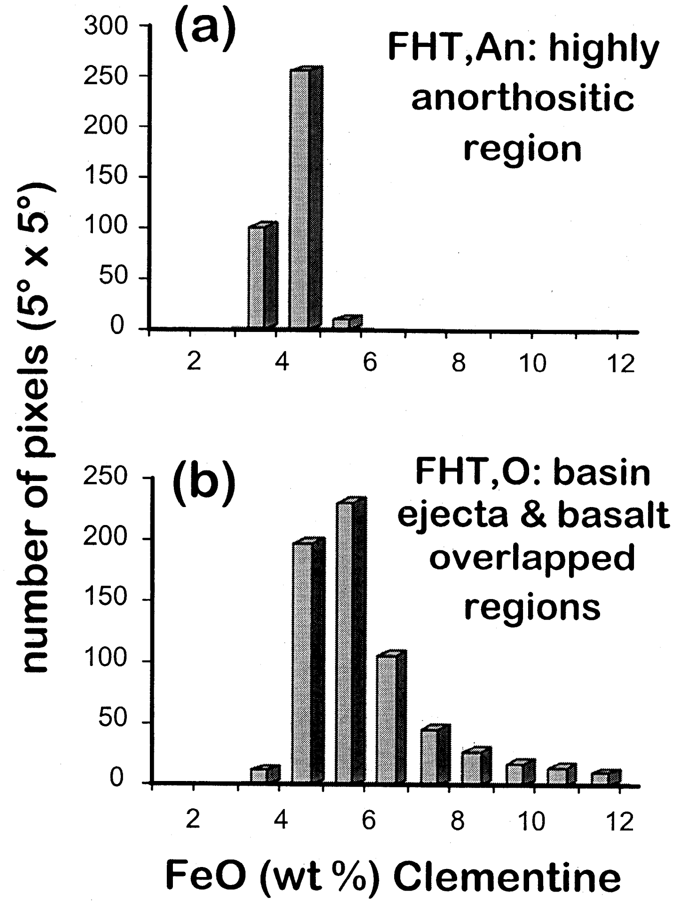


**Figure 1.** Distribution of FeO concentrations within the Feldspathic Highlands Terrane, separated according to (a) the highly feldspathic central region and (b) other parts of the terrane where impact-basin ejecta and basalt (cryptomare) overlie or mix with surface materials. FeO concentrations are averages derived from Clementine ultraviolet-visible (UV-VIS) data [*Lucey et al.*, 1998a], binned so as to correspond to the 5° equal-area pixels or regions of the Lunar Prospector gamma-ray data.

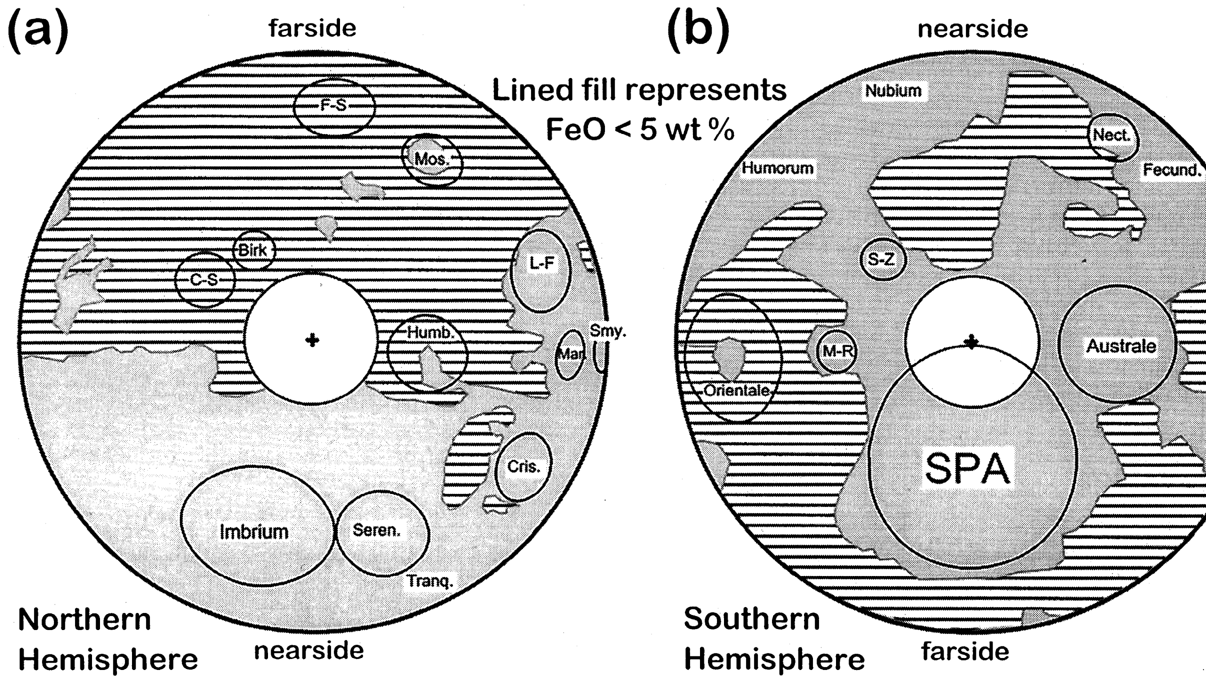


**Figure 2**. Polar projections of the lunar surface showing regions containing <5 wt % FeO as areas with lined fill: (a) northern hemisphere and (b) southern hemisphere. Approximate locations of major impact basins are outlined for reference. The large proportion of area in the northern hemisphere that has FeO <5 wt % reflects the concentration there of the FHT highly anorthositic central region. In the northern hemisphere, regions that have >5 wt % FeO are associated mostly with the PKT. In the southern hemisphere, however, FeO-rich regions are also associated with SPA and in extensive regions associated with poorly defined, ancient basins such as Australe and possibly some extensive regions of cryptomare in the nearside southern hemisphere. Data are not shown for latitudes 75° to the poles. FeO was derived from Clementine UVVIS [*Lucey et al.*, 1998a]. Abbreviations: C-S, Coulomb-Sartung; F-S, Freundlich-Sharanov; L-F, Lomonosov-Fleming; M-R, Mendel-Rydburg; S-Z, Schiller-Zucchius.

that in the vicinity of the central anorthositic region, the lower crust is more likely to be dominated by the petrogenetic mafic complement of the anorthositic rocks, specifically, ferroan-suite materials (i.e., high FeO/(FeO+MgO)). Support for this idea comes from the feldspathic lunar meteorites [*Korotev*, 1999c] such as Yamato 791197, Yamato 82192/3, Yamato 86032, MAC88104/5, QUE93069, and Dar al Gani 262, whose compositions and clastic components indicate precursors dominated by ferroan-suite lithologies [e.g., *Lindstrom et al.*, 1986; *Jolliff et al.*, 1991b; *Korotev et al.*, 1996; *Jolliff et al.*, 1999] (see section 5). Ferroan mafic mineral chemistry is the expected outcome of the crystallization of residual melt of a magma ocean that would have also crystallized the bulk of the plagioclase of the early lunar crust (*Warren and Kallemeyn* [1998] and many earlier references).

Although we consider the basin- and volcanic-modified parts of the FHT to be a part of that terrane, we recognize that they represent a complex part of the lunar crust. In the two polar projections of Figure 2, which distinguish those regions where FeO is <5 wt %, it appears that the FHT is more concentrated in the northern hemisphere and that the southern hemisphere seems to have some extensive areas associated with old basins such as South Pole–Aitken, Australe, and possibly ancient cryptomare. This may mean that there are significant differences in some of the southern regions (in addition to SPAT), perhaps warranting other distinct terrane designations. Further characterization of one or more additional terranes in these complex areas awaits higher spatial and spectral resolution Lunar Prospector data.

### 2.2. Procellarum KREEP Terrane

The boundaries shown in Plate 1b for the Procellarum KREEP Terrane were located so as to include the 5° equal-area Lunar Prospector data [*Lawrence et al.*, 1998] that have ~3.5 or more ppm Th, which coincides approximately with the resurfaced area extending to the outer boundaries of Oceanus Procellarum. This also includes parts of Maria Imbrium, Frigoris, Cognitum, Insularum, Vaporum, Nubium, and Humorum (~20°E–80°W, 30°S–70°N). This area corresponds to the "high-Th Oval Region" of *Haskin* [1998] and the "Great Lunar Hot Spot" of *Korotev* [1999b, this issue]. Depending on the Th concentration used to define its boundaries, it occupies about 16% of the Moon's surface (using 3.5 ppm; Table 1). Some of the highest concentrations of Th (up to 9 ppm) are located in the vicinity of the Apollo 14 site, between Copernicus and Kepler craters, and in Mare Insularum (Plate 1b), and in several areas associated with large impact craters around the rim of the Imbrium basin (see below).

The PKT contains materials of both light and dark albedo, i.e., nonmare "highlands" (light) and volcanic flows (dark). In addition to typical Apollo-like mare basalts, the volcanic flows may include Th-rich KREEP basalts or high-Fe variants

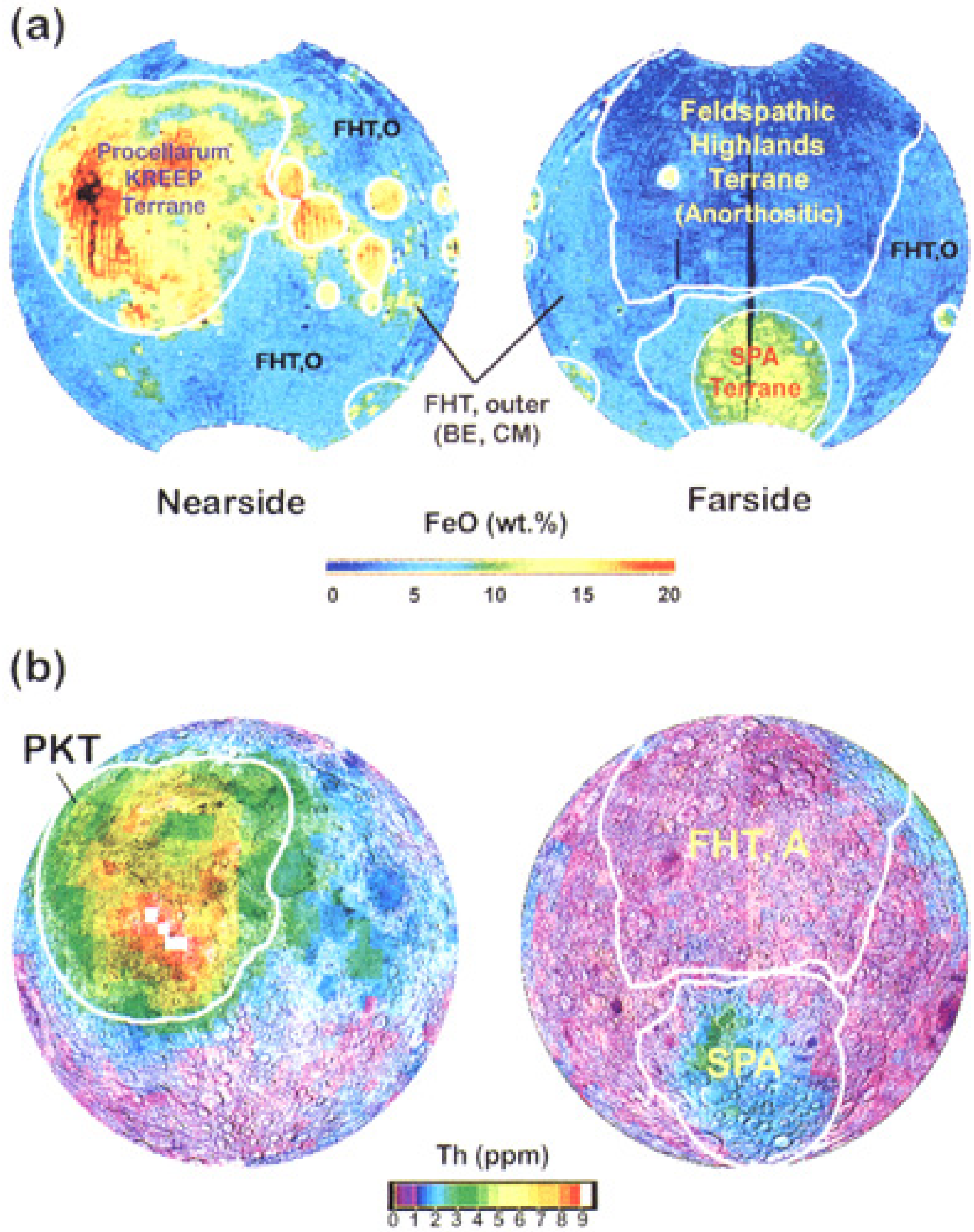


**Plate 1.** (a) Surface expressions of major lunar crustal terranes delineated on the Clementine global FeO map after the method of *Lucey et al.* [1995], using the projection from *Spudis and Bussey* [1997]. The Procellarum KREEP Terrane (PKT) is defined as the main nearside, oval-shaped region of Th enrichment, which corresponds to the Procellarum-Imbrium resurfaced areas. The South Pole–Aitken Terrane (SPAT) is subdivided into an inner region of primary topographic depression and an outer region corresponding to rim and presumed proximal ejecta deposits. The Feldspathic Highlands Terrane (FHT) is defined by a central, highly anorthositic region, which corresponds to the thickest parts of the crust, concentrated mainly on the lunar farside. The outer FHT (FHT-O) consists of those regions where basin ejecta (BE) or basalts (cryptomare, CM) obscure the older, presumably feldspathic surface. The remainder of the lunar surface that is not part of the PKT, SPAT, or basin-filling mare (e.g., Serenitatis, Tranquillitatis, Crisium, and Australe) is included within FHT-O. (b) Th concentration map merged with a global shaded relief image [*Gillis et al.*, 1999]. Outlined regions include the PKT, the anorthositic central region of the FHT (FHT,A), and the SPAT. The PKT boundary is drawn so as to incorporate most pixels that have >3.5 ppm Th.

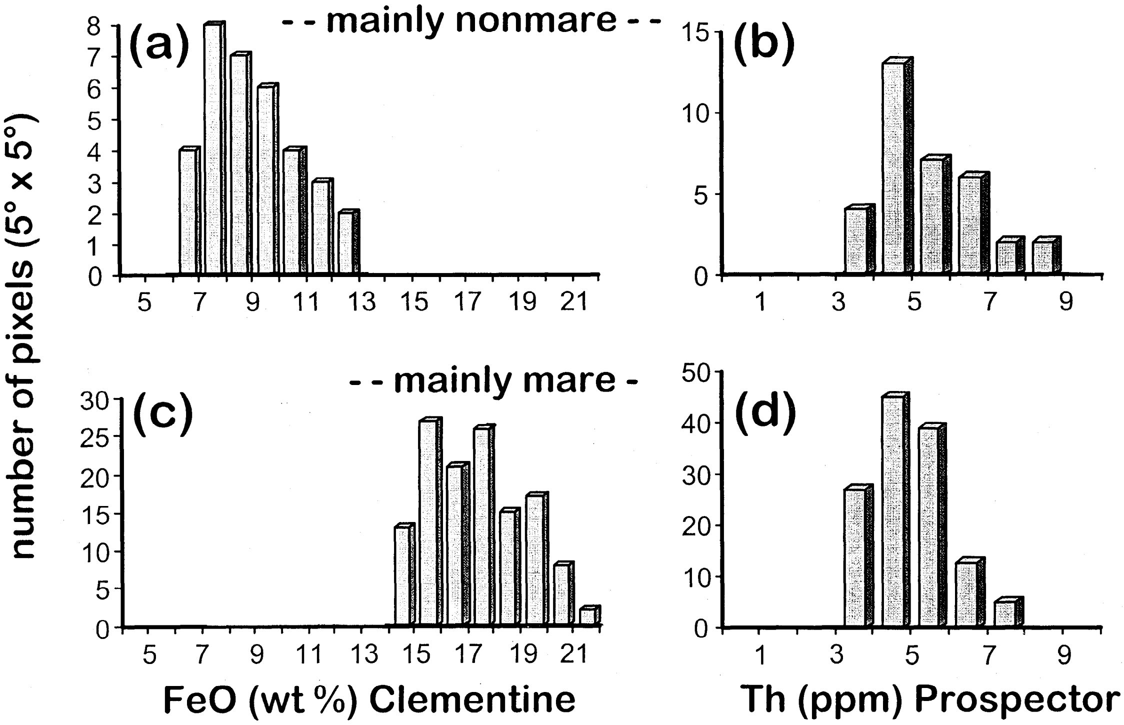


**Figure 3.** Distribution of FeO and Th concentrations within the Procellarum KREEP Terrane: (a) FeO in mainly nonmare regions, (b) Th in mainly nonmare regions, (c) FeO in mainly mare regions, and (d) Th in mainly mare regions. FeO concentrations are averages derived from Clementine UVVIS data [*Lucey et al.*, 1998a], binned into 5° equal-area pixels. The assignment of individual pixels to either mare or nonmare designations was based on an assessment of surface roughness and albedo, which corresponds to a separation at an average FeO concentration of ~15 wt %. Although the highest concentrations of Th occur mainly in nonmare regions, the distribution of Th concentrations and the means are very similar between the mare and nonmare regions, suggesting that some of the basalts, themselves, are significantly enriched in Th beyond levels measured in Apollo basalt samples.

in areas that are mainly resurfaced (e.g., central Oceanus Procellarum) and that have average Th concentration as high as some regions dominated by nonmare formations. Well over half of the PKT was resurfaced by volcanism. The FeO concentrations readily distinguish the mare volcanic plains from otherwise rough topography, including basin ring structures, ejecta deposits such as the Fra Mauro Formation, and materials associated with midsize craters (Figure 3). However, the distribution of Th concentrations within rough terrain at the 5° scale does not differ significantly from that within smooth, volcanic plains. In fact, within the PKT, these two terrain types have approximately the same mean Th concentration (~5 ppm; Table 1, Figure 3) at the 5° scale. A preliminary look at the 2° data indicates that the most Th-rich areas are indeed associated with large craters that uncover nonmare materials [*Lawrence et al.*, 1999a, b]. Nonetheless, the observation that large numbers of mostly mare pixels and mostly nonmare pixels have about the same mean Th concentrations suggests that the basalts themselves in many places must have elevated Th concentrations.

Although extensively resurfaced, the PKT contains a variety of different nonmare formations that attest to its subsurface makeup. It contains remnants of prebasin highlands material within rugged mountain ranges such as the Apennines, Alpes, and Caucasus. These mountains represent basin ring structures, and they are typically relatively mafic for lunar upper-crustal materials. Concentrations of FeO exceed 10 wt % in many of these regions [*Bussey and Spudis*, 1998], indicating that this material is as mafic as the basin impact-melt breccias derived from deep within the terrane. Nonmare materials exhumed from beneath mare basalts by moderate to large impacts such as Kepler, Aristarchus, and Aristillus have elevated Th concentrations (7–10 ppm [*Lawrence et al.*, 1999a, b]) as well as relatively mafic bulk compositions. In some instances the uncovered materials may be KREEP basalts, or they may even be parts of basin melt sheets [*Gillis and Jolliff*, 1999]. However, they may instead represent buried, widespread formations such as the Fra Mauro and Alpes Formations, which are different facies of materials ultimately derived from Imbrium ejecta [*Wilhelms*, 1987]. These formations include not only mafic, KREEP-like impact melt, but also remnants of igneous rocks such as magnesian and alkali norite, and more evolved igneous differentiates [e.g., *Papike et al.*, 1998].

The geochemistry of the mafic impact-melt breccias indicates that they may also include a mantle component. *Korotev* [1999b, this issue] has shown that geochemical mixing models provide the most satisfactory matches to measured compositions by incorporating a magnesian olivine component, and the most plausible candidate is olivine from mantle cumulates. Such cumulates, whether formed deep or in a perched layer at some intermediate depth, are less dense than later formed, higher-level, Fe-rich cumulates and would therefore be brought to the upper mantle by cumulate overturn driven by density contrasts [*Hess and Parmentier*, 1995; *Parmentier and Hess*, 1999].

### 2.3. South Pole–Aitken Terrane

The depth and diameter of South Pole–Aitken basin were established definitively by Clementine altimetry [*Spudis et al.*, 1994; *Smith et al.*, 1997], but the basin is also distinctive on any compositional map (e.g., Plate 1) and was detected in Apollo orbital GRS data [*Metzger et al.*, 1977]. We regard the South Pole–Aitken basin and its surroundings as a separate terrane for the following reasons: (1) It has a high average FeO concentration relative to typical nonmare lunar crust (7–14 wt %, [*Lucey et al.*, 1998b]). (2) With a diameter of 2600 km, it is the largest impact basin in the Solar System [*Spudis et al.,* 1994]. (3) It occurred early in the Moon's history and undoubtedly had a great effect on the Moon's subsequent thermal evolution, especially in the crustal/upper mantle section where the impactor struck. (4) It occupies a broad region of extreme topographic depression, reaching a depth of some 12 km below the surrounding highlands [*Spudis et al.*, 1994; *Smith et al.*, 1997]. (5) Despite its depth and thinning of the crust, significant resurfacing by mare basalt did not occur. (6) Crustal thickness modeling indicates that a significant thickness of crustal material is present beneath the basin floor even though impact-crater-scaling laws predict that the impact should have excavated well into the mantle [*Wieczorek and Phillips*, 1999b].

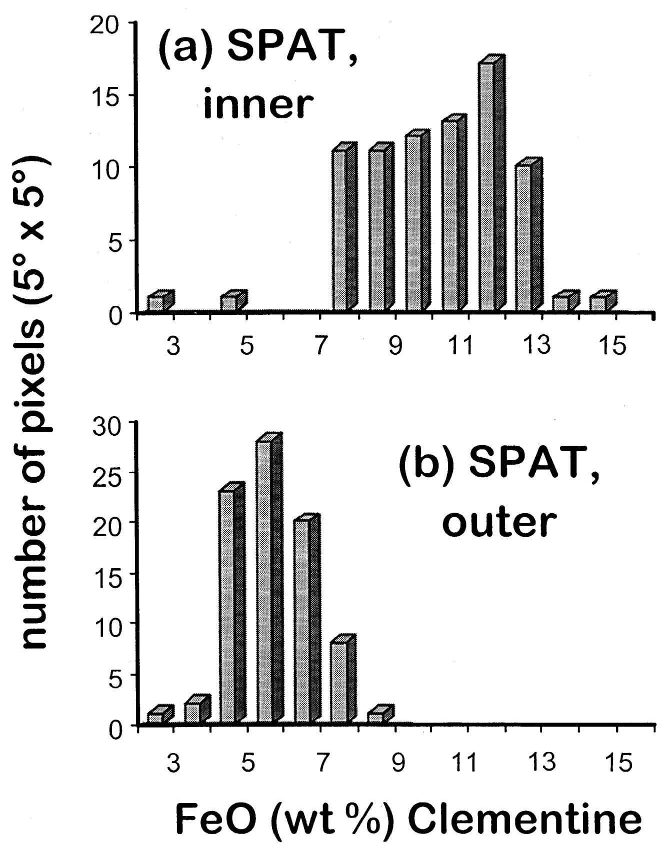


**Figure 4.** FeO concentrations in the South Pole–Aitken Terrane. (a) FeO concentrations in the inner part of the SPAT, which corresponds to the most topographically depressed part or floor of the basin (Plate 1a). (b) FeO concentrations in the outer parts of the terrane, which represent basin walls and slumped material, and some areas of proximal ejecta. FeO concentrations are significantly lower than in the central region but well above the level of the surrounding FHT. The main distribution is very similar, however, to that of the basin-ejecta and basalt-overlapped regions of the FHT (Figure 1), peaking at about 6–7 wt %. Concentrations of FeO represent averages derived from Clementine UVVIS data [*Lucey et al.*, 1998a], binned into 5° equal-area pixels.

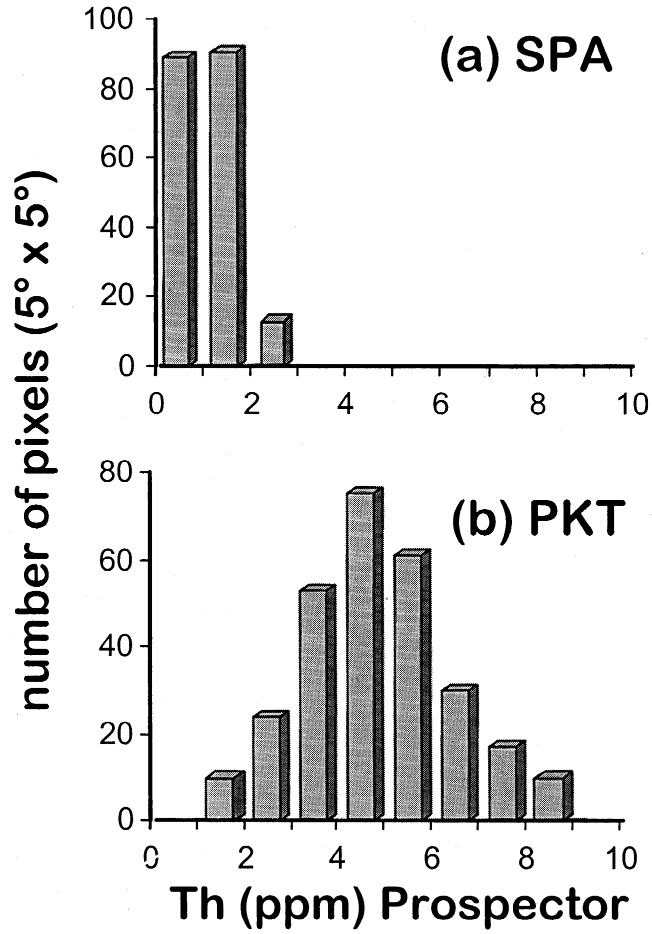


**Figure 5.** Comparison of the Th concentrations of (a) the SPAT (undivided) to those of (b) the PKT. Although the lower cutoff for the PKT was taken to be ~3.5 ppm Th, it is evident that these two distributions are fundamentally different, with no broad areas (at the 5° scale) in the SPAT exceeding 4 ppm Th.

We distinguish an inner region of the SPAT from the outer parts because the central area and the walls or outer parts represent different provenances (depths) within the crust. The central region lies within an area of thinned crust ~1000 km across [*Neumann et al.*, 1996] and may represent a mixture of lower crust and upper mantle [*Lucey et al.*, 1998b; *Blewett et al.*, 1999]. The outer regions lie over thickened crust and probably represent a lower to midcrustal section in the form of ejected material mixed with ancient surface materials along the degraded topographic rim and proximal exterior. The asymmetric pattern of ejecta reflected by the outline of elevated FeO concentrations indicates an unusual, perhaps low-angle, oblique impact [*Schultz*, 1997] that produced extended lobes to the northeast and northwest (note an approximately butterfly-wing-shaped outline; Plate 1a).

Within the inner SPAT the average FeO concentration is ~10 wt % (Table 1), whereas the average FeO content of the outer region is only 5.7 wt % (Figure 4), virtually the same as the basin-ejecta part of the FHT (5.8 wt %). Concentrations of Th are low, especially compared to the PKT (Figure 5). Despite its mafic character, which may reflect a lower crust – upper mantle component [*Lucey et al.*, 1998b], it has only slightly elevated Th concentrations (average ~2 ppm [*Gillis et al.*, 1999]) relative to the FHT and significantly less than the PKT, which averages ~5–6 ppm Th, see section 5). A mixture of KREEP-poor mafic cumulates of the upper mantle with lower crust having the composition of, for example samples 15445 or 15455, which are at the Th-poor end (~3 ppm) of the range for rocks whose compositions have been referred to as "LKFM" [*Ryder and Spudis*, 1987; *Lindstrom et al.*, 1988], would produce FeO and Th concentrations consistent with those observed [*Lucey et al.*, 1998b]. However, materials that have been categorized as LKFM (see *Korotev,* this issue) have Th concentrations ranging up to those of KREEP basalt and higher (e.g., 15 ppm). No widespread areas of significant Th enrichment (>5 ppm) have yet been detected in the SPA region, reinforcing the notion that significant concentrations of a KREEP component (i.e., KREEP-like incompatible-element enrichments as opposed to less evolved trapped melt) were not present in the lower crust in the SPA region. Furthermore, some of the Th enrichment in the SPAT is probably related to Imbrium antipodal deposits (L. A. Haskin et al., The Th enrichment in lunar surface materials and its relationship to the Imbrium event, submitted to Journal of Geophysical Research, 1999)(hereinafter referred to as Haskin et al., submitted manuscript, 1999).

The SPA Terrane may in part represent exposed, more mafic crust belonging to the FHT, but the lithology of the mafic floor material remains unknown. *Lucey et al.* [1998b] argued on the basis of FeO and $TiO_2$ concentrations derived from Clementine UVVIS data that the materials exposed represent a mixture of the upper mantle and lower crust. On the other hand, *Pieters et al.* [1997] argued, on the basis of a strip of Clementine UVVIS data through the SPAT, that the predominantly noritic character of the rocks as reflected by their spectra means that predominantly lower crust is exposed in the basin floor. *Morrison* [1998] argued that some of the exposed materials may be consistent with products of a deep, differentiated melt sheet, which would imply that the exposed surface compositions within the SPA basin may not represent the average composition of the SPA impact melt. As indicated above, the SPA basin is anomalous in that crustal thickness modeling suggests the basin is underlain by a significant thickness of material of crustal, not mantle density [*Wieczorek and Phillips*, 1999b]; however, that might prove to be consistent with a thick layer of hybrid crust-mantle mixed impact melt. The issue of crust/mantle components in SPA floor rock formations is not resolved here, but we may now add to the evidence a low average Th content, less than expected if the lower crust is LKFM-like or KREEP-rich (Figure 5).

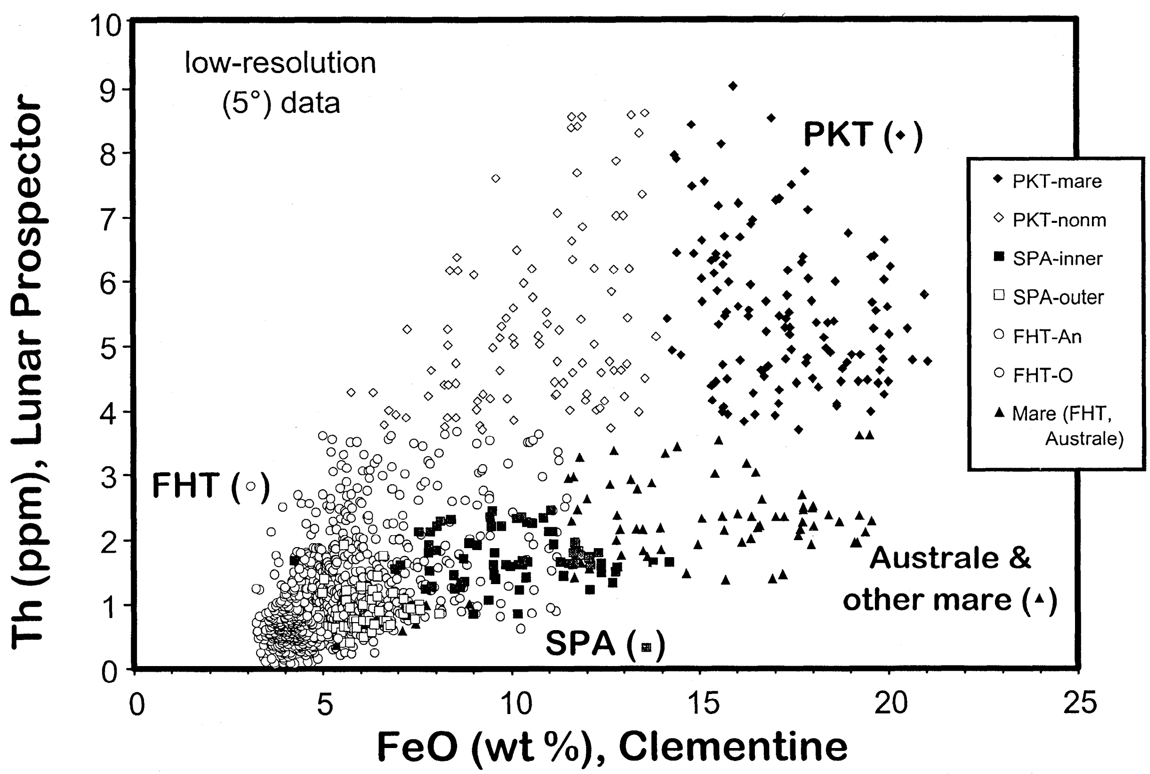


**Figure 6.** Concentrations of FeO versus Th for the three major crustal terranes, with the Australe region and other basin-filling mare basalts outside of the PKT and SPA also plotted. Diamond symbols are for 5° equal-area regions within the PKT, squares represent the SPAT, circles represent the FHT, and triangles represent other mare basalts. FeO was derived from Clementine UVVIS data, binned into 5° equal-area pixels. Note the clear separation in Th content between the mare basalts outside of the PKT (triangles) and those within the PKT (e.g., >15 wt % FeO).

## 3. Data Analysis: FeO and Th Concentrations of the Major Crustal Terranes

### 3.1. Clementine FeO versus Lunar Prospector Th

Comparing Lunar Prospector Th GRS data and FeO concentrations derived from Clementine UVVIS data, resampled to the same 5° equal-area bins (pixels), reveals a distribution of compositions ranging to about 20 wt % FeO and 10 ppm Th (Figure 6). In Figure 6, the data are subdivided according to the three main crustal terranes: FHT, PKT, SPA, and other mare-basalt-filled basins, including the Australe basin. Figure 7 compares the distribution of remotely sensed data to that for different groups of lunar rock types. In general, mare-basalt groups and the picritic pyroclastic glasses occupy the high FeO concentrations; mafic impact-melt breccias (and KREEP basalt) have high Th concentrations; and feldspathic upper-crustal lithologies and ferroan-anorthositic-suite (FAS) materials have very low Th concentrations.

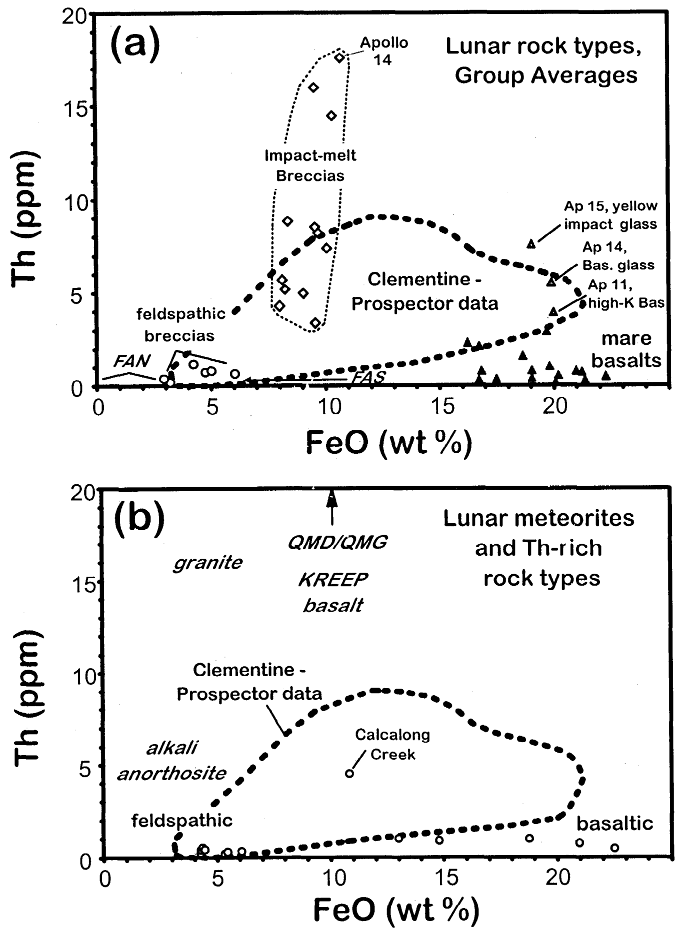


**Figure 7.** Concentrations of FeO versus Th for different groups of lunar materials. (a) Major groups of Apollo lunar rock types, including mare basalts (triangles), impact-melt breccias (diamonds), feldspathic (including granulitic) breccias (circles), and ferroan anorthosite (FAN) and ferroan-anorthositic-suite (FAS) samples (no symbols). Apollo 14 and Apollo 15 Th-rich basaltic glasses (impact-produced) are also shown. (b) Lunar soils (Apollo and Luna), lunar meteorites, and several Th-rich rock types (italicized) found among the Apollo samples. Samples of lunar granite/felsite and alkali-anorthosite have variable compositions but tend to have high Th/FeO, as suggested by the locations of the italicized labels in the figure. Quartz monzodiorite or monzogabbro (QMD/QMG) have very high Th concentrations, which plot off the diagram. KREEP basalt as found at the Apollo 15 site has a composition that plots in the vicinity of the label. Ap15nm refers to the average composition of Apollo 15 nonmare soil, Ap17nm refers to average Apollo 17 nonmare soil, and Ap16C refers to average Apollo 16 Cayley Plains soil [*Korotev*, 1998]. The two Apollo 12 data points correspond to the basalt-rich (mare) and KREEP-rich (nonmare) extremes (see Figure 9).

### 3.2. Relation of Lunar Rock Types to Crustal Terranes

The average compositions of the groups of rock types known from Apollo samples mostly encompass the field of remotely-sensed data (Figure 7a). Thus one could interpret the remotely sensed data mainly as mixtures of these known components, with the possible exception of Th-rich, high-FeO data. Aside from some Apollo 11 high-K basalts that have Th as high as 4 ppm [*Basaltic Volcanism Study Project*, 1981], the sampled crystalline mare basalts generally have <3 ppm Th, and most have <2 ppm [*Korotev*, 1998]. However, several basaltic (FeO-rich) glasses have been found that have significant Th enrichment. One basaltic glass bead (14161, 7127) containing 5.4 ppm Th and 19.7 wt % FeO was found among the Apollo 14 soils [*Jolliff et al.*, 1991a]. Apollo 15 yellow impact glasses (15010,3189) have Th concentrations as high as 8 ppm and 19 wt % FeO [*Delano et al.*, 1982]. Siderophile element concentrations indicate that these glasses had an impact origin, and Delano et al. argued on the basis of composition and clast content that these were derived as ballistic ejecta from Eratosthenian lava flows in Oceanus Procellarum and Mare Imbrium, and that the high large-ion, lithophile (LIL) contents were indigenous to mare sources. However, both the Apollo 14 and Apollo 15 glasses have intermediate concentrations of $TiO_2$ (4–5 wt %), suggesting that they do not derive from the youngest Eratosthenian flows, which, on the basis of the latest $TiO_2$ calibration of the Clementine UVVIS data set [*Lucey et al.*, this issue], appear to have higher $TiO_2$ concentrations (e.g., >6 wt %).

From the distribution of data shown in Figure 6, there appears to be a separation of compositions in terms of Th concentrations for regions of mare basalt outside of the PKT and SPAT relative to those that occur within the PKT, which mostly have Th >3.5 ppm. Many of the mare basalts, including two of the basaltic lunar meteorites (Asuka 881757 and Yamato 793169), have FeO >20 wt % and Th <1 ppm [*Warren and Kallemeyn*, 1993; *Jolliff et al.*, 1993], but there appear to be no areas at the 5°-pixel scale composed solely of such basalt compositions (Figure 7). That basalts occurring within the PKT have systematically higher Th concentrations than those occurring outside of the PKT provides additional support for the idea that the crustal terranes are coupled geochemically to the underlying mantle and mare basalt sources by means of mixing (mantle) or assimilation (crustal) processes. The occurrence of the Apollo 11 high-K basalts in Mare Tranquillitatis, however, complicates that scenario.

Although Th-rich igneous rock types such as alkali-anorthosite, granite, quartz-monzodiorite, and monzogabbro occur among the Apollo samples, no 5° equal-area regions have Th and FeO concentrations that would indicate significant, widespread enrichments in any one of these specific components (Figure 7b). All of these rock types have high Th concentrations coupled with a high Th/FeO ratio [*Korotev, 1998*]. Sodic ferrogabbro and alkali-gabbronorite are two Th- and FeO-rich igneous rock types known primarily from the Apollo 16 samples; however, they are rare and have Th enrichment well above the field of the Lunar Prospector data. KREEP basalt, the Apollo 14 soil, and some of the mafic impact-melt breccia groups have compositions that lie near but still above the Th-rich apex of the data field in Figure 7. Higher-resolution Th data (~2° × 2° equal-area) from the extended Lunar Prospector mapping mission [*Lawrence et al.*, 1999b] show compositions that border the gap but do not bridge it. However, the abundances reported by *Lawrence et al.* [1999b] are based on an absolute calibration, and the maximum values appear to be lower than we expect for the Apollo 14 Fra Mauro region.

### 3.3. Relation of Lunar Soils to Crustal Terranes

Although one of the primary goals of interpreting the remotely sensed data is to recover information about bedrock, it is almost exclusively the soils that are sensed remotely; thus we consider the terrane compositions in comparison to known compositions of the lunar soils. As a result of impact-related "gardening," including vertical and lateral mixing, lunar soils represent integrated average compositions of potentially broad areas and as such represent average compositions of the major rock types from which they are derived. Thus it is useful to consider the compositions of the Apollo soils as mixtures of three major sets of components: (1) KREEP basalt and impact-melt breccias, (2) feldspathic upper-crustal materials, and (3) mare basalts and volcanic glasses (Figure 8a).

Given our current knowledge of end-member rock types, Apollo soils cover nearly the entire expected range of compositions. The Apollo soils tend to have elevated Th concentrations (Figure 8b), reflecting their proximity to the PKT and the effects of Imbrium ejecta, especially Apollo 14 and Apollo 12 soils, but also the nonmare soils from Apollo sites 15, 16, and 17 (2–5 ppm Th). The predominantly basaltic Apollo soils lie at high FeO (15–21 wt %) and generally have Th concentrations below the Clementine–Lunar Prospector distribution (Figure 8b).

Perhaps to be expected is the fact that only a few of the soils are dominated by materials of a single terrane; most are mixtures. Compositions of the PKT are represented by Apollo 12 and Apollo 14 soils. To a first approximation, Apollo 12 soils represent a two-component mixture between a KREEP component and mare basalt. Apollo 14 soils, which represent the most Th-enriched PKT surface materials, are dominated by mafic, KREEP-rich impact-melt breccias mixed with minor proportions of more feldspathic rock types and mare basalt. Apollo 16 soils represent mainly mixtures between feldspathic, upper-crustal materials, which are characteristic of the FHT, and KREEP components, delivered from the PKT as Imbrium ejecta. Some Apollo 17 soils (central valley) represent mixtures of mare basalt and feldspathic, upper crustal materials (FHT), whereas Apollo 17 massif soils and Apollo 15 nonmare soils reflect mixtures of all three groups of components. An unresolved issue is the extent to which the Apollo 17 nonmare components (mainly the impact-melt breccias) represent typical midcrustal or lower crustal components typical of the FHT, as suggested by their location in what we designate the "FHT-O" region or whether they represent a hybrid PKT-FHT source at depth. On the basis of the moderate Th concentrations of the impact-melt breccias (5–8 ppm), we suspect the latter to be the case.

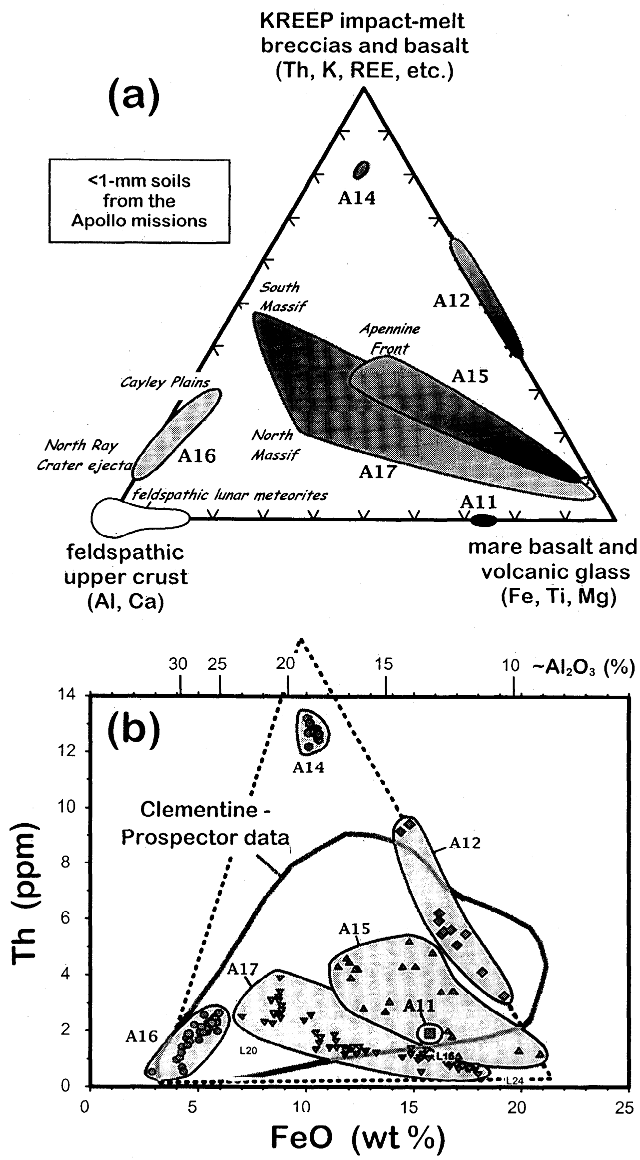


**Figure 8.** (a) Relationship of lunar soil compositions to major groups of lunar rock types, KREEP-rich rock types, mare basalts and volcanic glasses, and feldspathic materials. Fields represent the results of mass-balance models [*Korotev*, 1997] for regolith of the Apollo sites. The Apollo 15 and 17 sites were at the interface of maria and highlands, and both were in or near the PKT. Soils from Apollo 11 and 12, both mare sites, are substantially contaminated with material from the FHT (Apollo 11) and the PKT (Apollo 12). Few Apollo soils are >80% mare basalt, and only those from North Ray Crater at Apollo 16 approach the composition of typical feldspathic highlands. (b) Raw concentration data for Th and FeO ($Al_2O_3$ inferred from FeO- $Al_2O_3$ correlation). Each point represents an Apollo surface soil sample (symbols within labeled fields) or a Soviet Luna site (L).

As a group, compositions of materials within the inner SPAT do not match any of the Apollo or Luna soil compositions, although there is overlap with some of the Apollo 17 mare-nonmare mixed soils at about 8–13 wt % FeO and 1–3 ppm Th. However, in the SPAT, there appears to be a rough positive correlation between FeO and Th (Figure 6), whereas the Apollo 17 soils show the opposite (Figure 8b).

As in the case of the soils, the feldspathic lunar meteorites, which are regolith breccias, may also represent broad surface regions. These meteorites have extremely low Th concentrations (0.2–0.5 ppm) and consist largely of ferroan-anorthositic components, with the exception of ALHA 81005, which, although Th-poor, is relatively magnesian [*Kallemeyn and Warren*, 1983]. The feldspathic regolith breccias are good candidates for samples from the central parts of the FHT. Among the lunar meteorites, only Calcalong Creek has a relatively Th-rich composition (~4.5 ppm [*Hill et al.*, 1991]), suggesting that it came from an impact into the PKT.

## 4. Discussion

### 4.1. Distribution of Th in the Procellarum KREEP Terrane

One of the key questions relating to the enrichment of Th in the PKT is what rock type or rock formation is the principal carrier of Th? From the Apollo 14 samples the Fra Mauro Formation as represented at that location is enriched in Th, and the dominant carrier is known to be impact-melt breccias, presumably derived from the Imbrium basin. We do not know the abundance and potential variability of KREEP basalt, nor do we know whether any of the mare basalts, themselves, have elevated Th concentrations. Also, we do not know how deep the Th enrichment goes, or whether it is a surface phenomenon, i.e., an impact-ejecta veneer.

The Apollo 12 site is one key to understanding what was mixed to produce some of the high-Th and high-FeO data within the PKT and what controls or constraints affect the limits of the data. The 5° equal-area "pixel" containing the Apollo 12 site comprises mostly volcanic material, yet the bulk Th concentration is high (7 ppm), and, not surprisingly, the Apollo 12 soils contain a Th-rich component. A plot of FeO versus Th concentrations for soil data [*Korotev and Rockow*, 1995] shows that the soil compositions extrapolate toward a KREEP-basalt or an Apollo 14-like soil or impact-melt component at 9–10% FeO and 14–16 ppm Th (Figure 9). The more basaltic soils extrapolate, at 20% FeO, to about 1–2 ppm Th, consistent with Apollo 12 basalt samples analyzed in the laboratory. The Apollo 12 soils do not reflect the presence of a Th- and FeO-rich basalt such as the glasses from Apollo 14 and Apollo 15 mentioned previously. The Th-rich component clearly is not some unusual Th-rich rock type such as lunar granite or quartz-monzodiorite or monzogabbro. However, the Th-rich component may be represented by ropy glass fragments found in the soils [*Wentworth et al.*, 1994]. The ropy glasses have compositions similar to Apollo 14 soil and a subset of impact glasses found in the Apollo 14 soil. Also, the Apollo 12 ropy glasses contain a variety of lithic clast types, including anorthosite, KREEP basalt, and felsite [*Wentworth et al.*, 1994]; thus they appear to represent impacted surface material similar to that exposed in the Fra Mauro Formation at the Apollo 14 site. At the Apollo 12 site, there may be crater materials from Reinhold, which excavated through mare basalt [see *Wilhelms and McCauley*, 1971], that have FeO concentrations around 12 wt %. This FeO concentration is consistent with the FeO content of KREEP basalt or Fra Mauro (or Alpes) materials that are dominated by Th-rich,

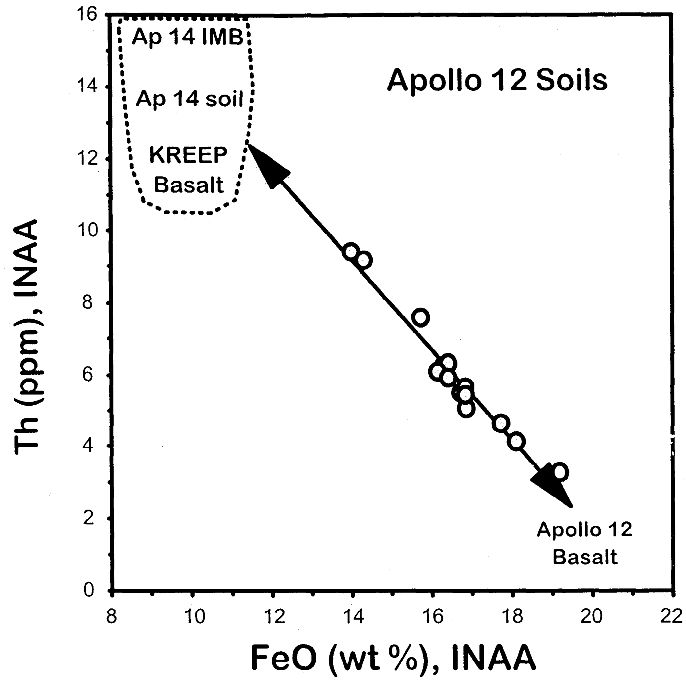


**Figure 9.** Concentrations of Th versus FeO in Apollo 12 soils determined by instrumental neutron activation analysis (INAA) [*Korotev and Rockow*, 1995]. The data extrapolate toward the composition of Apollo 12 basalt samples at the high-FeO end and toward the compositions of ropy glasses found in the soils [*Wentworth et al.*, 1994], which are similar to the bulk composition of Apollo 14 soil, and breccias and glasses contained therein [*Jolliff et al.*, 1991a].

mafic impact melt and mixed with a small proportion of mare basalt. Alternatively, the KREEP-bearing glasses at Apollo 12 may represent ray material from Copernicus, but in that case they would still represent a mixed Fra Mauro-like component. Materials excavated by Kepler and distributed onto surrounding mare plains are also Th-rich and probably represent buried Alpes Formation, similar to that exposed in the vicinity of the crater [*Gillis and Jolliff*, 1999].

Regarding the distribution of FeO and Th concentrations at the 5° scale, at issue is the nature and composition of the materials that form end-members for the rather tightly defined compositional fields (e.g., Figure 10). Mare basalt and KREEP compositions do not lie at the apices (FeO rich and Th-rich, respectively) of the roughly triangular envelope of data (Figure 10a). Judging from preliminary high-resolution (2° scale) Lunar Prospector data [*Lawrence et al.*, 1999b], there are localized areas within the PKT whose compositions extend toward that of KREEP basalt. From examination of the 5° data, however, we note that points within the PKT lying along the Th-rich edge of the distribution up to about 12 wt % FeO are mainly areas of rugged topography. As implied in Figure 10b, these points correspond in part to pre-Imbrium upper crustal material that now occurs as uplifted ring structures, material excavated from beneath mare basalts by relatively large craters such as Copernicus, Aristillus, and Kepler, and in part material ejected from the Imbrium basin, which represents a range of crustal depths extending to perhaps 60 km [see also *Haskin et al.*, 1999]. In the volcanic resurfaced areas, basalt and mixtures of basalt plus the underlying

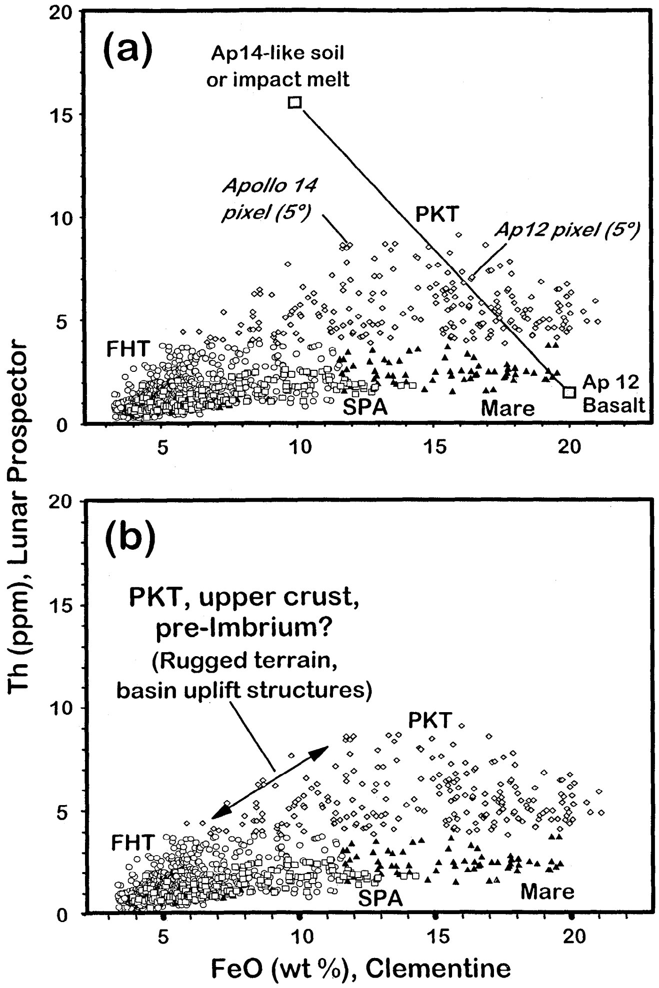


**Figure 10.** (a) FeO (derived from Clementine, UVVIS data) versus Th (Lunar Prospector gamma-ray data) for the Feldspathic Highlands Terrane (FHT), Procellarum KREEP Terrane (PKT), South Pole–Aitken Terrane (SPA), and mare basalt not associated with the PKT or SPA (data points are the same as in Figure 6, but the Th scale is expanded to 20 ppm). The Apollo 12 soil mixing line is copied from Figure 9, with Apollo 12 basalt at the FeO-rich end and a hypothetical KREEP basalt at 15 ppm Th and 10 wt % FeO at the other end. (b) Same plot as Figure 10a, but showing a hypothetical mixing line for upper crustal nonmare materials within the PKT. Data points lying along the Th-rich edge of the PKT data envelope correspond mainly to nonmare regions, such as basin uplift structures, basin ejecta formations, and otherwise rugged terrain.

KREEP basalt or impact melt, as well as overlaps with other nonmare materials, populate the distribution of data (i.e., >12 wt % FeO). Mixtures of the upper crustal materials plus KREEP basalt or impact melt, if present, would be rare, especially at the 5° scale, because the KREEP basalt and impact melt are likely to be low lying and covered by mare basalt. Thus impacts that expose KREEP basalt or impact melt tend to mix those materials with mare basalt, producing FeO-rich mixed deposits. We interpret the Th-rich side of the data envelope as bounded by the average compositions of large chunks of PKT midcrustal to upper crustal materials whose average FeO concentrations range from ~6 to >10 wt % and whose Th concentrations range from ~4 to >9 ppm. Evidence of heterogeneity on a large scale comes also from the variable nature of ejecta from Copernicus suggested by the FeO and Th maps.

### 4.2. Lunar Th Mass Balance

The fundamentally distinctive feature of the PKT that sets it apart from the rest of the lunar crust is the concentration of Th and, by inference, the other heat-producing elements, U and K. As argued here and by *Wieczorek and Phillips* [1999a, this issue], this characteristic has great significance for the thermal evolution of the underlying mantle as well as for the plutonic and volcanic evolution of the corresponding crustal section. A simple calculation of the Th mass balance between the different major terranes, the crust and mantle, and the bulk Moon places some constraints on the concentration of Th throughout the depth of crust associated with the PKT.

Using simplifying assumptions about the bulk Th content of the Moon and the thickness of the crust, upper and lower mantle, and a possible core, coupled with the proportions of the major crustal terranes as exposed at the lunar surface, we can explore the implications of specific concentrations of Th in different regions. Using a series of concentric spherical shell sections coupled with proportions of terranes as exposed at the surface, the volumes associated with key regions can be estimated (Tables 2 and 3). Assumed densities and Th concentrations used for this mass balance are also given in Tables 2 and 3. The values shown are only one example of a set of (nonunique) starting conditions that may be used to investigate the plausibility of some of the assumptions and results.

For the purpose of discussion, we calculate the distribution of Th in the crust as summarized in Table 2. We take the thickness of the crust in the PKT to be 60 km, which is consistent with limited seismic data and with geophysical modeling of the gravity field [*Neumann et al.*, 1996; *Wieczorek and Phillips*, 1998a, 1999b]. We assume the crustal section beneath SPA to be 40 km thick [e.g., *Wieczorek and Phillips*, 1999b] and the FHT to average 90 km thick beneath the central anorthositic region and 70 km elsewhere. These thicknesses yield an integrated average crustal thickness of 70 km, which is somewhat greater than the 61 km average computed by *Neumann et al.* [1996] and the 66 km average obtained by *Wieczorek and Phillips* [1998a] from single-layer models.

The whole-Moon Th concentration is sensitive to several parameters, mainly the volume of the PKT (or the volume in which elevated Th concentrations occur), the average Th concentration of the PKT, the average Th concentration of the FHT, and the Th concentration of the mantle. Some of the effects of varying these parameters are shown in Figure 11.

Although mantle Th concentrations are not known directly, they can be estimated from Th concentrations of mare basalts and pyroclastic glasses, and because the mantle accounts for about 90% of the mass of the Moon (Table 2), the mantle Th content can not be ignored. To avoid the effects of assimilation or other potential secondary enrichment processes on Th concentrations of mare basalts, we consider only the picritic glasses. Using values at the lower end of the range for Th concentrations in the picritic glasses (using the REE as analogues for Th, and from compilations by *Taylor et al.* [1991] and *Papike et al.* [1998]), we may estimate the concentration of Th in the mantle from which the picritic glasses derived. Assuming a range of bulk $D$ values of 0.02 to 0.05 for melt in

**Table 2.** Example Th Concentrations and Volumes Used to Calculate Th Mass Balance

| | Th, ppm | Surface Area, % | Depth, km | Volume Adjusted | Volume % (crust) | Density, g cm$^{-3}$ | Mass, % | Sum, mass % | % Th (crust) | |
|---|---|---|---|---|---|---|---|---|---|---|
| FHT-An* | 0.3 | 24.8 | 90 | $9.86\times10^8$ | 41.3 | 2.85 | 40.3 | 84.5 | 53.6 | (FHT total) |
| FHT-O* | 1.0 | 48.2 | 70 | $1.12\times10^9$ | 43.7 | 2.95 | 44.2 | | | |
| PKT undiff. | 4.8 | 10.0 | 60 | $2.20\times10^8$ | 8.5 | 3.03 | 8.9 | 8.9 | 40.4 | (PKT total) |
| SPAT-inner | 1.4 | 5.3 | 40 | $7.87\times10^7$ | 3.1 | 3.05 | 3.2 | 6.5 | 5.8 | (SPAT total) |
| SPAT-outer | 0.7 | 5.7 | 40 | $8.46\times10^7$ | 3.3 | 2.95 | 3.3 | | | |
| Other mare† | 2.2 | 6.0 | 1 | $2.28\times10^6$ | 0.1 | 3.10 | 0.1 | 0.1 | 0.2 | (other mare) |
| Average crust‡ | 1.05 | | 70 | $2.55\times10^9$ | | 2.93 | | | | |

*Th values for FHT-An and FHT-O assume that the average Th concentrations of surface materials as given in Table 1 represent a veneer that incorporates material added by Imbrium ejecta [*Haskin et al.,* 1999] Otherwise, FHT-O is taken to be representative of material in the lower 40 km throughout the terrane. To calculate the adjusted volumes, the FHT-An is taken to be 50 km thick above 40 km of lower crust with the composition of FHT-O. In this example the outer part of the FHT is taken to have a thin veneer of basin ejecta over an upper crust (30 km) of FHT-An composition and a lower crust of FHT-O composition. Also, compared to Table 1 values, the surface area of the PKT is reduced to 10% to compensate for lateral distribution of Th-rich material by multiple basin impacts.

†"Other mare" refers to prominent, basin-filling mare basalt located within the boundaries of the FHT. For these calculations, "other mare, mare-nonmare mixed" pixels of Table 1 have been distributed between "other mare" and "FHT-O."

‡The volume listed for "average crust" is the sum of the individual terranes.

Densities are estimated.

equilibrium with an olivine-pyroxene residue (see *Snyder et al.* [1995b] compilation of mineral/melt *D* values), the measured Th concentrations of 0.2–0.5 ppm for Apollo 15 green glass and Apollo 17 orange glass, respectively [*Taylor et al.,* 1991; *Korotev,* 1998], indicate mantle residue compositions as low as 0.005–0.025 ppm Th, significantly less than the value of 0.04 ppm in the Th mass-balance model of Table 3. At the high end of the range, however, picritic glasses that have Th concentrations 50–100 times chondrite levels may have been derived from mantle sources of significantly higher Th concentration, e.g., 0.13 ppm. If we assume that the source regions of higher Th concentration are localized beneath the PKT, making up some 15% of the mantle volume, then 0.04 ppm is a reasonable estimate of the bulk-mantle Th concentration. At 0.04 ppm the mantle (lower plus upper) would contain only on the order of 20% of the Moon's Th.

Using the surface areas as shown in Table 1 to calculate the crustal Th mass balance and adding a mantle component yields a bulk lunar Th concentration of 0.168 ppm. This estimate is significantly greater than the 0.125 ppm estimated by *Taylor* [1982], the ~0.07 ppm estimated by *Rasmussen and Warren* [1985] and *Warren and Rasmussen* [1987], and the 0.112 ppm estimated by *Drake* [1986]. This value can be reduced significantly if the surface area of the PKT is less than it appears from the surface distribution of Th. This is likely to be the case, especially if one considers that some 8–10 basin impacts have struck the PKT region [*De Hon*, 1974; *Wilhelms*, 1987; *Spudis*, 1993], and especially if there was a giant Procellarum impact event [e.g., *Wilhelms*, 1987]. In the model described below, we assume that lateral mixing as a result of basin impacts within the PKT has increased its areal distribution by 50%; thus we reduce its areal signature from 16.7% (Table 1) to 10% (Table 2).

Furthermore, the crustal Th concentrations used in the model reflected in Table 2 are based on a presumption that the surface exposures of the SPAT and the FHT were contaminated significantly by Th-rich Imbrium ejecta [*Haskin*, 1998; *Haskin et al.,* 1999; *Haskin et al.*, submitted manuscript, 1999]. Thus the Th concentrations shown in Table 2 are lower than those that characterize surface materials, as listed

**Table 3.** Mass Balance for Whole-Moon Th Content

| | Thickness, km | Volume, km$^3$ | Density, g cm$^{-1}$ | Mass, % of total | Th,* ppm | % Th (whole Moon) |
|---|---|---|---|---|---|---|
| Whole Moon | 1738 | $2.20\times10^{10}$ | 3.34 | 100.0 | 0.142 | |
| Core | 300 | $1.13\times10^8$ | 4.20† | 0.7 | 0.00 | 0 |
| Lower mantle (LM) | 968 | $8.43\times10^9$ | 3.45 | 39.4 | 0.04 | 11.1 |
| Upper mantle (UM) | 400 | $1.09\times10^{10}$ | 3.35 | 49.7 | 0.04 | 14.0 |
| Crust (average) | 70 | $2.55\times10^9$ | 2.92 | 10.2 | 1.05 | 74.9 |

*Values for the core and mantle Th concentrations are assumed (see text). The crustal average Th concentration of 1.05 ppm is the output from Table 2. The Th mass balance for the whole Moon is the sum of the mass fraction of each section of the Moon times its average Th concentration.

†Core density from *Taylor* [1982].

According to this model, the whole-Moon Th concentration would require a bulk Moon of ~5 times the CI chondritic average Th concentration (29.4 ppb; [*Anders and Grevesse*, 1989]).

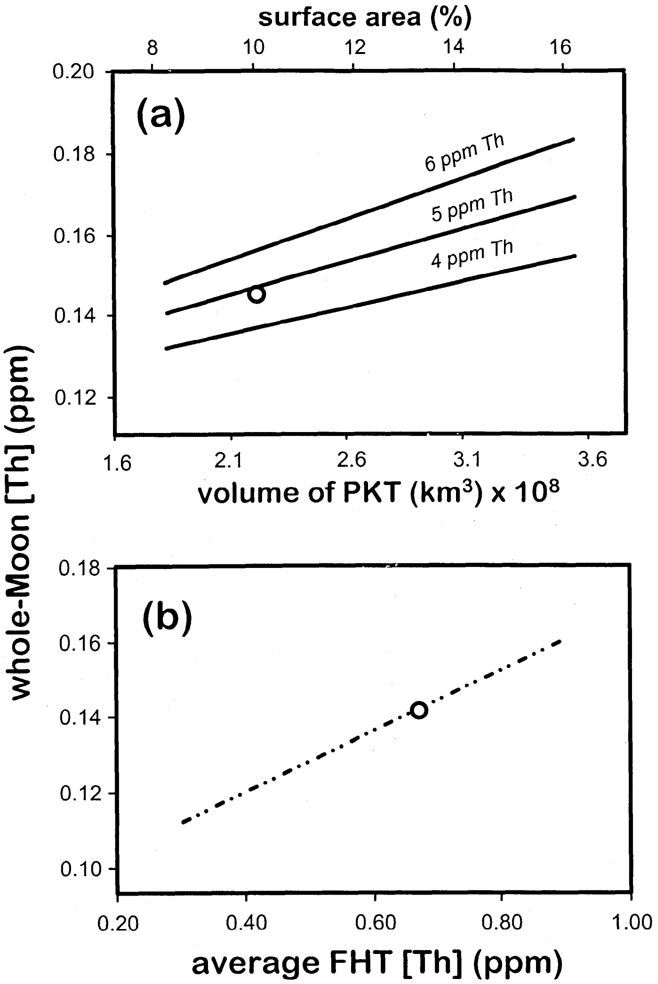


**Figure 11.** Variation in calculated whole-Moon Th concentration as a function of varying key parameters in Th mass balance. (a) Whole-Moon Th concentration as a function of volume of the Procellarum KREEP Terrane (PKT) and average Th concentration within the PKT. The volume of the PKT may vary either because its true depth is <60 km or because its areal extent is less than the 14.3% estimated herein (filled circle; conditions as in Tables 2 and 3). The variations in volume corresponding either to depth of the PKT or to its areal extent are indicated by the superimposed scales. (b) Variation of whole-Moon Th concentration as a function of the average Th concentration within the Feldspathic Highlands Terrane (FHT). The average concentration of FHT Th corresponding to the model reflected in Tables 2 and 3 is 0.67 ppm (filled circle).

in Table 1. For example, if the Th concentration of the FHT-An were as low as 0.25 ppm, similar to the feldspathic lunar meteorites, and the Th concentration of the lower crust of the FHT as represented by FHT-O (Table 1) were as low as 0.5 ppm, the bulk crustal Th content would be equivalent to about 0.11 ppm for the whole Moon. To further reduce the estimate of bulk Moon Th concentrations significantly would require an average PKT Th concentration substantially less than 5 ppm; minor changes in the average mantle Th concentration make little difference.

Given these assumptions and an average Th concentration of 4.8 ppm for the entire PKT throughout its 60 km thickness, the amount of Th sequestered in the PKT would be about 40% of the Th in the crust, the FHT would contain 54%, and the SPAT would contain ~6%. At these values the Th concentration in the crust alone would correspond to a whole-Moon concentration of 0.107 ppm, and with the addition of mantle Th the global Th concentration would be 0.142 ppm. Adding a similar mantle component as above to the *Drake* [1986] crustal estimate would yield 0.147 ppm bulk Moon Th, which is in close agreement with our estimate.

The preceding discussion treats the terranes in terms of average Th concentrations. We emphasize, however, that rock samples from the Apollo sites provide evidence of a range of Th concentrations for crustal materials within the PKT. Impact-melt breccias such as those sampled at Apollo 14 and 15 have compositions that reflect integrated crustal sections exhumed by basin impacts (i.e., Imbrium). Some of these impact-melt breccias have Th concentrations >15 ppm. Apollo 15 KREEP basalts, which are compositionally very similar to the mafic impact-melt breccias, have 12–14 ppm Th, and a few rare, KREEP-like rocks have even higher Th concentrations (Apollo 12 KREEP basalt 12023,118: 49 ppm [*Laul*, 1986]; Apollo 16 ultraKREEP impact melt: 21–36 ppm Th [*Lindstrom*, 1984]; and Apollo 14 ultra-KREEP impact melt 14161,7233: 50 ppm Th [*Jolliff*, 1998]). Thus it is likely that some regions of the PKT crust have local Th concentrations well in excess of 5 ppm and others have less.

The mass-balance model described above is driven by Th concentrations at the surface, as indicated by remote sensing and by the Th concentrations of sampled lunar materials. Using reasonable inputs, we obtain a bulk Moon Th concentration of 0.142 ppm, similar to the estimate stemming from the analysis of *Drake* [1986]. Although some of the assumptions of our mass-balance model are debatable, this result supports Taylor's [1982] contention that the bulk Moon is enriched in Th, a refractory trace element, relative to the primitive Earth mantle. Using a Th/U ratio of 3.67 [*Korotev*, 1998], a Th concentration of 0.142 ppm translates to a U concentration of 0.039 ppm, again supporting higher estimates such as that corresponding to the upper end of the range predicted on the basis of heat-flow measurements [*Langseth et al.,* 1976; *Keihm and Langseth*, 1977, as reviewed by *Drake*, 1986]. Although these values, considered as global estimates, are within the limits suggested by the heat-flow measurements, we note that if Th and U are as strongly concentrated within the PKT as suggested herein, then present day heat flow in some regions of the PKT would be expected to be several times higher than what was measured at the Apollo 15 site but the whole Moon should be much lower.

### 4.3. Implications for Crust-Mantle Interactions

Figure 12 illustrates schematically some of the possible relationships that we infer to exist at depth in the crust associated with the PKT, along with some possible mantle connections. The key petrogenetic driver is the concentration of Th and other heat-producing elements (U and K) within the PKT and their dearth in other parts of the Moon, particularly the mantle, and in the Feldspathic Highlands Terrane of the crust. The importance of this was recognized and considered by *Wasson and Warren* [1980] in their evaluation of nearside – farside asymmetry and in a subsequent series of papers [*Rasmussen and Warren*, 1985; *Warren and Rasmussen*, 1987; *Warren et al.*, 1991]. It now appears that the asymmetric distribution is such that Th is highly localized within the PKT

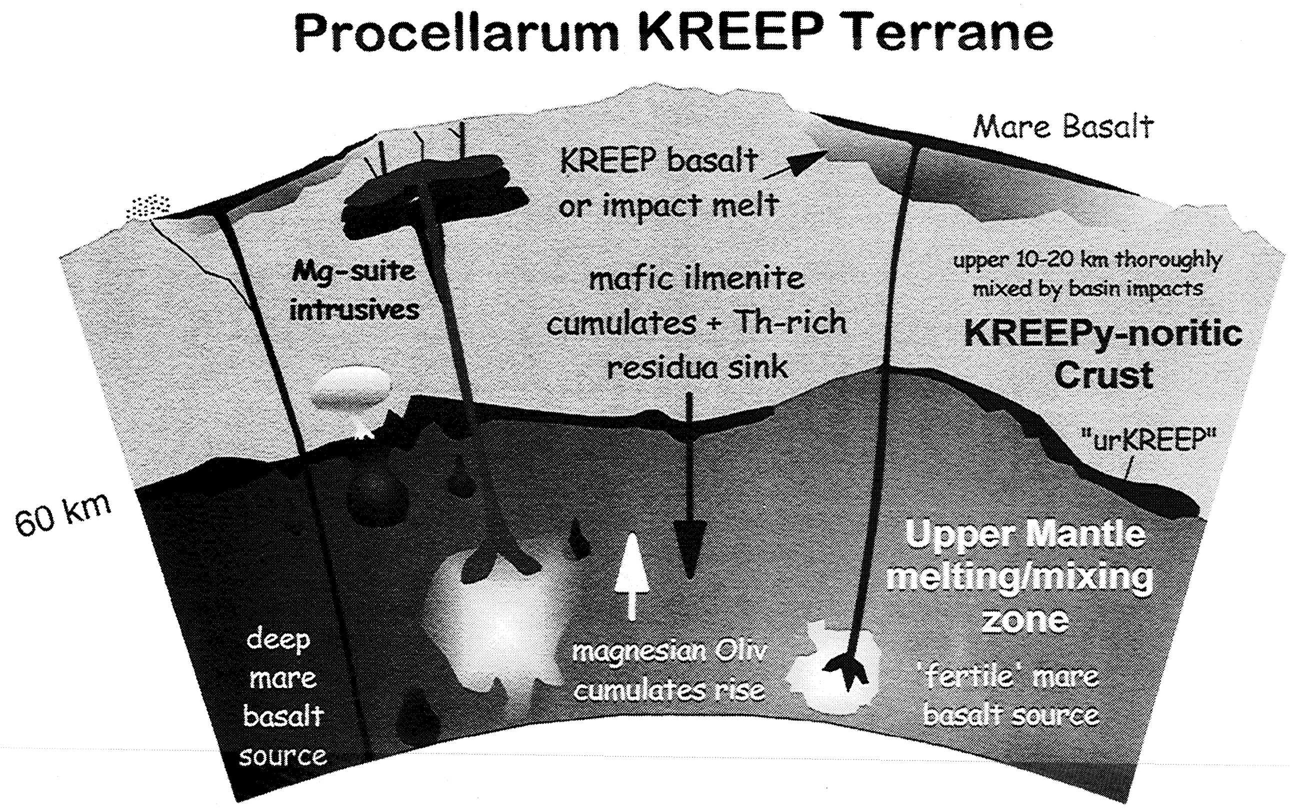


**Figure 12.** Schematic cross section of the Procellarum KREEP Terrane. In this region the crust is taken to be ~60 km thick and consists throughout its entire thickness of relatively mafic, Th-rich material. As depicted in this figure, the lower crust in this terrane was where the urKREEP residue of early differentiation (magma ocean) became concentrated. It would have been associated with ilmenite and ferropyroxene cumulates that sank and interacted with the underlying mantle. Such residua would have provided fertile melting zones within the upper mantle for mare basalts or may have reacted with magnesian olivine-rich cumulates brought to the upper mantle by density inversion. Deep-sinking, Th-bearing residua may have provided an additional heat source to assist melting of otherwise refractory mantle cumulates. The differentiation of segregated bodies of urKREEP as well as of magnesian-suite intrusives that had KREEP-like parent magmas gave rise to the alkalic suite of lunar rocks in this terrane. Only one magnesian-suite intrusive complex is illustrated; however, we envision many such intrusives occurring throughout this terrane.

and the underlying slice of the mantle. Key questions are when and how did this highly localized distribution develop?

By the simple mass-balance calculations described above, the PKT, which constitutes only about 10% of the mass of the crust, would have contained some 40% of the crustal Th, which amounts to about 30% of the entire Th budget of the Moon (compare to 40% estimated by other means by *Korotev* [this issue]). As described below, this concentration of Th may not necessarily be sequestered solely within the crust, but may have been transferred in part to the underlying mantle by means of sinking late stage, Fe- and Ti-rich magma-ocean cumulates and by interaction with magnesian cumulates brought to the upper mantle by convective overturn in the manner described by *Ryder* [1991].

We hypothesize that the PKT is and always was fundamentally different from the FHT, and that it may never have had a thick upper layer of anorthositic rock [see also *Korotev*, 1999b, this issue]. Judging from the composition of sampled basin ejecta in the form of mafic impact-melt breccias and igneous rocks that occur as lithic clasts in breccias, the nonmare components of the PKT appear to be relatively mafic near the surface (e.g., noritic) as well as mafic to a depth of tens of kilometers. Furthermore, the PKT may be the source of essentially all materials with the KREEP chemical signature and may be the main source of the magnesian-suite intrusive rocks [e.g., *Korotev*, 1999b, this issue]. According to this hypothesis, both the FHT and the PKT are results of magma-ocean solidification. It follows from this hypothesis that a simple mare-highlands dichotomy of lunar rock types is no longer appropriate; rocks exist in the Apollo collection (e.g., Th-rich impact-melt breccias and KREEP basalt) that are of neither mare nor highlands origin in the conventional sense because of their specialized petrogenesis within the PKT.

We envision the PKT as having been a dynamic environment, a long-lived hotspot as a consequence of internal heat from the high concentrations of Th, U, and K. Intrusive magmatism as well as mare volcanism continued within the boundaries of this terrane from the end of early differentiation (magma ocean) to the end of resurfacing by the youngest mare basalts (e.g., extending to 1.1 Ga, [*Schultz and Spudis*, 1983]). Deep within the crust, dense, mafic, Th-rich residua, which logically would have been associated with ilmenite

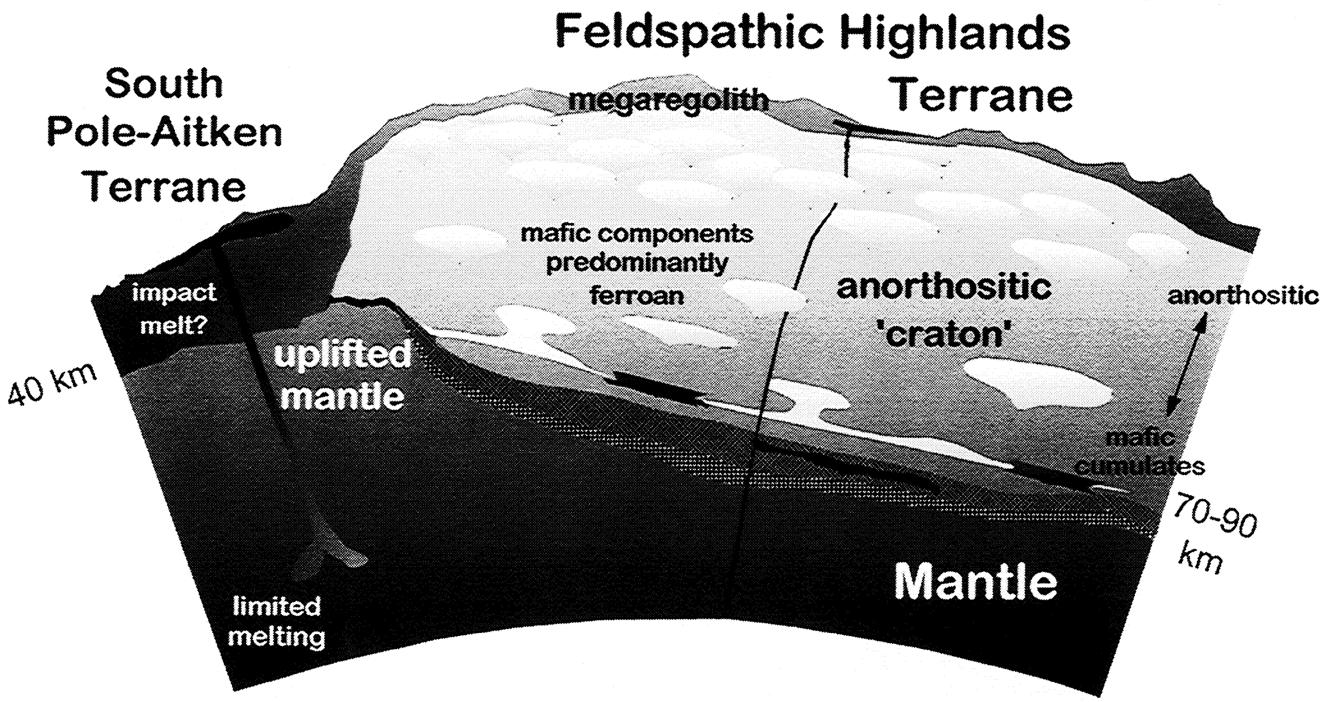


**Figure 13.** Schematic cross section of the Feldspathic Highlands Terrane (FHT) and South Pole–Aitken Terrane (SPAT). The central anorthositic region of the FHT represents the thickest parts of the lunar crust, and, judging by the makeup of the feldspathic lunar meteorites, it is composed dominantly of ferroan-anorthositic-suite rocks. The terrane is surfaced by a thick megaregolith consisting partly of basin ejecta, which is especially thick adjacent to the SPA basin, and including a late, Th-enriched veneer from Imbrium, mixed with the ferroan, noritic-anorthosite substrate. Bodies of locally concentrated residual melt that gave rise to more mafic rocks such as anorthositic norite or gabbro may occur throughout the terrane or they may have segregated downward owing to gravitational instability. Basin ejecta from the outer, thinner parts of the FHT suggest that the terrane is more mafic at depth. As depicted in this figure, SPA, although considered here to be a separate terrane, may simply have excavated the lower crust that is otherwise typical of the FHT. Regions such as Australe may be analogous but on a smaller scale.

cumulates [*Ringwood and Kesson*, 1976; *Hess and Parmentier*, 1995], exchanged with upper mantle, magnesian, olivine-rich cumulates, brought up by density inversion, or perhaps deep-sinking residual material provided a heat source for otherwise barren cumulates [*Ringwood and Kesson*, 1976; *Ryder*, 1991; *Parmentier and Hess*, 1999]. Mafic, incompatible-element-rich residua from the dregs of differentiation of the crust and mantle provide a ready source of heat for remelting to generate magnesian- and alkali-suite magmas and mare basalts. Modeling by *Wieczorek and Phillips* [this issue] shows that a concentration of heat-producing elements equivalent to a 10 km thick layer of KREEP within the PKT would produce a thermal perturbation capable of inducing melting in the underlying mantle for much of the Moon's history. It provides a heat source to generate mare basalts, and the fact that most basalts are located in the PKT is consistent with this model. However, if physical mixing were involved, such basalts should also bear a signature of KREEP contamination. Judging by surface Th concentrations sensed remotely, some of the basalts, particularly some of the younger ones, may be more enriched in Th than the typical basalts that were sampled by the Apollo program. Such Th enrichment in the basalts themselves would be expected unless radiogenic heating was purely by conduction. Other than a few FeO-rich basaltic impact glasses, however, no high-Fe crystalline mare basalts that have >4 ppm Th have yet been found among the Apollo 12, 14, or 15 samples where we might expect to find at least some fragments in the soils.

*Parmentier and Hess* [1999] further suggested that the process of downwelling of dense residua may have been the driving force that led to global volcanic and compositional asymmetry and that, with continued heating amid cooling cumulates, masses of sunken residua would develop thermal buoyancy, rise, and initiate remelting. Others have suggested a process driven by tidal forces or a process somehow effected by an early giant impact (i.e., Procellarum [*Wilhelms*, 1993]). There is as yet no firm theoretical basis for melt migration related to tidal forces, and the existence of a giant Procellarum impact has been disputed [*Spudis*, 1993; *Zuber et al.*, 1994]. *Wasson and Warren* [1980] concluded that the global asymmetry was a consequence of heterogeneous solidification of the magma ocean and that crustal asymmetry would be mirrored by mantle heterogeneity. Along similar lines, we offer that the asymmetry may have developed in conjunction with the formation of the FHT, with mafic residua perhaps forced to the margins (laterally and at depth) of the central anorthositic craton. This differs from the anorthositic-continent model discussed by Wasson and Warren, wherein the anorthositic material provided thermal insulation over the nearside of the Moon, keeping the residua molten for a longer period of time and allowing extensive differentiation to produce urKREEP.

The Feldspathic Highlands Terrane (Figure 13) lacked significant concentrations of heat-producing residua to effect melting in the underlying mantle, and, as a result, magmatic activity subsequent to early differentiation was minimal. The extensive region of the farside that makes up the central anorthositic region of the FHT, which is dominated by highly feldspathic surface exposure, is possibly the surface expression of an ancient, ferroan "supercontinent." We envision such an anorthositic mass as essentially an extension of the anorthositic rock-berg concept of *Longhi and Ashwal* [1985]. This mass is anorthositic toward the surface and becomes more mafic with depth, as evidenced by the haloes of more FeO-rich ejecta surrounding basins in other parts of the FHT (average FeO of ~6 wt % (BE in Table 1), such as can be seen in the FeO map around the Crisium and South Pole–Aitken basins). The deeper, mafic materials are most likely dominated by the pyroxene-rich mafic complement of the anorthositic rocks, i.e., ferroan noritic or gabbroic rocks as opposed to the more magnesian LKFM [see also *Korotev*, this issue]. The anorthositic nature of the upper tens of kilometers of the FHT presumably results from a combination of effects related to density, beginning with the positive buoyancy of anorthositic cumulates. Local concentrations of mafic trapped melt may have coalesced to form small mafic plutonic bodies; however, once solidified, they would have been gravitationally unstable and may, during the first 100 Myr or so, while the crust was sufficiently hot, have foundered and settled into the lower crust or to the crust-mantle boundary [*Hess and Parmentier*, 1997].

The idea that magnesian-suite intrusive rocks (and the alkalic suite as well) are concentrated with the PKT and not at depth within the FHT is supported by studies that show many of these rocks to be of relatively shallow origin [e.g., *McCallum and O'Brien*, 1996] and to have mineral compositions that are consistent with crystallization from KREEP-like parent magmas [*Longhi*, 1989; *Papike et al.*, 1994, 1996; *Snyder et al.*, 1995a, b], even if their bulk compositions are not KREEP-like.

South Pole–Aitken basin is also shown schematically in Figure 13; the similarity of FeO concentrations between the outer parts of the SPAT and the basin-ejecta modified parts of the FHT suggest that the SPAT may simply have exhumed the deeply exposed lower crust that otherwise characterizes the FHT. The material that comprises the basin floor, in the inner parts of the SPAT have FeO concentrations greater than any known crustal rock types and it appears from their Th concentrations that they are not simply "LKFM" (defined in this case as the moderately Th-rich material of a group of Apollo impact-melt glasses and rocks [e.g., *Vaniman and Papike*, 1980]), thought by some to be the type material of the lunar lower crust. We can not rule out the possibility that they are a mixture of mantle rocks plus an LKFM-like lower-crustal component. Although local pockets of intercumulus mafic rocks containing heat-producing residua may reside within the FHT, they are probably not abundant. Where mafic rocks were exhumed by deep impacts, such as, for example Tsiolkovsky [*Tompkins and Pieters*, 1999; *Pieters and Tompkins*, 1999], their extent appears to be limited. In the case of SPA, the ensuing mantle uplift may have contributed to local, minor generation of melting and mare basalt production if the impact event occurred early enough that the underlying mantle was still hot or even partially molten.

## 5. Conclusions

In this paper, we divide the lunar surface into three major terranes, the Procellarum KREEP Terrane (PKT), the Feldspathic Highlands Terrane (FHT), and the South Pole–Aitken Terrane (SPAT), largely on the basis of geochemical, petrologic, and geophysical criteria that indicate each terrane experienced a fundamentally different geologic evolution. Two of these, the PKT and the FHT, owe their differences to a global-scale differentiation developed during the magma-ocean stage. The PKT, which constitutes only about 15% or less of the crust, owes much of its unique character to the sequestration there of a large portion of the Moon's radioactive heat-producing elements. Mass balance models for Th that are based on surface expressions of the terranes indicate that some 75% of the Moon's Th is located within the crust and that 40% of this occurs within the PKT.

Comparing the range of FeO concentrations calculated from Clementine UVVIS data and Th concentrations from the low-resolution Lunar Prospector GRS data to the Apollo samples and lunar meteorites, the known samples appear to cover most of the range of remotely sensed compositions. However, the remotely sensed data indicate the occurrence of relatively Th-rich (5 ppm or greater) basalts in the Procellarum region, which remain unsampled, except perhaps indirectly by Apollo 14 and 15 impact glasses. Although many Th-rich (i.e., >15 ppm) nonmare rock types exist, the remotely sensed data do not support widespread exposures of such materials having Th more concentrated than the Fra Mauro Formation soils as sampled at the Apollo 14 site. The feldspathic lunar meteorites are good candidates for samples of regolith developed within the FHT; however, there appear to be no candidates among the Apollo impactite samples or lunar meteorites for mafic materials from the SPAT.

The strongly asymmetric character of the lunar crust has several first-order implications for the Moon's thermal and magmatic evolution:

1. As a result of the concentration of Th and other heat-producing elements in magma-ocean residual melt, and the association of that material with dense, ferroan ilmenite cumulates, the residua probably interacted with underlying mantle. The ilmenite cumulates plus residua would have been denser than magnesian mantle cumulates brought from depth by mantle overturn. Interactions between these two disparate source materials provided a potential source for magnesian-suite magmas that subsequently rose into the crust and which may therefore be concentrated now within the PKT.

2. Interaction of Th-rich residua within the sub-PKT mantle would also provide a source of heat and a flux to promote melting and sustain mare-basalt production, consistent with voluminous basalt production and inferred young ages of flows.

3. The dearth of Th and other heat-producing elements within the FHT and SPAT, even for materials that appear to characterize the deep portions of these terranes, is consistent with reduced production of mare basalts.

4. Ferroan-suite mafic lithologies, which appear to be increasingly more abundant in the deep crust, may be associated mainly with the FHT.

5. Concentrations of FeO within the SPAT suggest that the rocks there include a mafic component derived from the upper mantle, and Th concentrations are consistent with materials typical of the lower crust of the FHT but are less than expected if composed mainly of the rock type referred to as LKFM. Thus South Pole–Aitken floor materials remain a high-priority target for future investigations.

The determination of Mg concentrations from the Lunar Prospector GRS data potentially will provide a test of several of these inferences.

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