PLANETARY SCIENCE RESEARCH PSRD Discoveries

Headline Article
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Leftovers from Ancient Lunar Impactors

--- A systematic search for meteorite fragments in ancient regolith breccias confirms chondritic impactors on the Moon.

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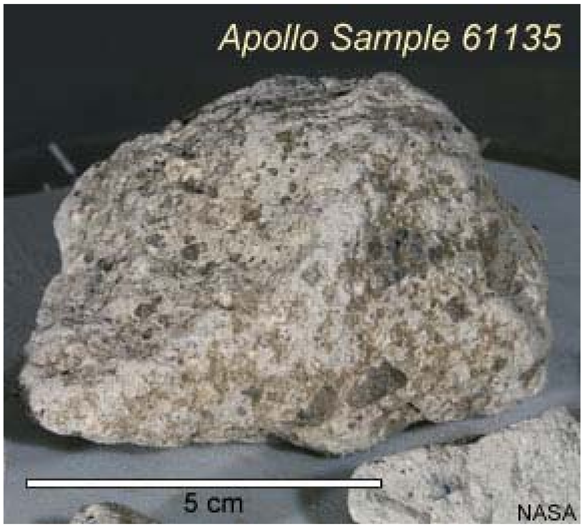


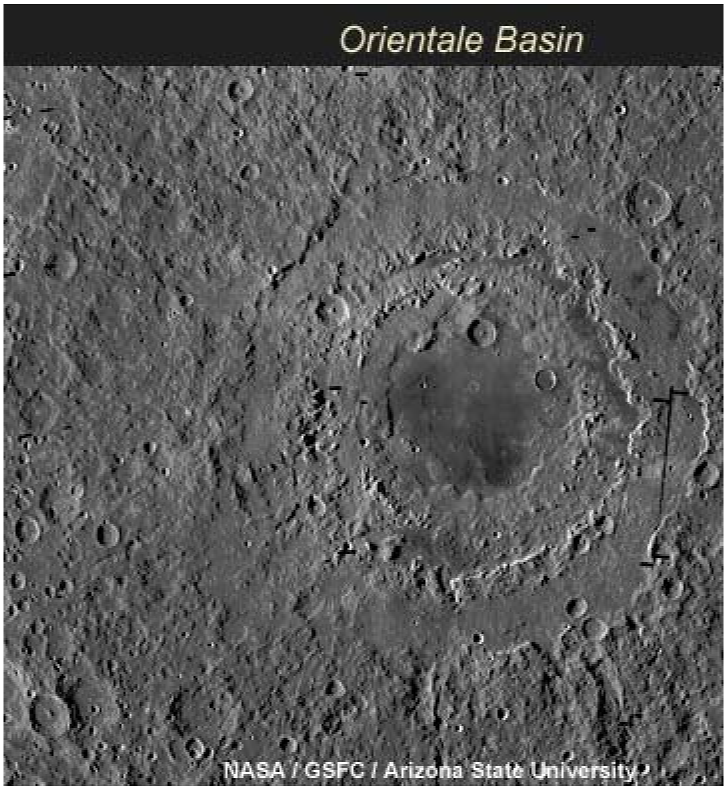
The lunar basins mark a time, over three and a half billion years ago, of extreme bombardment in the early Solar System, including in the young Earth-Moon system. What hit the Moon (and by proxy, Earth) at the end of the basin-forming epoch has now been determined directly, for the first time, from the analyses of impactor debris found in samples returned from the Apollo 16 landing site. Katie Joy (Lunar and Planetary Institute, NASA Lunar Science Institute) and colleagues working in Houston and Honolulu identified 30 tiny mineral and rock relics of **chondritic** impactors during their systematic search of **regolith breccias** formed between about 3.8—3.4 billion years ago. The relatively uniform composition of these chondritic **meteorite** fragments is in contrast to the variety of meteorites in our collections, supporting the idea that the influx of materials bombarding the Moon and Earth ≥3.4 billion years ago was different from more recent times.

Reference:

- Katherine H. Joy, Michael E. Zolensky, Kazuhide Nagashima, Gary R. Huss, D. Kent Ross, David S. McKay, and David A. Kring (2012) Direct Detection of Projectile Relics from the End of the Lunar Basin-Forming Epoch, *Science,* v. 336, p. 1426-1429, doi: 10.1126/science.1219633.

Basin Formation

Lunar basins are defined as impact craters larger than 300 kilometers in diameter with two or more concentric rims and no central peak. There are about 45 basins on the Moon. They document a time of intense bombardment that may have spanned the first 700 million years of lunar history, spiking in intensity 3.85 to 3.95 billion years ago (see PSRD article: **Lunar Meteorites and the Lunar Cataclysm**). The cataclysmic spike (if it happened) may have been triggered, as one idea—the Nice model—suggests, by the scattering of countless planetesimals due to the migration of orbits of the giant planets (see PSRD article: **Wandering Gas Giants and Lunar Bombardment**). Understanding the bombardment history of the Moon at this time of basin formation is crucial to understanding the geologic history of the terrestrial planets. The collisions not only sculpted basins and craters but also blasted subsurface rocks and generated the layers upon layers of regolith debris. While researchers actively study the bombardment flux, timing, and impact dynamics of basin formation, Joy and colleagues focused attention on the very pieces of Solar System stuff that collided with the Moon, causing all the large-scale excavation and geologic mayhem.



A beautiful example of a multi-ring lunar basin is shown in this mosaic of Orientale made from Wide Angle Camera images from NASA's Lunar Reconnaissance Orbiter Camera. Orientale was only partially filled by later eruptions of dark, mare basalt, so details of its internal structure are still visible. The outer ring has a diameter of about 950 kilometers. The width of the image is 1350 kilometers. The black stripes are data gaps. Click the image for more information and higher resolution options.

Deciphering What Hit the Moon Using Chemical Fingerprints

Competing models of basin formation on the Moon suggest at least four possible types of impactors: asteroids, comets, even mixtures of the two, or pieces from a single shattered asteroid or protoplanet. In previous work, people have used chemical signatures and crater size-frequency data to figure out what hit the Moon. These studies implicate asteroids instead of comets as the dominant impactors. We'll briefly review the cosmochemical case.

Rocks returned by the Apollo missions show clear evidence for impact reworking of the crust, including melting by large impacts. This is consistent with the presence of so many impact basins and craters on the Moon. Beginning in the early 1970s, Edward Anders (University of Chicago) and John Morgan (U.S. Geological Survey) and their coworkers began a series of measurements of **siderophile** elements in lunar impact breccias. These elements, which include platinum, palladium, and iridium, have very low concentrations in planetary crusts. Morgan and Anders figured that the enhanced concentrations they measured in impact breccias would contain information about the composition of the impactors that made all those basins and craters. This work, which continues today, has implicated several types of asteroidal impactors (**chondritic** and **differentiated** bodies) as perpetrators of the demolition and mixing of lunar crustal rocks. However, the situation is not always clear cut because element ratios change with the concentration of the siderophile elements, and post-impact processes such as crystallization can also change element ratios. Wouldn't it be nice to have unmodified pieces of the impacting objects, rather than relying on cryptic chemical fingerprints (valuable though they are)? This led the **NASA Lunar Science Institute team** at the Lunar and Planetary Institute and Johnson Space Center, led by David Kring, to launch a search for chunks of ancient impactors.

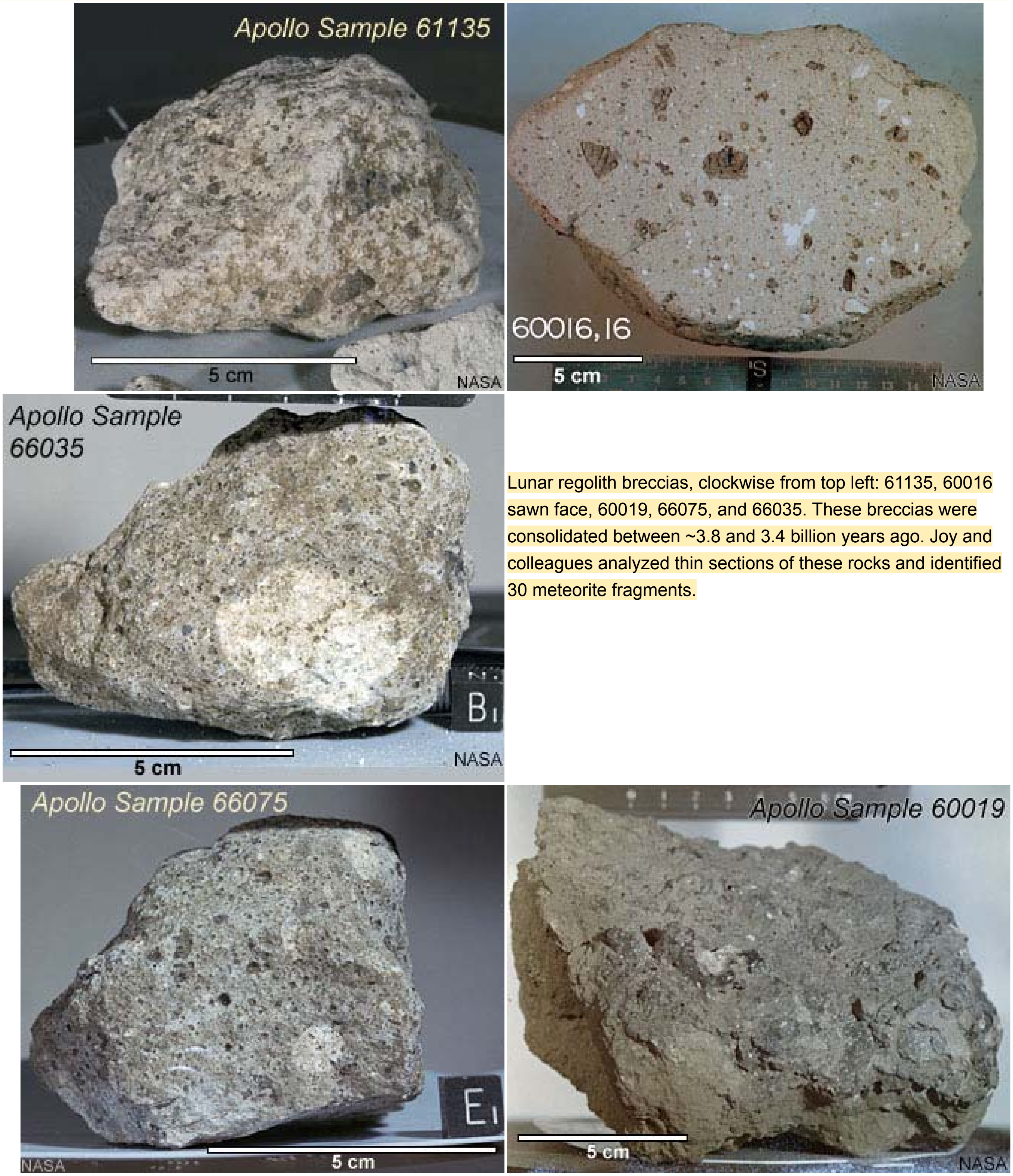
Deciphering What Hit the Moon by Looking at the Rubble

The lunar surface is covered by regolith, the fine-grained debris that preserves the geologic history of the Moon itself and the record of the Moon's interaction with the space environment, including impact events (and astronaut boots). Large impacts bust up additional rocks, making more regolith, but also bond some of the debris into coherent rocks called breccias. These rocks preserve the mineralogical and chemical characteristics of the regolith at the time they formed. Dating the regolith breccias means we can track the changes in the regolith with time. Joy and coauthors searched lunar regolith breccias for impactor relics that were produced during the basin-forming epoch. Their work required ancient lunar rocks of known age.

Dating fragmental rocks is not easy, but in the 1980s Otto Eugster, Johannes Geiss, and their colleagues at the University of Bern in Switzerland, suggested a way to date regolith breccias using the relation between rock formation time and the ratio of argon-40 to argon-36 trapped in a rock. The trick to this innovative approach is the source of the argon-40. This **isotope** forms by the decay of potassium-40 and is the basis of the potassium-argon dating system. However, different rock fragments inside a breccia will give different ages and a measurement of the entire rock just gives an average age. Fortunately, in the early 1970s, Dieter Heymann and Akiva Yaniv at Rice University showed that a considerable amount of the argon-40 generated by potassium-40 decay leaks out of the Moon, flies around in the flimsy lunar atmosphere (properly called the exosphere), is ionized by ultraviolet light, and gets implanted onto surface grains. It then ends up in regolith breccias. By correcting for the amount of potassium-40 decay inside a fragmental breccia, the ratio of the implanted argon-40 to argon-36 (which comes from the solar wind) can be used as a chronometer.

Co-author David McKay and colleagues at the NASA Johnson Space Center used the technique in 1986 to date a group of Apollo 16 regolith breccias. Otto Eugster and colleagues updated the method in 2001, and Katie Joy and colleagues tweaked the method a bit more in 2011. The technique is now reasonably well calibrated. Joy and colleagues found that the ancient lunar rocks they studied ranged in age from 3.8 billion years to 3.4 billion years. A separate group of rocks were much younger, less than 1.7 billion years. With ages duly calculated, Joy and colleagues began their analysis of the regolith breccias, including 61135, 60016, 66035, 66075, and 60019 (pictured below).

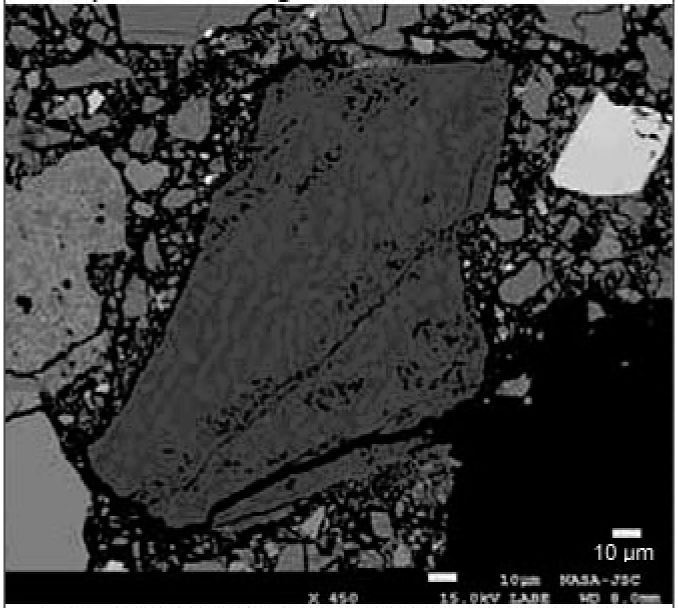
LUNAR REGOLITH BRECCIAS



Lunar regolith breccias, clockwise from top left: 61135, 60016 sawn face, 60019, 66075, and 66035. These breccias were consolidated between ~3.8 and 3.4 billion years ago. Joy and colleagues analyzed thin sections of these rocks and identified 30 meteorite fragments.

The researchers applied field emission scanning electron microscopy to rapidly scan and chemically map each rock thin-section in ultra-high (nanometer) resolution. They looked for mineral or rock fragments chemically and/or texturally distinct from lunar material, including hydrated, magnesian-rich, sulphide-rich, and refractory minerals. Joy and colleagues identified 52 magnesian-rich particles 30 of which were large enough (20 to 225 micrometers) to be further characterized by electron microprobe. The team compared the compositions of these 30 fragments to a library of lunar, meteorite, micrometeorite, **IDP**, and cometary materials to classify the fragments' origins. Hence, the procedure was not biased toward any particular type of impactor debris.

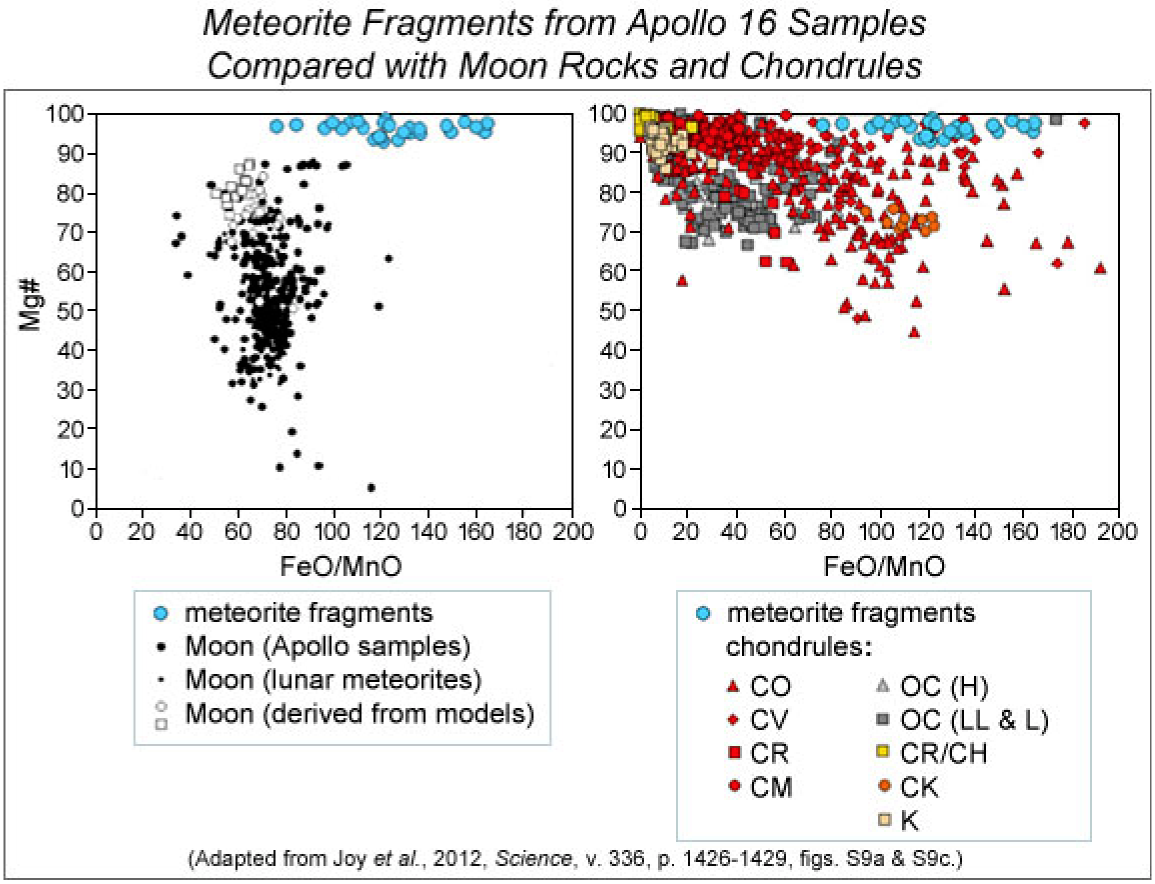
Meteorite Fragment in Apollo 16 Regolith Breccia 60016



(From Joy *et al.*, 2012, *Science*, v. 336, p. 1426-1429, fig.1.)

This backscattered electron image (left) of a thin section of Apollo 16 sample 60016,83 shows one of the meteorite fragments identified by Joy and colleagues (in the center of the image) surrounded by regolith-breccia matrix. The grey patterns in the meteorite fragment are due to intergrowths of the minerals olivine and pyroxene.

All fragments have bulk compositions that are highly magnesian (Mg# = 93 to 99 and FeO/MnO = 76 to 165), which means they contain the magnesium-rich endmembers of **olivine** and **pyroxene**. These 30 fragments are easily distinguished from Moon bulk rock compositions (graph on the left shown below). The ratio of Fe to Mn in mafic minerals is also particularly useful in fingerprinting the origin of meteorite fragments. The graph shown below on the right compares the 30 fragments to **chondrules** in nine different types of **chondrite meteorites**. The team found that not only do all the fragments have igneous textures similar to those in chondrules of primitive chondrites, but also the olivines in these fragments are as magnesian as olivines from type-1 chondrules in carbonaceous chondrite groups.

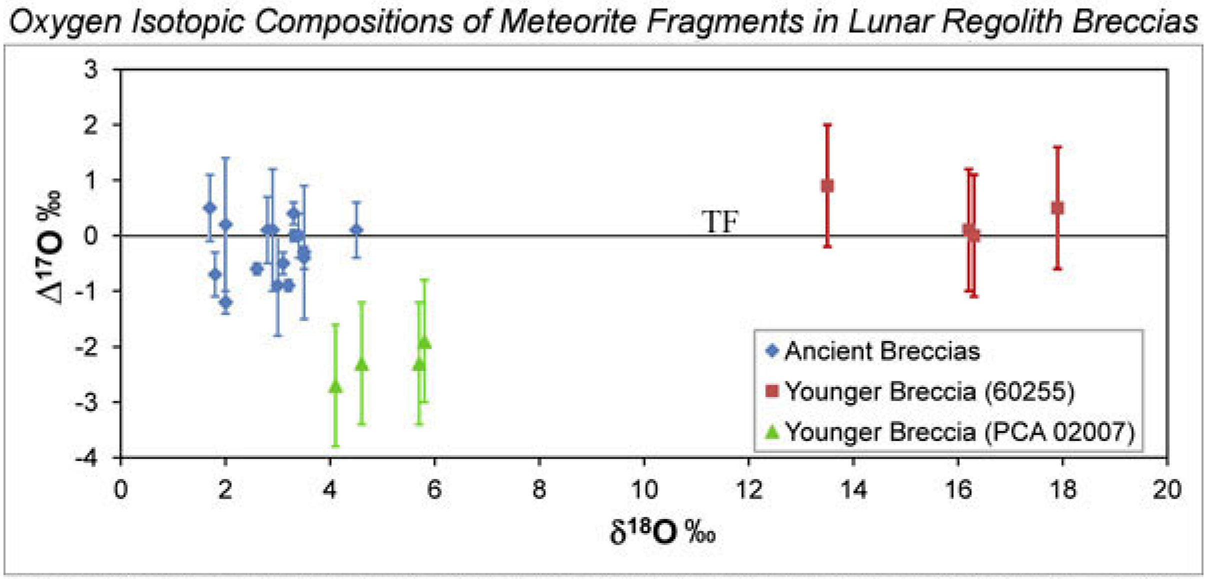


(Adapted from Joy *et al.*, 2012, *Science*, v. 336, p. 1426-1429, figs. S9a & S9c.)

Bulk composition of the magnesium-rich mafic fragments—the meteorite fragments— found in the Apollo 16 ancient regolith breccias (cyan circles) are compared with (on the left) Apollo samples, lunar meteorite bulk rock compositions, and experimental petrology model results and (on the right) with individual chondrule bulk compositions. Joy and coauthors found the fragments are distinct from lunar rock bulk compositions and have high FeO/MnO ratios most similar to examples found in the CV group of carbonaceous chondrites.

Another very useful way to compare planetary materials is to measure the relative abundances of the three oxygen isotopes in them. On plots of $^{17}O/^{16}O$ vs $^{18}O/^{16}O$ normalized to standard mean ocean water (**SMOW**), cosmochemists can distinguish among meteorite groups and individual chondrules and calcium-aluminum-rich inclusions (**CAIs**) in chondrites, and between Earth and Mars. The Moon and Earth fall on a well-defined line. The three-isotope plot is informative, but not always the simplest thing to read, so cosmochemists often use the difference between the Earth-Moon line on the $^{17}O/^{16}O$ axis as a distinguishing parameter, which they call $\Delta^{17}O$ (pronounced "big delta 17"). It can be plotted against $^{18}O/^{16}O$ (see diagram below) or just listed as a useful parameter. Moon and Earth samples all have $\Delta^{17}O$ of 0.

The oxygen isotope compositions of the meteorite fragments are within the ranges exhibited by ordinary and carbonaceous chondrites. But, because of the large analytical uncertainties in the analyses of such small particles, most of the meteorite fragments in the ancient Apollo 16 regolith breccias are not distinguishable from the Earth-Moon line (labeled TF, for "terrestrial fractionation" in the diagram below), although some clasts have error bars that do not overlap the TF line. Joy and her colleagues suggest that the ancient impactors came from a region of the early Solar System where the oxygen isotopic composition was similar to that of Earth. The fragments from younger impactors, such as those in lunar sample 60255 and lunar meteorite PCA 02007 (see diagram) have distinctly different oxygen isotopic compositions. The data suggest a change in the nature of impactors from about 3.8 billion years ago to now. No doubt experts in orbital dynamics of planets and asteroids will use this to test their elaborate computer simulations.



(PSRD graphic based on data in Joy *et al.*, 2012, *Science*, v. 336, p. 1426-1429 & supplementary materials, doi: 10.1126/science.1219633.)

Oxygen isotopic compositions of the meteorite fragments in lunar regolith breccias, expressed as the deviation from the terrestrial fractionation line (TF) where samples from Earth plot. This diagram plots Δ^{17}O versus $\delta\ ^{18}$O. The $\delta\ ^{18}$O is simply the ratio of ^{18}O to ^{16}O, but normalized to the Earth value as represented by standard mean ocean water (SMOW). Bulk analyses of the meteorite fragments in Apollo 16 regolith breccias 60016, 61135, 66035, and 60275 are in blue. Analyses of olivine in the younger Apollo 16 regolith breccia 60255 are in red. Analyses of olivine in regolith breccia lunar meteorite PCA 02007 are in green.

Deciphering What Else Hit the Moon

Katie Joy and her colleagues have reported a new way to use the Moon as a Rosetta stone. Earth's close neighbor contains information about the formation of our planetary home, the origin of Earth's water, impact bombardment in the Solar System, and, now, direct evidence about the compositions of the impactors. The Moon also contains proof that it formed in a substantially or totally molten state and a detailed record of how that ocean of magma crystallized. Its surface materials even contain a record of the history of the Sun.

The lunar regolith is a vast rock collection. As Joy and colleagues show, ancient and younger samples from it contain the record of the types of materials whacking into the Moon throughout geologic time. The work is just beginning. Regolith breccias from other Apollo landing sites and lunar meteorites await examination by the sharp eyes of cosmochemists.

One of the interesting sources of the projectiles that hit the Moon might be the Earth. Of particular interest is the early Earth, say older than 3.8 billion years, the time when life was taking hold here. John Armstrong (University of Washington) and colleagues looked into the possibilities. They estimated that the lunar surface contains about 10 parts per million Earth debris, blasted off the Earth by large impacts. But, would these rocks survive the high-speed landing on the Moon? Ian Crawford (Birkbeck College, London) and colleagues looked at this issue and concluded that a substantial fraction of Earth debris would survive delivery to the Moon. Joy and her colleagues show that exotic non-lunar needles can be identified in the regolith haystack. They have found quite a few pieces of chondrite-like impactors. Will they find pieces of the ancient Earth next?

Additional Resources

Links open in a new window.

- **PSRDpresents:** Leftovers from Ancient Lunar Impactors --**Short Slide Summary** (with accompanying notes).
- Armstrong, J. C., Wells, L. E., and Gonzalez, G. (2002) Rummaging Through Earth's Attic for Remains of Ancient Life, *Icarus,* v. 160(1), p. 183-196, doi: 10.1006/icar.2002.6957. [**NASA ADS entry**]
- Cohen, B. A. (2001) Lunar Meteorites and the Lunar Cataclysm. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Jan01/lunarCataclysm.html**.
- Crawford, I. A., Baldwin, E. C., Taylor, E. A., Bailey, J., and Tsembelis, K. (2008) On the Survivability and Detectability of Terrestrial Meteorites on the Moon, *Astrobiology,* v. 8(2), p. 242-252. [**NASA ADS entry**]
- Eugster, O., Terribilini, D., Polnau, E. and Kramers, J. (2001) The Antiquity Indicator argon-40/argon-36 for Lunar samples Calibrated by uranium-235-xenon-136 Dating, *Meteoritics & Planetary Science,* v. 36(8), p. 1097-1115. [**NASA ADS entry**]
- Joy, K. H., Zolensky, M. E., Nagashima, K., Huss, G. R., Ross, D. K., McKay, D. S., and Kring, D. A. (2012) Direct Detection of Projectile Relics from the End of the Lunar Basin-Forming Epoch, *Science,* v. 336, p. 1426-1429, doi: 10.1126/science.1219633. [**NASA ADS entry**]
- Joy, K. H., Kring, D. A., Bogard, D. D., McKay, D. S., and Zolensky, M. E. (2011) Re-examination of the formation ages of the Apollo 16 regolith breccias, *Geochim. Cosmochim. Acta,* v. 75, p. 7208, doi:10.1016/j.gca.2011.09.018. [**NASA ADS entry**]
- McKay, D. S., Bogard, D. D., Morris, R. V., Korotev, R. L., Johnson, P., and Wentworth, S. J. (1986) Apollo 16 Regolith Breccias: Characterization and Evidence for Early Formation in the Megaregolith, *Proceedings of the Sixteenth Lunar and Planetary Science Conference, Journal of Geophysical Research,* v. 91, p. D277-D303. [**NASA ADS entry**]
- Taylor, G. J. (2006) Wandering Gas Giants and Lunar Bombardment. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Aug06/cataclysmDynamics.html**.
- Yaniv, A. and Heymann, D. (1972) Atmospheric Argon-40 in Lunar Fines, *Proceedings of the Third Lunar Science Conference, Supplement 3, Geochimica et Cosmochimica Acta,* v. 2, p. 1967-1980. [**NASA ADS entry**]

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