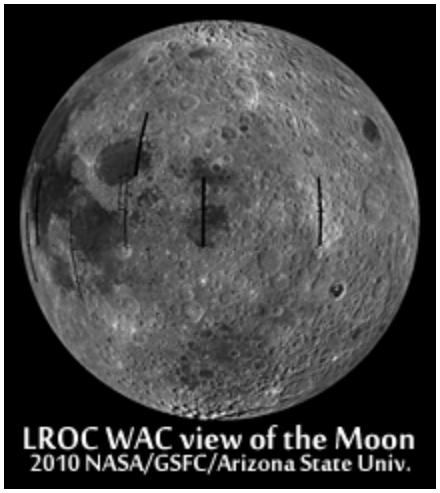
Headline Article

September 30, 2010

Unraveling the Origin of the Lunar Highlands Crust



--- Lunar meteorites contain clasts that may plausibly be samples of post-magma-ocean plutons that helped build the highlands crust.

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The non**mare** rocks that dominate the **highlands** of the Moon are particularly fascinating because they tell us about the origin of the most ancient crust. Two random samples of highlands rocks arrived to Earth as lunar meteorites Allan Hills (ALH) A81005 and Dhofar 309. Researchers Allan Treiman, Amy Maloy, Juliane Gross (Lunar and Planetary Institute, Houston) and Chip Shearer (University of New Mexico) took a look at a particular kind of fragment inside these meteorites so geochemically distinct from other highlands materials as to warrant further investigations of their mineral, bulk, and trace element compositions. The attention-grabbing fragments are magnesium-rich **anorthositic** granulites that tell part of the story of lunar crustal evolution, though the details of the story are still being worked out. Magnesian anorthositic granulites, found in several distinct lunar meteorites, may represent a widespread rock type in the highlands, a notion supported by remote sensing chemical data. These fragments could be metamorphosed relicts of **KREEP**-free **plutons** that intruded into the plagioclase-rich ancient crust.

Reference:

- Treiman, A. H., Maloy, A. K., Shearer Fr., C. K., and Gross, J. (2010) Magnesian Anorthositic Granulites in Lunar Meteorites Allan Hills A81005 and Dhofar 309: Geochemistry and Global Significance, *Meteoritics and Planetary Science*, v. 45(2), p. 163-180, doi: 10.1111/j.1945-5100.2010.01014.x.
- **PSRDpresents:** Unraveling the origin of the Lunar Highlands Crust --**Short Slide Summary** (with accompanying notes).

Lunar Highlands Rocks

Highlands rock samples are typically **breccias** formed as the young Moon's original igneous crust was demolished during millions of years of impact bombardment; imagine wrecking balls falling from the sky, over and over. The Moon's original crust was shattered, pulverized, and partially melted to several kilometers below the surface, but enough pieces of that crust survived that we actually know something about it. Most of these pieces are clasts (fragments) mixed into highlands impact breccias. Cosmochemists call these relicts *pristine* rocks and most can be classified into three chemically distinct groups. These groupings were recognized from analyses of the **Apollo** samples, **Luna** samples, and lunar meteorites. The factors used to distinguish the groups include: mineral proportions, **magnesium number**, rare earth element (**REE**) abundances, and low concentrations of **siderophile** elements (these elements are added to rock breccias by impacting meteorites rich in siderophile elements). Information drawn from published literature is summarized in a few words, below, for the oldest to youngest highlands pristine rocks.

Highland rock	Geochemistry	Formation Hypothesis
Ferroan Anorthosite Suite (FAN)	Most common highlands rock type, these are coarsely crystalline cumulates full of calcium-rich plagioclase (averaging about 96 vol% plagioclase) and characterized by low magnesium number (Mg#), low Na/(Na+Ca), low concentrations of incompatible lithophile elements (for example, La and Th), low abundances of siderophile elements, and high Al_2O_3. The next most abundant mineral is pyroxene. Age dates based on pyroxene data are about 4.5 billion years old.	Formed by plagioclase floatation in the **magma ocean** to make the primary crust. Four chemical subgroups are also identified based on their different plagioclase compositions and REE patterns, and this range suggests multiple parent magmas or the rocks formed at different stages of fractional crystallization of a chemically complex magma ocean.
Mg-Suite	Rocks composed of cumulates of plagioclase plus a mafic silicate, either olivine (the troctolites) or low-Ca pyroxene (the norites) or high-Ca pyroxene (the gabbros). These rocks have relatively high Mg# and trace-element concentrations and are enriched in **KREEP** compared to FAN rocks. Mg-suite rocks are only found in samples from the Apollo landing sites (all in or near the Procellarum KREEP Terrane) and none found, so far, in meteorites. Age dates range from 4.5 to 4.1 billion years old.	The association with the Procellarum KREEP Terrane suggests that KREEP plays an important role in the formation of Mg-suite rocks. One formation hypothesis says that during vast overturns of the mantle, sinking KREEP rock mixed with rising magnesian olivine cumulates to make a hybrid mantle rock that subsequently melted to produce the Mg-Suite plutonic rocks. An alternative model suggests there was decompression melting of deep-seated magnesian olivine cumulates that rose and incorporated KREEP.
Alkali Suite	Set of rock types generally richer in alkalis than other lunar highlands rocks. They are characterized by high REE concentrations, higher Na/Ca, La, and Th than other highlands rocks, and have a large range in Mg#. Not abundant in the sample collections. Like the Mg-suite, they seem to be confined to the Procellarum KREEP Terrane. Age dates range from 4.3 to 3.8 billion years old, overlapping those of the Mg-suite and extending to younger ages.	Unlikely to be a major crustal rock type. Magmas similar to KREEP basalt fractionated to form this series of differentiated rocks and cumulates.

The rocks tell us that the chemical evolution of the **magma ocean** was complex (and still a hot research topic). Not only was there sinking and accumulation of magnesium-rich olivine and pyroxene crystals followed by a plagioclase floatation crust, but also convection, partial melting, eventual enrichment of KREEP in the last leftover magma, wholesale overturn of the mantle, and shock melting caused by impact bombardment that probably influenced the formation of Mg-Suite and Alkali Suite rocks. This chemical

evolution also set the stage for later magmatic activity on the Moon, and that's when granulites enter the story.

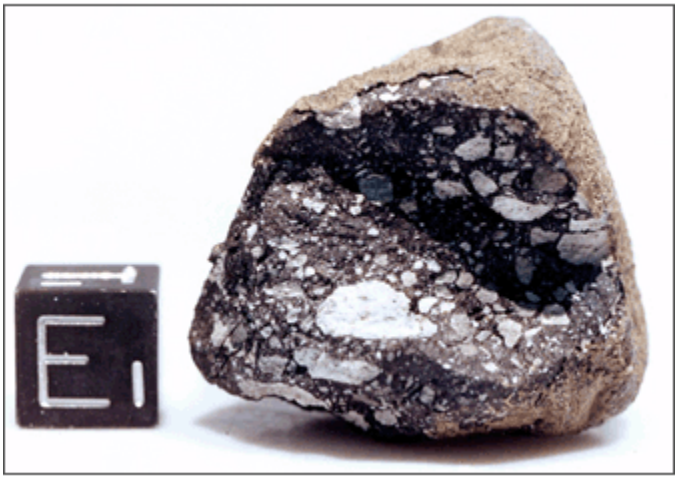
Lunar Granulite Clasts in ALHA81005 and Dhofar 309

Lunar granulites are breccias, with metamorphic textures, mixed and possibly melted by impact events. They are commonly referred to as polymict impact breccias, where polymict describes the assortment of clasts of many different compositions and textures. They contain meteoritic siderophiles and hence are not themselves pristine highlands rocks like those listed in the table above nor are their bulk compositions explained as mixtures of (or fractionates from) the known highlands rock types. Recognized as early as the mid-1970s in the Apollo sample collection and described well in the 1986 paper by Lindstrom and Lindstrom, granulites fall into two groups, ferroan and magnesian, contain little to no KREEP component, and more closely resemble estimates of average highlands composition than any other returned lunar materials.

Treiman and coauthors analyzed five clasts of magnesian anorthositic granulites in two lunar meteorites, Allan Hills (ALH) A81005 and Dhofar 309, to assess the clasts' mineralogical and chemical data in light of the current hypotheses of lunar geologic eveolution.

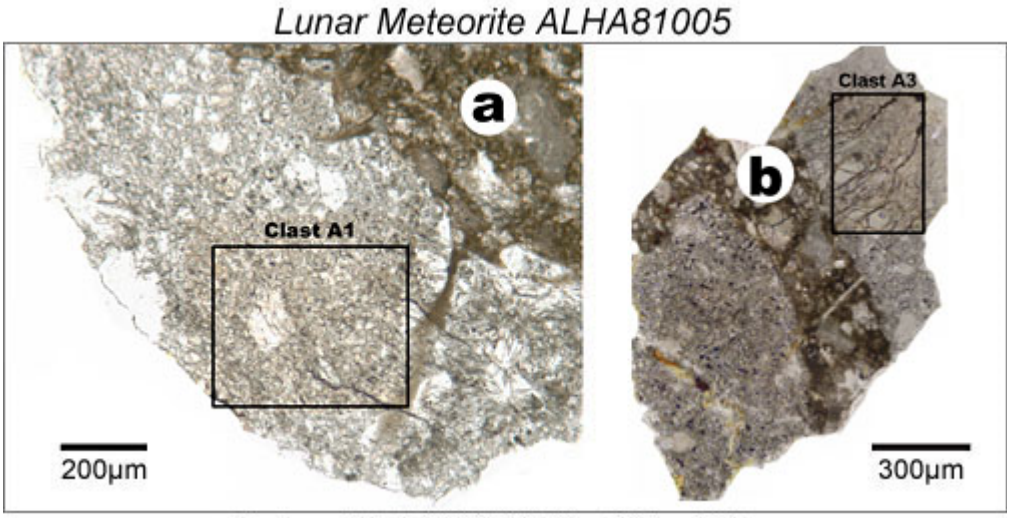
ALHA A81005 [**Data link** from the Meteoritical Bulletin] is a polymict regolith breccia that contains clasts of granulites and other breccias, impact melt, anorthosite, some Mg-suite rocks, and mare basalts. It also has regolith components, and mineral and glass fragments (see photo below, left). The team focused on two granulitic clasts (photos on the right) in ALHA81005.

Lunar Meteorite ALHA81005



NASA

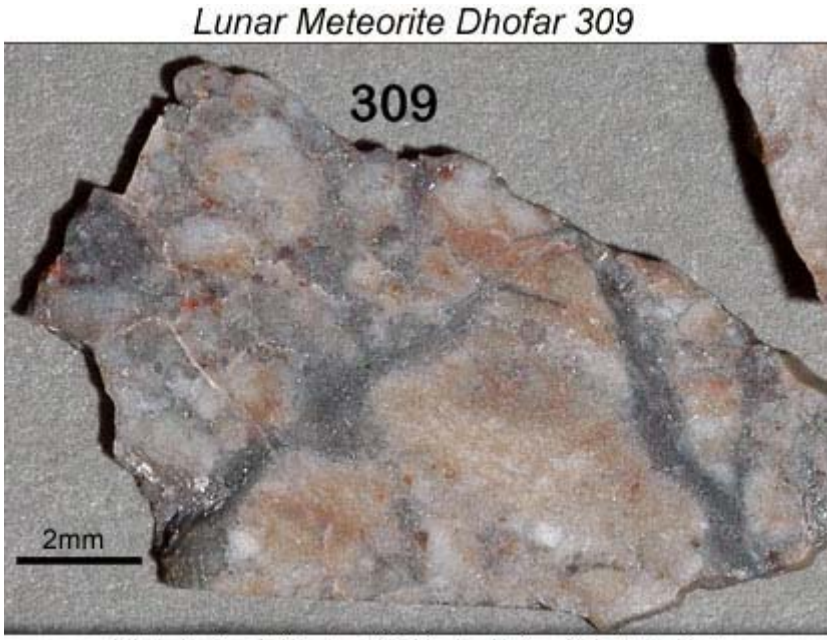
ALHA81005, 31-gram stone about 4-centimeters across, was collected in Antarctica in 1982 by the ANSMET team and recognized in 1983 as the first lunar meteorite ever seen. Some clasts inside this breccia are themselves breccias--testifying to repeated impacts onto earlier impact rocks, *themselves* composed of rocks broken in still earlier impacts--a consequence of the Moon's early impact bombardment history. See more photos at meteorites.wustl.edu.



(Treiman, A.H. *et al.*, 2010, *M&PS*, v. 45(2), p. 163.)

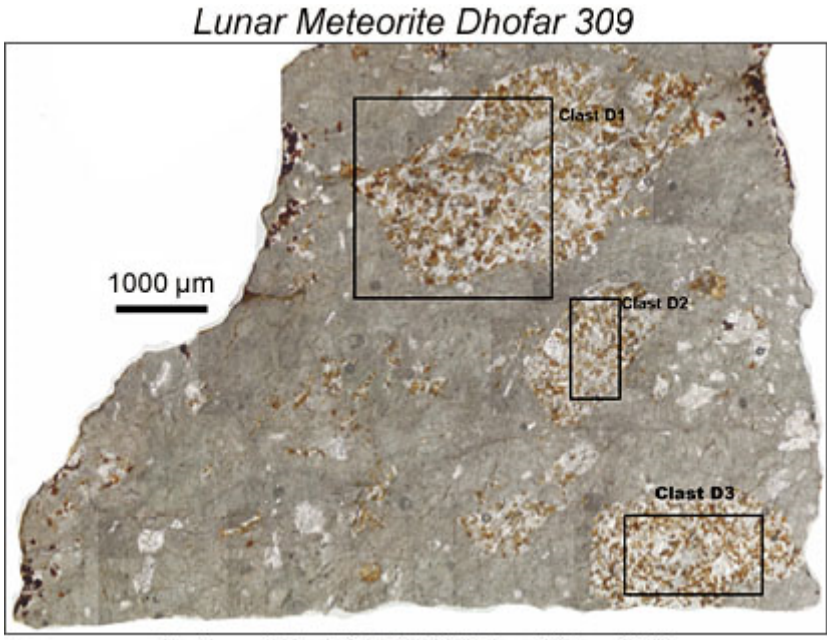
Two thin-section photomicrographs taken in reflected light showing lighter-colored granulite clasts and darker regolith matrix in ALHA81005. Black outlines indicate areas analyzed by Treiman and colleagues.

Dhofar 309 [**Data link** from the Meteoritical Bulletin] is an anorthositic impact melt breccia, where granulites dominate the clast population; three clasts were chosen for analysis (see photos below).



(Photo by Randy Korotev, Washington University in St. Louis.)

Dhofar 309 was collected in the Dhofar region of Oman in 2002. This slice is about 12 centimeters across. See more photos at meteorites.wustl.edu.

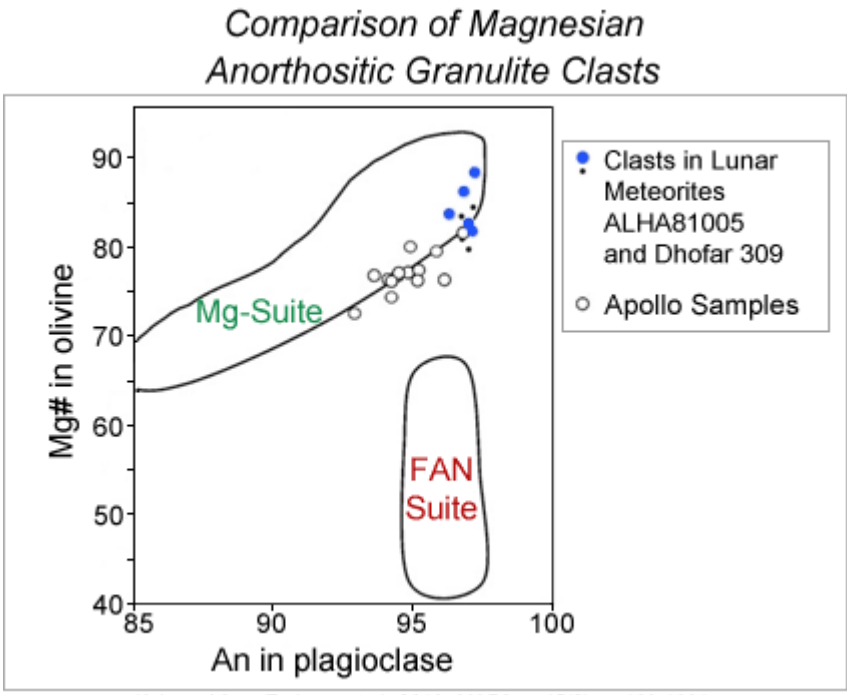


(Treiman, A.H. *et al.*, 2010, *M&PS*, v. 45(2), p. 163.)

A thin-section photomicrograph taken in reflected light showing three lighter-colored granulite clasts (black outlines) analyzed by Treiman and colleagues.

Using the electron microprobe and ion microprobe (SIMS, see **PSRD** article, **Ion Microprobe**) to collect mineral analyses (major and trace elements), Treiman and coauthors also used x-ray mapping techniques to determine mineral proportions, which allowed them to calculate the bulk chemical compositions of the five clasts.

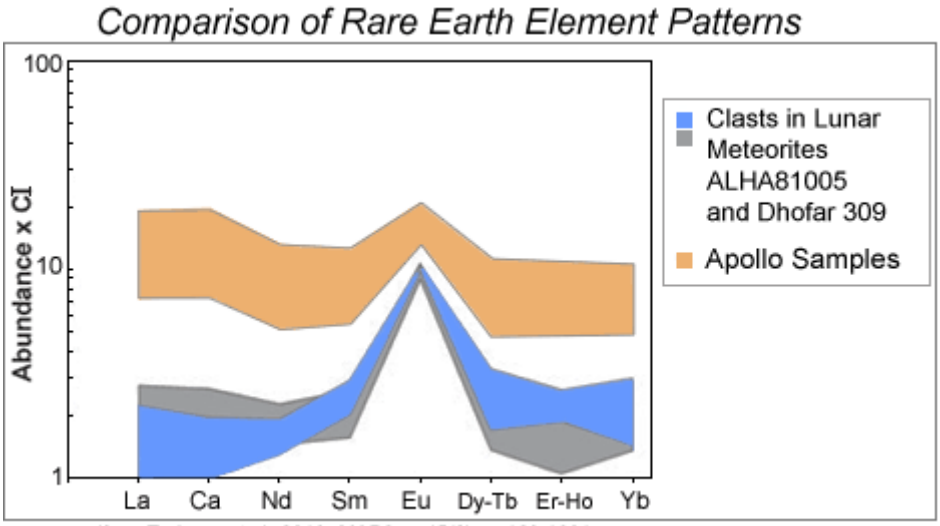
The magnesian anorthositic granulite clasts in both meteorites have high magnesium to iron ratios, low concentrations of thorium, limited ranges of Mg# (81-86) and heavy REE abundances of about 2-3 x CI (relative to abundances in CI **chondrites**). In the graph below, Mg# is plotted against plagioclase composition (expressed as fraction of anorthite (An), the calcium-rich end-member of the solid solution series). It shows that the magnesian anorthositic granulites from the lunar meteorites and the Apollo collection are clearly distinct from the FAN suite, but plot in or near the Mg-Suite. The Mg# in the magnesian anorthositic granulites is too high for a close relationship to the FAN Suite or to have formed as floatation cumulates in the magma ocean.



(Adapted from Treiman *et al.*, 2010, *M&PS*, v. 45(2), p. 163-180.)

Data points for the five clasts analyzed by Treiman and coauthors are shown in blue. Additional analyses of magnesian anorthositic granulite clasts analyzed previously by others are shown in black. Open circles are data points for Apollo magnesian granulites. Fields for pristine Mg-Suite and FAN suite are outlined for comparison. Plagioclase composition is expressed as fraction of anorthite (An), the calcium-rich end-member of the solid solution series.

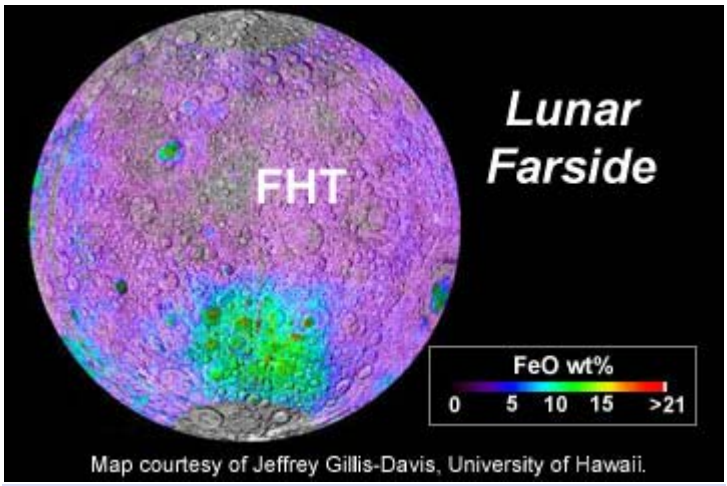
The REE patterns (see plot below) of the magnesian anorthositic granulites analyzed by Treiman and colleagues (blue range) and others (gray range) are distinct from patterns obtained previously by others for Apollo magnesian granulites (gold range). In addition, the analyzed clasts have 5% FeO, 22% Al_2O_3, and their Ti/Sm and Sc/Sm ratios are distinct from other highlands materials. In total, the mineralogical and chemical data show that the analyzed magnesian anorthositic granulite clasts have nearly identical chemical compositions, even though they are in different host meteorites (that came from different places on the Moon...more on that in the next section). These five rock fragments are chemically distinct from other lunar rocks and compositional components.



(from Treiman *et al.*, 2010, *M&PS*, v. 45(2), p. 163-180.)

The REE abundances of magnesian anorthositic granulite clasts analyzed by Treiman and coauthors plot in the range colored blue. Magnesian anorthositic granulite clasts in ALHA81005 and Dhofar 309 are low in REE (<5 x CI, except Eu). Gray range shows similar abundances for magnesian anorthositic granulite clasts in ALHA81005 analyzed previously by another team of researchers. The range for Apollo magnesian granultic breccias is shown in gold for comparison.

Global Significance



Surface concentration of iron (FeO) on the lunar farside is shown on this map created from spectral reflectance data taken by the Clementine mission, set on a shaded relief basemap. Low-FeO areas correspond to the Feldspathic Highlands Terrane. Map courtesy of Jeffrey Gillis-Davis, University of Hawaii; also available from http://meteorites.wustl.edu/lunar/moon_meteorites.htm.

ALHA81005 and Dhofar 309 are not paired meteorites, meaning there is no evidence they came from the same place on the Moon or were ejected in the same impact event. The bulk chemistry of these two meteorites is different, multiple analyses show that ALHA81005 is richer in Al and Mg and has lower abundances of incompatible elements compared to Dhofar 309. Most importantly, researchers have shown the two meteorites were ejected from the Moon at completely different times, ALHA81005 at about 60,000 years ago and Dhofar 309 at about 300,000 years ago. Yet, the five analyzed clasts of magnesian anorthositic granulites have nearly identical chemical compositions and researchers have identified similar clasts in other feldspathic lunar meteorites, which suggests magnesian anorthositic granulite is in different locations across the lunar surface. Remote sensing chemical data originally from **Lunar Prospector** and **Clementine** confirmed widespread anorthositic compositions in the highlands crust, which Brad Jolliff (Washington University in St. Louis) and colleagues used to define a major crustal terrane on the farside called the Feldspathic Highlands Terrane (FHT), see **PSRD** article: **A New Moon for the Twenty-First Century**. It turns out the bulk compositions of analyzed clasts in the unpaired meteorites are comparable to those inferred for parts of the FHT: about 4.5 wt% FeO, about 28 wt% Al_2O_3, and <1 ppm thorium. Instruments onboard NASA's current mission, **Lunar Reconnaissance Orbiter**, are collecting data consistent with these compositions, as well as tantalizing new information that expands the compositional range of the anorthosites, further demonstrating the Moon is home to a diverse set of igneous processes.

How Did Magnesian Anorthositic Granulites Form?

Research, like the careful work by Treiman and colleagues, shows that magnesian anorthositic granulites are geochemically distinct yet widespread across the lunar highlands. They are too rich in magnesium to be related to, or derived from, the FAN rocks, and too feldspathic and lacking in KREEP to come from the Mg-Suite. These magnesium-rich granulites are not directly addressed in current hypotheses of lunar geologic evolution; they do not fit in the magma ocean hypothesis. For one thing, plagioclase will not float in a magma too rich in magnesium. Treiman and coauthors propose that the clasts represent rock derived from **plutons** that intruded into the crust after solidification of the lunar magma ocean. A similar origin has been attributed to Mg-Suite rocks sampled in the Apollo and Lunar collections (troctolites and Mg-gabbronorites), although not of the same chemistry--Mg-Suite rocks are loaded with KREEP and the analyzed clasts are KREEP-poor.

In fact, it has not been clear if KREEP is an essential ingredient in the formation of post-magma-ocean plutons. The potassium, uranium, and thorium could have provided the necessary heat for remelting magma ocean cumulates. Alternatively, KREEP could have been a passive component that was assimilated and transported by otherwise-KREEP-free magmas. The story of the granulite clasts in lunar meteorites ALHA81005 and Dhofar 309 suggests KREEP was not necessary and that post-magma-ocean plutons may or may not contain KREEP, depending on whether or not they passed through the nearside or farside. But this is another issue, and another story of the lunar crust to be unraveled.

Additional Resources

Links open in a new window.

- **PSRDpresents:** Unraveling the Origin of the Lunar Highlands Crust --**Short Slide Summary** (with accompanying notes).

- Jolliff, B. L., Gillis, J. J., Haskin, L. A., Korotev, R. L., and Wieczorek, M. A. (2000) Major Lunar Crustal Terranes: Surface Expressions and Crust-Mantle Origins, *Journal of Geophysical Research*, v. 105, p. 4197-4216, doi: 10.1029/1999JE001103.
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- Taylor, S. R., Taylor, G. J., and Taylor L. A. (2006) The Moon: A Taylor Perspective, *Geochimica et Cosmochimica Acta*, v. 70, p. 5904-5918.
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