THE HIGH-TH OVAL REGION OF THE MOON. LARRY A. HASKIN, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, One Brookings Drive, St. Louis, MO 63130. (lah@levee.wustl.edu)

As is well known to lunar scientists, the Apollo γ-ray experiments detected low surface concentrations of Th (~0.2 - 1.5 parts-per-million) over most of the highlands they overflew, but they encountered much higher concentrations (up to ~20 ppm) in the Oceanus Procellarum-Mare Imbrium region [1-8]. Metzger et al. [2] showed a graph of Th (and K) concentrations versus longitude with a concentration peak between 0 to ~80° W and a monotonic dropoff in both directions. The region of high Th is easily seen in color maps (e.g., Frontispiece Plate 1 [9]; Plate 10.1, [10]). Fig. 1 is a rough map of the gamma-ray observations, with a tentative outline of a broad region we will refer to as the High-Th Oval Region. Two areas of this proposed region were overflown by the Apollo γ-ray experiments.

On the Moon, the High-Th Oval Region appears to be a unique feature. The γ-ray experiments detected no other regions of comparably high surface Th concentrations; they found no highland areas (as defined in [3] distant from the High-Th Oval Region with Th concentrations higher than ~4 ppm (e.g., [10], Plate 10.1). In accord with ideas from [11] and inferences from [2] and [12], we suggest that the High-Th Oval Region is a Th-rich, mafic geochemical province, that we believe existed prior to the Imbrium impact. We have drawn tentative boundaries of the High-Th Oval Region (Fig. 1) to enclose all regions of the lunar surface in the Imbrium-Procellarum area with ≥4 ppm Th.

Enlightening spatial detail of regions showing relatively high Th concentrations has been provided by deconvolution of the γ-ray data [4, 5, 7, 8]. Some of the considerable variations in surface concentrations of Th within the High-Th Oval Region (Fig. 1) correlate with topographic features, e.g., highland material excavated from beneath surface lava flows by craters such as Aristarchus, Timocharus, Ptolemaeus. Others are associated with lava flows, either KREEP basalts (high Th) or regions covered by mare basalts (low Th) (for a general discussion, see [7]). The high Th concentrations are likely accompanied by high concentrations of all trace elements characteristic of the materials regarded as KREEPy; the U and K γ-ray data confirm this conjecture for those two elements [2]. We suggest this large group of incompatible trace elements is present in the High-Th Oval Region as a consequence of early lunar igneous differentiation. We also suggest that the variation in surface concentrations similar to those observed at present have been characteristic of the region since its inception.

According to magma ocean models of lunar crustal differentiation [e.g., 14], the final product of magma ocean solidification was KREEPy residual magma (urKREEP [15]). Warren [14] suggested that urKREEP is in pockets beneath the anorthosite layer. The limited coverage of the Apollo γ-ray experiments does not show the Th source to be obviously global, or at least not easily excavated. The γ-ray experiments did not observe high Th concentrations where they flew over ejecta deposits of deep basins such as South Pole-Aitken and Crisium (see [16] for elevations). The urKREEP source has not previously been regarded as restricted to, or mainly present in, the confines of the High-Th Oval Region, as we suggest here; Apollo 17 Th-rich mafic impact melt breccias are regarded by most investigators to be Serenitatis ejecta (e.g.,[16-18]). The Apollo γ-ray experiments did not pass over a Th halo surrounding Mare Serenitatis, however [3]. The lunar heat flow [19], the presence of substantial Th concentrations (but still <4 ppm) in some maria [3], and the high Th concentration in Apollo 11 high-K mare basalts (e.g., [20]) nevertheless indicate that K, U, and Th are widespread beneath the Moon's surface. High near-surface Th concentrations accessible to large crater or basin-sized impacts appear to be present only in the High-Th Oval Region.

As drawn (Fig. 1), the High-Th Oval Region covers about 5% of the Moon's surface. It probably does not contain more than a small fraction of the Moon's overall budget of KREEPy elements. Suppose, arbitrarily, that the heat flow in the High-Th Oval Region is 2-3 times that observed at the edges of the mare basins [19]. The U concentration of the bulk Moon has been estimated at 19 to 54 ppb [19, 21, 22]. If the lunar Th/U is chondritic (3.7, [23]), the estimated bulk Moon Th concentration is 70 to 200 ppb. If the "extra" Th near the surface of the High-Th Oval Region is present at an average concentration of 5 ppm, the thickness of the layer containing it (as required to produce the heat flow) is ~20 to 50 km.

Formation of the High-Th Oval Region as envisioned here seems to require lateral as well as vertical migration of Th and other KREEPy elements. An east-west difference in lunar rock compositions and an association of high-Th materials with the western lunar nearside is well known [e.g., 24] Wasson and Warren [25] have reviewed types of geochemical models that might produce a lateral compositional gradient in KREEPy materials on the lunar nearside. The fundamental mechanism they considered was fractional crystallization of a lunar magma ocean. Models they found most promising for lateral enrichment of the Imbrium-Procellarum area in urKREEP involve a floating continent [15] or an asymmetric core that developed during crystallization of the lunar magma ocean [26]. Shervais and Taylor [27] have also discussed lateral heterogeneity in the

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lunar crust and mantle, including the possibility that large basin-forming impacts might be the cause. A giant Procellarum impact event could perhaps have affected the development of the High-Th Oval Region by removal of overlying crust or deep injection of heat. Perhaps such an impact would trigger a major differentiation event such as mantle turnover involving material from the deep interior of the Moon. The high surface Th concentrations in the High-Th Oval Region have been interpreted in part as resulting from excavation by the Procellarum impact or by a series of smaller impacts [13], presumably into an urKREEP source. If a giant basin-forming event is somehow responsible for the existence or nature of the High-Th Oval Region, the connection to Procellarum is obscure, however. The borders of the High-Th Oval Region (as estimated here) do not match those of Oceanus Procellarum [13] or the pattern of continuous ejecta deposits of Imbrium. Also, the Procellarum Basin [13, 28, 29] remains hypothetical; its expected topographic profile is absent [16, 30]. Ideas for large-scale lateral enrichment in KREEPy elements have not been developed in detail, so no quantitative descriptions of these proposed processes are available for testing.

References: [1] Metzger et al., Science, 179, 800-803, 1973; [2] Metzger et al., PLSC5 1067-1078, 1974;[3] Metzger et al.PLPSC8 949-999, 1977; [4] Metzger et al., PLPSC10 1701-1718, 1979; [5] Metzger et al., PLPSC12 751-766, 1981; [6] Bielefeld et al., PLSC7 661-2676, 1976; [7] Haines et al., PLPSC9 2985-3011, 1978; [8] Etchegaray-Ramirez et al., PLPSC13 A529-A543, 1983; [9] Arnold et al., PLPSC8 945-948, 1977; [10] Spudis and Pieters, Lunar Sourcebook 595-632, 1991; [11] Evenson et al. PLSC5 1401-1417, 1974; [12] Tera et al. EPSL22 1-21, 1974; [13] Wilhelms, USGS Prof. Paper 1348, 1987; [14] Warren, Rev. Geophys. Space Phys. 13 201-240, 1985; [15] Warren and Wasson, Rev. Geophys. Space Phys. 17 73-88,1979; [16] Zuber et al., Science 266 1839-1843, 1995; [16] Wood, The Moon 14, 505-517, 1975; [17] Ryder and Wood, PLSC8 655–668, 1977; [18] Spudis and Ryder, Multi-ring Basins, PLPSC12 Part A, 133-138, 1981; [19] Langseth et al., PLSC7 3143–3171, 1976; [20] Haskin and Warren, Lunar Sourcebook 357–474, 1991; [21] Rasmussen and Warren, Nature 313, 121-124, 1985; [22] Drake, Origin of the Moon 105-143, 1986; [23] Anders and Grevesse, Geochim. Cosmochim. Acta 53, 197-214, 1989; [24] Warren and Wasson, PLPSC11 431-470, 1980; [25] Wasson and Warren, Icarus 44, 752-771, 1980; [26] Stevenson, Nature 287, 520-521, 1980; [27] Shervais and Taylor, Origin of the Moon, 173-201, 1986; [28] Cadogan, Nature 250, 315-316, 1974; [29] Whitaker, Conference on Multi-ring Basins, LPI Contr. 414 101-102, 1980; [30] Neumann et al., J. Geophys. Res. 101, 16,841-16,843, 1996.

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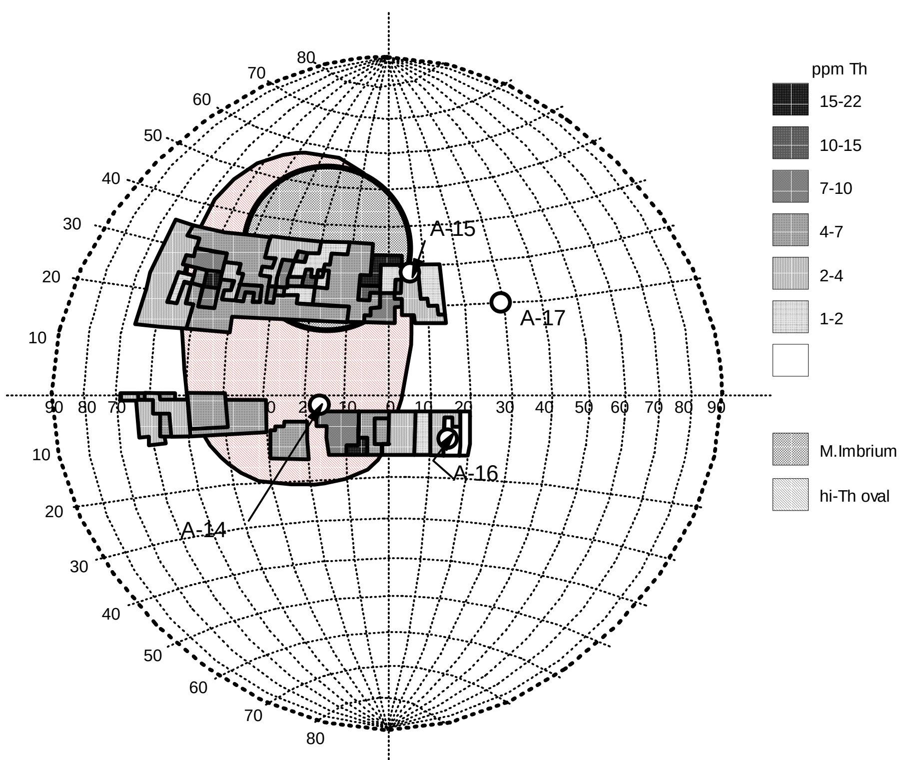

Fig. 1. Tentative outline of the proposed High-Th Oval Region, a possible geochemical province produced by the Moon's igneous differentiation. Outline contains all regions with ≥4 ppm Th [data from 1-9].