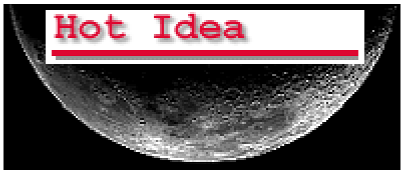
PLANETARY SCIENCE RESEARCH
PSRD Discoveries



Recent Gas Escape from the Moon

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--- Gases may have escaped from the Moon as recently as a million years ago, implying that the lunar interior is not as lethargic as conventional wisdom dictates.

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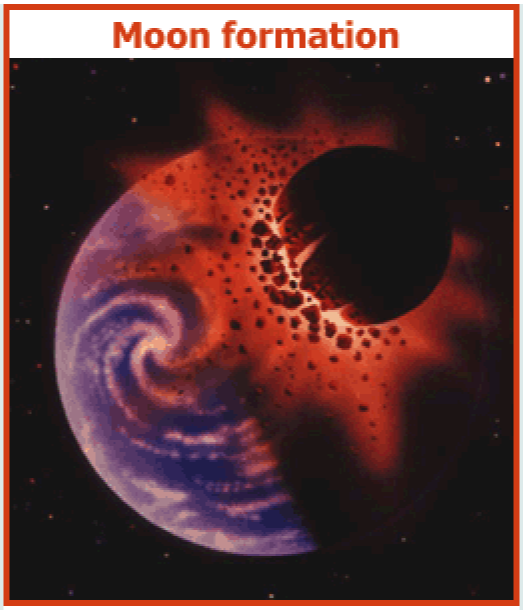
The Moon is generally thought to be geologically inactive, except for being pummeled by meteoroids of various sizes. The youngest returned igneous rocks are about 3 billion years old, although crater counting suggest some lava flows as young as a billion years. However, Peter Schultz (Brown University), Matthew Staid (Planetary Sciences Institute, Tucson), and Carlé Pieters (Brown University) report an array of data that indicate that the Moon may be active enough inside to occasionally spew puffs of gases that blow off the fine-grained, busted up surface materials known as the regolith. The researchers studied a feature called the Ina structure, a depression containing numerous steep-sided hills, located in a mare region known as Lacus Felicitatis. Ina is fresh in appearance both photographically and spectrally. Calibration of crater counts and spectra with other craters dated by cosmochemists using Apollo lunar samples indicate that Ina could be as young as 1 million years.

Reference:

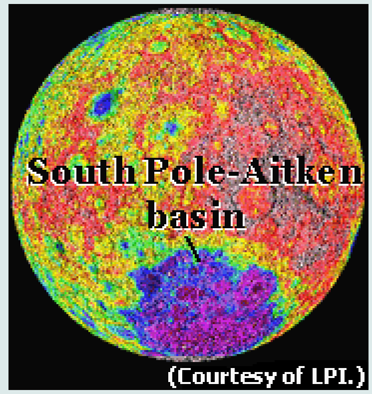
- Schultz, P. H., M. I. Staid, and C. M. Pieters (2006) Lunar activity from recent gas release. *Nature*, v. 444, p. 184-186.

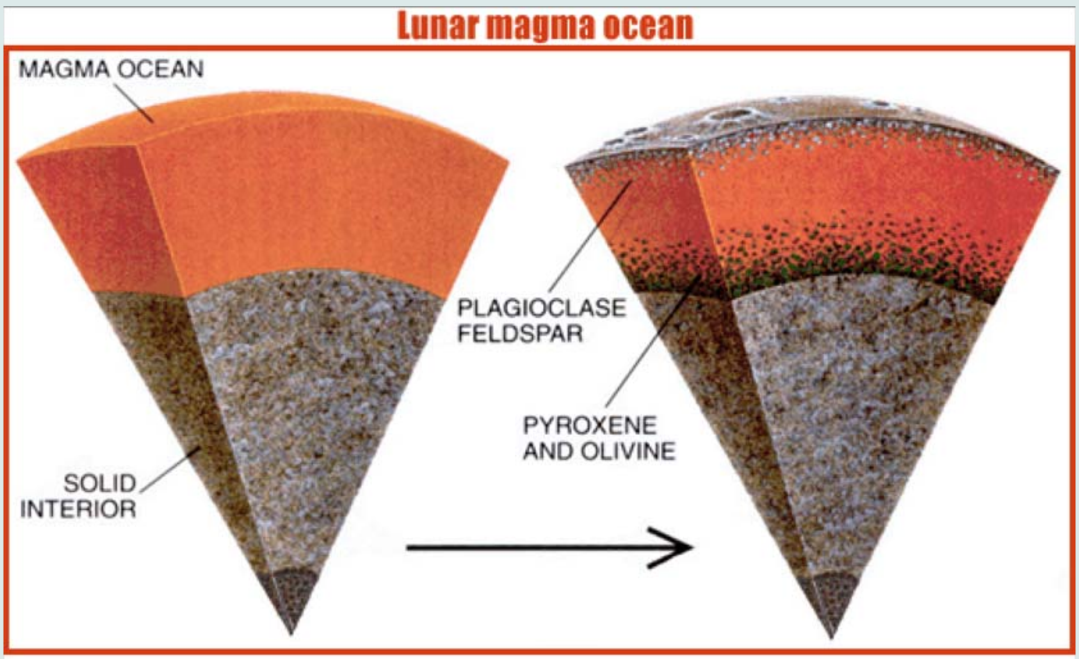
The Progressively Lethargic Moon

Measurements of lava rocks returned from the lunar maria during the Apollo program established that the Moon's geologic engine shifted into low gear but did not stop around 3.2 billion years ago. This led to a common, though incorrect, belief that the Moon became geologically dead about 3 billion years ago. One prominent space scientist even called the Moon "a burnt-out cinder" implying that the Moon was also boring. This remark not only insulted lunar scientists, but also anyone who worked on other long-dead cinders such as asteroids, most satellites of the outer planets, and possibly Mercury. It is also incorrect. The Moon is the prime recorder of the impact history of the inner solar system, contains the record of its initial differentiation into core, mantle, and crust, and provides crucial information about how the Earth and other inner planets formed. All the bodies in the Solar System are pieces of a marvelous puzzle, whether they died out 4.5 billion years ago or are still active geologically. And besides, the Moon did not conk out 3 billion years ago.



(Adapted from G. J. Taylor (1994) The scientific legacy of Apollo, *Scientific American*, v. 271, p. 40-47.)

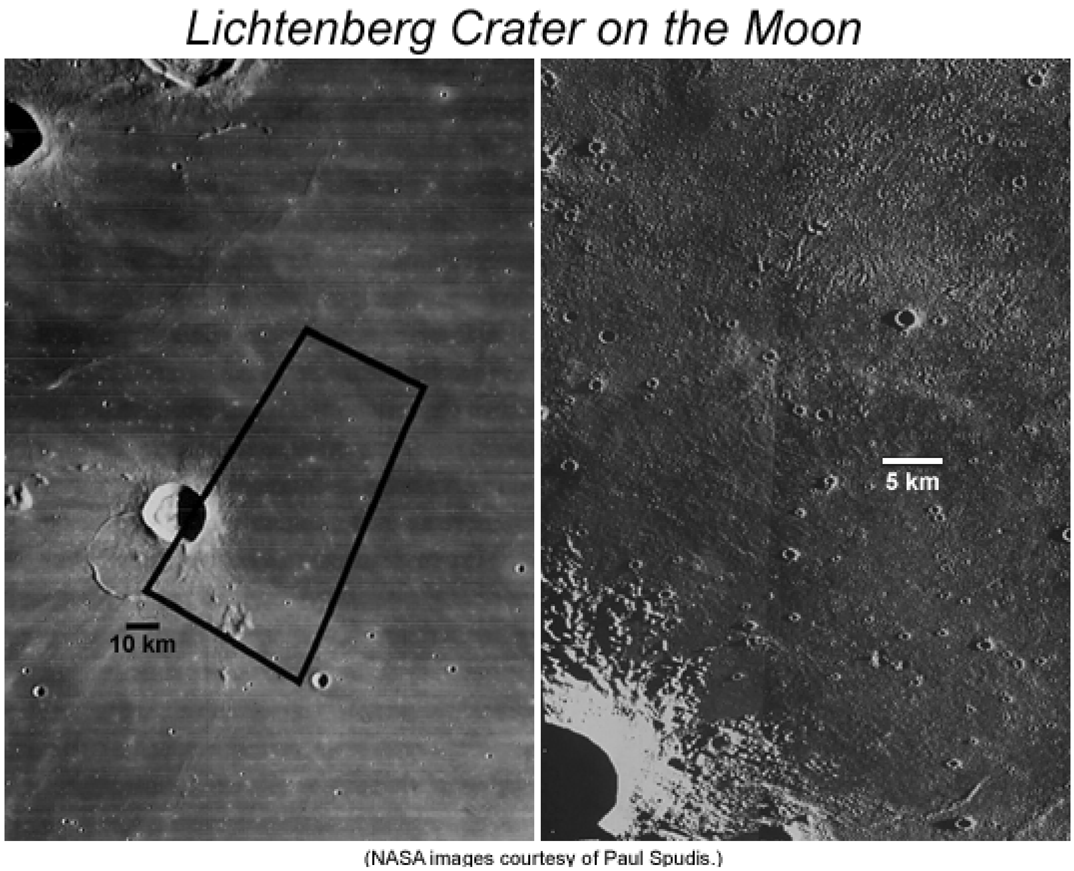




(Adapted from G. J. Taylor (1994) The scientific legacy of Apollo, *Scientific American*, v. 271, p. 40-47.)

The Moon contains high-fidelity information about the origin of the Earth-Moon system (depicted on the top left) and origin of the terrestrial planets in general, how planets differentiate into core, mantle, and crust (illustrated in the lower diagram), and the bombardment history of the inner solar system (represented by the top right map of the immense South Pole-Aitken impact basin).

Planetary geologists have counted thousands of craters on the Moon to establish a relative chronology of surfaces, especially in the maria. Cosmochemists dated the returned lunar samples, providing a solid calibration between the number of craters and the ages of regions on the Moon. These studies showed that volcanism continued to as recently as 2 billion years ago. One such study by Pete Schultz and Paul Spudis (then at the U.S. Geological Survey, Flagstaff, and now at Applied Physics Laboratory, The Johns Hopkins University) showed that the ejecta from one prominent young crater, Lichtenberg, was partly covered by younger mare basalt lava flows (see below). Licthenberg is thought to be roughly the same age as Copernicus, about 1 billion years (as dated by samples from the Apollo 12 mission). Thus, the lava flows must be younger than Licthenberg, so about 1 billion years or less. Nevertheless, 1 billion years is a long time ago, and no lava flows appear to be significantly younger.



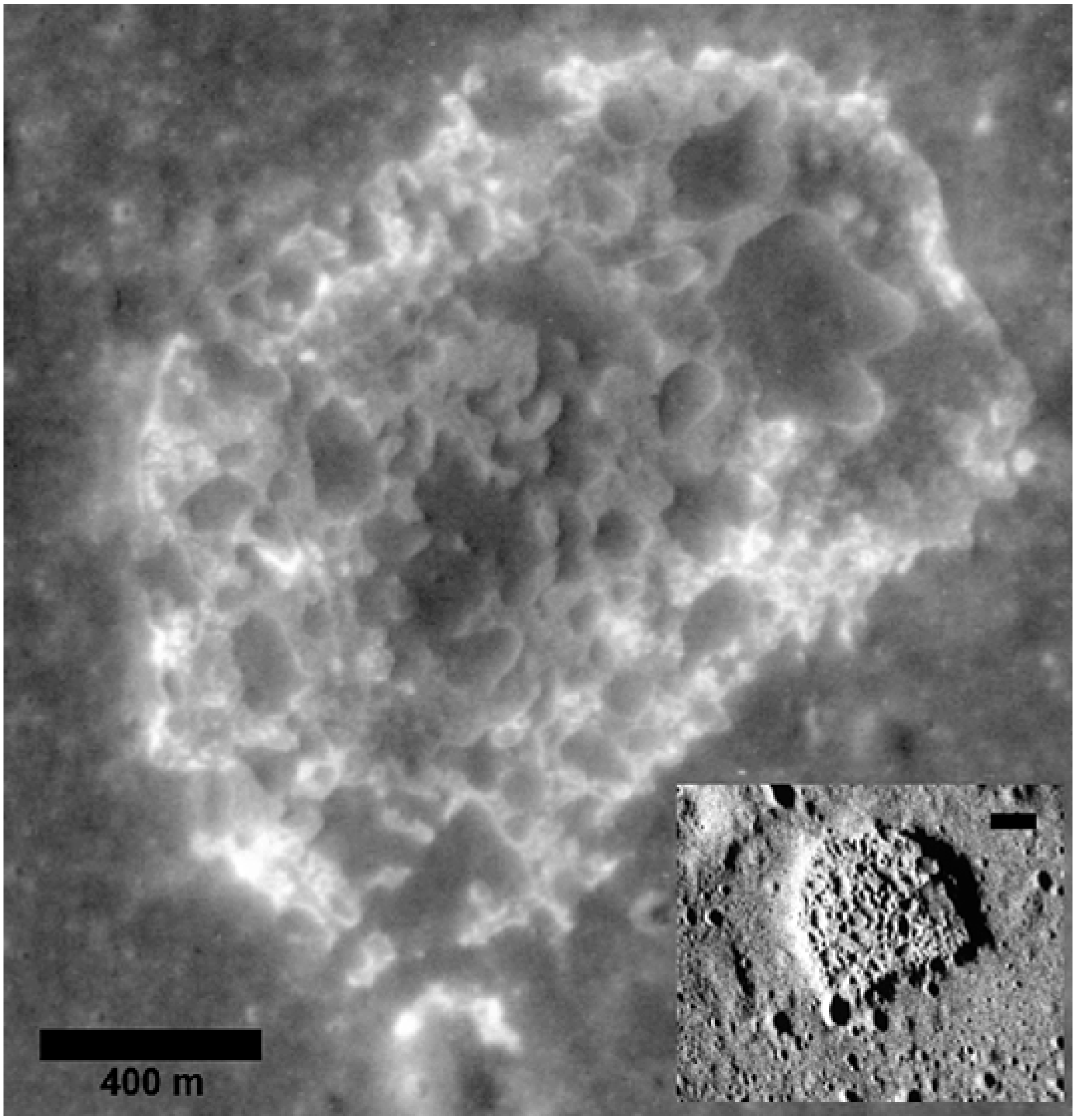
Ejecta from the young crater Licthenberg is embayed by younger, darker lava flows. The flows must be somewhat younger than the crater, which is about 1 billion years old. The black frame on the left hand photograph roughly outlines the area shown in the photograph on the right.

Lethargic Moon but Not Dead

The Ina structure was identified as an unusual feature during the Apollo program, but nobody showed that it could be geologically recent until Pete Schultz started to study it in 1991. Teaming up with Matt Staid and Carlé Pieters, experts in lunar spectroscopy, added a new dimension to his analysis, leading to the recent report. Schultz and his colleagues point to three lines of evidence for Ina being a geological youngster: steep slopes, few superimposed impact craters, and a spectral signature that screams "young."

Ina was first thought from Apollo imagery to be a caldera atop a volcano. The depression lies on the summit of a wide (15 kilometers) but low (only 300 meters high) dome. Inside Ina there are dark hills 5 to 25 meters high with steep sides. The hills are surrounded by brighter, rougher floor materials. The relatively sharp delineation of these features suggests that the smooth hills are young--otherwise they would be much more subdued.

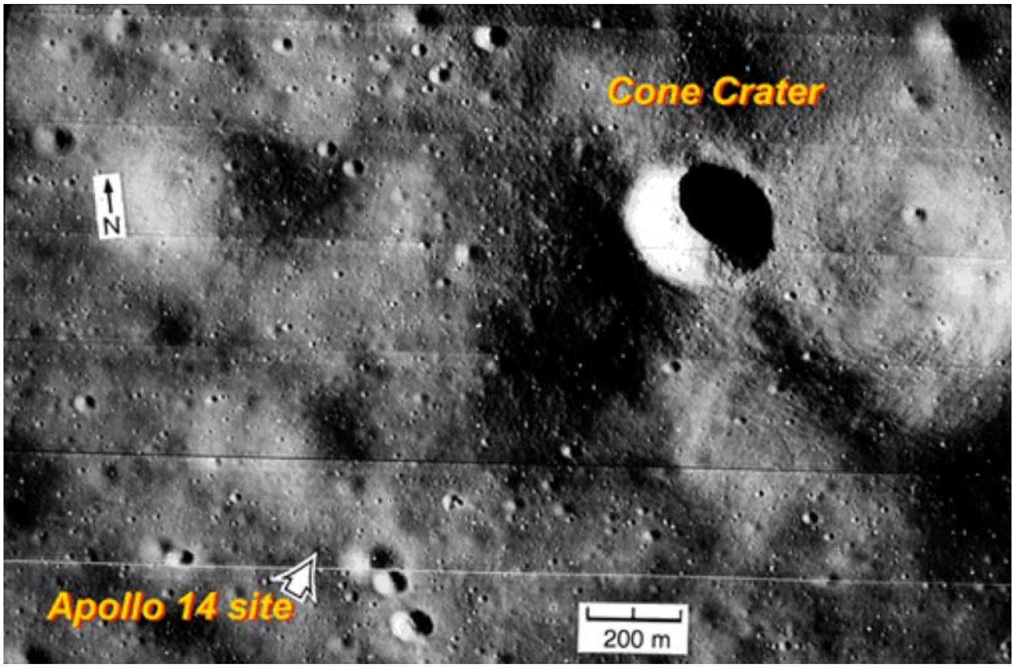
Ina Structure on the Moon



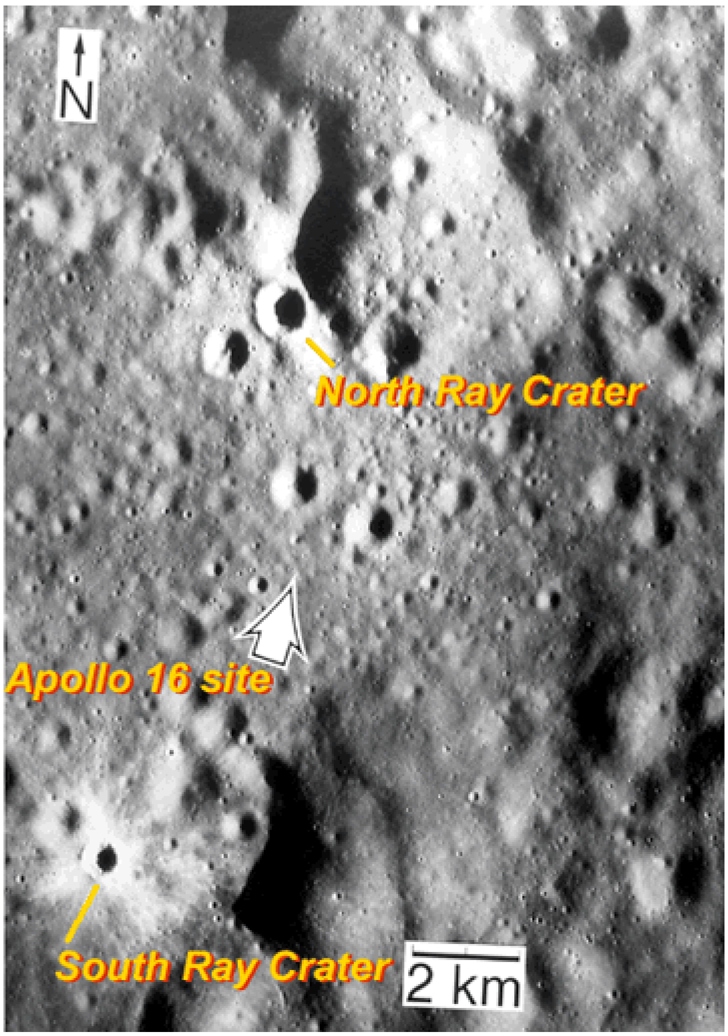
(Schultz, *et al.*, 2006, *Nature*, v. 444, Fig.1.)

These are photographs taken from orbit during the Apollo 15 mission of the Ina structure, a 60-meter-deep depression shaped like the letter D, 2.8 kilometers in diameter. The insert is a low-resolution picture taken with the Apollo hand-held camera. The large picture was taken with the high-resolution panoramic camera. The interior consists of smooth mounds of darker materials surrounded by a brighter, rubbly floor. Note that the boundaries appear sharp, indicating little erosion by impacts. The interior and the surrounding rim materials contain few craters, also indicating a young age.

The number of craters on a surface is a good measure of its relative age. However, the number of craters needs to be related to the absolute surface age for us to make quantitative use of it. Fortunately, cosmochemists have dated several craters on the Moon. Some are large, such as Copernicus (93 kilometers in diameter) and Tycho (85 kilometers), but others are in the right range to be pertinent for the Ina problem. These are Cone Crater at the Apollo 14 site, and North and South Ray Craters at the Apollo 16 site (see images below).

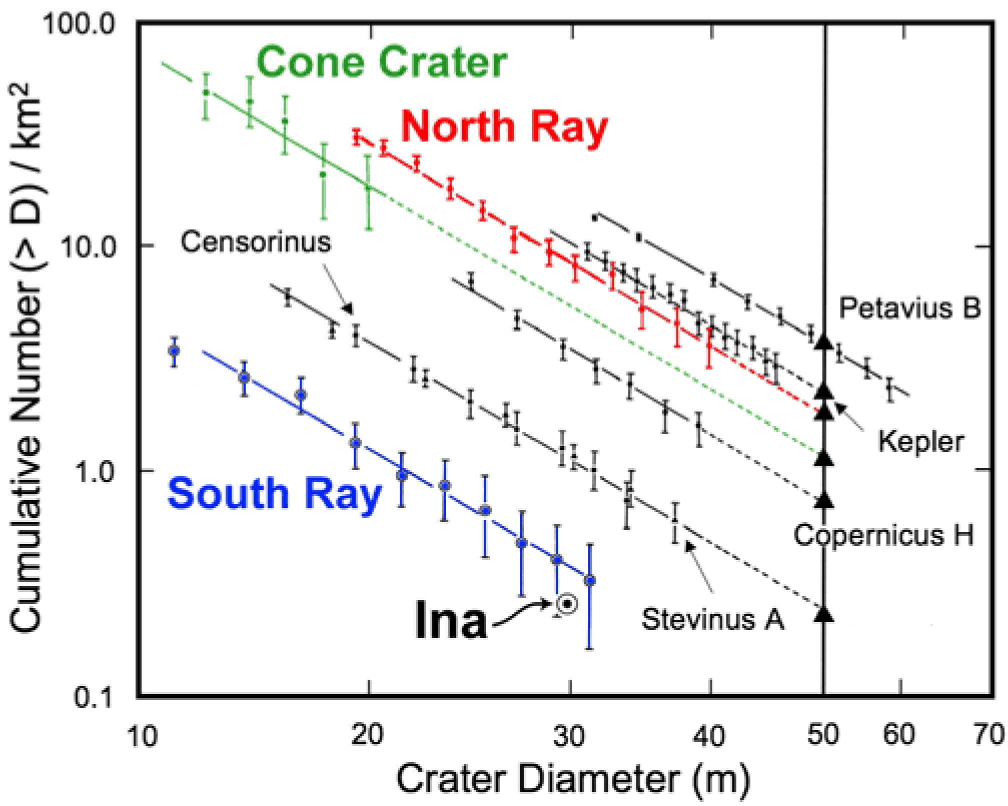


These are NASA orbital photographs of the lunar surface showing on the top: Cone Crater near the Apollo 14 landing site (white arrow), and on the bottom: North Ray and South Ray Craters near the Apollo 16 landing site (white arrow).



The smaller craters like Cone are dated by measuring the concentrations of isotopes produced by cosmic rays in rocks on the crater rims. Cosmic rays are high energy particles that interact with elements in the rocks they slam into, producing an array of nuclear products, such as neon-21, argon-36, and assorted krypton isotopes. Rocks are shielded from cosmic rays if they are buried beneath a meter of rock. If an astronaut sampled a rock that was always buried by a meter of overlying rock, such as those inside a lava flow, then its cosmic ray exposure age would be zero. When a crater forms, it excavates lots of rocks from beneath the surface. Some end up buried beneath a meter again, remaining shielded. Some, however, lie on the surface of the ejecta blanket surrounding a crater, and their cosmic ray exposure clock begins ticking. Astronauts collected several such rocks from the debris blankets from Cone Crater and North Ray Crater, and from a ray from South Ray Crater. Cosmochemists determined their ages by measuring a variety of cosmic-ray-produced isotopes in their laboratories. The results show that North Ray Crater is 50 million years old, Cone Crater is 25 million years old, and South Ray Crater is 2 million years old.

Schultz counted smaller impact craters on the dated craters and on several other bright rayed craters, and on Ina. He found only two probable impact craters larger than 30 meters within the Ina structure, which encompasses 8 square kilometers. This is less than found on the ejecta and floor of South Ray Crater, which is only 2 million years old. The graph below shows the data for the young craters, with a lone dot for Ina. (The fact that Ina has a dot rather than a collection of dots indicates its young age, too.)



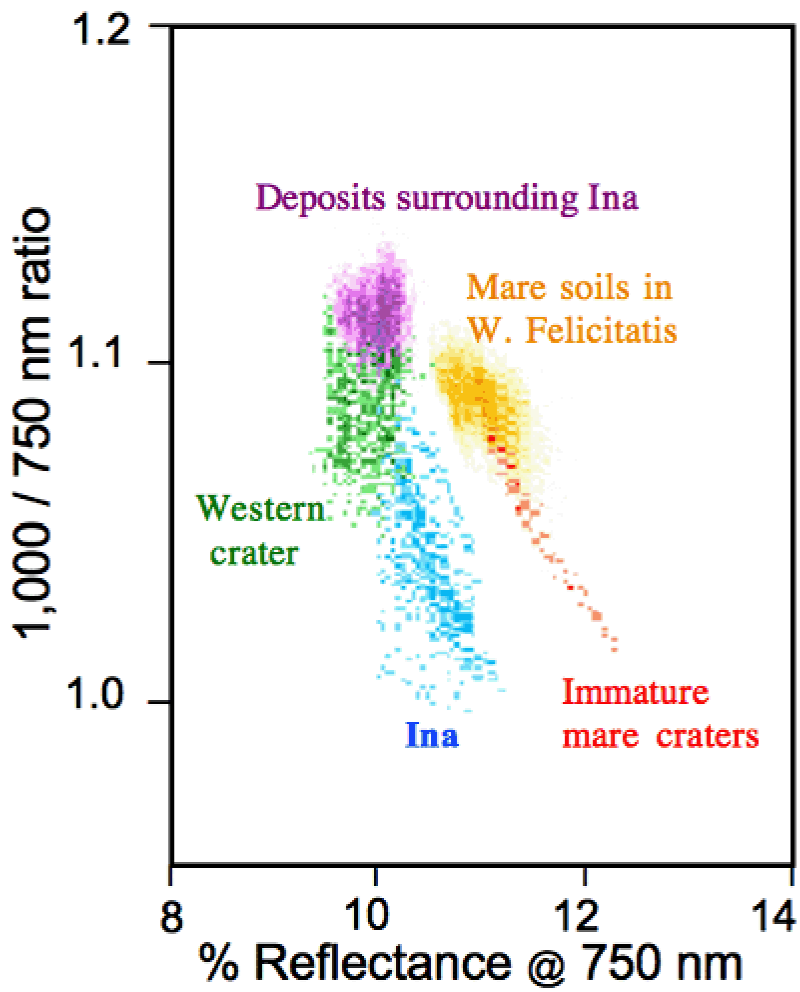
(From Schultz *et al.*, 2006, *Nature*, v. 444, Fig. 2.)

This graph shows measurements of the number of small craters superimposed on young, fresh craters on the Moon, including three dated with lunar samples collected from their ejecta. The vertical axis shows the number of craters per square kilometer larger than the diameter plotted on the horizontal axis. The Ina structure has only two craters larger than 30 meters in the 8-square-kilometer area examined. The point for Ina plots a bit below the line for the 2-million-year-old South Ray Crater, though within the experimental uncertainty (shown by the bars). Thus, Ina is about the age of South Ray Crater, or possibly a bit younger.

There is a long and distinguished history of multispectral observations of the Moon. Planetary scientists have used telescopes and spacecraft (such as Galileo on its way to Jupiter and Clementine) to measure the intensity of sunlight reflected off the Moon in a range of wavelengths. The spectra provide information about the mineralogy and elemental composition of the surface. Carlé Pieters is a pioneer in using spectral observations to determine the composition of the lunar surface.

The Clementine spacecraft orbited the Moon in 1994, returning images in several wavelengths, covering almost the entire lunar globe.

Reflectance spectra tell us more than mineral abundances. They also contain important information about the maturity of the surface--how long the surface has been exposed to solar wind and micrometeorite bombardment, or "space weathering." (See PSRD article: Moonbeams and Elements.) One of the key parameters in determining the surface age is the ratio of reflected light in two wavelengths in the near-infrared, 1000 nanometers and 750 nanometers, as shown in the graph below. Spectral measurements made on returned lunar samples show that the lower this ratio, the less exposure to space weathering, hence the younger the surface. When plotted against the reflectance at 750 nanometers, a measure of how bright the surface appears (i.e., its albedo), we also obtain information about the concentration of iron oxide. However, for our purposes, the key point is that materials within Ina have a low 1000/750 nanometer ratio, indicative of short exposure. In other words, Ina is young and has not been affected greatly by impact reworking, a conclusion consistent with other data. The spectral data also indicate that the deposit is composed of high-titanium basalt, consistent with its location near Mare Tranquillitatis.



(From Schultz, *et al.*, 2006, *Nature*, v. 444, Fig.4.)

This is a plot of Clementine spectral data. The ratio of reflected light at 1000 nanometers to that at 750 nanometers (y-axis) is plotted against the reflectance at 750 nanometers (x-axis). The lower the 1000/750 ratio, the less exposure the surface has to space weathering. Ina is clearly young, or immature, consistent with morphological and crater-count data.

How Did Ina Form?

The bright, rubbled materials on Ida's floor appear to consist of fresh exposures of high-titanium mare basalt, with the regolith removed. The heights of the hills suggest that the regolith is thicker than 12 meters. An alternative is that the surface consists of pyroclastic volcanic materials, or a combination of regolith and pyroclastic debris. The basalts are old, probably as old as the Apollo 11 mare basalts, about 3.5 billion years. Schultz and colleagues suggest that the regolith or pyroclastic layer was blown away by the sudden release of pressurized gases. The subdued ejecta surrounding the structure indicates that the process was not as energetic as an impact, consistent with a gas eruption. Which gases is unknown, but they must have come from deep within the Moon, and collected beneath the surface until their pressure built up enough to suddenly burp out, blowing regolith around, a rare case of wind on the airless Moon.

Schultz has found three other features similar to Ina. All are related to structural features associated with linear rilles associated with the Imbrium impact basin. These areas may be places of crustal weaknesses that allow interior gases to escape.

Schultz and his coworkers also point out that the Apollo alpha-particle spectrometer gave hints of recent gas releases from the lunar interior. Ina is adjacent to one of the broad regions having elevated polonium-210 alpha particles. Polonium-210, which forms from radon (produced during uranium decay), has a short half-life, so its radon parent must have been released during the past 60 years. Thus, the Moon appears to be leaking gases now, and occasionally does so in bursts, forming or modifying features like Ina.

The Sleepy Yet Vibrant Moon

This research involves analysis of photographs, counting of numerous craters, and spectral analysis, all on a base of lunar sample analysis. It shows the way science advances as we learn more. Tne Ina structure was thought to be a young feature back in the early 1970s, but lunar scientists could not be quantitative about it. The dating of craters to quantify how the number of craters changes with time gave one important piece of information. Studies of the spectra of lunar samples and analysis of telescopic spectra improved our knowledge of how to quantitatively interpret the light reflected off the Moon. Then, in the 1990s, we gained a firmer understanding of the processes that modify the spectra of lunar regolith as it is exposed to micrometeorite bombardment (see **PSRD** article: New Mineral Proves an Old Idea about Space Weathering), and finally had global spectra data for the Moon from the Clementine mission. All that research over decades was needed before Pete Schultz and his colleagues could unravel the story of young Ina. It is a great story of geology, spectroscopy, and cosmochemistry blending to provide evidence that the lunar interior is at least active in some ways, even to today.

Ina and similar features are good targets for future exploration. The displaced deposits might hold clues to the constituents in the escaping gases. The areas stripped of regolith or pyroclastic debris might show us what the interface between the regolith and the underlying bedrock is like, currently an unknown in lunar science. Perhaps astronauts will visit Ina someday, examining its fluffy deposits and rugged underlying rock. It might not, however, be such a great place to establish a lunar base. Imagine sitting in your habitat, working on some samples you collected from the lunar surface or from a biological experiment, when the habitat shakes and your view of the outside is obscured by regolith being lifted by gases spewing from the interior of the not-so-burnt-out cinder!

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Martel, L.M.V. (2004) New Mineral Proves an Old Idea about Space Weathering. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/July04/newMineral.html).
- Schultz, P. H., M. I. Staid, and C. M. Pieters (2006) Lunar activity from recent gas release. *Nature*, v. 444, p. 184-186.
- Taylor, G. J. (1997) Moonbeams and Elements. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Oct97/MoonFeO.html.

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