MAGNESIAN ANORTHOSITIC GRANULITE: AN ABUNDANT, SIGNIFICANT, AND POORLY UNDERSTOOD LUNAR ROCK TYPE OF THE LUNAR HIGHLANDS. A. H. Treiman[1], A. K. Maloy[1,2], and C. K. Shearer Jr. [3] [2]Lunar and Planetary Institute, Houston TX. 77058 <treiman#lpi.usra.edu>, [2]Department of Earth Science, Rice University, Houston, Texas 77005. [3]Institute of Meteoritics, University of New Mexico, Albuquerque, New Mexico 87131.

Fragments of magnesian anorthositic granulite (MAG) are found in all feldspathic lunar meteorites. Because the lunar meteorites apparently come from random locations on the Moon, MAG must be a widespread constituent of the lunar crust; its chemical composition is consistent with remotely sensed data on the Farside Highlands Terrane (FHT). Nearly all lunar meteorite compositions can be explained (to first order) as mixtures of MAG, ferroan anorthosites (FAN), and basalt, without requiring significant abundances of peridotite (mantle or intrusive). The MAG composition does not arise simply within the magma ocean theory of the Moon's origin.

Methods: EMP and SIMS were used to obtain major and trace element abundances in minerals of five magnesian anorthositic clasts in the feldspathic lunar meteorites ALHA81005 and Dho309. The former is a regolith breccia, the latter a clast-rich impact melt. Mineral proportions were calculated from EMP X-ray maps using computer codes for multispectral image analyses [1]. The clasts' mineral compositions fall in the field of 'Mg-suite' plutonic rocks on an An-En graph (Fig. 1), though they are too rich in feldspar to be typical Mg-suite rocks.

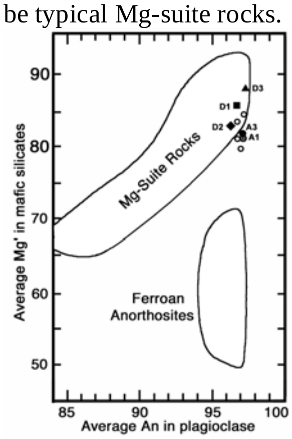

Fig. 1 Mg′ [molar Mg/(Mg+Fe)] versus plagioclase composition [An = molar Ca / (Ca + Na)] for clasts A1, A3, D1, D2, and D3. Also plotted are INAA data for similar magnesian clasts from ALHA81005 (open circles; [4]).

Bulk compositions of clasts are calculated from mineral analyses, volume proportions, and densities. Where a mineral analysis was impossible (e.g., augite or merrillite grains too small for SIMS), compositions were calculated using literature D values from comparable metamorphosed lunar rocks [2,3].

%	A1	A3	D1	D2	D3
Plagioclase	63	70	65	62	72
Olivine	20	11	25	25	28
Orthopyx	14	16	10	12	0.4
Augite	2.4	2.1	4	0.3	
Chromite	0.4	0.02	0.6	0.7	0.03
Al-Spinel				0.1	

Table. Mineral proportions in MAG clasts. A are in ALHA 81005; D are in Dho309.

Bulk Compositions: The magnesian anorthositic granulite clasts in ALHA 81005 and Dho 309 are chemically similar: Mg* (molar Mg/(Mg+Fe)) = 81-87, ~5% FeO, ~21-24% Al_2O_3, Eu at ~ 10 x CI, and other rare earth elements (REEs) at 0.5-2 x CI. Low Ni and Co abundances (20-50 ppm and 10-25 ppm respectively) and Ni/Co = 0.04-0.2 x CI suggest limited meteoritic contributions. Cr_2O_3 varies from 0.01 to 0.4%, and Sc from 3-8 ppm. Clasts in ALHA 81005 have more TiO_2 than those in Dho 309 (0.15% vs. <0.1%). These results are consistent with analyses by other methods [4-6].

Implications. The Lindstroms and Korotev noted that the Apollo MAGs were not explained readily in current petrogenetic models [7,8]. Worse, the lunar meteorite MAGs are equally inexplicable and are distinct from the Apollo MAGs, as the former have Th/Sm(CI) near 1, and the latter have Th/Sm(CI) near 3 [6,7,9]. The lunar meteorite MAGs, representing samples from across the lunar surface, suggest inferences of global scope.

Inference 1: Farside Highlands Terrane. Magnesian anorthositic granulite represents a widespread and abundant constituent of feldspathic lunar meteorites, and thus of the moon, as suggested by several authors [6,10,11]. We have documented MAG clasts from two such meteorites; clasts with similar mineral compositions and textures are found in most/all of the others, including Dho025, DaG400, MAC88104, and PCA02007 [2,10-12].

The feldspathic lunar meteorites are inferred to be a random sampling from the lunar highlands, most of which is on the far side, the Farside Highlands Terrane (FHT). The surface composition of the FHT, determined from Lunar Prospector data (~4.5 wt% FeO, ~28 wt% Al_2O_3, < 1 ppm Th [10,13,14]) is consistent with a mixture of MAG and FAN, as are many feldspathic lunar meteorites (e.g., Dho309 [6], blue squares of Fig. 2). Thus, it seems reasonable that the rocks and regolith of MAG compositions are essential constituents of the FHT.

Inference 2: MAG, FAN, & Peridotite. Not only are MAG lithologies constituents of felsdspathic lunar meteorites, they are also a critical contributor to mixed-composition lunar meteorites (green dots, Fig. 2). The compositions of mixed lunar meteorites plot among the compositions of FAN, MAG and lunar meteorite basalts (blue, black & green lines, Fig. 2), suggesting (to first order) that the lunar surface consists of mixtures of these three components. In this mixing, MAG could be replaced by peridotite (e.g., lunar mantle [11]; Fig. 2). However, peridotite is not required because no mixed meteorite compositions fall to the left of the MAG-basalt mixing line (in green, Fig. 2).

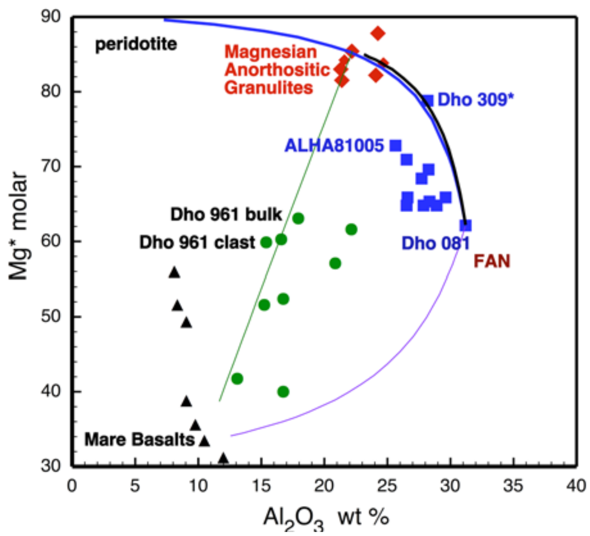

Figure 2. Chemical compositions of lunar meteorites and some clasts, with a hypothetical mantle peridotite and mixing lines, after [11]. MAG compositions from this work (red diamonds) and [5,6] (small red diamonds); Dho309* composition includes it and paired meteorites. Feldspathic (blue squares) and mixed (green circles) lunar meteorites are consistent with being mixtures of ferroan anorthosite (e.g., Dho081), basalt (black triangles) and MAG. The composition of meteorite Dho961, possibly from the South Pole-Aitkin Basin [15], is consistent with a mixture of MAG and mare

In fact, several lunar meteorites are nearly binary mixtures of MAG and basalt in Fig. 2 (as is a gabbronorite clast in ALHA81005 [16]), which suggests that some areas of the lunar crust are essentially devoid of FAN. The Dho 961 meteorite is noteworthy, as it has been suggested to be from the South Pole / Aitkin (SPA) basin [15]. The compositions of Dho961 and its mafic clasts fall near the MAG-basalt mixing lines, although the high Th content of Dho961 implies that the basalt is not the VLT typical of most lunar meteorites. If Dho961 is from the SPA, then the mafic material in the basin is likely to be basaltic [17], and the SPA target may have included little FAN (as with Imbrium [18] and Serenetatis [19]).

Inference 3: Origin of MAG. Magnesian anorthositic granulites are not direct products of a lunar magma ocean (e.g., [20]; they are too magnesian). Nor can they be represented as impact mixtures of magma ocean products [8]. By Fig. 2 (blue line), MAG could represent mixtures of FAN and mantle peridotite, which could be rationalized through overturn of the Moon's mantle following the magma ocean [21,22] and impact mixing. However, MAG has too little Ni and Co to contain a significant proportion of admixed lunar mantle material (as currently understood) [23].

In effect, then, we re-occupy the conclusions of [8], that MAG is a poorly understood, widespread, abundant rock type in the lunar highlands. MAGs are important constituents of the lunar crust, and must be explained in any model of lunar crustal evolution. In comparison with [8], we now have many more examples of MAG, and a broader chemical and spatial context for understanding them (Fig. 2). It is clear that MAGs represent a suite of compositions, showing significant ranges of Mg*, and abundances of several element groups (incompatible trace elements (Th, La), Cr, Ni & Co; data here, [8]). How the MAG compositions arise, in the broader scope of lunar petrogenesis, is under investigation.

We are grateful to R. Korotev for continuing inspiration and assistance. C. Schwandt (Jacobs) assisted with EMP analyses; P. Burger assisted with SIMS analyses. This work is based on A. Maloy's MS thesis work (Rice University), supported by a Graduate Fellowship from the LPI. Also supported in part by NASA Cosmochemistry grant NNX08AH78G.

References: [1] Maloy A.K. and Treiman A.H. (2007) *Amer. Mineral.* 92, 1781-1788. [2] Cahill et al. (2004) *Meteorit. Planet. Sci. 39,* 503-529. [3] Treiman A.H. et al. (2008?) in prep. [4] Goodrich C.A. et al. (1984) *JGR* 89:C87-C94. [5] Takeda H. et al. (2006) *Earth Planet. Sci. Lett.* 247, 171–184. [6] Takeda H. et al. (2008) *LPS XXXIX*, Abstract #1574. [7] Korotev R.L. and Jolliff B.L. (2001) *LPS* XXXII, Abstract #1455. [8] Lindstrom D. and Lindstrom M. (1986) *JGR* 91, D263-D276. [9] Maloy A.K. and Treiman A.H. (2007) *Meteorit. Planet. Sci.* 42, Abstract #5109. [10] Korotev R.L. et al. (2003) *GCA* 67, 4895-4923. [11] Warren P. (2005) *Meteorit. Planet. Sci. 40,* 989-1014. [12] Korotev R.L. et al. (2006) *GCA* 70, 5935-5956. [13] Jolliff B.L. et al. (2000) *JGR* 105, 4197-4216. [14] Gillis J.J. et al. (2004) *GCA* 68, 3791-3805. [15] Jolliff B.L. et al. (2008) *LPS XXXIX*, Abstract #2519. [16] Maloy A.K. et al. (2004) *LPS XXXV*, Abstract #1159. [17] Lucey P.G. (2004) GRL 31, L08701. [18] Spudis P.D. et al. (1991) *Proc. Lunar Planet. Sci. Conf. 21*, 151-165. [19] Ryder G. et al. (1997) GCA 61, 1083-1105. [20] Warren P.H. (1990) *Amer. Mineral. 75*, 46-58. [21] Shearer C.K. and Papike J.J. (1999) *Amer. Mineral. 84*, 1469-1494. [22] Elkins-Tanton L. et al. (2002) *Earth Planet. Sci. Lett*. 196, 239-249. [23] Delano, J. W. (1986) 231-247 in *Origin of the Moon*.