

Hot Idea

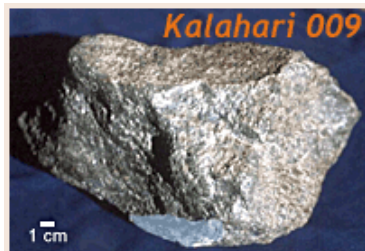
December 19, 2007

Chips Off an Old Lava Flow

--- Lunar meteorite Kalahari 009 contains fragments of basalt about 4.35 billion years old, a record-breaking old age for mare basalt.

Written by [G. Jeffrey Taylor](#)

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(Photo courtesy of Addi Bischoff.)

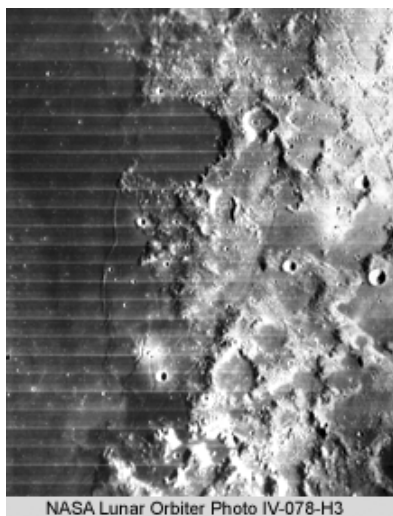
Photogeologic and remote sensing studies of the Moon show that many light-colored, smooth areas in the highlands contain craters surrounded by dark piles of excavated debris. The dark deposits resemble the dark basalts that make up the lunar maria. They contain the same diagnostic minerals (especially high-calcium pyroxene) and chemical compositions (high iron oxide) as do mare basalts. The deposits formed when vast amounts of material ejected during the formation of giant impact basins covered pre-existing lava plains. Since the smooth plains are older than the youngest impact basin (about 3.8 billion years old), the lavas must have erupted before formation of the visible maria. In fact, they were visible maria for a while eons ago, but were buried by ejecta when the basins formed.

We have samples of these ancient mare basalts. They reside in breccias collected from the lunar highlands. Age dating indicates that the chips have ages of 3.9 billion years and older. The oldest dated mare basalt in the Apollo collection is 4.23 billion years. Now Kentaro Terada (Hiroshima University, Japan), Mahesh Anand (Open University, UK), Anna Sokol and Addi Bischoff (Institute for Planetology, Muenster, Germany), and Yuji Sano (The University of Tokyo, Japan) have determined the age of pieces of an ancient lava flow in a lunar meteorite, Kalahari 009, found in Botswana in 1999. The team dated this very low-titanium mare basalt by using an ion microprobe to measure the isotopic composition of lead and uranium in phosphate minerals. They found that the basalt fragments in the rock have an age of about 4.35 (plus or minus 0.15) billion years. This overlaps with the ages of chemically-distinct igneous rocks from the highlands, indicating that diverse magmas were being produced early in the history of the Moon.

Reference:

- Terada, K., Anand, M., Sokol, A. K., Bischoff, A., and Sano, Y. (2007) Cryptomare Magmatism 4.35 Billion Years Ago Recorded in Lunar Meteorite Kalahari 009. *Nature*, v. 450, p. 849-853.

PSRDpresents: Chips Off an Old Lava Flow --[Short Slide Summary](#) (with accompanying notes).

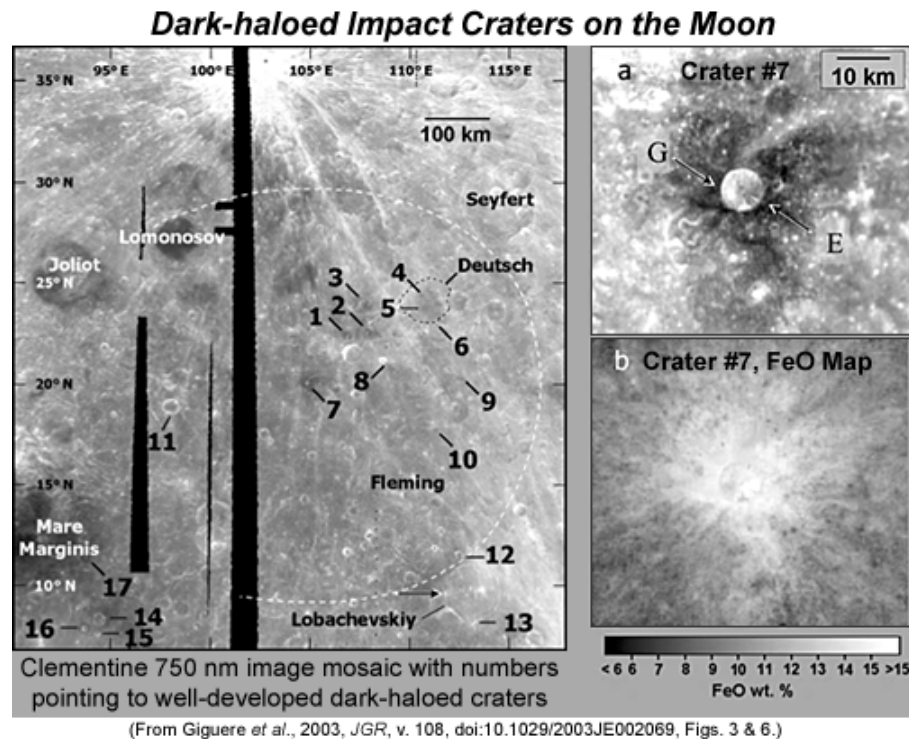
**Visible and Hidden Lava Plains**

From the moment Galileo peered at the Moon through his homemade telescope, he recognized two main areas on the Moon (see photograph): the rugged, light-colored [highlands](#) (which he named "terra") and the smoother, darker areas ("maria"). [Maria](#) is the Latin word for sea, which Galileo figured they might be. We did not know for sure what they were until Apollo 11 astronauts retrieved samples from Mare Tranquillitatis. They are basalts--ancient lava flows that flooded low areas, many the interiors of large impact basins.

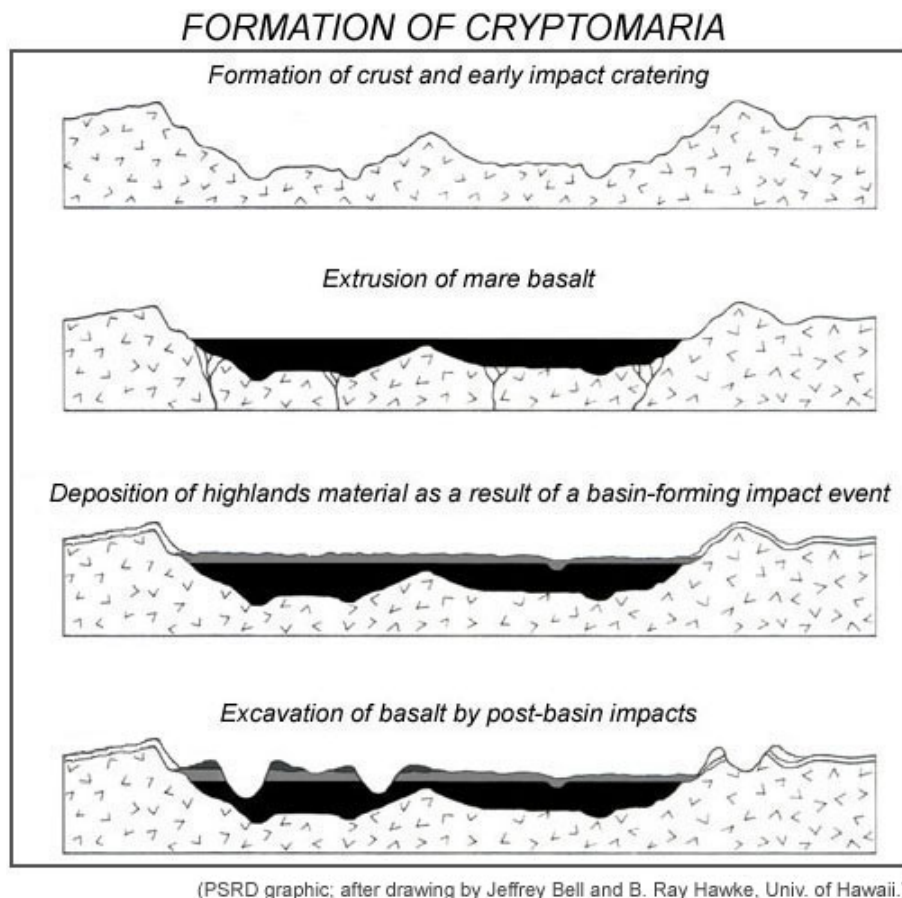
Analyses of samples and remote sensing measurements show that the maria are dark because the lavas contain a lot more FeO (iron oxide) than do highland rocks. FeO inside a mineral such as [pyroxene](#) makes it darker. In addition, the mare basalts contain less [plagioclase feldspar](#), a light-colored mineral. Hence, the maria are dark. They are smooth in part because they are so much younger than the highlands and so did not accumulate

as many craters. However, they are also smoother because lava flows fill up low areas, tending to produce smooth plains.

Many areas in the highlands are smooth plains, but they are light colored, hence low in FeO. Remote sensing shows that they are not composed of mare basalts. However, many light plains deposits are decorated with impact craters surrounded by dark piles of ejecta, nicknamed "dark-haloed craters." These curious features were debated for years. Finally, Pete Schultz (now at Brown University) and Paul Spudis (now at the Lunar and Planetary Institute, Houston) assembled all the available evidence to make a good case that the dark-haloed craters formed when mare basalt lava flows were covered with ejecta from large impact craters and basins, and then small craters punctured through the ejecta to toss out mare basalt. Detailed studies during the 1980s by B. Ray Hawke and Jeff Bell (University of Hawaii), and investigators elsewhere, provided further evidence that many light plains in the highlands are underlain by dark basaltic rock. In 1992, Jim Head (Brown University) and Lionel Wilson (Lancaster University, UK) named these widespread deposits "[cryptomaria](#)," meaning hidden maria.



LEFT: Seventeen dark-haloed craters are indicated by numbers on this image mosaic from Clementine 750 nm remote sensing data of the Lomonosov-Fleming region. TOP RIGHT: Clementine 750 nm image of crater #7. This crater is 8 kilometers in diameter. The arrows show where additional remote sensing spectra were obtained. BOTTOM RIGHT: FeO map of crater #7.

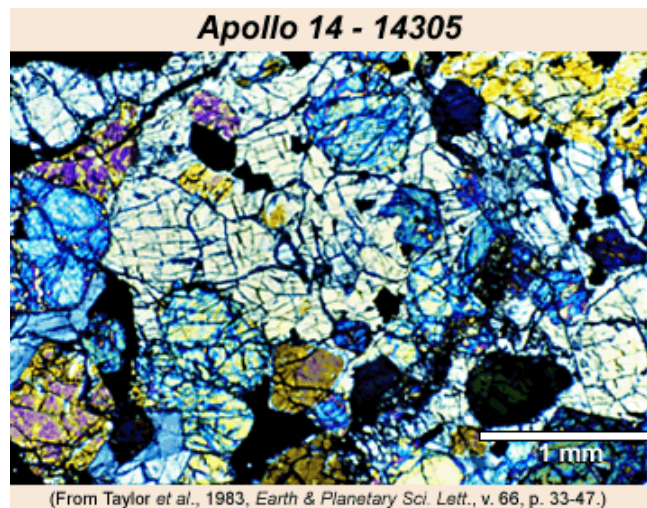


The four panels in this diagram show cutaway, side views into the Moon to describe the basic formation of a cryptomare. Cryptomaria formed when low-lying areas in the heavily-cratered ancient highlands (TOP panel) were flooded by mare basalt lava flows (black deposit, SECOND panel). A subsequent basin-forming impact, hundreds to thousands of kilometers away, deposited ejecta on top of the surface (THIRD panel). During deposition, some of the mare basalt was mixed with ejecta from the basin, forming a deposit consisting of broken and mixed highland rocks with fragments of mare basalt (grey deposit). Eventually, smaller craters punctured through the ejecta, (BOTTOM panel) depositing debris from the underlying mare basalts around them, creating dark-haloed craters and revealing the existence of the buried mare basalt. The bottom panel shows two dark-haloed craters on the left side of the panel. The small crater on the right side does not have a dark halo.

Ancient Samples

While geologic studies of dark haloed craters were leading to the idea of mare-like volcanism that pre-dates the visible maria, cosmochemists were getting hints of ancient mare volcanism from samples of the lunar highlands. One of the first studies (in 1976) was by Graham Ryder (then at the Smithsonian Astrophysical Observatory) and me (then at Washington University in St. Louis). While studying impact breccias formed in ancient, pre-mare events, we noticed small rock fragments that looked just like mare basalts (high FeO, small amount of plagioclase feldspar). The way the minerals were intergrown and their compositions indicated that the rock fragments were volcanic. We proposed that they were pieces of mare-like lava flows that formed before the visible maria. Aside from some debate (which Graham and I referred to as whining) about whether it was proper to call them "mare" basalt when they did not come from a visible maria, the work was well received, and promptly ignored.

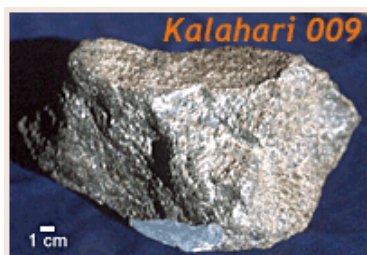
Part of the reason for ignoring the idea of mare-like volcanism before 3.8 billion years ago was that individual basalts had not been dated. That problem was solved when the age daters started to extract samples from highland breccias and date them by a variety of isotopic techniques. Sure enough, the ages started coming in older than 3.8 billion years. Many were 3.9 to 3.95 billion years, and one, dated by Larry Taylor (University of Tennessee) and his colleagues was 4.23 billion years old. The rock was mineralogically and compositionally a mare basalt. It was the oldest mare basalt (or pre-mare mare basalt!) dated...until now.



(From Taylor et al., 1983, *Earth & Planetary Sci. Lett.*, v. 66, p. 33-47.)

Photomicrograph in cross polarized light of the mare basalt fragment in lunar highlands breccia 14305, dated by Lawrence Taylor and his colleagues. The view is dominated by pyroxene, olivine, and chromium and titanium oxides. The rock's age is 4.23 billion years.

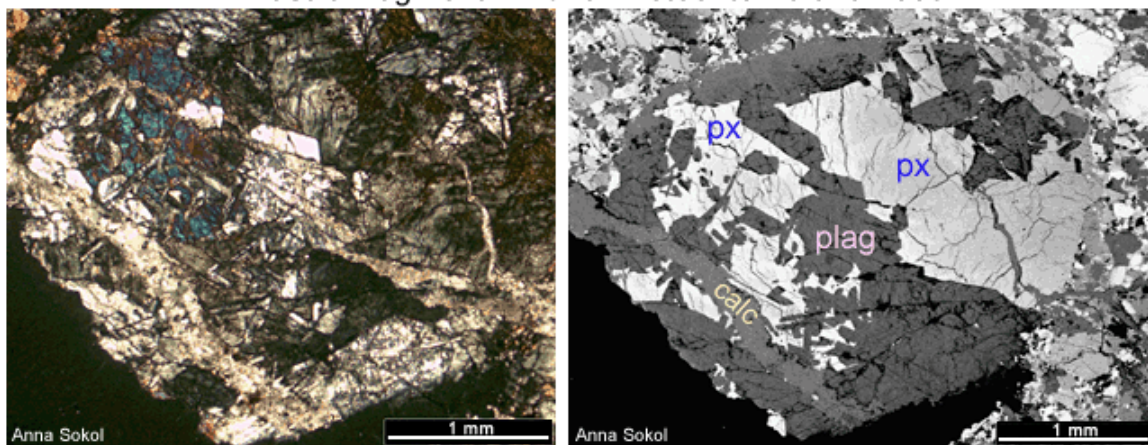
The Oldest Mare Basalt (so far)



(Photo courtesy of Addi Bischoff.)

Kalahari 009 was found in September 1999 near the small village of Kuke in the Kalahari Desert, Botswana. It was first described in a paper by Anna Sokol and Addi Bischoff (Institute for Planetology, Muenster, Germany). Sokol and Bischoff show that the rock is composed of fragments of lunar mare basalt and minerals derived from the basalt. Their data indicate that the rock is a very-low-Ti mare basalt. An important observation is that the minerals making up the rock show clear evidence for high-pressure shock, such as feldspar converted partly to glass (called maskelynite). Thus, the rock's Ar-Ar age might have been partially or completely reset by an impact event.

Basalt Fragment in Lunar Meteorite Kalahari 009



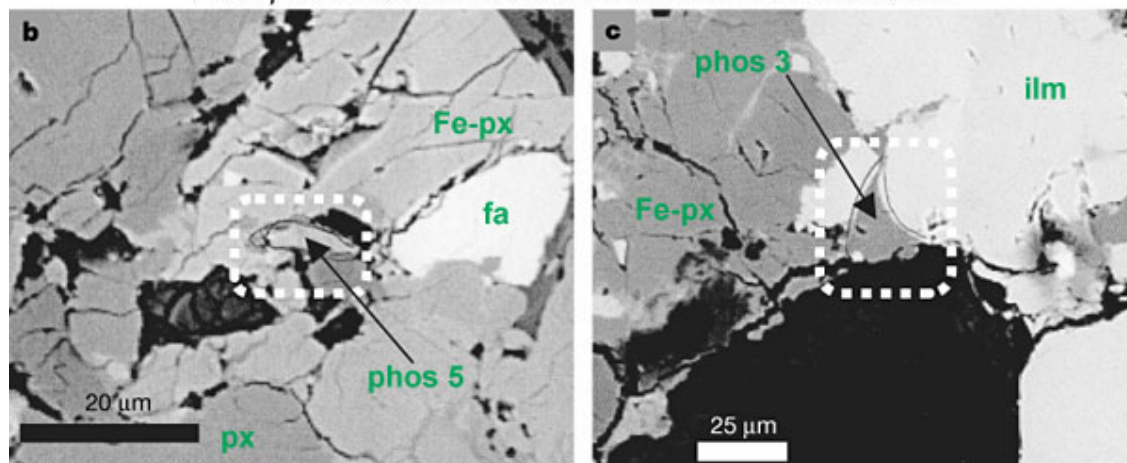
(From Sokol and Bischoff, 2005, *MAPS*, v. 40, p.A177-A184.)

LEFT: Photomicrograph of basalt fragment in Kalahari 009, taken in cross polarized light. Medium to bright gray is plagioclase feldspar, while blue and darkest gray is pyroxene. The texture is typical of crystallized lava, but the minerals have been damaged by shock caused by a meteorite impact on the Moon. RIGHT: Backscattered electron image of the same area as in the photomicrograph. Brightest mineral is pyroxene, dark is plagioclase. The vein along the lower left is calcite (calcium carbonate), a terrestrial contaminant.

The age of Kalahari 009 was first determined by Vera Fernandes (University of California, Berkeley), using the argon-argon technique. This is the modern way geochronologists determine the potassium-argon age for a rock (radioactive potassium-40 decays to argon-40). Its advantage is that it gives information about gas loss caused by a reheating event after initial crystallization of a rock. Fernandes' analyses indicated a well-defined age of 1.70 ± 0.04 billion years. An important question is whether that age represented the time the basalt formed, or a subsequent event that produced the shock effects observed in the rock.

To get a better idea of the rock's age, Kentaro Terada and his colleagues concentrated on the phosphate minerals (apatite and merrillite) that occur between the abundant plagioclase and pyroxene crystals. Phosphates are the main repositories of uranium in lunar basalts, making them efficient recorders of uranium-lead ages. (Uranium-238 decays to lead-206, uranium-235 decays to lead-207. In general, the higher the uranium concentration, the higher the precision of the ages determined.) Phosphates also have the great virtue of being relatively resistant to lead redistribution by heating, so are less likely to have been affected by the shock event the Kalahari 009 basalt experienced.

Phosphate Grains in Lunar Meteorite Kalahari 009



(From Terada *et al.*, 2007, *Nature*, v. 450, p. 849-853.)

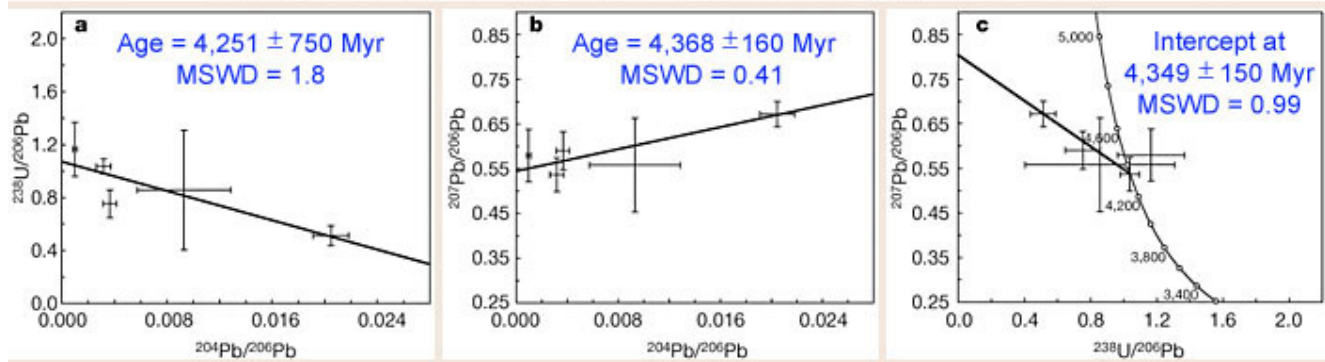
These are scanning electron microscope images of two of the phosphate grains (labeled phos 5 and phos 3) used for determining the age of basalt in Kalahari 009. The crystals are too small to separate efficiently, so their uranium and lead isotopes were measured using an ion microprobe at the Hiroshima University. Fe=px is iron pyroxene, fa is fayalite, and ilm is ilmenite.

The phosphate crystals are not abundant in the rock, and they are too small to separate physically, so Kentaro Terada used an ion microprobe called SHRIMP to measure the isotopic abundances of uranium and lead. (For more information about ion microprobe analysis, see [PSRD-Instruments of Cosmochemistry](#) article: [Ion Microprobe](#).) The laboratory at the University of Hiroshima is experienced in making such measurements on a range of terrestrial and extraterrestrial materials, including accurately dating shark teeth hundreds of millions of years old.

The results can be plotted on graphs in a number of ways that geochronologists understand well, but baffle those of us who do not use them regularly. The diagrams are complicated because there are two parent isotopes (uranium-235 and uranium-238) and two daughter isotopes (lead-206 and lead-207), plus the isotope lead-204 that does not form by decay. Cosmochemists use plots of different isotope ratios to estimate an age, but often, as in this case, the ages differ somewhat (see diagram below). To plot all the isotopes at once you need a three-dimensional diagram, which is what Terada and his colleagues used to make their best estimate of the age of the basalt in Kalahari 009. The diagram is not really three dimensional. Instead, it is a projection from three dimensions onto a two-dimensional plot [\[more information\]](#). This results in a best estimate of 4.35 ± 0.15 billion years for the age of the basalt in Kalahari 009.

Maybe not the most precise age ever determined, but it clearly shows that the rock is ancient and almost certainly older than the basalt fragment dated by Larry Taylor and his colleagues.

Isotope Ratios in Phosphate Grains in Lunar Meteorite Kalahari 009



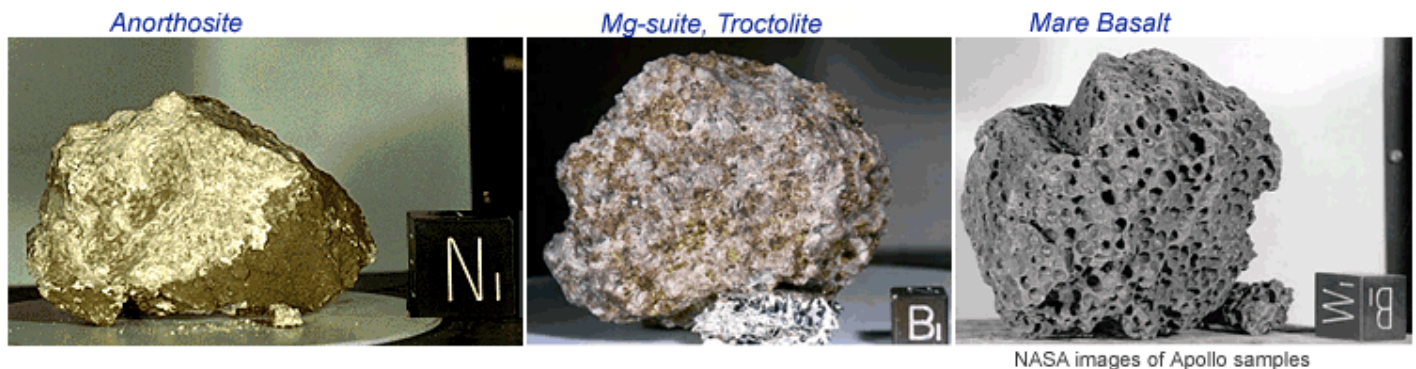
(From Terada *et al.*, 2007, *Nature*, v. 450, p. 849-853.)

Graphs of isotope ratios in phosphate minerals measured by ion microprobe in a basalt fragment in Kalahari 009. The relatively well-defined lines (called isochrons) in graphs a and b yield ages for a particular set of isotopes. The diagram on the right (c) shows a projection from three-dimensions, so uses all isotopic data, and gives an age of 4.35 ± 0.15 billion years, which Terada and his colleagues suggest is the best estimate of the age of the lava flows represented in Kalahari 009. The uncertainty in the age is based on the uncertainties in the individual measurements (see error bars) and is at the 95% confidence level. (MSWD is the mean square weighted deviate, a measure of the scatter in the data.)

We now know that mare-like basalts erupted very early in lunar history and that lunar cryptomaria range in age from 4.35 to about 3.9 billion years. The cryptomaria and lunar impact breccias returned by Apollo and found as lunar meteorites record an extensive record of pre-mare mare-like volcanism. The early start to lunar volcanism, as noted by Terada and co-workers and by Larry Taylor and his co-workers, indicates that many types of magmas were produced early in the Moon's history.

Magma Magma Everywhere

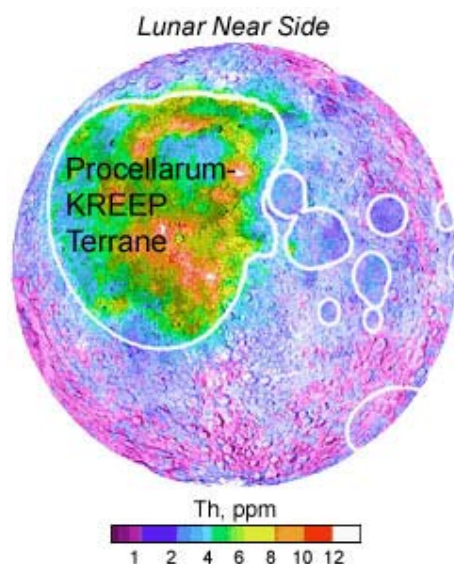
In broad terms there are three groups of lunar rocks: (1) **Anorthosite (nicknamed FAS)**, which formed by floatation in an ocean of magma surrounding the Moon soon after it formed. Determining their ages is tricky, but they likely formed by 4.46 billion years ago (see [PSRD article: The Oldest Moon Rocks](#)). (2) **Highlands magnesian-suite (Mg-suite)**, which formed soon after the FAS crust formed and continued until about 3.9 billion years ago. It is composed of several rock types, including [intrusive](#) igneous rocks ([norites](#) and [troctolites](#)) and lava flows called [KREEP](#) basalts. (3) **Mare basalts**, which we now know began to form by 4.35 billion years ago and continued for over 2 billion years (on the basis of crater counts, the youngest are possibly as young as 1 billion years old).



For a long time we had a comfortable, somewhat simple picture of magma formation in the Moon. The FAS suite formed first, followed by assorted Mg-suite magmas, which was followed by mare basalts. Simple. Nice crisp divisions. One thing, then another. Early indications of mare basalts older than 3.9 billion years showed that mare and Mg-suite volcanism overlapped, but the overlap was concentrated near the end of Mg-suite volcanism. Now, with two mare basalt samples substantially older than 3.9 billion years, the picture is more complicated. Mare basalt volcanism continued after Mg-suite magmas were no longer being produced, but there was a time when both were operating robustly.

The interesting thing about such compositionally-diverse magmatism operating at the same time is that the two suites of magma must have formed in compositionally-diverse regions inside the Moon. These distinctive regions located deep inside the Moon had to partially melt to produce magma. The melting could have been triggered by a variety of mechanisms. The most common might have been the rise of plumes of solid mantle rock triggered by density differences caused by the way the magma ocean crystallized. When magma solidifies, the first crystals of olivine and pyroxene to form have high ratios of magnesium to iron, and end up forming a pile at the bottom of the magma pool. The ratio decreases as crystallization proceeds. Because density increases as magnesium/iron decreases, the final column has denser (hence heavier) rock on top and less dense rock below. This is unstable, so it overturns. The solid base rises and, as it does so, the lower pressure allows the rock to partially melt, producing magma.

The second mechanism is simply heating of portions of the interior by the decay of radioactive elements. This happens over a long time, accounting for the long duration of mare basalt magmatism, and is aided by high concentrations of radioactive elements (potassium, uranium, and thorium). Those elements and others like them (called large-ion lithophile elements) concentrate in the last dregs of the magma ocean, making up a material called KREEP. Terada and his colleagues suggest that high concentrations of radioactive elements in the mantle could not be the source of the mare basalt in Kalahari 009 because it contains only small concentrations of large-ion lithophile elements. However, Mark Wieczorek (now at the Institut de Physique du Globe, Paris) and colleagues at Washington University in St. Louis have shown that an upper mantle and crustal concentration of radioactive elements in the Procellarum-KREEP Terrane (see [PSRD article: A New Moon for the Twenty-First Century](#)) sent a heat pulse into the mantle, causing substantial overturn and basalt production, including melting of regions of the mantle low in radioactive and other large-ion lithophile elements.



(From Jolliff *et al.*, 2000, *JGR*, v. 105, p. 4197-4216.)

Procellarum KREEP Terrane is characterized by high thorium (and the other heat producing elements potassium and uranium). Heating by radioactive decay might have caused melting and overturn of the mantle, producing widespread mare basaltic volcanism.

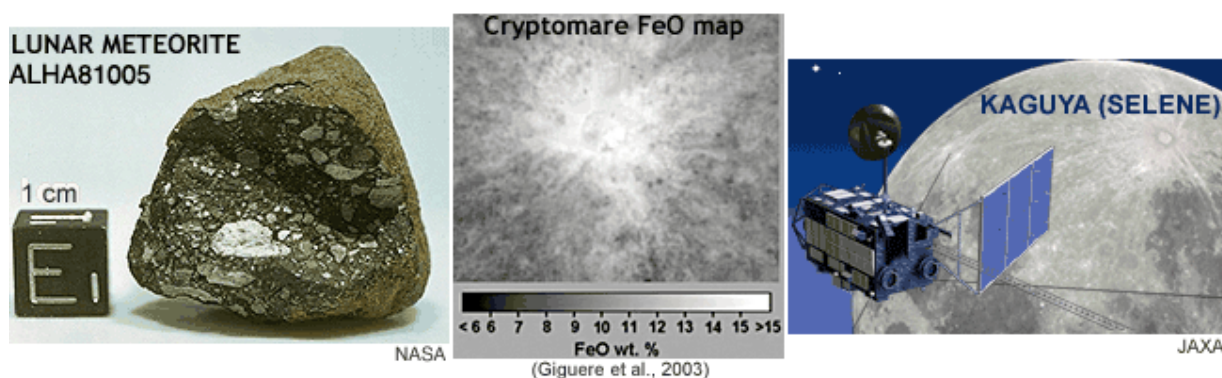
Terada and colleagues point out an intriguing alternative hypothesized by Linda Elkins-Tanton, Brad Hagar, and Tim Grove (Massachusetts Institute of Technology). They suggest that basin-forming impacts could have triggered substantial amounts of magmatism, some immediately, some years to 10,000 years after a huge impact, and more up to 350 million years after an impact. The instantaneous melting happens because of rapid decrease in the pressure at depth because of the removal of a large mass of rock. Their calculations indicate that subsequent upwelling of the upper mantle could cause convection to take place for up to 350 million years, perhaps producing ancient cryptomaria. Terada and his team suggest that the 4.35-billion-year-old basalt represented by Kalahari 009 could have formed as the result of an impact of approximately that age.

If this fascinating interpretation is correct (and it is far from proven), it suggests that not all large impacts occurred during a narrow interval from 3.95 to 3.85 billion years ago, the time of the hypothetical lunar cataclysm. The idea of the cataclysm is that there was a dramatic spike in the impact rate about 3.9 billion years ago, lasting only 100 million

years. (See **PSRD** articles: [Lunar Meteorites and the Lunar Cataclysm](#), [Wandering Gas Giants and Lunar Bombardment](#), [Uranus, Neptune, and the Mountains of the Moon](#).) While not a clear-cut case with only two very old basalt samples, it shows that ancient cryptomaria would be worthy targets of sample return missions from which we would learn more about not only when mare basaltic magmatism began, but perhaps about the bombardment history of the Moon as well.

Samples and Remote Sensing

The research on cryptomaria shows how remote sensing, geologic studies, and sample analysis combine to allow us to understand the volcanic history of the Moon. Remote sensing gives us an overview and geologic context. Sample analysis gives us detailed rock textures, mineralogy and chemical composition, and precise ages. In the future, continued remote sensing studies will reveal ideal targets for sample return missions by robots and people, leading to an improved understanding of the Moon's geologic history for comparison with Earth, Mars, and other rocky objects in the inner solar system.



Sample analyses and remote sensing are all necessary to understand the geologic history of the Moon.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** Chips Off an Old Lava Flow--[Short Slide Summary](#) (with accompanying notes).
- Cohen, B. A. (2001) Lunar Meteorites and the Lunar Cataclysm. *Planetary Science Research Discoveries*. <http://www.psrhawaii.edu/Jan01/lunarCataclysm.html>.
- Elkins-Tanton, L. T., Hager, B. H., and Grove, T. L. (2004) Magmatic Effects of the Lunar Late Heavy Bombardment. *Earth Planet. Sci. Lett.*, v. 222, p. 17-27.
- Giguere, T. A., Hawke, B. R., Blewett, D. T., Bussey, D. B. J., Lucey, P. G., Smith, G. A., Spudis, P. D., and Taylor, G. J. (2003) Remote Sensing Studies of the Lomonosov-Fleming Region of the Moon. *Journal of Geophysical Research*, v. 108, doi:10.1029/2003JE002069.
- Jolliff, B. L., Gillis, J. J., Haskin, L. A., Korotev, R. L., and Wieczorek, M. A. (2000) Major Lunar Crustal Terranes: Surface Expressions and Crust-Mantle Origins. *Journal of Geophysical Research*, vol. 105, p. 4197-4216.
- Kaguya (Selene) Mission to the Moon [Homepage](#), from Japan Aerospace Exploration Agency (JAXA).
- [Lunar Meteorites](#), comprehensive site from Randy Korotev, Washington University in St. Louis.
- Norman, M. (2004) The Oldest Moon Rocks. *Planetary Science Research Discoveries*. <http://www.psrhawaii.edu/April04/lunarAnorthosites.html>.
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- Sokol, A. and Bischoff, A. (2005) Meteorites from Botswana. *Meteoritics and Planetary Science*, v. 40, p. A177-A184.
- Taylor, G. J. (2000) A New Moon for the Twenty-First Century. *Planetary Science Research Discoveries*. <http://www.psrhawaii.edu/Aug00/newMoon.html>

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- Taylor, L. A., Shervais, J. W., Hunter, R. H., Shih, C.-Y., Bansal, B. M., Wooden, J., Nyquist, L. E., and Laul, L. C. (1983) Pre-4.2 AE Mare-Basalt Volcanism in the Lunar Highlands. *Earth and Planetary Science Letters*, v. 66, p. 33-47.
- Terada, K., Anand, M., Sokol, A. K., Bischoff, A., and Sano, Y. (2007) Cryptomare Magmatism 4.35 Billion Years Ago Recorded in Lunar Meteorite Kalahari 009. *Nature*, v. 450, p. 849-853.
- Wiczorek, M. A. and Phillips, R. J. (2000) The "Procellarum KREEP Terrane": Implications for Mare Volcanism and Lunar Evolution. *Journal of Geophysical Research*, v. 105, p. 20,417-20,430.



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2007

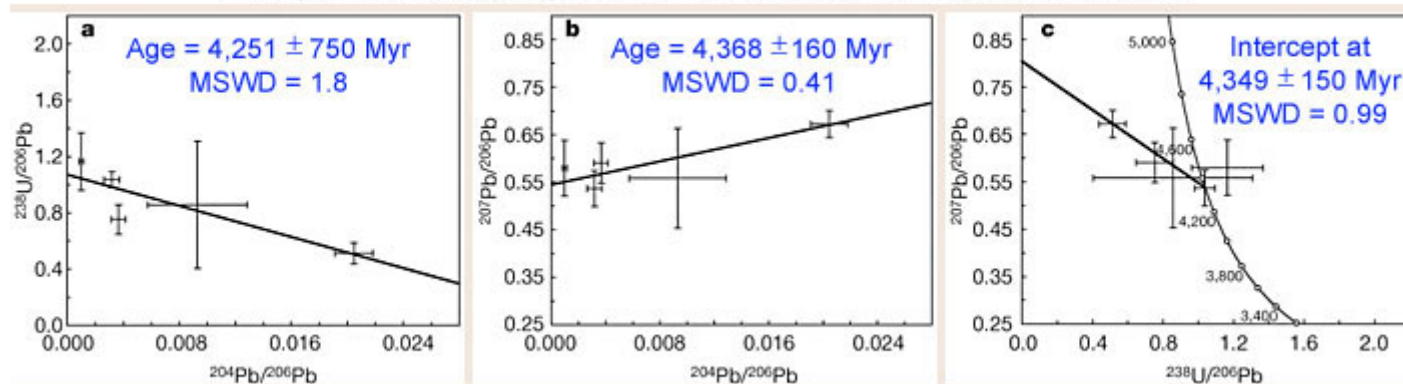
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Additional Notes for "Chips Off an Old Lava Flow"

Reference: Terada, K., Anand, M., Sokol, A. K., Bischoff, A., and Sano, Y. (2007) Cryptomare Magmatism 4.35 Billion Years Ago Recorded in Lunar Meteorite Kalahari 009. *Nature*, v. 450, p. 849-853.

Isotope Ratios in Phosphate Grains in Lunar Meteorite Kalahari 009



(From Terada *et al.*, 2007, *Nature*, v. 450, p. 849-853.)

Graphs of isotope ratios in phosphate minerals measured by ion microprobe in a basalt fragment in Kalahari 009. The relatively well-defined lines (called isochrons) in graphs a and b yield ages for a particular set of isotopes. The diagram on the right (c) shows a projection from three-dimensions, so uses all isotopic data, and gives an age of 4.35 ± 0.15 billion years, which Terada and his colleagues suggest is the best estimate of the age of the lava flows represented in Kalahari 009. The uncertainty in the age is based on the uncertainties in the individual measurements (see error bars) and is at the 95% confidence level. (MSWD is the mean square of weighted deviate, a measure of the scatter in the data.)

The advantages of the three dimensional diagram, figure c, are the following:

1. It is not necessary to know the isotopic composition of initial lead.
2. Both ^{238}U and ^{235}U decay schemes are used at the same time, yielding a smaller justifiable age uncertainty for the U-Pb systematics.
3. In some cases, two kinds of chronological information (formation age and alteration age) are simultaneously obtained. This is very important for lunar rocks, because some rocks might have been affected by secondary events such as impacts. If the U-Pb system were even slightly disturbed, the data will not plot on a straight line in figure c. For Kalahari 009, the data plot along a straight line, indicating that there was no heating event strong enough to affect the U-Pb system. (In many cases, data not plotting on a straight line tells us about both the formation age and the alteration age.)

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December, 2007