Lunar Meteorites Discussion Summary
Brendan Anzures

**Gross et al., 2014**

**Lunar Meteorites Reveal Apollo Sampling Bias**

Authors compare the mineral chemistry and petrology of Apollo samples, Luna samples, and lunar meteorites, and conclude that the current suite of lunar meteorites are more representative of the global moon because they theoretically “randomly sample” the surface. At the very least geochemical differences between lunar meteorites and Apollo samples (most from around the Imbrium basin on the near side) reveal a more complicated story of lunar crust and interior evolution. For example, anorthosites in lunar meteorites are more magnesian rich than Apollo samples. Some comparison between lunar feldspathic meteorites, Apollo Mg-suite, and Apollo ferroan anorthosites is shown in figure 3.

![Fig. 3](image)

**Lunar Magma Ocean or Serial Magmatism?**

After finding significant compositional differences between Apollo samples, Luna samples, and lunar meteorites, the authors suggest a simple global lunar magma ocean model is insufficient and that a more complex model that involves serial magmatism is necessary. Observations in favor of LMO are 1) Eu anomaly with plagioclase enriched and the basalt/residual depleted (Eu behaves as a compatible element in plagioclase for lunar magmas rather than terrestrial magmas because the Moon is more reducing resulting in Eu existing as 2+ rather than 3+ like the other REE’s), 2) ferroan anorthosite flotation crust (sample-biased Apollo rocks composed of >90% calcic plagioclase as the “primary” feldspathic crust which floated to the top of a global magma ocean), 3) detection of a KREEP component of lunar magmas (residual melt of the LMO enriched in incompatible elements) and 4) primary model for Moon formation involves a giant impact which requires a LMO of some scale. Observations in favor of serial magmatism include 1) Apollo Mg-suite requires intrusive volcanism (general consensus of community requires serial magmatism), 2) global distribution of lunar feldspathic meteorites in comparison with ferroan anorthosites showed that a global anorthosite flotation crust due to a LMO may not be necessary, 3) ages of ferroan anorthosites may be too old and also contemporaneous with Mg-suite rocks (in disagreement with LMO model with early crystallization of ferroan anorthosites and the Mg-suite crystallizing after and intruding as a “secondary” crust), and 4) lunar rock type magnesian granulites have no place in a LMO scenario (basaltic plutonic rocks pre-dating KREEP, inconsistent with a simple LMO model). The serial magmatism model favored here is shown in a schematic in figure 5.

![Fig. 5](image)

“All models are wrong, some are useful”

~George Box

Discussion also covered how many earlier models for lunar crust formation used partition coefficients from terrestrial systems which are not directly applicable to lunar systems due to differences in oxygen.
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fugacity especially. Previous researchers typically came from an impacting or geochemical perspective, whereas modern models integrate constraints from both impacting models and geochemical measurements. Now the community generally agrees some form of LMO is required due to the giant Moon-forming impact, and rather debate the extent (local or global, depth), timing, thickness of crust, and cumulate overturn mechanism/timing.

**Joy et al., 2010**

*Why study impact melt vs. bulk rock?*

Authors analyzed impact melt and impact melt breccia in four lunar regolith breccia meteorites using the electron microprobe and LA-ICP-MS for major, minor, and trace element analyses, focusing on impact melt for a variety of reasons. Impact melt (quenched coherent material) is advantageous in better distinguishing terrestrial contamination, comparing similar sample type in Apollo/Luna impact melt samples, and because samples (breccia/melt) are more reflective of impacted source rather than surface which may have contributions from around the Moon.

They find that the meteorites are compositionally similar to group 3 and 4 feldspathic impact melts from Apollo 16 (albeit more mafic and with a higher Eu anomaly). In addition, the major element compositions and Sc(andalous), Cr, Co, and Ni concentrations in the meteorite samples are similar to the Apollo 16 group 3 melts although Rb, Zr, Ba, and incompatible trace element concentrations are more comparable to Apollo 16 group 4 melts. These differences are due to these meteorites having a low KREEP component. Assuming these meteorites sample at least four regions, the meteorites also offer evidence in favor of lateral variation in Mg# for the lunar crust.

**Meteorite Samples vs. Remote Sensing, Tracing to the Source?**

Bulk Th ppm and FeO wt.% from global compositional maps produced by the Lunar Prospector were compared to these lunar meteorites to identify possible source regions as shown in figure 11. Discussion also covered more recent analyses of source regions for lunar meteorites using 48 meteorites and matching FeO, Th, and TiO$_2$ orbital data (Calzada-Diaz et al. 2015). In each analysis it was concluded that lunar meteorites come preferentially from the far side, possibly due to more impacts on far side because near side is tidally locked with the Earth.

![Fig. 11 Bulk Th ppm and FeO wt.% from meteorite samples are used to identify lunar regolith with](image-url)
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similar compositions. Global composition from Lunar Prospector. Regions of interest are white.
*https://www.youtube.com/watch?v=4r7wHMg5Yjg

Serial Magmatism Required?
The end of the discussion circled back to the lunar magma ocean vs. serial magmatism debate and concluded that serial magmatism is required to produce each of these four meteorites with different lithologies as seen in figure 12. MET 01210 is a basaltic regolith breccia that originated near ferroan anorthosite outcrops. DaG 400, PCA 02007, and MAC 88104/05 represent regoliths from either the Feldspathic Highlands Terrane or Outer Feldspathic Highlands Terrane, with MAC 88104/05 resembling low-Ti cryptomeria from the far side. The lunar crust has lateral heterogeneities which are due to different mixing of components in the melt. In addition, applying CIPW normative modal mineralogy to these impact clasts as this study did is not necessarily appropriate due to differences oxygen fugacity (Milliken and Basu 2000, Ralph’s first LPSC abstract!)

Fig. 12 Cartoon illustrating possible lunar launch localities and lithologies of meteorites

Korotev et al., 2003
Lunar Meteorites as “Ground Truth”
This paper presented new compositional data for six lunar feldspathic meteorites, which are then compared to remote sensing data. These meteorites sample the feldspathic highlands, the most common lithology on the Moon, which are not well represented in Apollo and Luna samples. The meteorites themselves are mostly polymict breccias which theoretically would allow them to represent an average of a region of lunar crust. It was also found that samples collected in hot rather than cold deserts were more contaminated due to terrestrial weathering.

# of Individual Stones, Lunar Meteorites, and Associated Impacts
The most recent count of lunar meteorites includes 131 lunar meteorites with 240 individual stones, with a wide range of estimates for the number of impacts from whom they derive. Lunar meteorites are paired by geochemistry, texture, and exposure dating. If the meteorite has the exact same lithology and geochemistry they may or may not be from the same source, unless they have the same exposure age. For example, NWA 773 has both mare basalt and olivine gabbro found in the same stone as seen in figure 1a. A big ongoing question is how many spots on the Moon have been sampled by meteorites, which is directly informed by assumptions of how homogenous or heterogenous the lunar surface is.

Fig. 1a Compositional range of lunar meteorites compared to soils from the Apollo and Luna missions where most of the lunar crust is feldspathic highland material.

Primary Lunar Magma Components
The primary lunar magma components are 1) basalt and volcanic glass from the maria, 2) feldspathic rocks of the highlands, and 3) Th-rich impact-melt breccias and glass often identified as KREEP as shown in figure 6. These three components can account for most of the
compositional variation in Apollo and Luna regolith samples as seen in figure 6a, as well as feldspathic lunar meteorites that are low in KREEP as seen in figure 6b. It is important to note that KREEP is not an actual terrain, but is rather a rich component in Procellarum KREEP. Apollo samples, in particular, lie in or near the Procellarum KREEP terrain influenced by the Imbrium basin and impact.

![Fig. 6 Regolith samples from Apollo, Luna, and lunar meteorites consist mainly of three compositionally distinct types of material given by the three apices](image)

**Lateral or Vertical Heterogeneity?**

The variation in composition between ferroan and magnesian feldspathic material indicates that there was either lateral or vertical heterogeneity in the lunar mantle. Discussion centered around whether or not it is testable to distinguish between lateral and vertical heterogeneities and concluded that one would have to look at Fe vs. Mg in anorthite and plagioclase, with more magnesian feldspathic material present at the surface of the highlands indicative of vertical redistribution by impacts.

References:


