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The Crazy Mixed-Up Lunar Crust

--- The horizontal and vertical distribution of well-mixed basin ejecta has lunar-wide geochemical ramifications.

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The Moon was pummeled to such a great extent that the materials we see today on the lunar surface are directly related to the materials excavated and ejected from ancient basin-forming events. The degree to which the far-flung ejecta from the Moon's largest basins influenced the distribution of observed geochemical terranes is the subject of work by Noah Petro (formerly of Brown University and now at NASA Goddard Space Flight Center) and Carlé Pieters (Brown University). Using a basin ejecta model, they address two key global issues: (1) the cumulative amount of basin ejecta transported to all areas of the lunar surface and (2) the depths to which the ejecta is mixed into a zone called the early megaregolith. The fact that so much mixing has occurred on the Moon makes it seem surprising, at first glance, that there are any unique geochemical terranes at all. Petro and Pieters' work provides a more detailed look at the distribution of basin ejecta and explains the important role basins played in the early evolution of the lunar crust.

Reference:

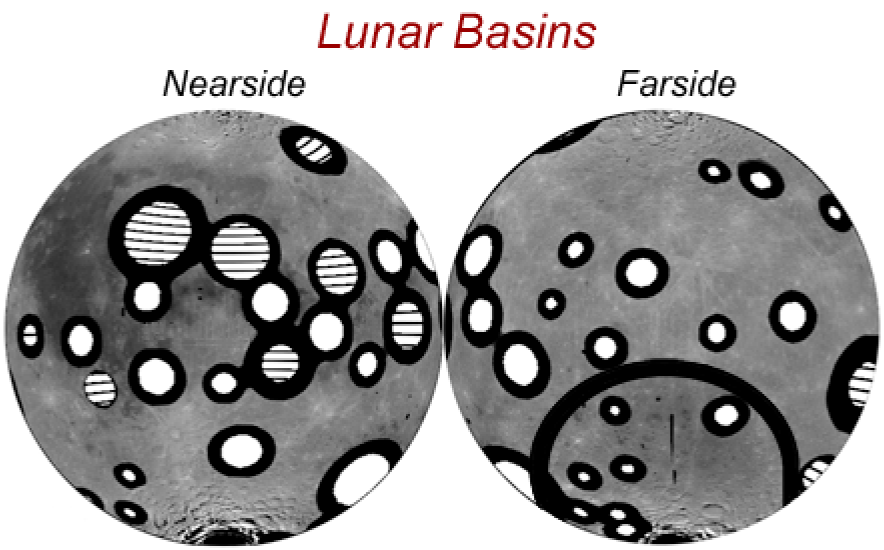
- Petro, N. E. and Pieters, C. M. (2008) The Lunar-Wide Effects of Basin Ejecta Distribution on the Early Megaregolith, *Meteoritics and Planetary Science*, v. 43(9), p. 1517-1529.

PSRDpresents: The Crazy Mixed-Up Lunar Crust --Short Slide Summary (with accompanying notes).

Lunar Basins

Impacts have a great effect on the lunar surface. They mix materials, melt them, produce new rocks made from other rocks, and distribute material all over the Moon. The largest impact events, those that produced basins, had the greatest effects. Some researchers, such as Lon Hood (University of Arizona) even propose that basin formation temporarily affected the magnetic field of the Moon and created strong magnetic anomalies antipodal to basins. Petro and Pieters worked with 43 basins on the lunar nearside and farside, identified previously by Don Wilhelms (U. S. Geological Survey) and Paul Spudis (Lunar and Planetary Institute); see figure below. Defined as impact craters larger than 300 kilometers in diameter with two or more concentric rims and no central peak, basins record a time of intense bombardment early in the history of the

Moon. This period of heavy bombardment lasted for the first 700 million years of lunar history, and may have spiked in intensity 3.85 to 3.95 billion years ago (see **PSRD** article: Lunar Meteorites and the Lunar Cataclysm). The spike (if it happened) may have been triggered, as one idea suggests, by the scattering of countless planetesimals due to the outward migration of Saturn's orbit (see **PSRD** article: Wandering Gas Giants and Lunar Bombardment).



(From Petro and Pieters (2008) *MAPS*, v. 43(8), p. 1517-1529. Clementine 750 nm albedo basemap.)

Like an Art Deco piece, these bold geometric shapes outline (in black) the main topographic rings of the 43 basins on the Moon. The mean size of the transient crater inside each basin is shown in white or a striped pattern. The oldest and largest basin, South Pole-Aitken (~2500 kilometers in diameter and between 6.2 and 8.2 kilometers deep), dwarfs the others.

For each basin, Petro and Pieters compiled statistics required for the modeling equations such as, a) the relative age of each basin, so as to consider the cumulative effects of the ejecta through time, b) an appropriate transient crater diameter, and c) the mapped diameter of the main topographic ring. Because the formation of South Pole-Aitken basin in the early evolution of the Moon is so significant, Petro and Pieters treat it as a special case, and consider its effects separately from the other 42 basins.

The maps (above) show clearly the scattered locations and different sizes of the basins. Notice especially the differences between the nearside and farside. This alone foretells the non-uniform distribution of basin ejecta--and a story of the mixed-up lunar crust. The work by Petro and Pieters improves the story by providing quantitative results for the amount of basin ejecta material and the depth to which it mixed with local materials for any basin event across the entire lunar surface.

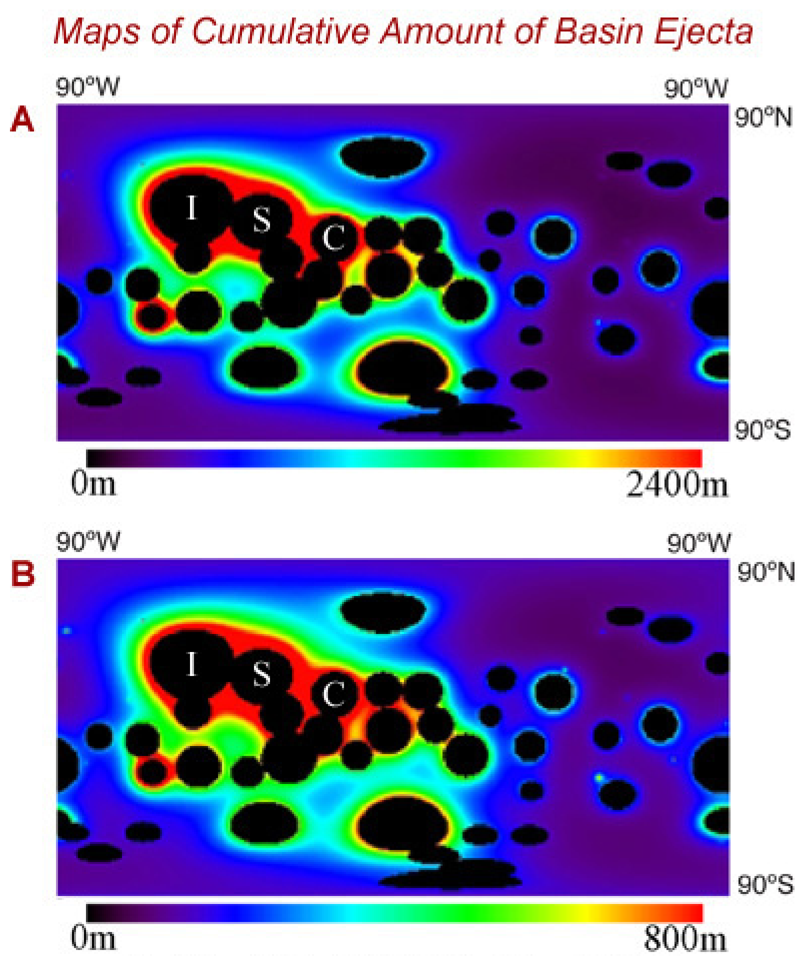
Models of Ejecta Transport

Since the 1970s planetary geologists have developed mathematical models to get a handle on how much ejecta was flung around the Moon from craters and basins. The significance of this issue was obvious during the Apollo missions when astronauts collected rocks from the six landing sites and geologists wanted to determine the provenance of those samples, i.e. were they looking at locally-derived rocks or material introduced to the site by a distant impact event?

To tackle the issue, Petro and Pieters created a global, 1^{o} x 1^{o} grid overlay to calculate the amount of ejected material at each grid-point. They used ejecta scaling equations derived previously by Richard Pike (U. S. Geological Survey) and Kevin Housen (Boeing Aerospace) and colleagues that predict the amount of material distributed to any location based on the amount of ejecta at the rim of the crater, the radius of the transient crater, and the range from the center of the crater to the location of interest (i.e., a specific grid-point). The contribution of ejecta from all basins to each location on the grid was summed, yielding the cumulative amount of basin-derived materials across the surface of the Moon.

Petro and Pieters made the following important assumptions during their work, a) the impacts were vertical, b) the ejecta curtain was continuous, and c) ejecta exited the transient crater at an angle of 45 degrees. They also applied a correction factor to the calculations to account for the spherical nature of the Moon, which enhances the estimated amount of ejecta at each basin's antipode. Their maps are shown below. Note that ejecta from the South Pole-Aitken basin is not included in the analysis--had it been, the entire lunar surface would be dominated by it.

Using Pike's equation, the estimated total amount of basin material is between 200 meters and roughly 3000 meters (top map, A). Using the equation by Housen and colleagues, the range is from about 100 meters to roughly 1000 meters (bottom map, B). The largest accumulation of basin-derived material occurs on the nearside surrounding the Imbrium, Serenitatis, and Crisium basins. Two regions on the farside have the lowest contributions from basin-derived materials, one in the northern farside and one in the south located within the South Pole-Aitken basin. The differences in the amounts of basin ejecta become particularly significant in estimating the depth of the mixed zone.

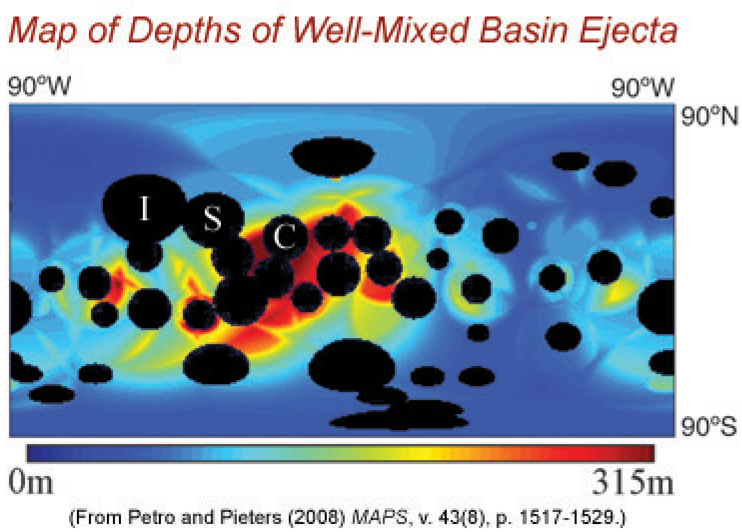


(From Petro and Pieters (2008) *MAPS*, v. 43(8), p. 1517-1529.)

These are global maps of the Moon in simple cylindrical projection centered on 0^{o} latitude, 90^{o} east longitude. The top map (A) was created using the Pike ejecta model. Bottom map (B) was created using the ejecta model by Housen and colleagues. They show no significant differences in the distribution of basin ejecta. Both maps show major differences between the nearside and farside in the thickness of the cumulative basin ejecta. The only difference between the two maps is that, in general, the top map shows two to three times greater amounts of basin ejecta than the bottom map (see scale bars). Imbrium (I), Serenitatis (S), and Crisium (C) basins are labeled for reference. The area inside of the main topographic ring of each of the 42 basins is filled in black. These areas were excluded from Petro and Pieters' analysis.

In addition to mapping the amount of basin-derived material transported laterally across the lunar surface, the researchers needed to study how the foreign material mixed vertically with the local regolith during emplacement. Using a variation of the 1975 concept of an ejecta mixing ratio by Verne Oberbeck (NASA Ames Research Center) and colleagues, and the ejecta model by Housen and colleagues, Petro and Pieters estimated the amount of mixing between local regolith and material arriving on ballistic trajectories from distant impact basins. The mixed zone, as the name implies, contains some proportion of both local rocks and ejecta materials. The result of this mixing was the development of a lunar-wide zone of fragmented material. This zone was developed further by subsequent impacts and is usually referred to as the megaregolith.

Petro and Pieters evaluated the maximum depth of the early megaregolith produced by a single basin-forming event and by all 42 basins in the relative order in which they are thought to have formed. They found very few basin events created mixed zones to greater than 200 meters while most of the basins mixed to depths of less than about 150 meters. Based on their calculations, a thoroughly mixed zone of a least 315-meters depth is achieved by five basin events. The resulting map (below) shows a clear contrast in depth of the mixed zone between the nearside and farside. A deeper mixed zone on the nearside, particularly in the eastern nearside, contrasts with relatively shallow mixed zones in the northern and southern farside. The depth of the mixed zone on the nearside is approximately five times greater than that on the farside. This contrast exists regardless of the ejecta model used, only the absolute values change--the greater thickness of ejecta predicted by the Pike model would result in a greater depth of mixing.

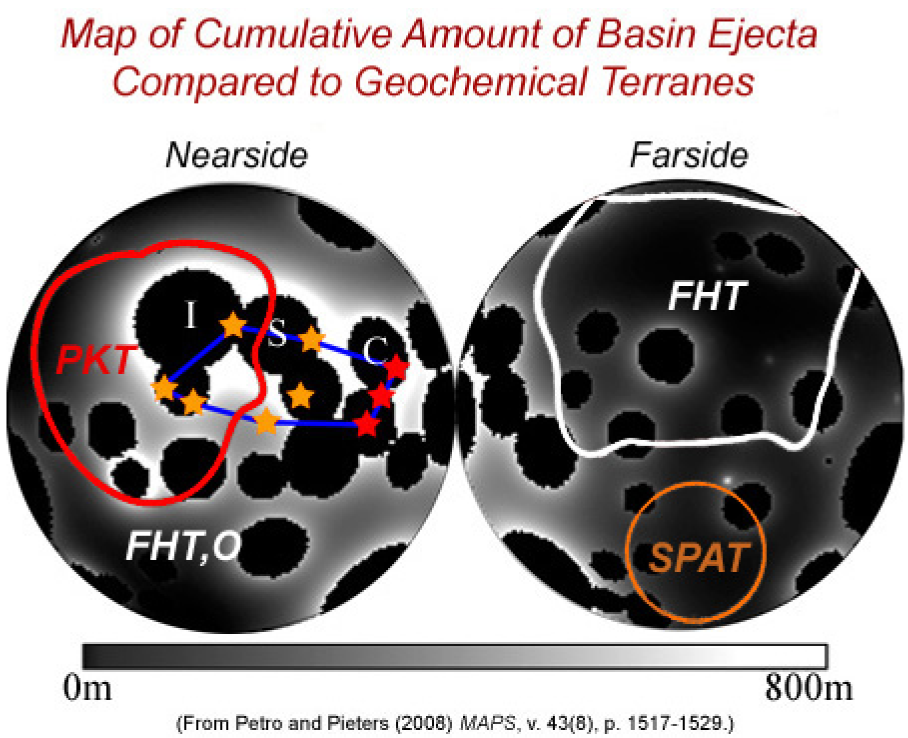


Global map of the Moon in cylindrical equal area projection centered on 0° latitude, 90° east longitude. Created using a variation of the Oberbeck mixing ratio and the ejecta model by Housen and colleagues, this map by Petro and Pieters shows the depth of early megaregolith mixed by five basin events. Imbrium (I), Serenitatis (S), and Crisium (C) basins are labeled for reference. The area inside of the main topographic ring of each of the 42 basins is filled in black. These areas were excluded from Petro and Pieters' analysis.

Geochemical Ramifications

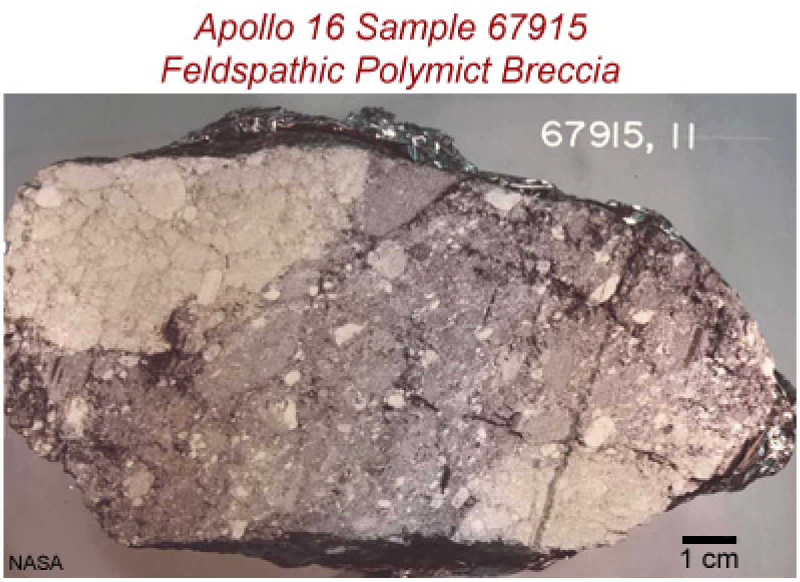
There are prominent regions on the Moon defined by chemical characteristics, specifically by the concentrations of iron oxide (FeO) and thorium (Th), and these were defined and mapped using global remote sensing data by Brad Jolliff (Washington University in St. Louis) and colleagues. The three major geochemical terranes they describe are (1) The Procellarum KREEP Terrane (PKT), which is characterized by high Th. It is a mixture of assorted rocks, including most of the mare basalts, and covers about 16% of the lunar surface. (2) The Feldspathic Highlands Terrane (FHT), including its somewhat different outer portion (FHT,O) has low FeO and Th. Its composition is anorthositic (ancient crust) and it covers about 65% of the lunar surface. (3) South Pole Aitken Terrane (SPAT), associated with the immense South Pole-Aitken Basin, has modest FeO and Th compared to the surrounding highlands. See **PSRD** article: A New Moon for the Twenty-First Century for more details.

What does all the horizontal and vertical mixing of basin ejecta mean for the composition of the Moon's crust, and specifically, for the terranes? First, Petro and Pieters show that the distribution of the basins is fundamental in the provenance of materials on the lunar surface--the material redistributed during impact basin events carried the geochemical signature of its source region. Remember the greater number of basins on the nearside compared to the number on the farside? This asymmetric distribution of the basins created a nearside-farside disparity in the cumulative amount of basin ejecta and the depth of the megaregolith, and hence the degree to which the crust was modified by basin ejecta. Petro and Pieters assessed how the materials excavated and ejected from ancient basin-forming events influenced the distribution of observed geochemical terranes.



The boundaries of the three major geochemical terranes on the Moon as defined by Jolliff and colleagues are compared to the the cumulative amount of basin ejecta on this map by Petro and Pieters. PKT is Procellarum KREEP Terrane, FHT and FHT,O are Feldspathic Highlands Terrane. SPAT is South Pole Aitken Terrane. The area inside of the main topographic ring of the post-SPA basins is filled in black. Imbrium (I), Serenitatis (S), and Crisium (C) basins are labeled for reference. Stars show locations of the six Apollo landing sites (gold stars) and three Luna landing sites (red stars).

On the lunar nearside the PKT extends over large regions that were modified significantly by basin ejecta, particularly ejecta from the Imbrium basin. Stars on Petro and Pieters' map show locations of the U. S. Apollo and unpiloted Soviet Luna landing sites, where rock and regolith samples were collected. These sites are all located in the region with the greatest amount of cumulative basin ejecta and some of the deepest early megaregolith mixing. The redistribution of materials by basins helped to create regolith with diverse compositions, which cosmochemists have studied in great detail in the lab.



Photograph of a sawn surface of lunar rock 67915, a breccia collected from the Apollo 16 landing site. A testament to the diversity of compositions, this sample is a conglomeration of rock types. The term polymict describes a rock with mixed clasts of different compositions and textures.

On the farside both the FHT and SPAT have little modification by post-SPA basins. Petro and Pieters' work shows that the FHT and the interior of SPA received relatively small amounts of foreign material ejected from the 42 (post-SPA) basins they studied, and what little they received was mixed to shallow depths. Such a combination would preserve the ancient crustal geochemical signatures in the FHT or any ejecta transported there from the South Pole-Aitken basin. As with the FHT, the unique composition of the SPAT, including its FeO and TiO_2 anomalies, appears to have been preserved because very little foreign materials ejected from other basins were introduced inside South Pole-Aitken basin after it formed.

The South Pole-Aitken Basin is a special case to consider (see **PSRD** article: The Biggest Hole in the Solar System). Petro and Pieters did not include ejecta from SPA in their models. In fact, they estimate the amount of SPA ejecta is roughly the equivalent to all other basins combined. And because it was the first basin to form, the global effects of the subsequent 42 basins would be superimposed on SPA ejecta. More details need to be figured out about the angle of impact and the size of the transient crater for the effects of SPA to be modeled.

Let us briefly consider the surface inside South Pole-Aitken basin. A significant result of Petro and Pieters' work is that ancient compositional signatures in certain locations, notably SPA basin, survived despite all the horizontal and vertical mixing of materials during the basin formation era early in lunar history. They predict approximately 75% of the regolith in the central region of SPA is locally derived. A robotic sample return mission to SPA basin could net ancient materials from the lower crust or upper mantle and allow us to determine when SPA basin formed. Such a mission concept is high on most lunar scientists' wish lists as it would help us understand lunar differentiation, crust formation, and bombardment history.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** The Crazy Mixed-Up Lunar Crust --Short Slide Summary (with accompanying notes).

- Cohen, B. A. (2001) Lunar Meteorites and the Lunar Cataclysm. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Jan01/lunarCataclysm.html
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