

LUNAR ‘KREEP’ IS DIVERSE AND LOCAL. A. H. Treiman. Lunar and Planetary Institute / University Space Research Association (3600 Bay Area Boulevard, Houston TX 77058; treiman@lpi.usra.edu).

Introduction: Many of the Apollo lunar sample are enriched in trace elements that are incompatible in igneous petrogenesis (i.e., ITE), and the relative abundances of these elements are constant across a wide range of rock types. This constancy led to the idea that these ITE represent a single chemical component that was added to other compositions – the KREEP component [1-3]. KREEP was explained as representing the last liquid dregs of the global lunar magma ocean (called urKREEP), preserved at the top of the lunar mantle [4].

However, lunar samples and remote sensing data show this model is incomplete. Lunar rocks enriched in ITE do not all have the same relative abundances of ITE elements [5]. And, ITE-rich material is not distributed globally. Some impact basins that should have penetrated and dispersed urKREEP show no evidence of KREEP in their ejecta or fill [6,7]. These data imply that lunar enrichments in ITE reflect local events, and so are not consistent with that model of the differentiation of a global lunar magma ocean.

KREEP is Diverse: The concept of KREEP came from minor and trace element data on Apollo lunar samples, many of which are enriched in ITEs. Their ITEs have similar relative abundances over a wide range of absolute abundances [1-3], Figure 1. Some meteorites have identical ITE patterns, like Sayh al Umhaymir (SaU) 169 and Northwest Africa (NWA) 4472. However, several groups of ITE-rich (KREEPy or KREEPic) lunar samples have different relative abundances of ITE. (Felsites, granophyres, etc., are excluded, as they could be enriched in ITE without a KREEP-like component.)

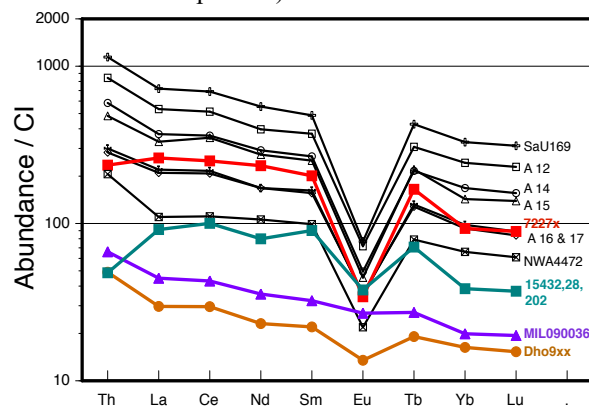


Figure 1. Th & REE in average or representative ITE-rich samples. Most Apollo KREEP samples, SaU169, & NWA 4472 in black [3,8,9]. Other data from: 722x5 [5], 15432 [10], MIL090036 [11], Dho9xx (925, 960, 961)[12,13u].

Most notable are samples from the Boulder 1, Site 2 of Apollo 17 (722x5, Fig. 1), which have flatter light REE patterns than typical Apollo KREEP, and $\text{Th/La} < 1(\times \text{CI})$ [5]. Another group, with steeper slopes in their light REE patterns (Fig. 1), includes the meteorites (and their pairs) Dhofar (Dho) 925, NWA 8673, and SaU 449, and maybe Miller Range (MIL) 090036 [11-13]. Another distinct group, with very low Th/Sm , includes the glass bead 15432, 28,202 [10] and meteorite Dhofar 287 [14].

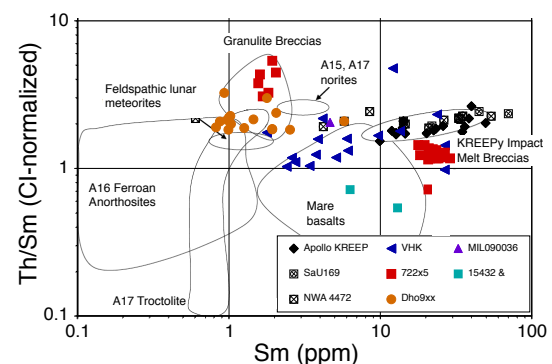


Figure 2. ITE abundances (as Sm) vs. enrichment of most incompatible ITE (Th/Sm) [15]. Apollo KREEP and related meteorites in black. See text for discussion. Data sourced across the literature.

Figure 2 compares overall ITE abundance (as Sm) of these samples with their relative enrichments of the most incompatible ITE (as Th/Sm) [15]. Apollo KREEP defines a trend of high Sm and Th/Sm increasing together. The trend of very high potassium (VKH) basalts [16] overlaps that of Apollo KREEP with the same slope (Fig. 2). Their trend is not consistent with component mixing, but rather igneous fractionation, i.e. progressive removal of material in which Sm is moderately incompatible and Th is highly incompatible.

Other samples have distinctly different ITE abundances. The 722x5 rocks have lower Th/Sm than Apollo KREEP [5]. The Dho and MIL samples have Th/Sm equal to or greater than Sm-rich Apollo KREEP, but at much lower Sm [17]. And the 15432 glass and Dhofar 287 have much lower Th/Sm . The granulites from 722x5 (~2 ppm Sm, $\text{Th/Sm}(\text{CI}) \geq 2$) are typical of many such across the moon [15]; they could represent a distinct ITE component, or could have been affected by a KREEP-related metasomatism [18].

Abundances of K provide another dimension to ITE variability, Fig. 3, in which the VKH [16] and Dho 9xx [12] are clearly distinct from Apollo KREEP.

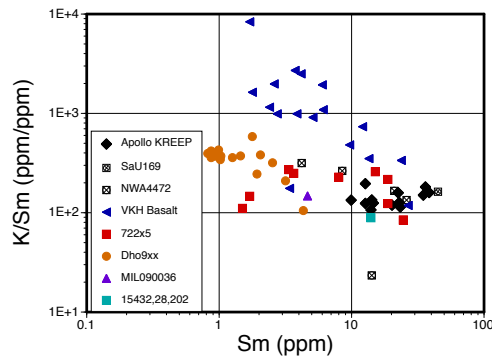


Figure 3. Potassium in ITE-enriched lunar rocks. Dho 9xx samples are enriched ~5-fold compared to Apollo KREEP (incl NWA4472 & SaU169). The 15432 glass has K/Sm like Apollo KREEP, despite its very low Th abundance (Figs 1, 2). Data sources as in Fig. 1, plus VHK basalts [16].

KREEP is Local: The early idea of a global layer KREEP layer was obsoleted by remotely sensed abundances of K, Th, and U on the lunar surface [7,19-21], which showed that ITE enrichment is centered on the Imbrium/Procellarum [22] and the South Pole Aitkin (SPA) basins (Fig. 4). ITE enrichment is clearly localized, in that that many basins large enough to have excavated an urKREEP layer (e.g., Orientale, Crisium, Moscoviense) show no or minimal ITE-enrichment in their ejecta or basin fills [6,19,23].

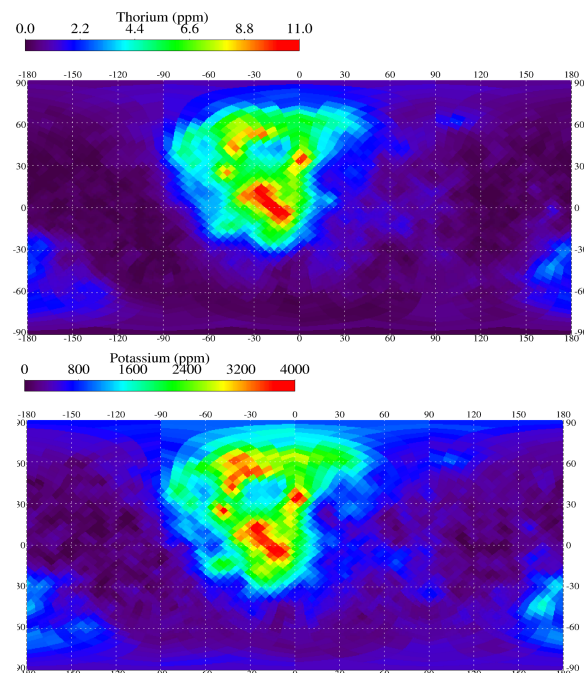


Figure 4. Abundances of Th and K across the lunar surface, calibrated Kaguya-GRS data [23]. SPA (lower right) has higher K/Th than the Procellarum region (upper center), consistent with the inference that the Dho 9xx group of meteorites (and pairs) and others come from the SPA [13,24,25].

Conclusions: Lunar rocks show a range of patterns of ITE-enrichment. The most common pattern is that of KREEP as defined for Apollo samples [2], but several other patterns are recognizable. ITE-enrichment is not ubiquitous across the Moon, but is localized around only a few large basins: Imbrium/Procellarum and SPA. No other lunar basins, independent of size or location, shows significant enrichments in the ITE. Further, the ITE associated with Imbrium/Procellarum (Apollo-style KREEP) is chemically distinct from that of the SPA basin (both from remote sensing and correlations with meteorites). VHK basalts are most abundant in the Apollo 14 area [5], and the 722x5 samples [16h] are likely not Imbrium ejecta but Serengetis (pre-Imbrium) material [26]. The source(s) of 15432,28,202 and NWA 278A are not known. Taken together, these observations suggest that ITE-enriched (i.e. KREEPy or KREEPic) lunar materials do not represent a single source (like the late differentiate of a magma ocean), but were generated in several independent batches in different locations.

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References: [1] Meyer C. Jr. et al. (1971) *Proc. Second Lunar Science Conference*, v. 1, 393-411. [2] Warren P.H. & Wasson J.T. (1979) *Rev. Geophys. Space Phys.* 17, 73-88. [3] Jolliff B.L. (1998) *Intl. Geol. Rev.* 40, 916-935. [4] Warren P.H. (1985) *Ann. Rev. Earth Planet. Sci.* 13, 201-240. [5] Salpas P.A. et al. (1987) *JGR:SolidEarth* 92, E340-E348. [6] Wieczorek M.A. et al. (2013) *Science* 399, 671-675. [7] Gillis J.J. et al. (2004) *GCA* 68, 3791-3805. [8] Joy K. et al. (2011) *GCA* 75, 2420-2452. [9] Gnos E. et al. (2004) *Science* 305, 657-659. [10] Ryder G. et al. (1996) *GCA* 60, 693-710. [11] Calzada-Diaz A. et al. (2017) *Meteoritics & Planet. Sci.* 52, 3-23. [12] Korotev R. (2012) *Meteoritics & Planet. Sci.* 47, 1365-1402. [13] Joy K. et al. (2014) *GCA* 144, 299-325. [14] Anand M. et al. (2003) *Meteoritics & Planet. Sci.* 38, 485-499. [15] Korotev R.L. et al. (2003) *GCA* 67, 4895-4923. [16] Shervais J.W. et al. (1985) *JGR:SolidEarth* 90, 3-18. [17] Korotev R. et al. (2009) *Meteoritics & Planet. Sci.* 44, 1287-1332. [18] Treiman A.H. et al. (2014) *Amer. Mineral.* 99, 1860-1870. [19] Warren, P. H. (2001) *Geophys. Res. Lett.* 28, 2565-2568. [20] Zhu M.-H. et al. (2013) *Scientific Reports* 3, 1611. [21] Yamashita N. et al. (2010) *Geophys. Res. Lett.* 37, L10201. [22] Haskin L.A. (1998) *J. Geophys. Res.* 103, 1679-1689. [23] Forni O. et al. (2010) *E.P.S.C. Abstracts* 5, EPSC2010-556. [24] Jolliff B.L. et al. (2009) *LPSC 40th*, Abstr. #2555. [25] Zeigler R.A. et al. (2013) *LPSC 44th*, Abstr. #2437. [26] Hurwitz D. & Kring D.A. (2016) *EPSL* 436, 64-70.