PLANETARY SCIENCE RESEARCH PSRD Discoveries

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Time to Solidify an Ocean of Magma

--- A small mineral grain places limits on how long it took the lunar magma ocean to solidify.

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Cosmochemists are reasonably sure that a global ocean of magma surrounded the Moon when it formed. This was a monumentally important event in lunar history, forming the primary feldspar-rich crust of the lunar highlands and setting the stage for subsequent melting inside the Moon to make additional crustal rocks. Numerous questions remain about the complex array of processes that could have operated in such a huge amount of magma, and about how long it took to solidify the magma ocean. Alex Nemchin and colleagues at Curtin University of Technology (Australia), Westfälische Wilhelms-Universität (Münster, Germany), and the Johnson Space Center (Houston, Texas, USA) dated a half-millimeter grain of the mineral zircon ($ZrSiO_4$) in an impact melt breccia from the Apollo 17 landing site. They used an ion microprobe to measure the concentrations of lead and uranium isotopes in the crystal, finding that one portion of the grain recorded an age of 4.417 ± 0.006 billion years. Because zircon does not crystallize until more than 95% of the magma ocean has crystallized, this age effectively marks the end of magma ocean crystallization. Magma ocean cooling and crystallization began soon after the Moon-forming giant impact. Other isotopic studies show that this monumental event occurred 4.517 billion years ago. Thus, the difference between the two ages means that the magma ocean took 100 million years to solidify.

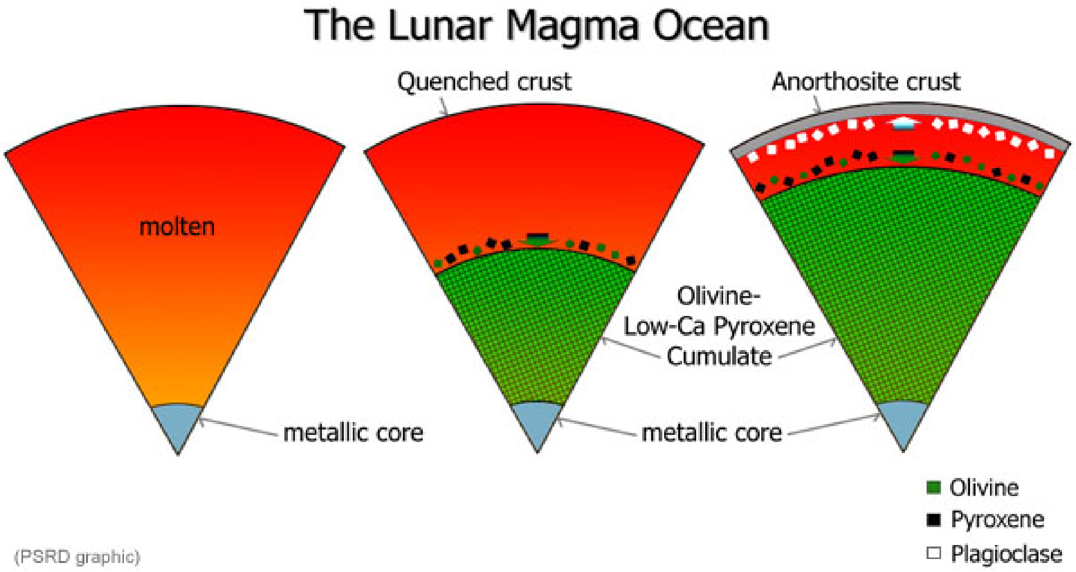
Reference:

- Nemchin, A., Timms, N., Pidgeon, R., Geisler, T., Reddy, S., and Meyer, C. (2009) Timing of Crystallization of the Lunar Magma Ocean Constrained by the Oldest Zircon. *Nature Geoscience*, 25 January 2009: doi: 10.1038/NGEO417.

PSRDpresents: Time to Solidify an Ocean of Magma --Short Slide Summary (with accompanying notes).

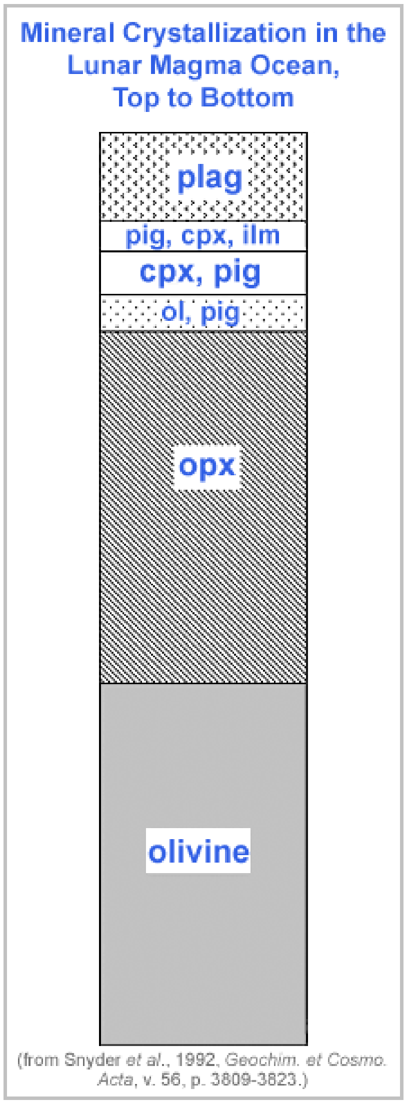
The Molten Moon

As we have recounted several times in **PSRD** articles, the composition of the lunar crust indicates that the little planet was almost completely molten when it formed. This central tenet of lunar science is consistent with formation of the Moon by a giant impact, which would have led to rapid accumulation of molten material orbiting the proto-Earth. Cosmochemists do not yet understand the magma ocean system in detail. They do know that it must have been wildly complicated! They also do not know how long it lasted. This is an important data point to determine because future sophisticated models for the solidification of the magma ocean may predict how long the magma ocean lasted.



The concept that the Moon melted substantially (possibly completely) when it formed, nicknamed the "magma ocean concept," is a fundamental tenet of lunar science. These three panels, from left to right, illustrate the lunar magma ocean concept. The basic concept suggests that as the molten Moon crystallized, lightweight minerals floated and heavy ones sank. The lighter minerals formed the primary crust of the Moon. The real magma ocean was much more complicated, with convection stirring the pot, crystallization taking place at both the bottom and top, and the magma changing in composition as crystals formed.

Like all magmas, the magma ocean did not crystallize all the minerals it produced at once. It followed a sequence determined by its chemical composition and the pressure within it. Cosmochemists have calculated the order in which minerals crystallized and how mineral formation affected the chemical composition of the remaining magma. One such calculation, by Greg Snyder and Larry Taylor (University of Tennessee), is shown in the diagram below. Not shown is that the last magma remaining would have concentrations of many elements, including zirconium, approaching 100 times that of the original, bulk Moon composition. These last dregs of the magma ocean could crystallize zircon, one crystal of which Alex Nemchin and his colleagues dated.



Mineral Crystallization in the Lunar Magma Ocean, Top to Bottom

(from Snyder *et al*., 1992, *Geochim. et Cosmo. Acta*, v. 56, p. 3809-3823.)

This is a cosmochemical cartoon showing crystallization sequences of the lunar magma ocean, a vertical view, with the first-formed crystals closest to the bottom. Plagioclase feldspar begins to form after about 75% of the magma has crystallized, and ends up floating, so appears at the top. The region labeled "pig, cpx, ilm" would contain pigeonite (pig), high-calcium, clinopyroxene (cpx), and ilmenite (ilm), and would have high concentrations of zirconium, rare earth elements, and other elements that do not enter olivine, orthopyroxene (opx), or plagioclase (plag).

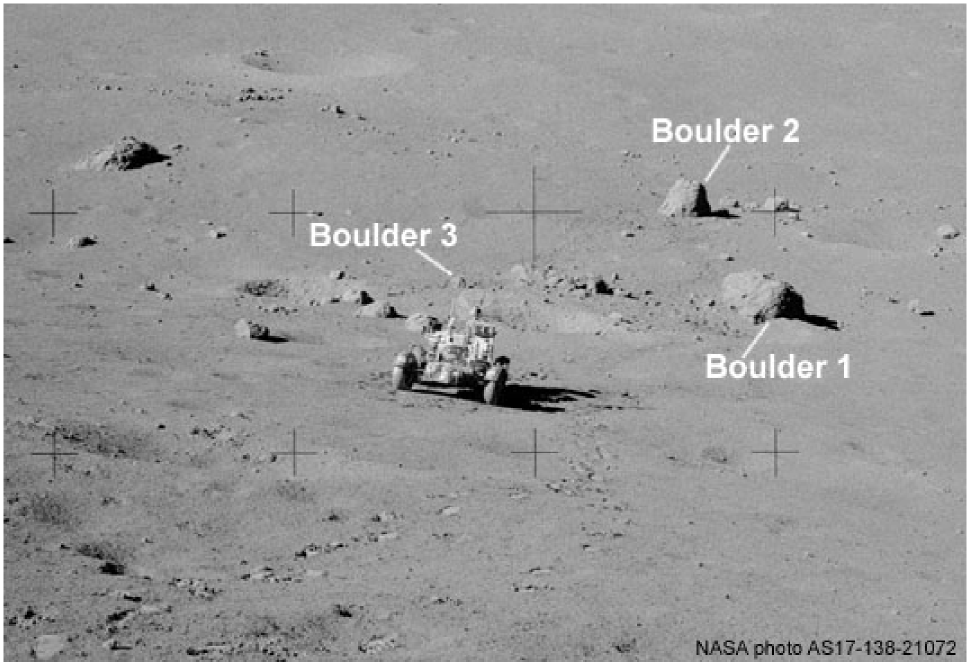
Magma Ocean Solidification Time

To pin down the time it took for the magma ocean to crystallize completely, we need to know when it started to cool and the age of the last crystal to solidify. Thanks to Alex Nemchin and his colleagues we have a good handle on the final crystallization. The beginning is reasonably taken as the time the Moon formed by a giant impact, if we can figure that out. Mathieu Touboul and colleagues at the Institute for Isotope Geochemistry and Mineral Resources in Zurich, Switzerland, report tungsten isotopic data indicating, when coupled with samarium-neodymium isotopic data, that the Moon-forming impact occurred 62 million years after solids began to form in the Solar System. The uncertainty in this age is +90, -10 million years. Thus, the earliest the Moon could have formed (and the magma ocean could begin to crystallize) is about 50 million years after Solar System formation, which corresponds to 4.517 billion years ago.

Alex Nemchin and co-workers searched for zircon crystals in impact melts among the rocks returned by the Apollo 17 mission. Zircon is a particularly useful mineral for age dating because its radiometric clock is not easy to reset by thermal events, such as those forming impact melts about 3.9 billion years ago. The mineral also contains easily measurable amounts of uranium, making it ideally suited for uranium-lead dating.

The oldest zircon they found was in breccia 72215, which was collected, along with other samples, from a two-meter boulder on the lower slope of South Massif at the Apollo 17 landing site. The boulder itself appears to be layered (see photo below), reflecting the complexity of the products of large impacts. The boulder has prominent knobs that consist of swirly intergrowths of light and dark material. Sample 72215 was collected from the side of the boulder.

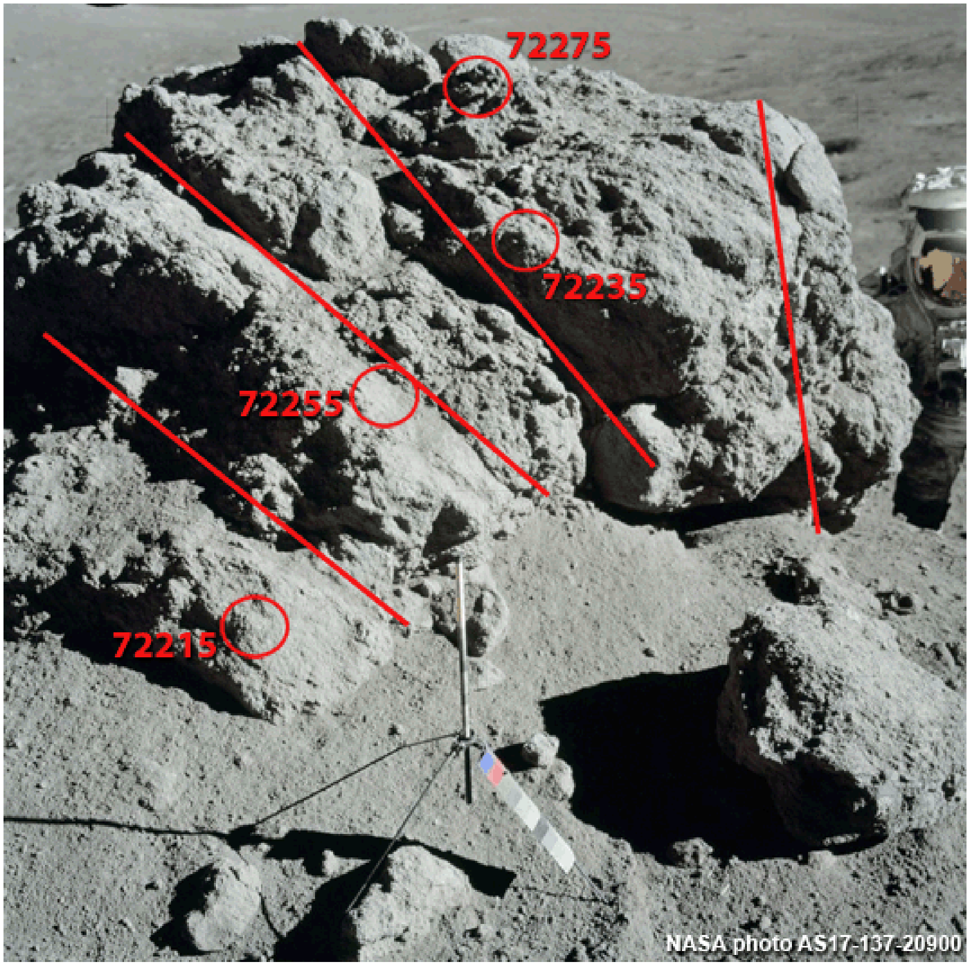
Apollo 17 Station 2 Collection Site



NASA photo AS17-138-21072

The photograph shown above is an astronaut's view looking south towards South Massif of the Apollo 17 Station 2 site. Sampled boulders are numbered. The distance from the lunar rover to boulder 2 is about 50 meters. All boulders appear to have rolled down from higher up on the massif. [Click on the picture to read details from NASA Johnson Space Center about the rocks collected here.]

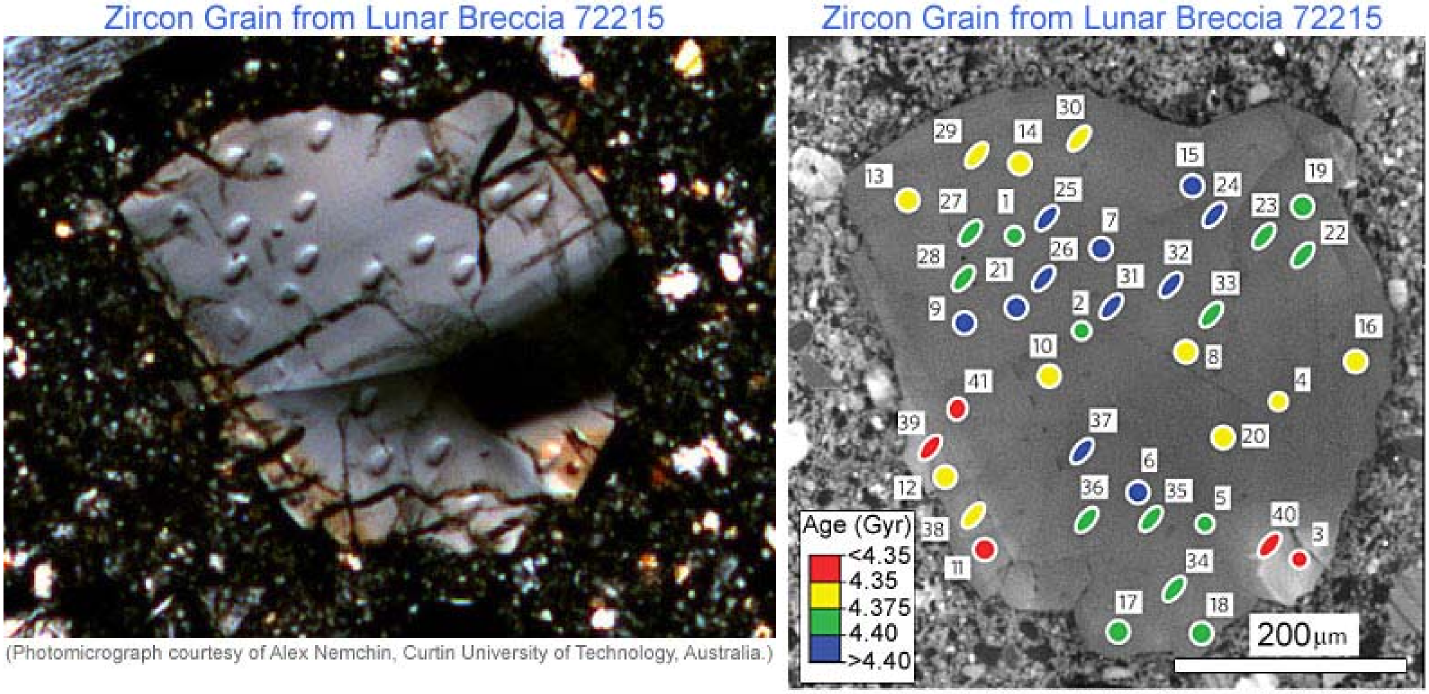
Boulder 1 at the Apollo 17 Station 2 Collection Site



NASA photo AS17-137-20900

Rock sample 72215 was collected from boulder 1, Station 2 at the Apollo 17 landing site, pictured above. This boulder, about two meters across, appears to be layered (boundaries between layers indicated by the red lines). The circles show where the astronauts collected four different rock samples off the boulder.

The special zircon grain appears in the image below. It is half a millimeter across and the photomicrograph (left) shows that it contains several distinctive regions. Ion microprobe measurements give a range of ages (right), demonstrating the talent zircon has for recording more than one event. The oldest spots are all older than 4.4 billion years. Detailed analysis of the isotopic composition indicates that their ^{207}Pb/^{206}Pb (lead-lead) age is 4.417 billion years. This age is about 100 million years younger than the suspected age of the Moon-forming event.

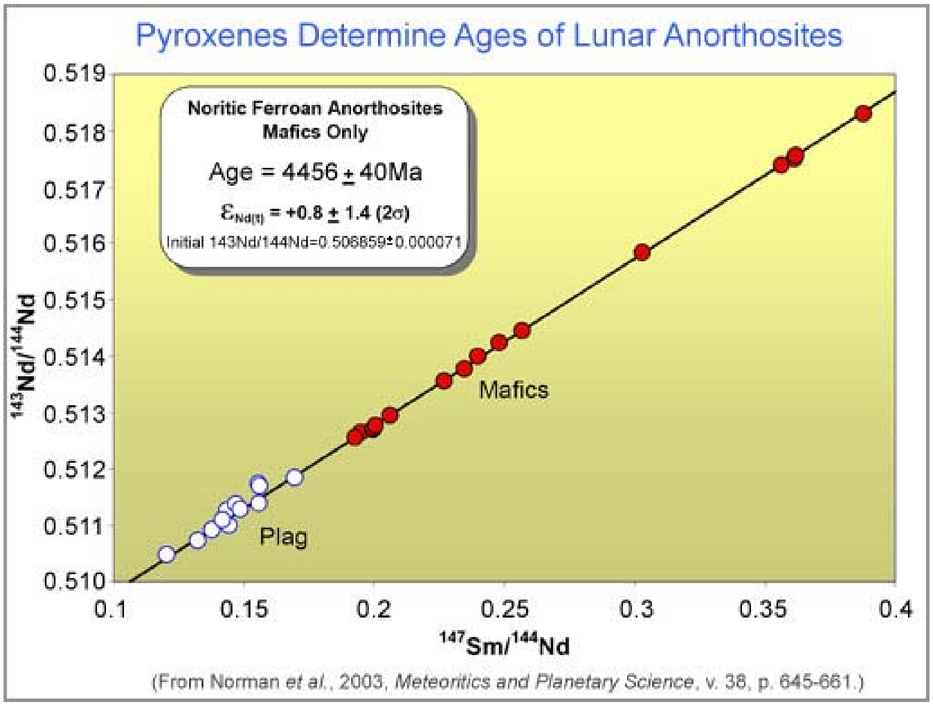


(Photomicrograph courtesy of Alex Nemchin, Curtin University of Technology, Australia.)

(From Nemchin *et al.*, 2009, *Nature Geoscience*, doi: 10.1038/NGEO417.)

The photo on the **left** shows what the zircon from lunar breccia 72215 looks like in an optical microscope in polarized light. Subtle differences in colors indicate distinctive domains. The numerous oval features are holes made during ion microprobe analysis. The material surrounding the zircon grain is fine-grained with crystal shapes typical of impact melt breccias. The photo on the **right** was taken with cathodoluminescence, in which most of the grain is uniform in color, though two regions are distinctly lighter. The ovals show where ion microprobe measurements were made. They are color-coded to show their ages, indicated in the scale on the lower left.

Anorthosites, the feldspar-rich rocks making up the ancient crust of the Moon, have been difficult to date. Impact events messed up all isotopic systems to some degree. Also, precise age dates require physically separating minerals and determining their isotopic compositions separately, producing a plot called an isochron. Only a few anorthosites contain enough grains of minerals other than plagioclase to analyze, and in those cases their ages range widely, from 4.54 to 4.29 billion years. However, Marc Norman (Australian National University) and colleagues at the Johnson Space Center showed that the samarium-neodymium isotopic data for pyroxene forms a well-defined isochron that indicates an age of 4.456 ± 0.040 billion years. This is only a mean age--some anorthosites may have formed earlier, some later--but it is 39 million years earlier than Nemchin's ancient zircon.



(From Norman *et al.*, 2003, *Meteoritics and Planetary Science*, v. 38, p. 645-661.)

Isochron plot for Nd and Sm isotopes in lunar anorthosites. The red circles are for pyroxene crystals in four lunar anorthosites. The white circles are for plagioclase feldspar. The pyroxene data define a very precise line, the slope of which defines the age, 4.456 billion years. Plagioclase data scatter more because of chemical exchange of Sm and Nd caused by reheating by a large impact event that seems to have affected almost all anorthosites. Pyroxene is more resistant to isotopic exchange, and so records the original crystallization age of these rocks.

Putting it all together, you get this:

1. **Origin of Moon at 4.517 billion years ago**
2. **Formation of much of the anorthosite crust (crystallization 75% completed), 61 million years later**
3. **End of crystallization (maybe a few percent magma left over), 39 million years later**

As Nemchin and his colleagues discuss, it is not clear whether the cooling was gradual between the origin of the Moon with its magma ocean and formation of the anorthosite crust, or dropped rapidly until the crust formed. However, even rough calculations of the cooling of a hot body like the magma ocean shows that it cools fast until it gets a thick, insulating cover. On the Moon, that means a thick cover of rock, namely anorthosite, which happens once plagioclase crystallizes after about 75% of the original magma has solidified. Thus, it is a good bet that 75% of the magma ocean crystallized in about 50 million years, but the final 25% took an additional 50 million years, finally making a bunch of zircon crystals. Some zircon crystals survived other melting events and large impacts, were collected by Apollo 17 astronauts, and identified and studied by Alex Nemchin to reveal that it took 100 million years for the lunar magma ocean to solidify.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:**Time to Solidify an Ocean of Magma --Short Slide Summary (with accompanying notes).
- Nemchin, A., Timms, N., Pidgeon, R., Geisler, T., Reddy, S., and Meyer, C. (2009) Timing of Crystallization of the Lunar Magma Ocean Constrained by the Oldest Zircon. *Nature Geoscience*, 25 January 2009: doi: 10.1038/NGEO417.
- Norman, M. D., Borg, L. E., Nyquist, L. E., Bogard, D. D. (2003) Chronology, Geochemistry, and Petrology of a Ferroan Noritic Anorthosite Clast from Descarts Breccia 67215: Clues to the Age, Origin, Structure, and Impact History of the Lunar Crust. *Meteoritics and Planetary Science*, v. 38, p. 645-661.
- Snyder, G. A., Taylor, L. A., and Neal, C. R. (1992) A Chemical Model for Generating the Sources of Mare Basalts: Combined Equilibrium and Fractional Crystallization of the Lunar Magmasphere. *Geochimica et Cosmochimica Acta*, v. 56, p. 3809-3823.
- Apollo 17 Lunar Surface Journal, from the NASA History site.