Headline Article

June 2, 2016

A Sample from an Ancient Sea of Impact Melt

--- A lunar breccia from the Apollo 16 site contains a fragment formed in a sea of impact melt 4.2 billion years ago.

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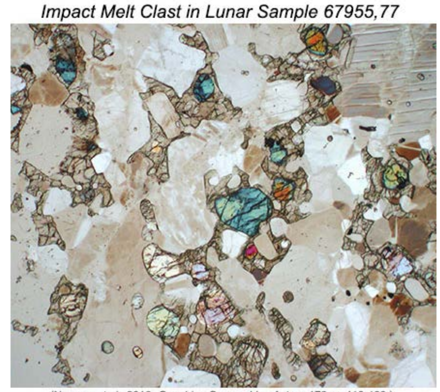
Impact Melt Clast in Lunar Sample 67955,77



(Norman *et al.*, 2016, *Geochim. Cosmochim. Acta*, v.172, p. 410-429.)

Sophisticated computer modeling of the formation of lunar multi-ringed basins by impact indicate that substantial volumes of impact melt are produced, leading to melt bodies hundreds of kilometers in diameter and tens of kilometers deep. The impressively large bodies of magma created by the impact of a projectile 50 to 300 kilometers across might have differentiated, producing a zoned body with denser minerals concentrated towards the bottom and less dense minerals concentrated near the top, a process called fractional crystallization. Marc Norman (Australian National University) and colleagues at the University of Tennessee and the Johnson Space Center have studied a sample (67955) collected in the lunar highlands during the Apollo 16 mission. The overall texture, composition, and mineralogy of a clast (a fragment) in the rock indicate that it formed as an accumulation of crystals from a magma that was enriched in trace elements. Mineral compositions and crystal intergrowths suggest a similar depth of origin to lunar igneous rocks that formed more than 10 kilometers deep in the lunar crust, implying an impact melt pool at least as deep. Such a deep melt pool would have formed in an impact basin the size of Orientale, a multi-ringed basin whose inner ring is 480 kilometers across. Norman and co-workers also determined from samarium and neodymium isotopes that the igneous clast is 4.2 billion years old, clearly older than the typical age of 3.8–3.9 billion years assigned to visible lunar basins. The authors conclude that the clast in 67955 is a sample of a differentiated impact melt sea formed in an impact basin on the nearside of the Moon 4.2 billion years ago. The rock was part of a pile of ejecta thrown to the Apollo 16 site, possibly by the impact event that excavated the Imbrium basin.

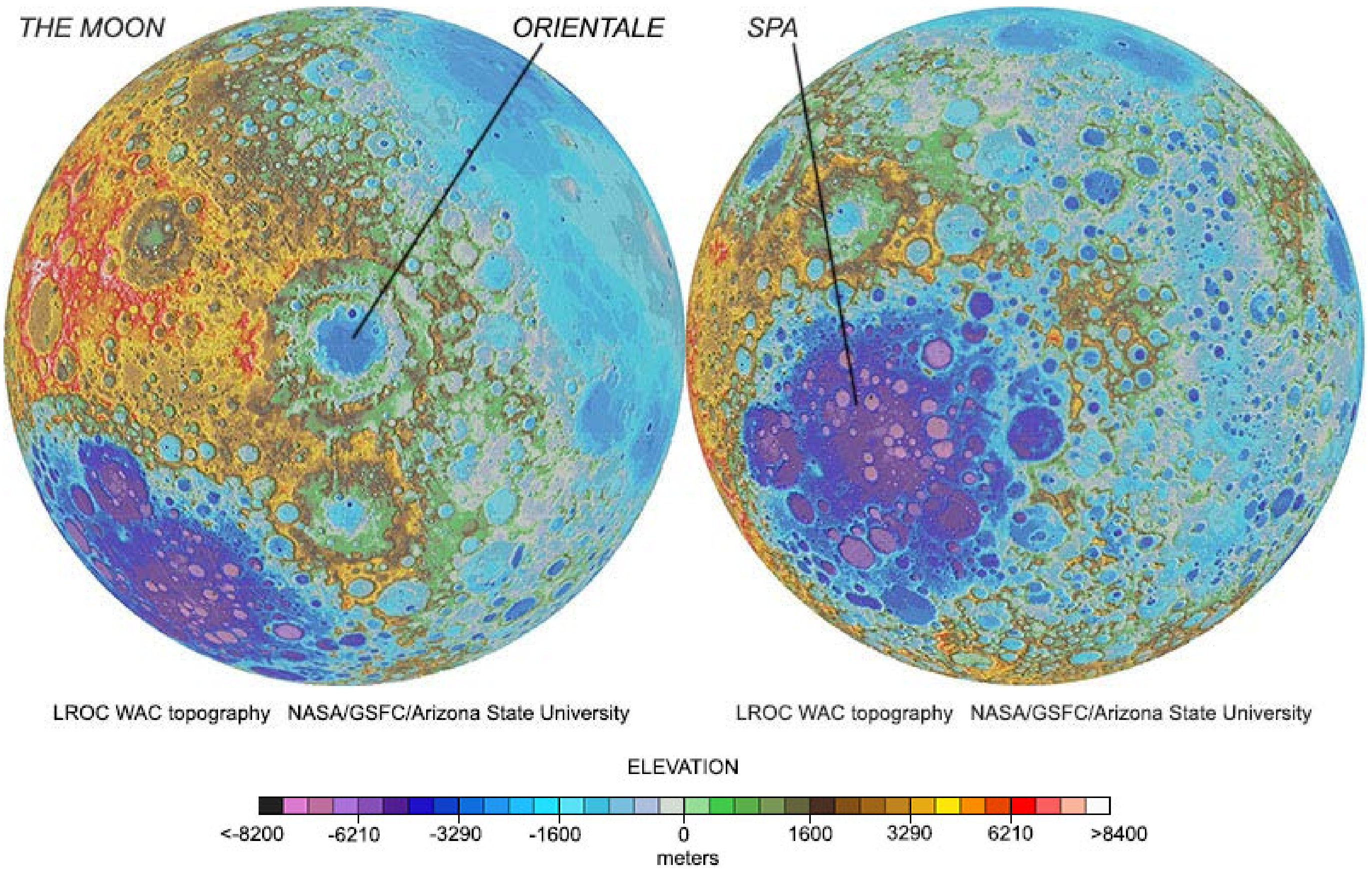
Reference:

- Norman, M. D., Taylor, L. A., Shih, C.-Y., and Nyquist, L. E. (2016) Crystal Accumulation in a 4.2 Ga Lunar Impact Melt. *Geochimica et Cosmochimica Acta,* v. 172, p. 410-429, doi: 10.1016/j.gca.2015.09.021. [**abstract**]
- **PSRDpresents:** A Sample from an Ancient Sea of Impact Melt --**Short Slide Summary** (with accompanying notes).

Impact Melt Sheets and Seas

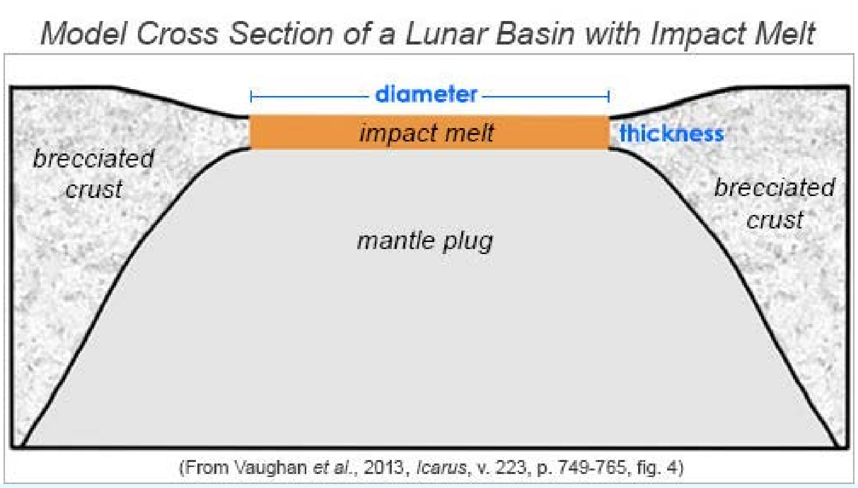
The Moon is adorned (or marred, depending on your viewpoint) with countless craters produced when speedy objects smashed into its surface. These pits range in size from a micron to 2500 kilometers. About 45 of them have inner rings larger than 300 kilometers in diameter. This intense cratering has greatly affected the surface materials, mostly by breaking, crushing, and mixing assorted rock types into massive rubble piles. An impact is so energetic that it also melts some of the target, with the amount of melt produced ranging from millimeter-sized droplets to impressive seas of melt. Larger craters produce disproportionally larger amounts of impact melt than do smaller craters. Modeling the process using an intricate computer program called iSALE [**link**] indicates that a large basin ends up with a central **magma** sea that can be tens of kilometers deep and hundreds of kilometers across, big enough to allow for slow cooling and accumulation of crystals to produce a pile of rocks that vary in mineralogy and chemical composition.

Crystallization of two examples of suspected melt seas have been modeled geochemically (see illustrations below). One case is the Orientale basin, studied by William Vaughan and colleagues at Brown University (Providence, Rhode Island). The Orientale sea of impact melt is estimated to be confined within the inner ring of the basin (called the Inner Rook Ring), and have a diameter of about 350 kilometers and a depth of 10 kilometers. Crystallization of the melt sea in the giant South Pole–Aitken basin (nicknamed SPA) was studied by Debra Hurwitz and David Kring (Lunar and Planetary Institute, Houston). The SPA melt sea is estimated to be about 400 kilometers in diameter and 50 kilometers deep. In both cases, the melt is composed of a mixture of melted **crust** and **mantle**.



Topographic maps generated from stereo images from NASA's Lunar Reconnaissance Orbiter Camera–Wide Angle Camera showing Orientale (left) and SPA (right) basins. Elevations are color-coded according to the scale shown above.

Orientale impact melt
diameter ~350 km
thickness ~10 km



SPA impact melt
diameter ~400 km
thickness ~50 km

The estimated sizes of the pure melt sea produced by the two basin-forming impacts. The Orientale sea of impact melt is estimated to have a diameter of about 350 kilometers and a thickness of 10 kilometers. The SPA impact melt sea is estimated to have a diameter of about 400 kilometers and a thickness of 50 kilometers. In both cases, substantial crustal materials are excavated by the impact, up to a few tens of kilometers, leaving behind brecciated material. The impact melt seas are large enough to cool slowly, allowing for crystals to separate from melt during solidification, leading to a layered series of rocks.

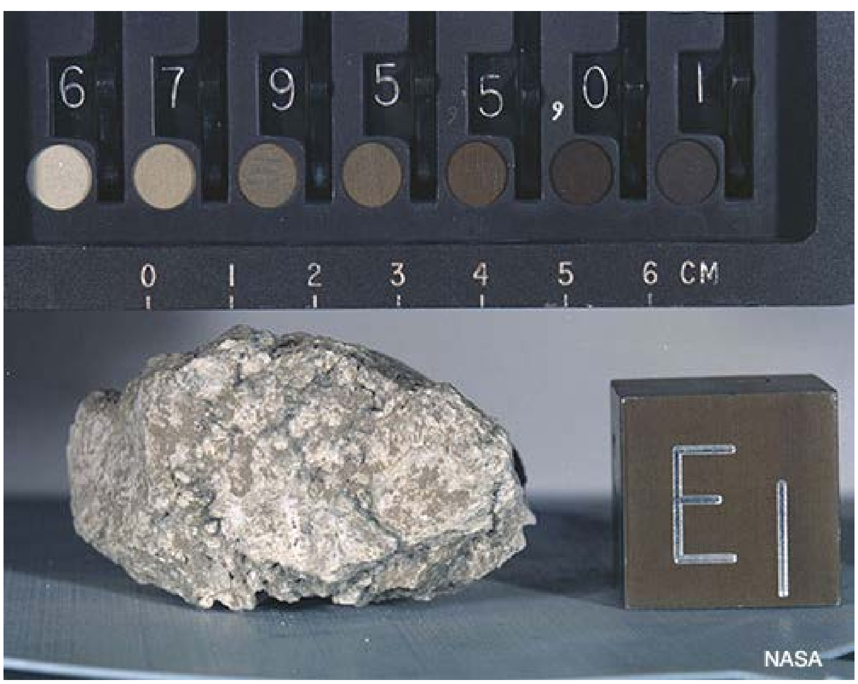
Crystallization modeling by Vaughan and coauthors used well-established phase equilibria diagrams, while Hurwitz and Kring used a computer program called Petrolog3 [**link**]. Both groups calculated the effects of **fractional crystallization**, a process in which minerals are separated from the residual melt (for example, by sinking). Removal of the crystals prevents their further interaction with the residual melt, causing large changes in the mineralogy and mineral compositions of the crystallizing set of minerals as solidification proceeds. Vaughan and co-workers also examined the case of equilibrium crystallization, which also produces layered sequences, but with a smaller range in rock types. The calculations are complicated by variation in density of the impact melt sea with depth, the extent to which the magma is uniform in composition to start with, whether inflowing crustal material contaminates the magma, and other factors. A major factor is the composition of the mantle that is mixed with crustal rock to make the impact melt seas. The mantle composition is not well established, with a huge uncertainty in whether the impact occurred before or after a major shuffling of mantle rocks formed in the lunar magma ocean. (See PSRD article: **Crystallizing the Lunar Magma Ocean**.) Nevertheless, the modeling efforts predict a final layered sequence that varies in mineralogy with depth that can be compared to the compositions of materials in the two basins.

Planetary scientists are reasonably confident that melt seas existed within large impact basins. The models for crystallization are also on firm ground, even if the starting conditions are difficult to pin down. But it sure would be good to have a sample or a set of related samples that formed in an impact melt sea so we could be sure they really existed and that they crystallized as expected. This is where Marc Norman and his colleagues come into the story.

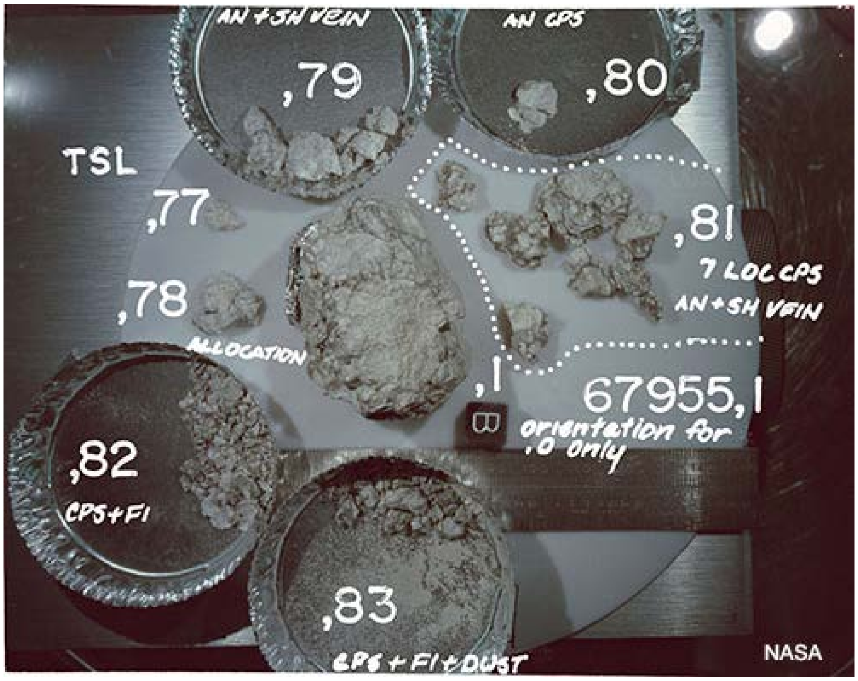
A Sample of a Crystallized Lunar Impact Melt Sea

Sample 67955 was collected from a large boulder near the rim of North Ray Crater at the Apollo 16 landing site. The rock fell apart into several pieces during its trip from the Moon to the Earth, consistent with Astronaut Charlie Duke's statement, "it's badly shattered...so I don't know whether it's going to stay together or not." The sample is actually a **breccia** with **igneous** clasts composed of **plagioclase feldspar** and **olivine** crystals enclosed by both low-calcium and high-calcium **pyroxene**. The overall texture indicates it is an igneous rock, specifically a cumulate rock formed in a large body of magma. However, it contains significant concentrations of nickel, iridium, and gold, elements diagnostic of meteorite contamination. Thus, 67955 appears to be a sample of a brecciated igneous cumulate with clasts of impact melt that **differentiated** as a deep sea of magma cooled slowly.

To study the sample in more detail, Marc Norman went to the lunar curatorial facility at NASA Johnson Space Center in March, 1992 (some projects take a long time!) and examined the largest pieces of 67955. He found a rock clast in one of the pieces that appeared to have relatively abundant olivine and pyroxenes (essential for accurate **radiometric age dating**). He picked a piece of the clast for age dating by his co-authors Nyquist and Shih, and obtained an adjacent piece to make into a thin section for microscopic examination and micro-analysis of individual minerals.



One of the larger pieces of 67955, though it is not very large (see the centimeter scale). An interesting thing about the curatorial lab photos of lunar rocks is most include an orientation cube, so that the locations of every subsample is known relative to each other. The unfortunate thing is that two sizes of cubes were used, a centimeter version and an inch version (pictured here). Fortunately, almost every picture includes a cube and/or a metric ruler. NASA photo S72-37515.



NASA curatorial photo of a set of samples of 67955, including ,77 and ,78 for use by Marc Norman and his colleagues. The designations indicate the type of materials. For example, CPS stands for chips, FI for fines (typically less than a millimeter in size), "AN+SH Vein" means anorthosite plus material from a vein formed by shock (SH). Note that ,77 and ,78 have the word allocation near them, indicating that they were going to be sent to Marc Norman for analysis. The official way of writing Marc's allocations is 67955,77 and 67955,78 showing the precision used to account and document samples by the lunar curatorial experts. NASA photo S92-32811.

Lunar Sample 67955,78

(Norman *et al.*, 2016, *Geochim. Cosmochim. Acta*, v.172, p. 410-429.)

Microphotograph of the fragment of 67955 separated for isotopic analysis. Whitest grains are plagioclase, light greenish areas are olivine, and brown regions are pyroxene. Image is about 2 centimeters across.

Marc Norman examined the thin section produced from sample 67955,77 (see photograph below) to verify the clast's igneous texture, and determined the compositions of plagioclase, olivine, and high- and low-calcium pyroxenes. Mineral abundances indicate that the clast's identification as a "noritic anorthosite" is reasonable. It means that it consists of more than 65% plagioclase (it contains about 78%) and that the most abundant other mineral is orthopyroxene. The mineral compositions and the roundish boundaries between crystals are similar to those seen in rocks of the magnesium suite, which are associated with the Procellarum **KREEP** Terrane (PKT). (See this **PSRD** article for more about Mg-suite rocks: **Unraveling the Origin of the Lunar Highlands Crust**.) Two such rocks, troctolite 76535 and norite 78235 are known from careful mineral compositional studies to have cooled slowly, at depths of around 10–20 kilometers. If the clast in 67955 cooled in an impact melt sea, therefore, the mineral and textural data suggest that the magma sea was likely on the order of 10 (or more) kilometers thick, not far from that estimated by William Vaughan and coworkers. Thus, the clast might be a sample from deep in the impact melt sea from a basin the size of the Orientale basin.

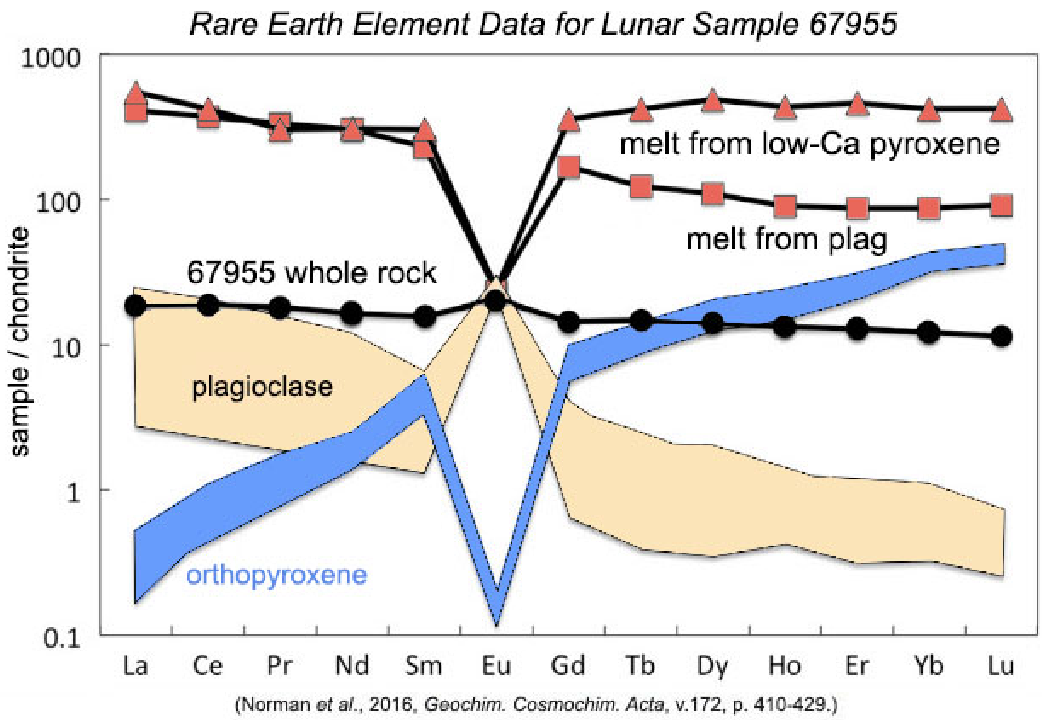
The abundances of minor and trace elements in these minerals were measured by zapping them with a finely-focused laser beam, creating a spray of atoms that are transported using a stream of gas (usually argon) into a device that ionizes all the atoms. The ionized gas (a plasma) is then introduced to a mass spectrometer system that identifies specific elements by their mass to charge ratios. The method is called Laser Ablation Inductively Coupled Mass Spectrometry, or LA-ICP-MS for short (but not necessarily for clarity). Analyzing rocks this way is highly sensitive for most elements and useful for microanalysis as the laser can be focused to tiny spots. It also gives geochemists the opportunity to use laser beams and to say "inductively coupled plasma."

Impact Melt Clast in Lunar Sample 67955,77

(Norman *et al.*, 2016, *Geochim. Cosmochim. Acta*, v.172, p. 410-429.)

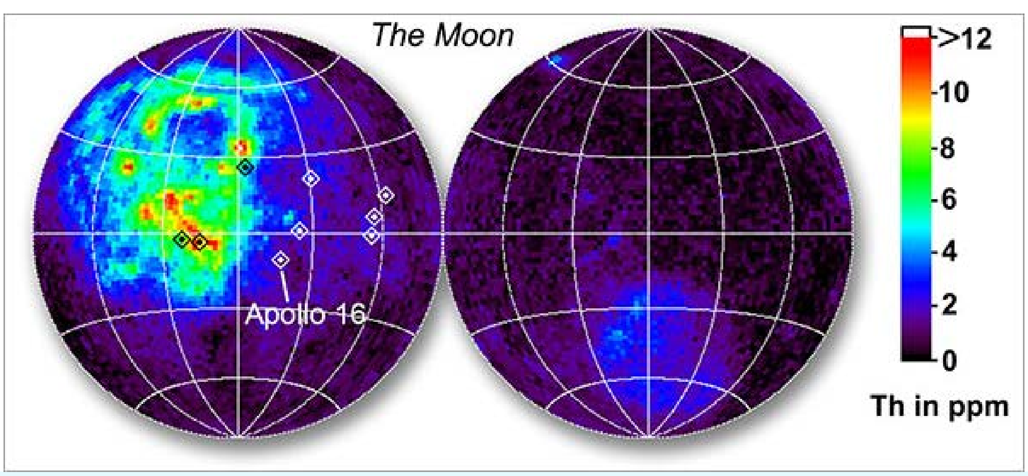
Thin section image (1 millimeter across) in partially crossed polarized light of the cumulate impact melt clast in 67955. Abundant light-colored mineral is plagioclase, blue and red crystals are olivine, and the brownish mineral surrounding plagioclase and olivine is pyroxene. The texture is called poikilitic and illustrates that the plagioclase and olivine crystals accumulated, then were surrounded by pyroxene from some of the remaining melt. The curvy rather than angular shapes of the minerals indicate slow cooling after crystallization, consistent with formation in a thick pool of magma.

The trace element analyses show clearly that the clast in 67955 crystallized from a magma enriched in potassium (K), rare earth elements (**REE**), and phosphorous (P), the elements that define the **KREEP** component in lunar rocks. An important clue to the nature of the 67955 magma is that the rare earth concentrations in the bulk sample are not particularly high, yet the concentrations of rare earth elements in individual mineral grains are high enough to infer that the magma contained lots of the KREEP component. This seemingly paradoxical deduction is based on laboratory experiments of how the rare earths and other elements go into different minerals during crystallization. Thus, if you know the concentration of some element in a mineral, you can calculate the amount that was in the magma from which it crystallized by multiplying the mineral concentration by the **partition coefficient**. There are, of course, some complications, such as redistribution among the minerals in the rock after it has completely solidified, but geochemists have a handle on such problems. Marc Norman and colleagues conclude that in spite of the relatively low rare earth (and associated) element concentrations in bulk samples of 67955, its mineral constituents formed in a magma that was high in REE and other trace elements such as barium and strontium.



Rare earth element concentrations in plagioclase and low-calcium (orthorhombic) pyroxene in cumulate lithology in 67955 are shown as the tan and blue fields, respectively. The whole rock concentrations (black dots) are not much higher than they are in plagioclase. The red symbols are calculated concentrations derived from data from the minerals in the clast and mineral-melt partition coefficients measured experimentally (see example in Cosmo*Sparks* article: **Partition Coefficients in Fe-rich Systems: Relevance to the Lunar Mantle**). The red data points are much higher than the black points of the whole rock analysis, which indicates that the minerals crystallized from a magma containing high concentrations of trace elements. The results for the elements on the right of the diagram (from Gd to Lu) are different for plagioclase and orthopyroxene, illustrating some complexity in the approach and in partition coefficients. The higher rare earth element concentrations in the calculated magma compared to whole rock analysis indicates that the clast formed as an accumulation of mineral crystals in a magma, but that the residual magma was not trapped in the final cumulate.

The high concentrations of rare earth elements in the magma that produced noritic anorthosite 67955 indicate that it formed somewhere in the PKT. The startling trace element enrichment in the PKT is evident from a map of thorium obtained from orbit by the Lunar Prospector mission (see below). Thorium behaves geochemically like the rare earth elements, so is an excellent marker of the distribution of the KREEP component. The Apollo 16 landing site is just outside of the PKT, so it is likely that high-KREEP sample 67955 originated inside the PKT. How and when was it delivered to the Apollo 16 landing site? We'll return to this.

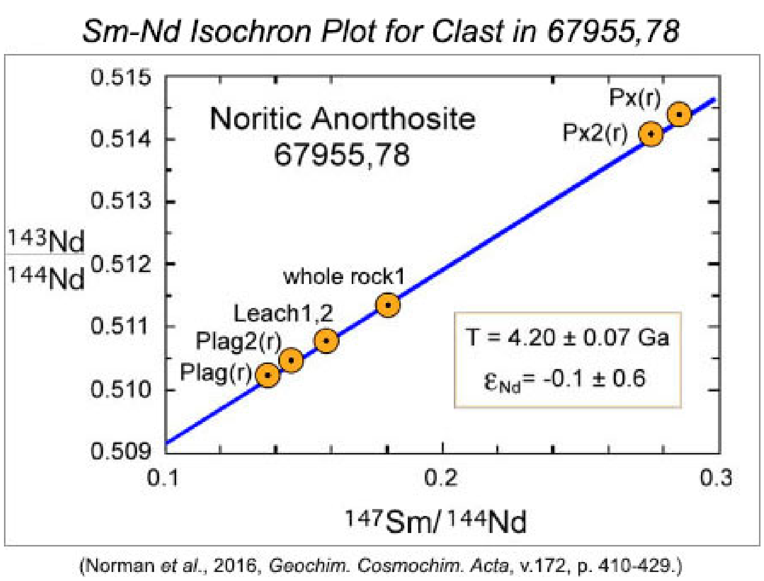


Distribution of thorium (Th) on the lunar nearside (left) and farside (right), determined by the Lunar Prospector Gamma-Ray Spectrometer. The high thorium area on the nearside is the Procellarum KREEP Terrane (PKT), which has considerably higher concentrations of thorium and other trace elements. Diamonds show Apollo and Luna landing sites, with Apollo 16 labeled. In spite of being found at the Apollo 16 landing site, 67955 is most likely to have formed somewhere inside the PKT. As explained below, it might have been delivered to the Apollo 16 site by the formation of the Imbrium basin.

Older than the Hills

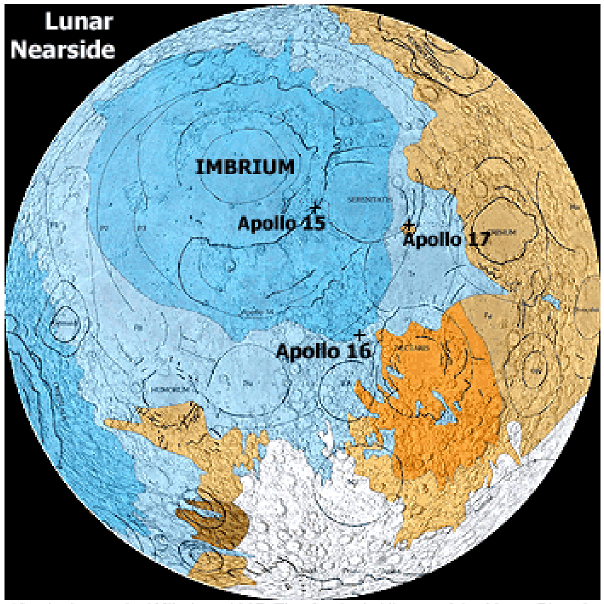
Understanding planetary evolution requires knowing when significant events happened. On the Moon, a special problem is knowing when the large impact basins formed. It was thought for a long time that almost all of them could have formed between 3.8 and 3.9 billion years ago, in a cataclysmic **late heavy bombardment**. (See **PSRD** article: **Lunar Meteorites and the Lunar Cataclysm**.) There are growing signs, however, that many impacts occurred earlier than this relatively short time frame. The 67955 clast appears to be a cumulate rock formed in an impact melt sea formed inside a basin the size of Orientale.

The age of the 67955 cumulate impact melt was determined by the samarium-neodymium and rubidium-strontium techniques in Larry Nyquist's and Chih-Yu Shih's lab at the NASA Johnson Space Center. Over the decades since Apollo 11 returned with a box full of rocks, the lab has produced a significant number of well-determined ages for lunar samples. The procedure requires painstaking mineral separations and some chemical processing before analysis by mass spectrometry. The samarium-neodymium data show that the noritic anorthosite clast in 67955 formed 4.20 ± 0.07 billion years ago; rubidium-strontium dating gives a less precise, but consistent age. This age can also be inferred from previous analyses of apatite and zirconolite ($CaZrTi_2O_7$), two minor minerals in 67955 dated by Marc Norman and Alex Nemchin (Curtin University, Perth, Australia). The agreement among three isotopic systems gives confidence that the age is correct (see **PSRD** article: **Age Rules**).



In the Samarium (Sm)-Neodymium (Nd) radiometric dating technique, ^{147}Sm decays to ^{143}Nd. These two isotopes are plotted normalized to ^{144}Nd, which is a stable isotope of Nd that is not involved in the radioactive decay process. For a reliable age, data from separated minerals should fall on the same line, though they differ in the relative abundances of samarium and neodymium (hence in the Sm/Nd ratio). Plag = plagiocalse, Leach = leachate, and Px = pyroxene + minor olivine. A rock starts with uniform $^{143}Nd/^{144}Nd$; with time, the ratio in each mineral changes in proportion to the Sm/Nd ratio. Using the radioactive decay equation, the age can be determined from the slope of the line. In this case, the age is 4.20 ± 0.07 billion years (Ga), where the uncertainty comes from the quality of the fit to the line. Other isotope systems give results consistent with this age, giving Marc Norman and his colleagues confidence that this sample is older than the conventional age of the late heavy bombardment, 3.8–3.9 billion years.

So, the story is that the cumulate noritic anorthosite in 67955 formed in a hefty puddle of impact melt at least 10 kilometers thick. High concentrations of trace elements associated with KREEP indicated that this basin was located in the Procellarum KREEP Terrane. Could it have formed from one of the visible basins in the PKT? Probably not, as they seem to be too young. The Imbrium basin has been dated reasonably well at 3.85 billion years, and Serentatis is possibly a bit older. Other circular features in this region are quite degraded, so absolute ages are uncertain. It is quite possible that the basin in which 67955 originally formed was obliterated by the enormous Imbrium impact, with some of the crystallized melt sea deposited at the Apollo 16 site. It was eventually excavated by the impact that formed North Ray Crater, and sampled by the Apollo 16 astronauts. The Apollo 16 site lies at the margin of mapped ejecta from Imbrium (see below).



(Geologic map by Wilhelms, 1987, The Geologic History of the Moon, Plate 3, overlaid on USGS shaded relief map, courtesy of Paul Spudis.)

The dark blue area surrounding Imbrium basin on this map shows Don Wilhelms' interpretation of the extent of primary ejecta for the Imbrium basin. The Apollo 16 landing site marked with a "+" is at the edge of this geologic unit, suggesting that some rocky materials at the Apollo 16 landing site may have originated in the Imbrium region and in the PKT.

Regardless of the precise location on the Moon where the analyzed clast in 67955 formed, it most likely cystallized in a deep pool of melt created during formation of a lunar impact basin. Thus, its old crystallization age of 4.2 billion years shows clearly that the era of basin formation extended back at least this far.

Additional Resources

Links open in a new window.

- **PSRDpresents:** A Sample from an Ancient Sea of Impact Melt --**Short Slide Summary** (with accompanying notes).

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

- Hurwitz, D. M. and Kring, D. A. (2014) Differentiation of the South Pole-Aitken Basin Impact Melt Sheet: Implications for Lunar Exploration, *Journal of Geophysical Research: Planets,* v. 119, p. 1110-1133, doi:10.1002/2013JE004530. [**abstract**]

- Martel, L. M. V. (Sept. 2010) Unraveling the Origin of the Lunar Highlands Crust. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Sept10/highlands-granulites.html**.

- Norman, M. D. and Nemchin, A. A. (2014) A 4.2 Billion Year Old Impact Basin on the Moon: U–Pb Dating of Zirconolite and Apatite in Lunar Melt Rock 67955, *Earth and Planetary Science Letters,* v. 388, p. 387-398, doi: 10.1016/j.epsl.2013.11.040. [**abstract**]

- Norman, M. D., Taylor, L. A., Shih, C.-Y., and Nyquist, L. E. (2016) Crystal Accumulation in a 4.2 Ga Lunar Impact Melt. *Geochimica et Cosmochimica Acta,* v. 172, p. 410-429, doi: 10.1016/j.gca.2015.09.021. [**abstract**]

- Taylor, G. J. (Aug. 2011) Crystallizing the Lunar Magma Ocean. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Aug11/LMO-crystallization.html**.

- Taylor, G. J. (Oct. 2015) Age Rules. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Oct15/age-rules.html**.

- Vaughan, W. M., Head, J. W., Wilson, L., and Hess, P. C. (2013) Geology and Petrology of Enormous Volumes of Impact Melt on the Moon: A Case Study of the Orientale Basin Impact Melt Sea, *Icarus*, v. 223, p. 749-765, doi: 10.1016/j.icarus.2013.01.017. [**abstract**]

- **Video Simulations of Impact Cratering Processes**, produced using the iSALE shock physics code. This site by Ross W. K. Potter and David A. Kring, hosted by the Lunar and Planetary Institute, Houston, TX, shows a simulation of the Orientale basin-forming event as well as numerous other impacts on the Moon and Earth.