**ON THE ORIGIN OF THE MOON'S FELDSPATHIC HIGHLANDS, PURE ANORTHOSITE, AND THE FELDSPATHIC LUNAR METEORITES.** R. L. Korotev, B. L. Jolliff, and R. A. Zeigler, Campus Box 1169, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis MO 63130; korotev@wustl.edu

Results reported by Ohtake et al. [1] are stunning and potentially have great petrologic significance. Using the Kaguya multiband imager and spectral mixing procedures, the team investigated "crater central peaks, walls, ejecta and basin rings," that is, outcrops of rock where there is little regolith. They observed numerous locations in the highlands where "anorthosite composed of nearly 100% anorthite is found in large exposures." They also noted a strong correlation between PAN ("purest-anorthosite," >98% plagioclase) rocks and crater size. They conclude that "PAN rocks are ubiquitously present within the depth range from 3 km to at least 30 km" and that "a global layer of PAN rock may exist within the upper crust." The results are important because the generation of pure anorthosite requires very efficient separation of plagioclase from coexisting (mafic) melt. At issue is whether anorthosite forms a global layer or it occurs as discrete intrusive bodies, similar to terrestrial Proterozoic massif anorthosites. Here we consider these observations within the context of the feldspathic lunar meteorites, which are a sample suite dominated by components of the Moon's upper crust.

The observation of anorthosite with >95% plagioclase has been made before. Hawke et al. [2] report numerous regions of anorthosite with <5% pyroxene exposed at the surface on the basis of Earth-based telescopic, Galileo, and Clementine spectral reflectance data. They conclude "The distribution and modes of occurrence of anorthosites clearly indicate that a thick, global layer of anorthosite is present at various depths beneath most portions of the lunar surface." Then there are the Apollo samples. The 269-g rock sample 15415 from Apollo 15 is pure plagioclase. Several equivalently large rocks from the Apollo 16 mission are nearly pure plagioclase. The question is how large and how pure are the bodies from which these anorthosites derive?

To address this question from a sample perspective, we consider the ~37 meteorites that originate from randomly distributed locations in the feldspathic highlands [3–6]. All of the feldspathic lunar meteorites are breccias and most consist of lithified regolith and fragmental near-surface material (meters to tens of meters). They are mechanical mixtures of many rock types but mainly represent an integrated accumulation of rocks ejected by craters of all sizes. In 2003, on the basis of the average composition of 8 feldspathic lunar meteorites (28.2% $Al_2O_3$), we estimated that the surface of the feldspathic highlands (and by inference, the integrated upper few tens of km of crust) has "79 [±3] mass%, or ~83 vol.%, plagioclase" [5]. Similar estimates have been made by others [7,8]. We showed that the mean FeO concentration of the meteorites was essentially the same as that determined for the mean surface of the feldspathic highlands globally by orbiting missions, Clementine and Lunar Prospector [5]. There are many more feldspathic lunar meteorites known today (Fig. 1) but the estimate remains the same, 28.4±0.6 % $Al_2O_3$ and 79±2 mass% plagioclase. A plutonic rock with the composition of a typical feldspathic lunar meteorite would be a noritic anorthosite, not an anorthosite (Fig. 1).

What is the cause of the discrepancy between the orbital observations and the makeup of the feldspathic lunar meteorites? If anorthosite with >98% plagioclase is widespread and abundant in the subsurface highlands, then the ~20% of mafic components in the surface regolith likely derives (via basin-forming impacts) from beneath the pure anorthosite layer [2]. If such a layer exists, we might expect to find at least some lunar meteorites that consist of 95% or more plagioclase, yet there is only one meteorite (NWA 2998) with (marginally) >90% plagioclase (Fig. 1). Moreover, pure anorthosite is not common even as lithic *clasts* in lunar meteorites (Fig. 2). Descriptions of feldspathic lunar meteorites mention clasts of anorthosite, but pyroxene- and olivine-bearing feldspathic lithologies such as impact-melt breccias, granulitic breccias, norites, and troctolites are mentioned just as frequently. Our own study of the 98 largest clasts in a thin section of Shişr 161 (25.2% $Al_2O_3$) yielded only 4 of pure plagioclase [9]. Of 100 lithic clasts in PCA 02007 (26.5% $Al_2O_3$), none were "pure anorthosite" [10]. The most feldspathic (32.5% $Al_2O_3$) had ~92 vol% plagioclase (Fig. 3). The fact that the mean composition of the clasts is more feldspathic than the bulk meteorite argues that anorthite fragments are not hiding in the fine-grained matrix.

If the lunar crust is feldspathic because of plagioclase buoyancy in the magma ocean [11], then the plagioclase cumulates would have retained a significant portion of intercumuls melt that became trapped when crystallization reached 70–85% (residual porosity 15–30%) [12]. On the other hand, plagioclase may have accumulated in a two-stage process, initially forming buoyant concentrations in the zone of crystallization, and subsequently rising diapirically to shallower depths coupled with dynamic expulsion of mafic trapped melt [13]. This process could give rise to very pure near-surface anorthosite massifs in an upper crust that also contains more mafic consituents in the form of basin-derived impact-melt products and other more mafic igneous intrusive rocks [14]. This zone of massif anorthosites of the primary crust may not be global, but may be absent throughout much of the Procellarum KREEP terrane [15]. We think that a scenario such as this is more consistent with the observations – both from orbit and from the perspective of the lunar meteorites - than is a global flotation cumulate layer of pure anorthosite.

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**References:** [1] Ohtake et al. (2009) *Nature* **461**, doi: 10.1038/nature 08317. [2] Hawke et al. (2003) *JGR* **108** doi: 10.1029/2002JE001890. [3] Yanai & Kojima (1984) *Mem. Nat. Inst. Polar Res., Spec. Iss.* **35**, 18–34. [4] Warren & Kallemeyn (1991) *GCA* **55**, 3123–3138. [5] Korotev et al. (2003) *GCA* **67**, 4895–4923. [6] Korotev (2009) *M&PS* **44**, 1287–1322. [7] Palme et al. (1991) *GCA* **55**, 3105–3122. [8] Warren et al. (2005) *M&PS* **40**, 989–1014. [9] Foreman et al. (2009) *LPSC40*, #2304. [10] Korotev et al. (2006) *GCA* **70**, 5935–5956. [11] Warren (1985) *Ann. Rev. Earth Planet. Sci.* **13**, 201–240. [12] Jolliff & Haskin (1995) *GCA* **59**, 2345–2374. [13] Longhi (2003) *JGR* **108**, E8, DOI 10.1029/2002JE001941. [14] Jolliff et al. (2000) *JGR* **105**, 4197–4416. [15] Haskin et al. (2000) *JGR* **105**, 20,403–20,415. [16] Stöffler et al. (1980) *Proc. Conf. Lunar Highlands Crust*, 51–70.

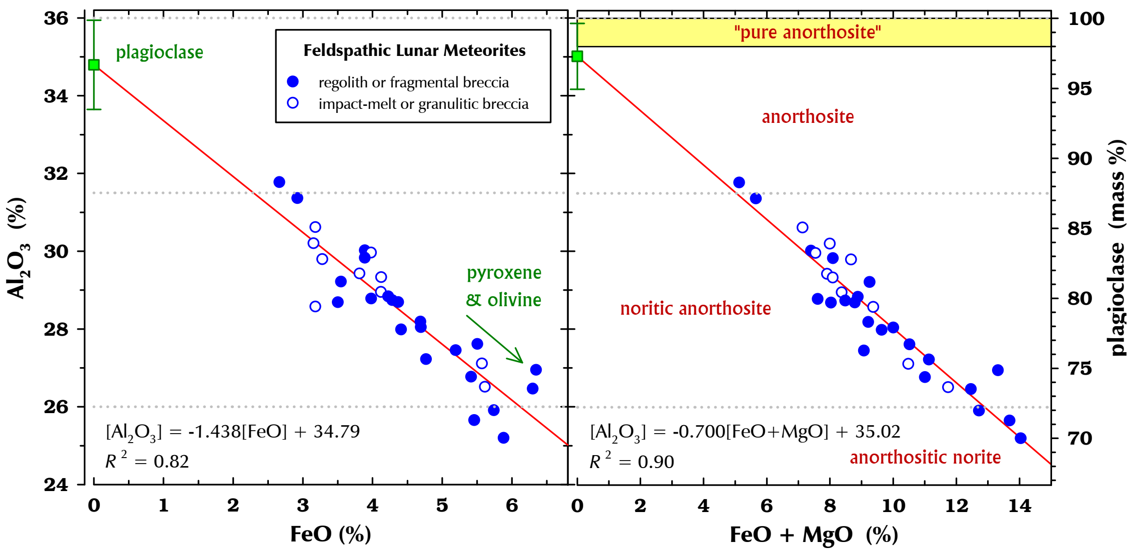


**Figure 1.** Data for bulk the composition of feldspathic lunar meteorites with <1 µg/g Sm. The percent plagioclase scale (right) assumes that pure $An_{96}$ plagioclase has 36% $Al_2O_3$. Lunar anorthosite, by definition [16], is a plutonic rock with >90 vol% plagioclase, which corresponds to about >87.5 mass%. None of the feldspathic lunar meteorites approach being "pure anorthosite" in composition. The diagonal lines are simple linear regressions to the data and the green squares (with 95% confidence limits) are the intercept of the regression. Data from many literature sources [5,6, references therein] and unpublished data of this lab.

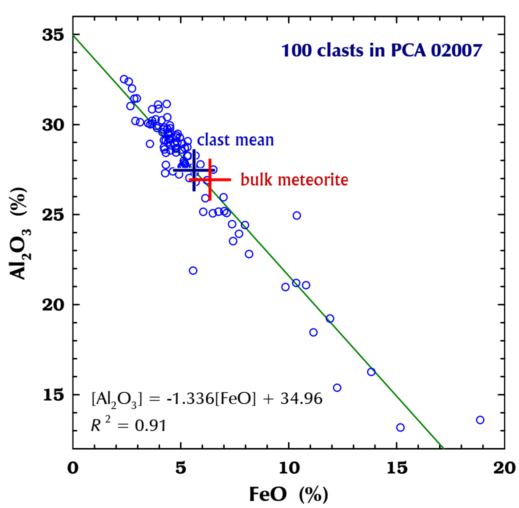


**Figure 3**. Data for the 100 largest clasts in a thin section of PCA 02007, from study of [5]. With 32.5% $Al_2O_3$, the most aluminous clast is 'only' 90% normative (mass %) feldspar or about 92 vol.% plagioclase.

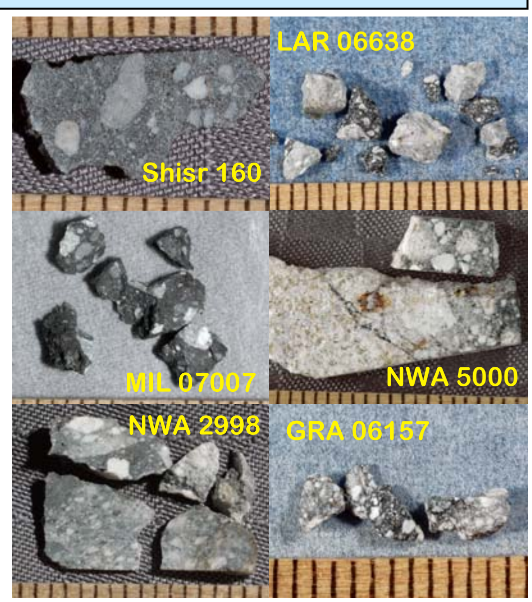


**Figure 2**. In feldspathic lunar meteorites, clasts of light-colored rocks and minerals are abundant. In our experience, most light-colored clasts are impact-melt breccias and granulitic breccias that are more mafic than anorthosite. In NWA 5000, the large light-colored clasts are gabbroic anorthosite with 5.1% FeO. Among >900 small subsamples of lunar meteorites that we have analyzed, only one, an 8-mg fragment from NWA 3190 with 0.20% FeO, would qualify as "pure anorthosite." None of the meteorites in the figure are well studied petrographically. Scale bars have 1-mm ticks..