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Hot Idea posted October 31, 2004

New Lunar Meteorite Provides its Lunar Address and Some Clues about Early Bombardment of the Moon

--- A newly discovered meteorite from the Moon provides a detailed record of its history, allowing scientists to make a reasonable guess about where it came from on the Moon and to test ideas for the timing of early impact bombardment.

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Maximum dimension is 7 centimeters. Photograph by Peter Vollenweider.

Edwin Gnos (University of Bern, Switzerland) and colleagues from Switzerland, Germany, Sweden, England, and the United States describe an information-packed meteorite found in Oman, Sayh al Uhaymir 169 (SaU 169). The complicated rock is composed mostly of an impact melt that contains an exceptionally large amount of thorium, indicative of an origin in the Imbrium-Procellarum region of the Moon. Gnos and his colleagues report that the impact melt has an age of 3.909 (±0.013) billion years, slightly older than estimates of when the huge Imbrium impact basin formed on the Moon (about 3.850 billion years ago). The meteorite was involved in a subsequent impact 2.8 billion years ago, then another 200 million years ago, and a relatively recent one no more than 340 thousand years ago. It landed on Earth about 10 thousand years ago. This amazingly detailed record led Gnos to conclude that the rock was blasted off the Moon from a place not far from Lalande Crater. The 3.9 billion year age of the impact melt adds to the debate about whether there was an increase in the impact rate 3.9 billion years ago or there was a continuous decline in the impact rate from 4.5 to 3.8 billon years. This debate may not be settled until we have samples from the South Pole-Aitken basin on the farside of the Moon.

Reference:

Gnos E., Hofmann B. A., Al-Kathiri A., Lorenzetti S., Eugster O., Whitehouse M. J., Villa I. M., Jull A. J. T., Eikenberg J., Spettle B., Krahenbuhl U., Franchi I. A., and Greenwood R. C. (2004) Pinpointing the source of a lunar meteorite: Implications for the evolution of the Moon. *Science,* v. 305, p. 657-659.

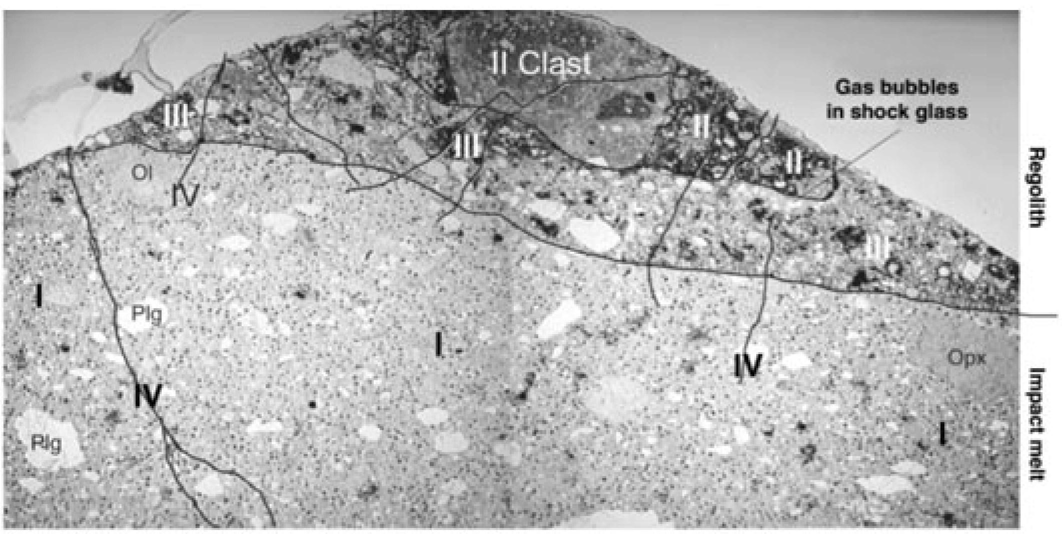
Lunar Meteorites: Free Samples of the Moon...but from what area?

Meteorites are a great bargain. They come to us for free, from all over the Solar System. We have them from asteroids, Mars, and the Moon. We usually do not know exactly where they come from (which asteroid, where on the Moon or Mars), but you can only expect so much for free. We have about thirty meteorites from the Moon and these free but valuable samples supplement the not free but priceless 380 kg of rock and regolith returned by the Apollo program. Randy Korotev (Washington University in St. Louis) maintains a list of all known lunar meteorites, a generous contribution to those of us who study lunar meteorites. Unfortunately, Korotev cannot list where each sample came from on the Moon. Their chemical and mineral compositions cannot be matched unambiguously with a specific locale on the Moon. Edwin Gnos and his colleagues think they might have figured out the location of one of the lunar meteorites on the basis of its history as revealed by the record of impact events in it and its chemical composition.

A Complicated (But Normal) Lunar Rock

Most of SaU 169 is a typical impact melt rock characterized by numerous unmelted fragments of minerals and rocks in a matrix of fine-grained igneous rock. Such rocks are called impact melt breccias. The impact melt breccia is associated with a regolith breccia, consisting of fragments of rocks and minerals all smashed together. The regolith breccia is intruded by yet another regolith breccia, and the whole intricate mess is crosscut by shock-melted veins. Sounds complicated, but most rocks from the lunar highlands are this complicated. They record a long history of igneous and impact events.

Lunar Meteorite SaU 169



(From Gnos, E. *et al.* 2004, *Science*, v. 305, Fig. 1, p. 658.)

The photograph above shows an entire thin section of SaU 169. The rock is composed mostly of an impact melt breccia (I) in which fragments (also called clasts) of plagioclase feldspar (Plg), olivine (Ol), and orthopyroxene (Opx) are suspended in a matrix of pyroxene and plagioclase that crystallized from an impact-generated magma. Two fragmental lithologies (II and III) occur along side the impact melt breccia. Both are regolith breccias, fragmental material formed at the very surface of the Moon as determined by the presence of glassy materials and solar wind gases. Regolith breccia II contains a large clast of impact melt breccia (II Clast). Regolith breccia III appears to cut across the boundary between I and II, and Gnos and coworkers infer that it formed after them. The rock is crisscrossed by dark, irregular lines (IV). These are shock-melted veins and represent the last impact event the rock experienced in its tortured history on the Moon.

Lunar Meteorite SaU 169

Centimeter scale bar. (Photo courtesy of Beda Hofmann, Natural History Museum of Berne.)

A sawn face of meteorite SaU169 is shown above. Click on image for more information. Link will open in a new window.

Anatomy of a Rock

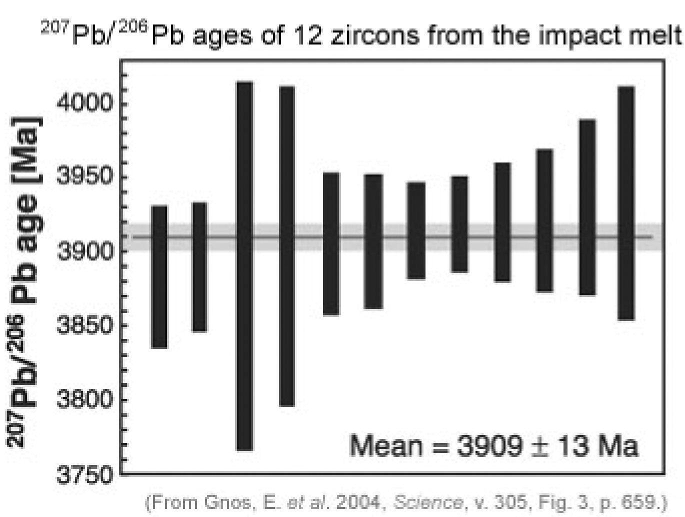
Gnos and his colleagues analyzed SaU 169 with a vast array of high-tech analytical gizmos, as summarized in the table below.

Property Measured	Why Measured	Technique	Laboratories
Mineralogy and rock textures	Identify rock type and geologic history	Optical microscopy, X-ray tomography, Raman spectroscopy	Inst. for Geology, Univ. of Bern, Switzerland; Federal Material Testing Laboratory, Dubendorf, Switzerland
Mineral compositions	Characterized source rocks, determine igneous and impact histories	Electron microprobe analysis	Inst. for Geology, Univ. of Bern, Switzerland
Chemical composition (major and trace elements)	Rock type, igneous history, extent of impact mixing, locale of origin on moon	Gamma-ray spectroscopy on entire sample, inductively coupled plasma mass spectrometry, inductively coupled optical emission spectroscopy, instrumental neutron activation analysis	Depart. of Chemistry, Univ. of Bern, Switzerland; Paul Scherrer Inst., Switzerland; Activation Laboratories, Ltd, Ancaster, Canada; Inst. for Planetology, Max Planck Inst., Mainz, Germany
Oxygen isotopic analysis	Prove lunar origin	Chemical separations followed by mass spectrometry	Open University, England
Lead isotopic analysis of zircons	Determine age of impact melt breccia	Secondary ion mass spectrometry	Swedish Museum of Natural History, Stockholm, Sweden
Argon isotopes in irradiated feldspar grains separated from the impact melt breccia	Determine ages of impact events in the rock's history	Mass spectrometry	McMasters Reactor, Canada; Inst. for Geology, Univ. of Bern, Switzerland
Noble gas measurements on impact melt and regolith areas	Cosmic ray exposure ages and test for presence of solar wind gases in regolith breccia	Mass spectrometry	Inst. for Physics, Univ. of Bern, Switzerland
Carbon-14 and Beryllium-10 concentrations in sample of impact melt breccia	Determine how long ago the meteorite arrived on Earth	Accelerator mass spectrometry	Univ. of Arizona, United States

They determined the meteorite's mineralogy and the rock textures (the geometrical relation of mineral crystals to each other) using optical microscopy; they measured its chemical composition using neutron activation analysis and inductively-coupled mass spectrometry; the lead isotopic composition of the mineral zircon by secondary ion mass spectrometry to determine the formation age of the impact melt breccia; the abundance of Ar-40 by neutron-irradiation and mass spectrometry to determine when subsequent impact events took place; an array other isotopes by assorted mass spectrometric techniques to determine how long the rock and its components were exposed to cosmic rays and how long ago the meteorite arrived on Earth. This was a very thorough study! "Very thorough" means they produced lots of data, and I can only summarize it here.

A Highly KREEPy rock: Highly evolved igneous rocks are present on the Moon. Evolved rocks formed from magmas that fractionally crystallized, leaving a residual magma rich in elements that do not readily enter the major rock-forming minerals. The most common class of evolved lunar rock is KREEP, an acronym referring to enrichments (compared to other lunar materials) in potassium (K), rare earth elements (REE), and phosphorus (P). They also contain enrichments in other elements such as zirconium, thorium, and uranium. The formation of evolved magmas involved extensive fractional crystallization in the lunar magma ocean, a huge magmatic system that surrounded the Moon soon after its formation, followed by partial melting of rocks formed from the residual magma. These secondary magmas could have fractionally crystallized further, creating rocks much richer than those observed so far. SaU 169 is without question a KREEP rock. Its thorium (Th) concentration is 33 parts per million in the large impact melt breccia that composes most of the rock. This is higher than all but a few small rock clasts in breccias brought back by the Apollo missions. An interesting feature of the SaU 169 impact melt breccia is that it has a much lower K/Th ratio (137) compared to the average KREEPy rocks (360). This indicates that K and Th, which usually have similar geochemical behavior in magmas, became decoupled from each other, signifying a complicated magmatic history of the lithologies that predated the formation of the impact melt. The rest of the rock is also KREEPy, but does not contain as much Th or REE as does the impact melt breccia, and K/Th is the normal KREEP value.

Age of the impact melt breccia: Gnos and his coworkers determined the lead-lead age of the impact melt breccia by measuring the abundances of lead isotopes with a secondary ion mass spectrometer. This technique is based on the decay of uranium isotopes to lead daughter isotopes. To increase accuracy and precision, they analyzed the mineral zircon ($ZrSiO_4$), which contained uranium when it formed, but little lead. The zircon grains crystallized from the impact melt, so determining their age gives the age of the impact event that produced the impact melt. The ages of the twelve samples analyzed scatter a bit, but give an excellent indication of the age of the impact melt: 3909 million years, with an uncertainty of 13 million years.



Lead-lead ages of 12 zircon crystals from the impact melt portion (lithology I) in SaU 169. Each bar represents the range of ages defined by each analysis. The range is really the uncertainty in each measurement. The horizontal line through the bars is the average of all the analyses. The age of 3.91 billion years is older than the nominal age for the Imbrium basin of about 3.85 billion years.

An age-resetting event: About half the impact melt breccia is composed of plagioclase feldspar. Like zircon, it crystallized from the impact melt, so its age ought to agree with that given by the zircon analyses. However, the Moon's impact history complicates that story. The plagioclase age was determined by determining its ^{39}Ar-^{40}Ar age on plagioclase separated from a crushed sample of the impact melt. The Ar-Ar method is really an advanced form of the potassium-argon method. The difference is that the sample is irradiated by neutrons in a nuclear reactor, converting some of the potassium-39 into argon-39. Then the sample is placed in an evacuated extraction line and heated sequentially to release argon-39 and argon-40, whose abundances are measured with a mass spectrometer. The ideal sample shows the same age for 60 to 80% of the gas released. SaU 169, however, gives messier results, a clear indication that the system has been disturbed by a reheating event after initial formation of the rock. Gnos and his coworkers show that the gas released at the highest temperature steps gives an age of about 2800 million years. They also make a good case that the data indicate an even younger disturbance that affected the potassium feldspar crystals less than 500 million years ago.

Exposure on the lunar surface: The lead-lead ages indicate formation of the impact melt from pre-existing rocks at 3909 million years ago, followed by additional impact events that heated, but did not melt, the rock at 2800 and 500 million years ago--a complicated history, but the story does not end there. The rock was sitting around near the lunar surface before being launched by another meteorite impact. Gnos and his colleagues determined what we call cosmic ray exposure ages for the impact melt and the regolith portions of the rock. This type of age gives the time the material resided in the upper meter of the regolith (the depth of penetration of cosmic rays). Cosmochemists determine such ages by melting samples and measuring the concentrations of isotopes of neon and argon produced by cosmic ray interaction with the rock. The results show that the impact melt breccia was placed into the upper meter of regolith about 200 million years ago, where it was mixed with the regolith portions. Analysis of the beryllium-10 concentration indicates that it was launched to Earth less than 0.34 million years ago (340 thousand years ago).

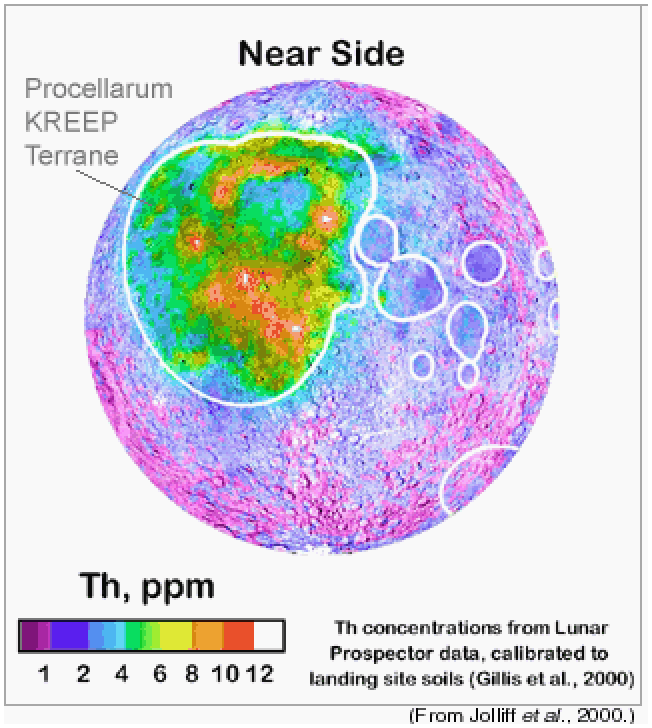
Arrival on Earth: While it was exposed to cosmic rays on the Moon, the components in SaU 169 built up carbon-14 and beryllium-10 to levels that were constant--as much decayed as was produced. Once it arrived on Earth, however, the cosmic ray bombardment effectively ceased, and these two isotopes began to decay. The saturation levels are known from data on meteorites that were collected as soon as they fell and from calculations. Gnos and his team determined that the rock arrived on Earth 9700 years ago (with an uncertainty of plus or minus 1300 years).

(Photo courtesy of Beda Hofmann, Natural History Museum of Berne.)

After falling to earth 9700 years ago, meteorite SaU 169 was found in the hot desert of Oman in 2002 by Drs. Beda Hofmann of the Natural History Museum of Berne, Edwin Gnos, and Ali Al-Kathiri both of the University of Berne, Switzerland. Divisions on the scale bar are in centimeters. (Photograph courtesy of Beda Hofmann. Click on the image to link to more information. Link will open in a new window.)

Narrowing Down SaU 169's Lunar Home

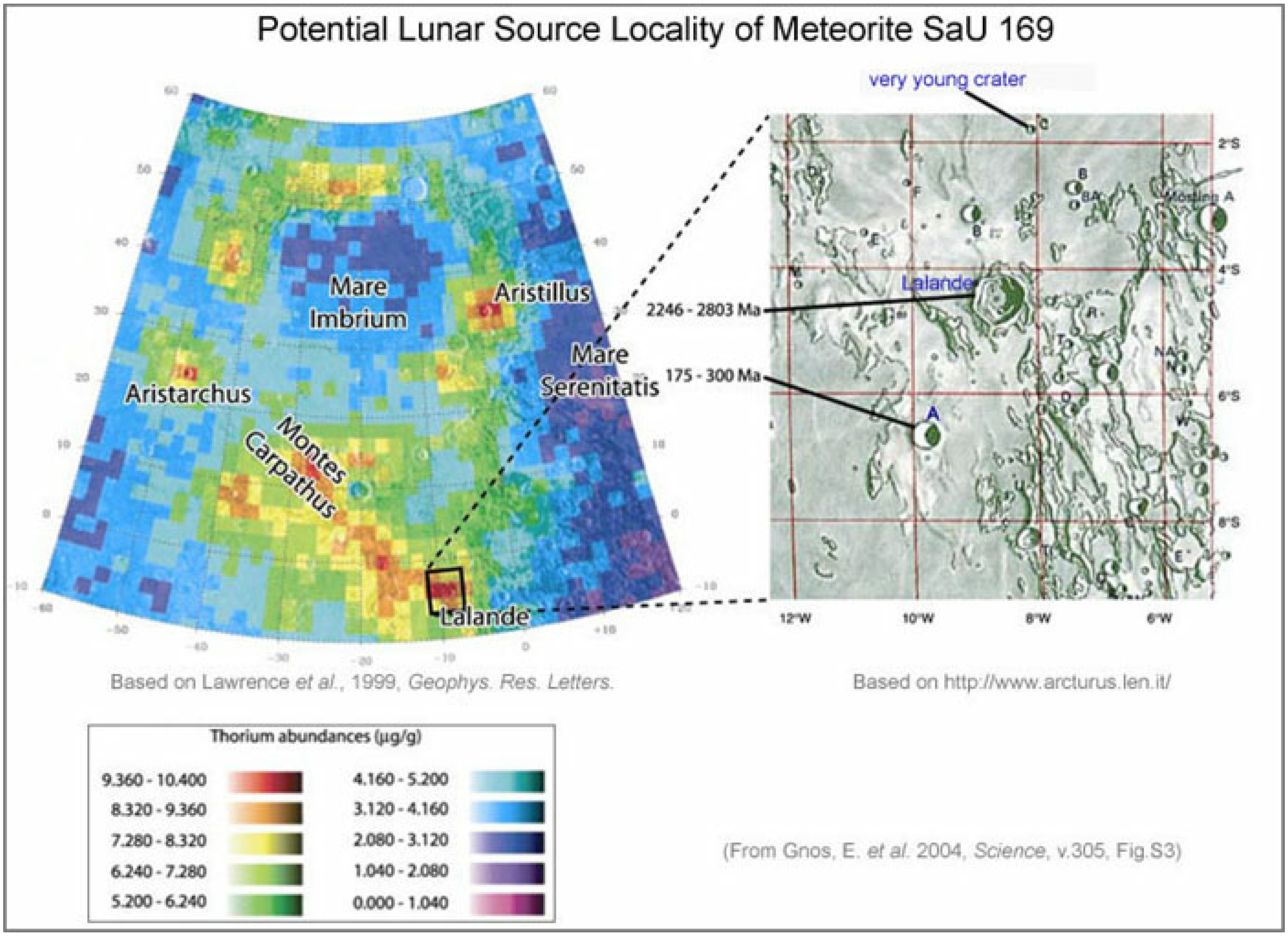
The chemical characteristics and detailed chronological history of SaU 169 led Gnos and his colleagues to make an intelligent guess about where on the Moon the rock came from. The high concentrations of KREEP elements show that it must come from the region of the Moon identified by Brad Jolliff and his colleagues at Washington University in St. Louis as the "Procellarum KREEP Terrane." [See **PSRD** article: A New Moon for the Twenty-First Century.] This region is characterized by the highest concentrations of thorium (which associates with all the other KREEP elements) as measured by the Lunar Prospector mission.



The region around the Imbrium and Procellarum areas of the Moon are characterized by large concentrations of thorium. SaU 169, which has very high concentrations of thorium, probably comes from the most thorium-rich areas in the Procellarum-KREEP terrane (outlined in white).

SaU 169 has whopping amounts of thorium and the other elements associated with KREEP, so it clearly comes from somewhere in the Procellarum-KREEP terrane. Gnos and colleagues have examined the remote sensing data in detail and identified places with the highest thorium in this region. They also used data from the Lunar Prospector and Clementine missions to find high-thorium areas with concentrations of iron and titanium like those in SaU 169. Finally, they searched for areas with these chemical properties that also appeared to have craters of the right sizes and estimated ages to match the chronology the deduced from their measurements of SaU 169.

They found some prominent thorium hot spots (see figure below), but only the area around the prominent craters Lalande and Aristillus have the right concentrations of iron and titanium. Both areas have a fresh young crater that could have launched the rock to Earth, but only the Lalande area has other craters whose estimated ages match the detailed chronology of SaU 169. They estimate the age of Lalande crater at 2200 to 2800 million years on the basis of crater counting from previous investigations. Formation of that large crater could have excavated the SaU impact melt breccia and partially reset the Ar-Ar age of the plagioclase feldspar. That event would have placed the impact melt breccia into a pile of ejecta, but buried deeper than a meter to prevent exposure to cosmic rays at that time. There is another crater, Lalande A, with an estimated age of 175 to 300 million years, an excellent choice for the event that moved the impact melt breccia into the upper meter and mixed it with regolith. Finally, there is a young crater that is suitable for launching the assembled rock to Earth less than 0.34 million years ago. If the bright young crater is the source, it requires that the formation of Lalande A tossed the impact melt breccia a few hundred kilometers to the northeast so it could be excavated by the youngest crater. The greatest uncertainty, in this complicated but interesting story, is in the estimated crater ages.



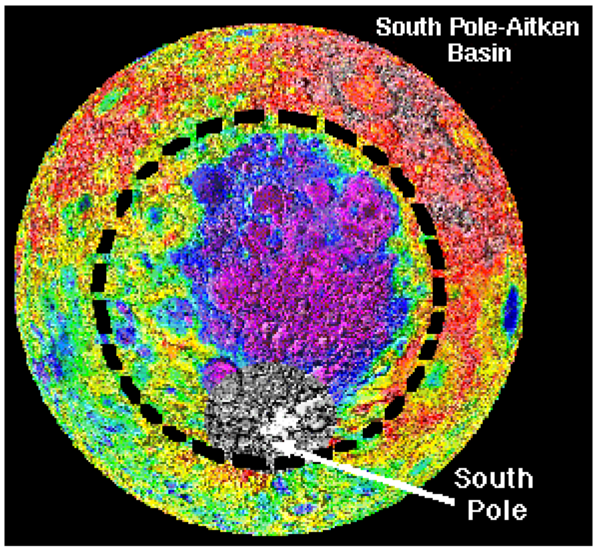
Thorium concentration in part of the Procellarum-KREEP terrane, showing areas with particularly high thorium concentrations (red). Gnos and his coworkers argue that the best bet for the lunar home for SaU 169 is the area around Lalande crater (right). It has a large crater (Lalande) of approximately the right age (2200 to 2800 million years) to reset the Ar chronometer in SaU 169, a younger crater (Lalande A) that could toss the impact melt close to the surface and mix it with regolith about 200 million years ago, and a bright, young crater that might be young enough to have been the launch site for SaU 169's trip to Earth.

Implications for Early Lunar Bombardment

A big debate in lunar science is whether the Moon experienced a sharp increase in bombardment rate between about 3.95 and 3.85 billion years ago. This concept, called the "lunar cataclysm," arose because almost all impact melt breccias have ages in that interval. The alternative is that the Moon experienced a declining bombardment rate and that the narrow age range reflects the preservation of only the youngest impact melts. Still another interpretation is that all the impact melt ages reflect the age of the event that formed the huge Imbrium impact basin, which might dominate the nearside chronology. For more information, see **PSRD** articles: Uranus, Neptune and the Mountains of the Moon and Lunar Meteorites and the Lunar Cataclysm.

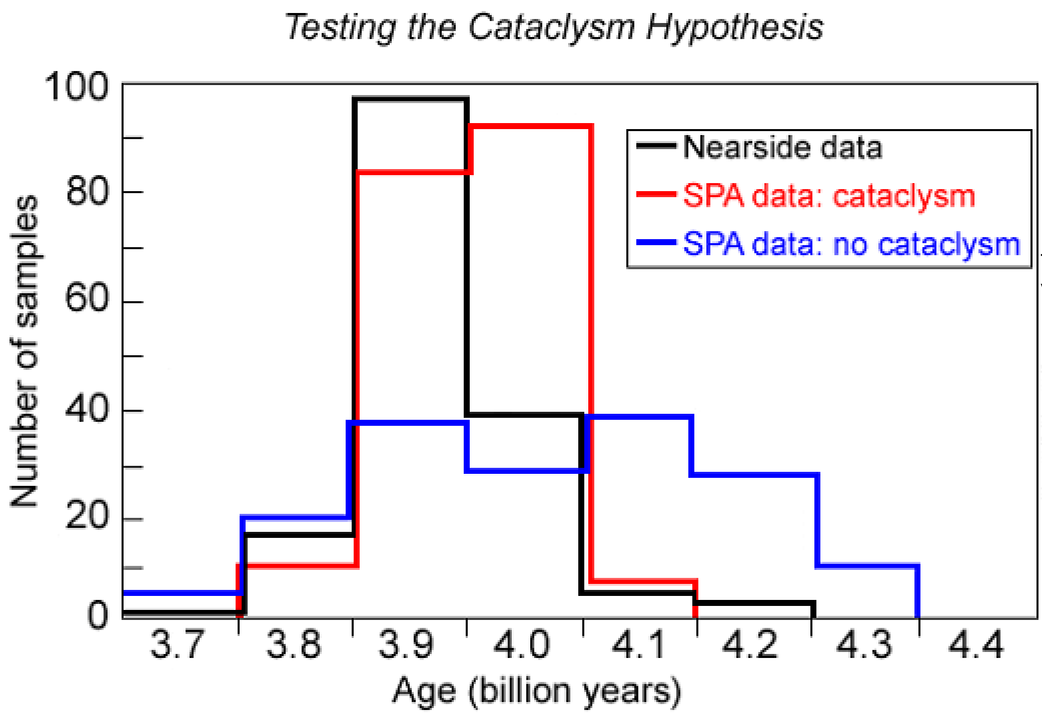
The age of the impact melt breccia in SaU 169 adds to this important debate. It is distinctly older (3.91 billion years) than the nominal age of the Imbrium event (3.85 billion years), perhaps reflecting formation before the Imbrium event. Or, it might suggest an older age for the Imbrium event. If it is older than Imbrium, then some other large impact occurred and survived resetting during formation of the Imbrium basin. If Imbrium is actually older than 3.85 billion years, then what does the 3.85 billion-year age represent? Unanswered questions abound.

The whole question of the style of early lunar bombardment is important as it describes what the environment was like on the early Earth, at the time when life was originating. It is not straightforward to settle the issue with our current sample sets (sample returns by the Apollo and Luna programs and lunar meteorites). We need to return samples from someplace on the Moon where the effects of Imbrium formation is minimized. The ideal place is the South Pole-Aitken basin on the lunar farside. Detailed geologic studies show that this is the oldest basin on the Moon. Returning samples of impact melt from South Pole-Aitken basin will allow lunar scientists to test the lunar cataclysm hypothesis. If the distribution of ages of impact melt breccias from the South Pole-Aitken region are similar, or perhaps slightly older, than that of nearside impact melt samples, then the cataclysm hypothesis is favored. If there is a significant number of samples with much older ages (in the 4.1 to 4.3 billion year range), then the cataclysm hypothesis is less likely to be correct.



(Courtesy of Lunar and Planetary Institute.)

The huge (2600-km across) South Pole-Aitken impact basin on the lunar farside is an ideal place to test the lunar cataclysm hypothesis because it is the oldest impact basin on the Moon and a sample collected from it will contain samples of impact melts produced by other basin-forming events. This image is a Clementine topographic map of the Moon (rotated to be centered on the SPA basin) red=high, purple=low. Each color equals 500 meters of elevation.



Move your cursor over the buttons below to view the hypothetical histograms.

If cataclysm is true

If cataclysm is false

(G. J. Taylor, University of Hawaii)

This figure shows three histograms of the ages of impact melts. Ages of Apollo and Luna nearside samples are shown in black. The two buttons allow you to see the cases when the cataclysm hypothesis may be true or not. Samples from the South Pole-Aitken (SPA) basin will test the idea of a lunar cataclysm. The hypothetical red distribution for SPA samples favors the cataclysm. The hypothetical blue distribution suggests that bombardment occurred over a much longer interval, tending to disfavor the cataclysm.

The detailed study of SaU 169 done by Edwin Gnos and his large, interdisciplinary team shows the value of continued studies of lunar samples, particularly of lunar meteorites. More research will certainly be done on SaU 169 before its full story is told, and additional finds of lunar meteorites, remote sensing observations of the Moon, sample return missions, and eventually field work by humans and teleoperated robots will lead to a much fuller understanding of the Moon and its igneous and bombardment history.

Additional Resources

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

Gnos E., Hofmann B. A., Al-Kathiri A., Lorenzetti S., Eugster O., Whitehouse M. J., Villa I. M., Jull A. J. T., Eikenberg J., Spettle B., Krahenbuhl U., Franchi I. A., and Greenwood R. C. (2004) Pinpointing the source of a lunar meteorite: Implications for the evolution of the Moon. *Science,* v. 305, p. 657-659.

Jolliff, Bradley L., Gillis, Jeffrey J., Haskin, Larry A., Korotev, Randy L., and Wieczorek, Mark A. (2000) Major lunar crustal terranes: Surface expressions and crust-mantle origins. *Journal of Geophysical Research,* vol. 105, p. 4197-4216.

Lunar Meteorites, comprehensive listing and information compiled by Randy Korotev, Washington University in St. Louis.

Taylor, G.J. (2000) A New Moon for the Twenty-First Century. *Planetary Science Research Discoveries.*

http://www.psrd.hawaii.edu/Aug00/newMoon.html

Taylor, G.J. (2001) Uranus, Neptune and the Mountains of the Moon. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Aug01/bombardment.html

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