Headline Article

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Age Rules

--- Rules for determining the most reliable ages for Moon rocks shed light on what rocks formed when during construction of the ancient lunar highlands crust.

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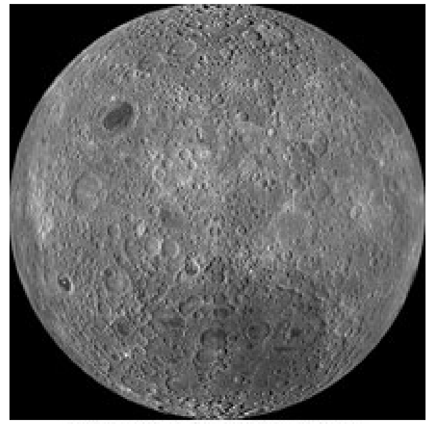


LROC WAC : NASA/GSFC/ASU

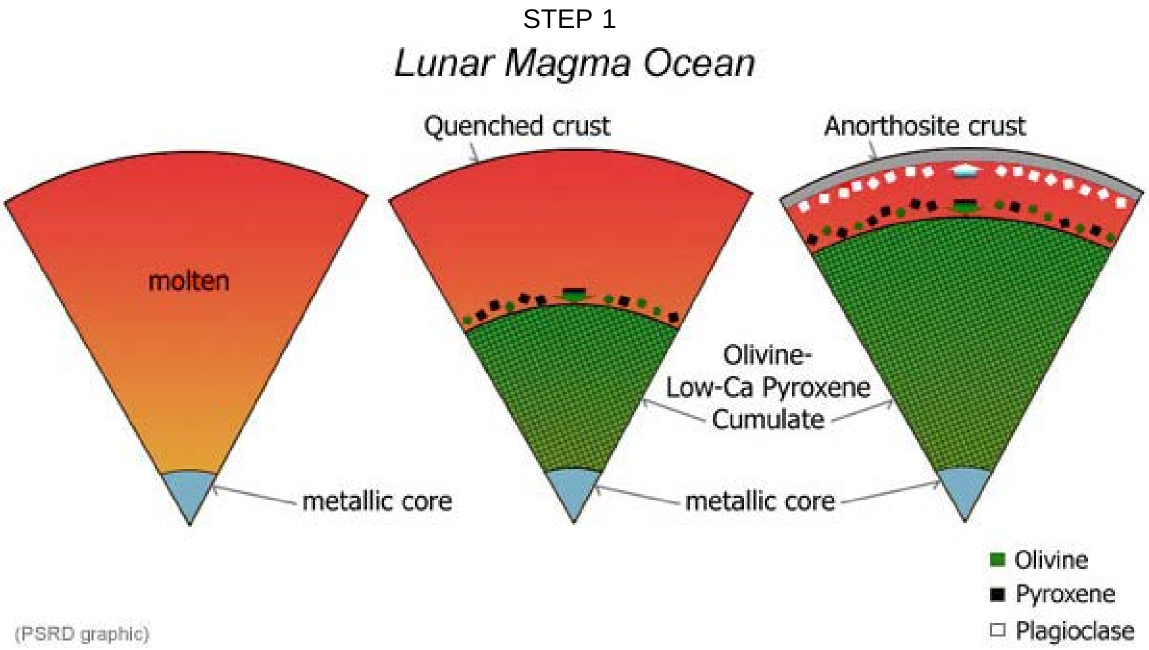
The ages of rocks from the lunar highlands vary widely, even for a single rock sample. This makes it difficult to quantitatively test ideas for early lunar differentiation and formation of the crust. Lars Borg and Amy Gaffney (Lawrence Livermore National Laboratory), and Charles Shearer (University of New Mexico) have devised a set of guidelines to apply to geochronological data that leads to a relative ranking of the reliability of the age determined for a sample. Applying their guidelines to existing data for lunar highland rocks shows an upper limit on rock ages between 4340 and 4370 million years. This is essentially the same as the so-called model ages of the formation of KREEP (a chemical component enriched in potassium, rare earth elements, and phosphorous) and of the formation of the deep source regions that melted to produce mare basalts. The numerous ages close to 4370 million years suggests a complicated and protracted cooling of the primordial lunar magma ocean or a widespread vigorous period of magmatic activity in the Moon.

Reference:

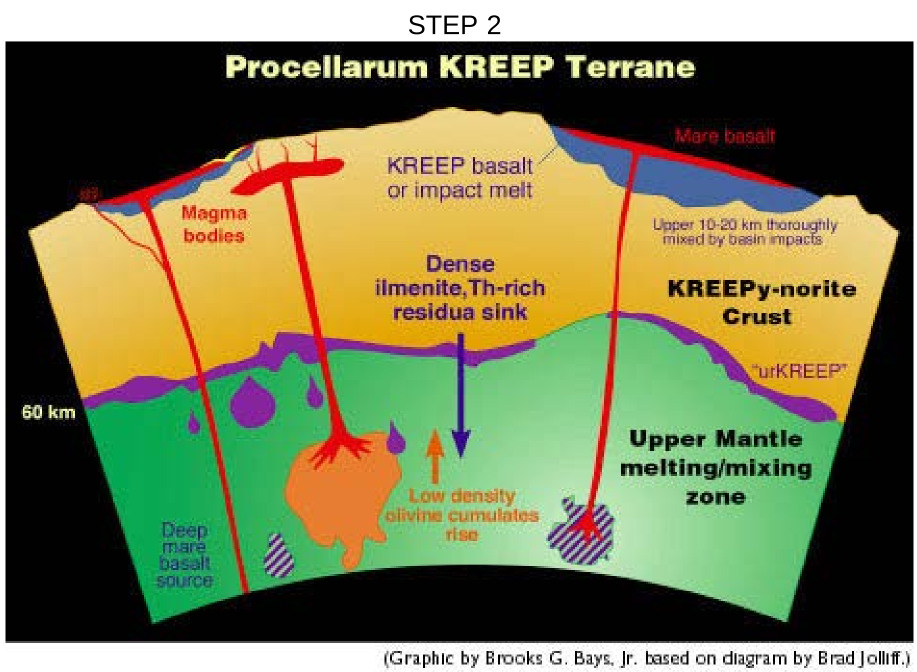
- Borg, L. E., Gaffney, A. M., and Shearer, C. K. (2015) A Review of Lunar Chronology Revealing a Preponderance of 4.34–4.37 Ga Ages, *Meteoritics & Planetary Science,* v. 50, p. 715-732, doi: 10.1111/maps.12373. [**abstract**]
- **PSRDpresents:** Age Rules--**Short Slide Summary** (with accompanying notes).

The Importance of Knowing *What* Happened *When*

Knowing precisely when major rock types formed during construction of the lunar crust builds a quantitative framework for understanding the origin and geochemical evolution of the lunar **highlands**. For example, a cherished idea in lunar science is that the Moon melted when it formed. As this **ocean of magma** crystallized, plagioclase feldspar floated to the top, accumulating in large masses of a rock type called **anorthosite** (also abbreviated FAN, for ferroan anorthosite). The anorthosite primary crust was then invaded by magmas formed by partial melting of the lunar mantle, which formed substantially by dense minerals sinking in the magma ocean. The last 1-2% of the magma ocean formed a layer of residual magma nicknamed "urKREEP," which was enriched in all the elements that did not readily go into the major sinking or floating minerals. (**KREEP** denotes that this chemical component is enriched in potassium (K), rare earth elements (REE), and phosphorus (P); a lot of other elements are also enriched in KREEP, such as thorium, uranium, and zirconium.) Determining the time when urKREEP formed would tell us when the magma ocean had effectively solidified.



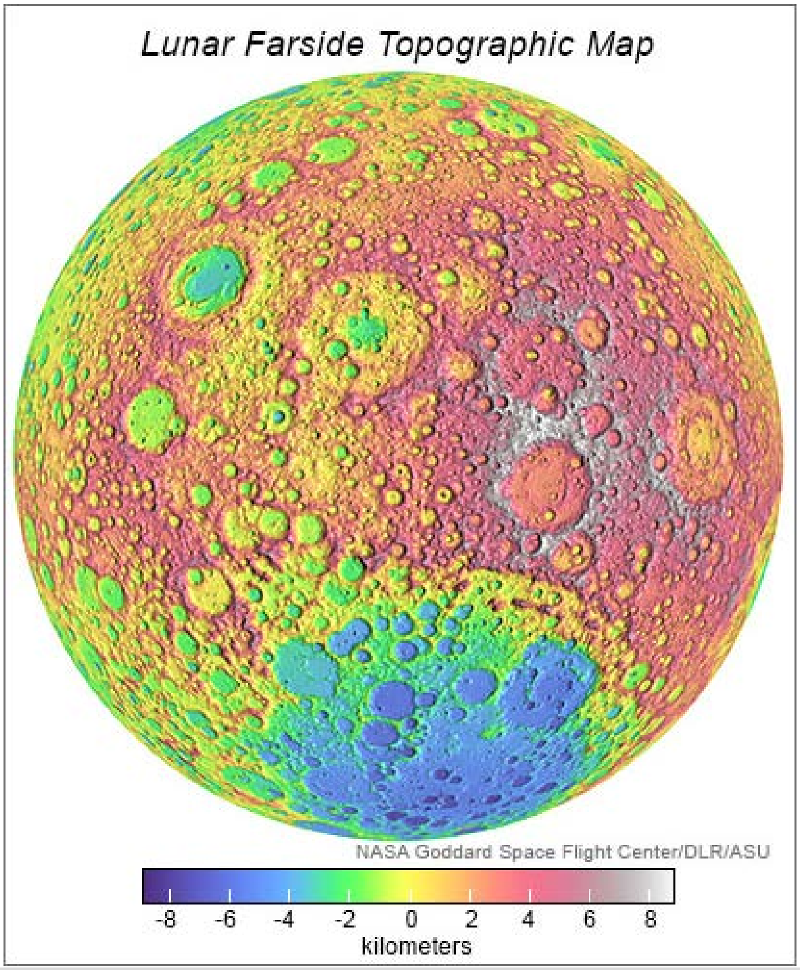
[Top] The central idea in lunar science is that the Moon melted substantially when it formed, creating a deep ocean of magma. As it crystallized, minerals denser than the magma sank while minerals less dense than the magma floated. The lighter minerals (predominately plagioclase feldspar) formed the primary crust of the Moon. [Below] After formation of the feldspar-rich crust, the sunken dense minerals partially melted and formed the magnesian suite of rocks now found as intrusions in the plagioclase-rich crust and the basalt lava flows that make up the maria. This satisfying picture can be rigorously tested by determining reliable ages of rocks from the lunar highlands.



It's a good story that has provided a framework for understanding the formation of the lunar crust. It can even be tested by dating the right rocks. If anorthosites make up the primary crust, they ought to be the oldest rocks on the Moon. The samples associated with KREEP might date the time that urKREEP solidified (or at least stopped exchanging **isotopes** with its surroundings), hence date the time when the magma ocean was completely solid. The group of rocks in the highlands called the magnesian suite ought to be younger than the anorthosites and younger than or the same age as urKREEP. Unfortunately, ages of lunar samples obtained over the past decades scatter annoyingly and do not allow a straightforward chronological test of the sequence of crust formation. In fact, the data suggest that the anorthosites and magnesian rocks overlap in age, but many of the ages are not determined well—a fault with the rocks, not the isotopic analyses, although geochronological techniques have improved over the years. We need a way to assess the probability that a rock's apparent age is correct. This is what Lars Borg and his colleagues set out to do. In fact, the work is based on Borg's perspective of spending 20 years trying to determine the solidification age of the Moon by dating lunar samples.

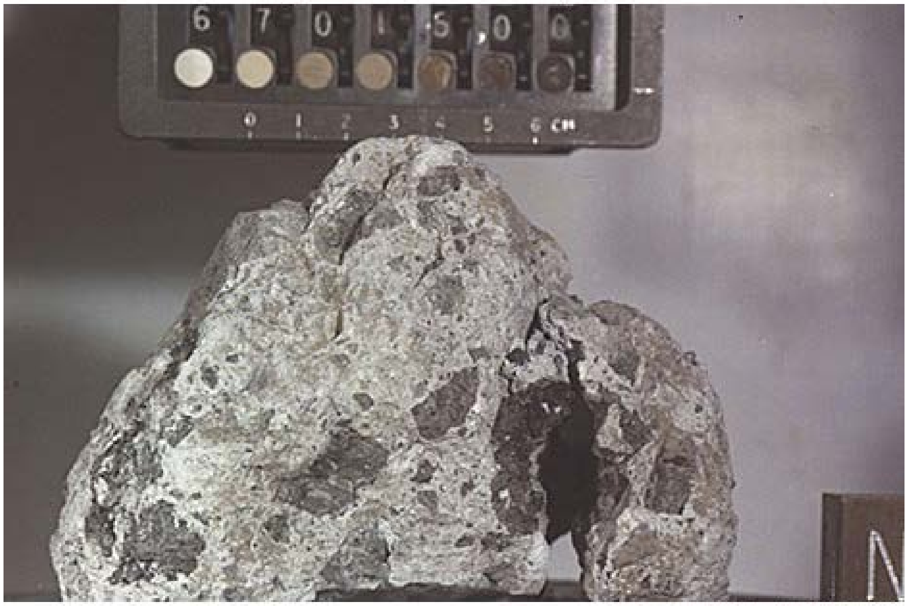
The Difficulty of Determining Ages of Rocks from the Pummeled Lunar Crust

The upper 10–20 kilometers of the lunar highlands is a mixed-up pile of rocky rubble formed when the Moon was bombarded early in its history by countless planetesimals. High-speed impacts created craters from kilometers to thousands of kilometers across, mixing, melting, and generally damaging the igneous rocks that compose the ancient lunar crust. Not only did this smashing epoch decorate the Moon with numerous circular structures, highly accurate measurements of lunar gravity by NASA's **GRAIL** mission show that the crust is much more porous than are the original igneous rocks composing it.



Color-coded topographic map of the farside of the Moon, obtained by millions of pings by a laser in the Lunar Observer Laser Altimeter (LOLA) on NASA's Lunar Reconnaissance Orbiter (LRO). Essentially all the variation in elevation is associated with impact craters. This bombardment of the Moon early in its history damaged igneous rocks, making it tricky, but not impossible, to extract precise ages from them.

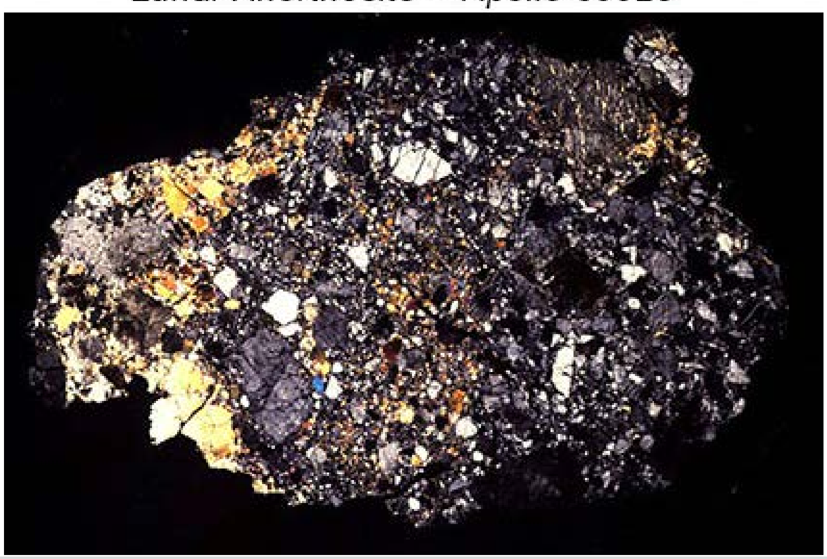
Lunar Impact Breccia -- Apollo 67015



NASA photo S72-37216

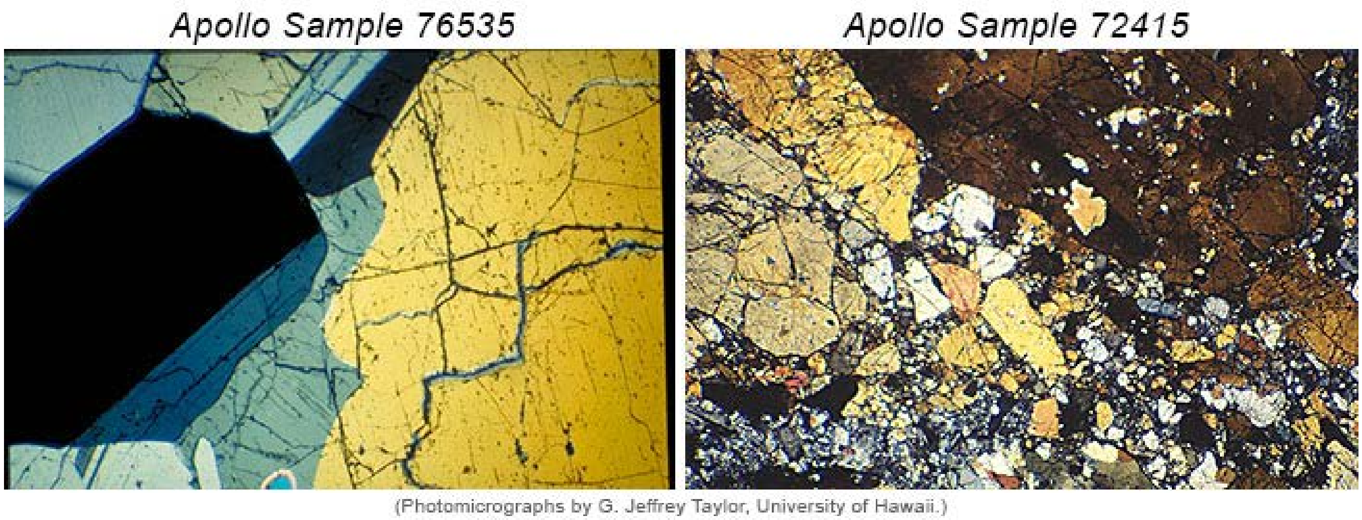
Apollo 16 astronauts collected Rock 67015, a typical impact breccia, from the lunar highlands. It is composed of rock and mineral fragments. Dark rock fragments are themselves impact melt breccias..

Lunar Anorthosite -- Apollo 60025



Photomicrograph taken in polarized light of a thin section of anorthosite 60025, collected on the Apollo 16 mission. The rock section is about 2 centimeters (0.8 inches) across. This region of the rock is especially rich in olivine and pyroxene compared to plagioclase. The rock has a distinctively fragmental appearance, not an igneous texture, although in places in other pieces of 60025 a good igneous texture is seen easily. The rock has been affected by one or more impacts, but in spite of its fragmentation it is possible to extract a reliable age from it.

Metamorphism affects rock ages. In fact, geochronologists can determine the time when the metamorphism took place if the temperature was hot enough for long enough to reset chronometers. On the Moon, however, the main metamorphic process is impact, which damages mineral crystals as the shock wave passes through the target rock. The shock also heats the rock, sometimes imparting a transient heat pulse, other times surrounding a chunk of rock in impact melt that might cool slowly, but not necessarily slow enough to reset the age. It just causes an unreliable age to be extracted from an isochron plot (see below) because the parent or daughter isotopes of a radioactive pair move around inside some mineral crystals in an attempt to equilibrate with other minerals. For example, rock 72415, which is composed of 93% olivine with smaller amounts of pyroxene and plagioclase, produced an age of 4.55 billion years using the rubidium-strontium system, about the age of the Solar System. This is simply too old to be correct. The shock perturbed the age of this rock.



[Left] Photomicrograph 2 millimeters across taken in polarized light of lunar rock 76535, which is composed of olivine and plagioclase with a little bit of pyroxene. The rock has a few cracks in it, but is generally unscathed by high-pressure shock associated with an impact event. [Right] Photomicrograph 3 millimeters across of olivine-rich lunar rock 72415. The sample is disturbingly damaged by shock, with mineral crystals disrupted and rotated, making it unlikely to yield a reliable age.

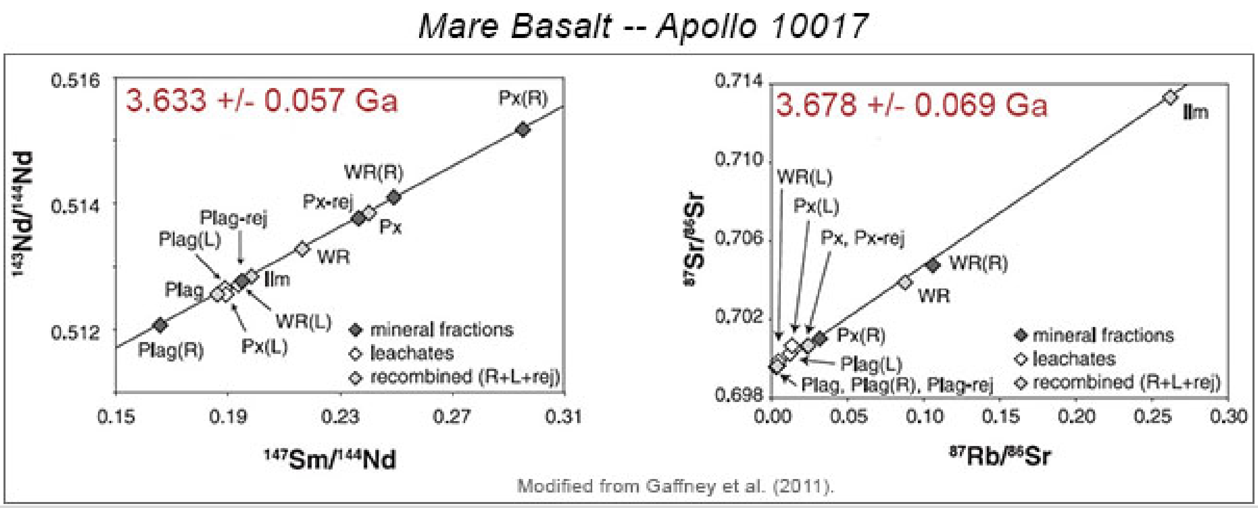
Rules for Picking the Most Reliable Ages

Some of us do not particularly like following rules, such as all those people who text while driving. *There ought to be a law.* We could use some rules for determining how likely isotopic data are to give us a reliable age for a moon rock. Lars Borg, Amy Gaffney, and Chip Shearer have developed such a set of rules. (They call them "criteria." Others might say "guidelines." I like "rules" because I went to a Catholic elementary school.)

Rule #1: Use multiple clocks

The main workhorses for determining rock ages are Sm-Nd (samarium-neodymium), Rb-Sr (rubidium-strontium), and Pb-Pb (lead-lead, which also involves the decay of two uranium isotopes and thorium). Each system is affected by heating differently. In general, Sm-Nd is more resistant to alteration than are the other two. Given that, one might think that we just need to use Sm-Nd. However, even that system is affected by heating, so the most reliable age is one that gives the same age by Rb-Sr or Pb-Pb as it does by Sm-Nd, and preferably the same age by all three methods. Thus, Lars Borg and colleagues suggest that reliable ages require getting the same age (within analytical uncertainties) by at least two methods.

A good example of a reliable age is shown in the diagram below. In each plot, the x-axis is the ratio of a radioactive to a stable (not radioactive) isotope of the element to which the radioactive isotope decays. The y-axis is the ratio of the decay product to the same stable isotope as in the denominator of the ratio on the x-axis. In a brand-new rock, different minerals contain different amounts of Sm and Nd, so plot along a horizontal line. (The data points represent separated minerals of one sort or another. As time passes, the line becomes steeper, and its slope, through a bit of math, gives the age of the rock. The Rb-Sr system behaves in the same way. The data points define the line (called an isochron). The data shown below is for a sample of lunar mare basalt, which has not been damaged or heated by impact at all. Both Sm-Nd and Rb-Sr give the same age within the analytical uncertainties.



Data reported in a 2011 paper by Amy Gaffney for a lunar mare basalt that shows no signs of heating after it erupted onto the lunar surface and then crystallized in a lava flow, collected as Apollo sample 10017. For both Sm-Nd and Rb-Sr, the subsamples all plot along a well-defined line. Some technical details: The data points represent individual measurements of the isotopes on minerals separated magnetically and by painstakingly picking them by hand while looking through a microscope, and chemical fractions created by leaching the sample with acids. WR stands for a sample of the entire rock (Whole Rock), plag = plagioclase, px = pyroxene, Ilm = ilmenite, R = the residue left behind by the chemical leaching treatment, and L = the acid solution that contains chemical leached from the sample.

Rule #2: Well-defined lines on isochron plots

A good rule is that the less scatter there is on an isotope plot, the better. Geochronologists want all their mineral separates to fall on well-defined lines. Statistical measures are used to quantify the quality of a fit to a line. Disturbances to the system, such as a rock being excavated from an original position kilometers below the surface, cause the data to deviate from nice lines. The uncertainty in the ages is related to the deviation of the data points to a line. Borg and coworkers suggest that reliable ages of rocks around 4 billion years old have uncertainties of less than 85 million years (0.085 billion years).

Rule #3: Chronometer stands up to metamorphism

Some of the isotopic systems used to date rocks are particularly susceptible to thermal events. For example, heating events fractionate uranium and lead from each other and even can lead to loss of lead from a rock, thereby compromising the age information in a measurement. On the other hand, Sm-Nd is the most resistant to changes. So, although two or more chronometers are preferred (rule #1), sometimes geochronologists need to use the one system that is most resistant to thermally-induced changes, Sm-Nd. Nevertheless, a well-defined Sm-Nd age is deemed more reliable if it is accompanied by a somewhat scattered isochron plot for Rb-Sr and other isotope systems.

Rule #4: Isotopic compositions are consistent with element concentrations and inferred genesis of a rock

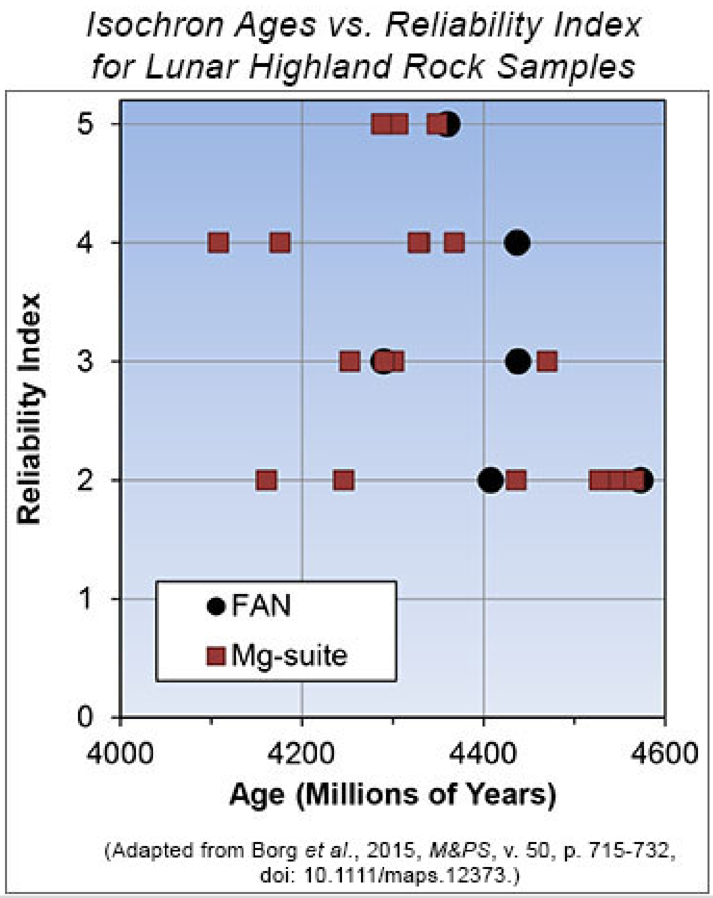
This rule puts isotopic data into a broader geochemical context. For example, one of the important numbers derived from an isochron plot is the initial ratio of the decay product to a stable isotope of the same element, such as $^{143}Nd/^{144}Nd$ or $^{87}Sr/^{86}Sr$. This is given by the y-axis intercept where the x-axis value goes to zero. The initial ratio allows inferences to be made about the overall geochemistry of a rock. As an example, Borg points out that the initial Nd ratio for anorthosites and Mg-suite rocks indicate that these rocks must derive from a source rock that has lower concentrations of rare earth elements with low atomic weights (lanthanum, cerium, neodymium) than those with heavy atomic weights (ytterbium, lutetium). In contrast, the abundances of rare earth elements in minerals (determined by secondary ion mass spectrometry) indicate clearly that the rocks formed in magmas that the opposite rare earth characteristics—high in the light rare earths and low in the heavy ones. Inconsistencies like these might indicate contamination of a sample or analytical problems.

Rule #5: Element concentrations in mineral separates match concentrations measured by *in situ* techniques

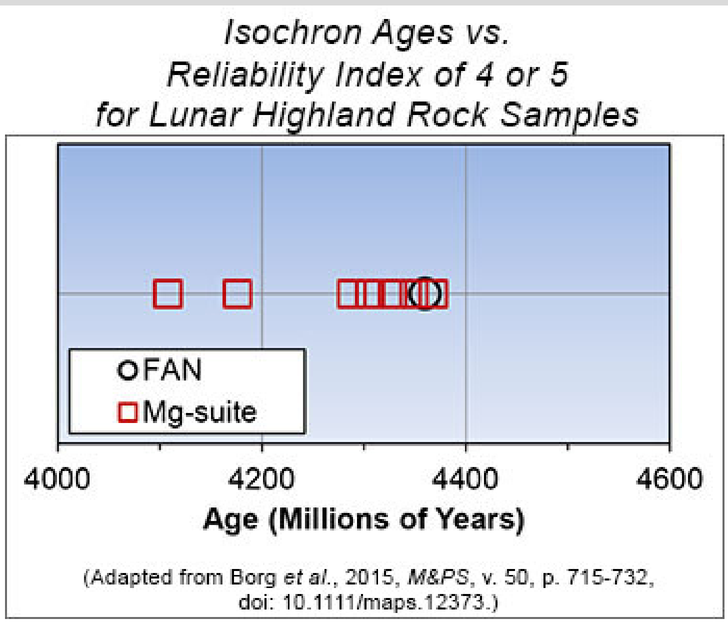
In principle, the concentrations of the elements involve in age dating (e.g., Rb and Sr, Sm and Nd) should be the same in minerals separated from a crushed sample as they are in mineral grains measured directly by microbeam techniques. This is especially important for the iron-magnesium minerals olivine, low-calcium pyroxene, and high-calcium pyroxene because they have similar magnetic properties, making it difficult to concentrate them magnetically or by density. In fact, they are not that easy to distinguish in a microscope. In contrast, plagioclase can be separated relatively easily. Thus, to test for purity of mineral separates, Borg and colleagues suggest that the concentrations of Sm and Nd measured as part of the isotopic dating procedures should match the average concentrations measured by *in situ* techniques in highland rocks to within a factor of two. A match between *in situ* measurements and compositions of mineral separates helps to rule out cases where contaminants due to shock metamorphism lurk in the sample, such as small quantities of impact melt.

Reliable Lunar Rock Ages

The ages of igneous rocks from the lunar highlands are shown in the diagram below, along with their reliability index. The index is simply how many of the five rules are satisfied for each sample. It gives an estimate of the reliability of a specific age for a rock. Some samples are shown more than once because they have been analyzed in more than one lab taking more than one approach. The important point is that the lower the reliability index, the greater the percentage of samples that have apparent ages greater than 4400 million years. In many cases, such as anorthosite 60025 and magnesian-suite troctolite 76535, older ages with a low reliability index have been replaced by younger ages with higher reliability index. This is shown more clearly on the smaller diagram that shows only ages with reliability indices of 4 or 5. The most reliable ages seem to slam up against a chronological barrier around 4370 million years. Younger ages exist, showing that magmas were intruding the crust after 4370 million years, but existing data indicate a maximum age of less than 4400 million years.

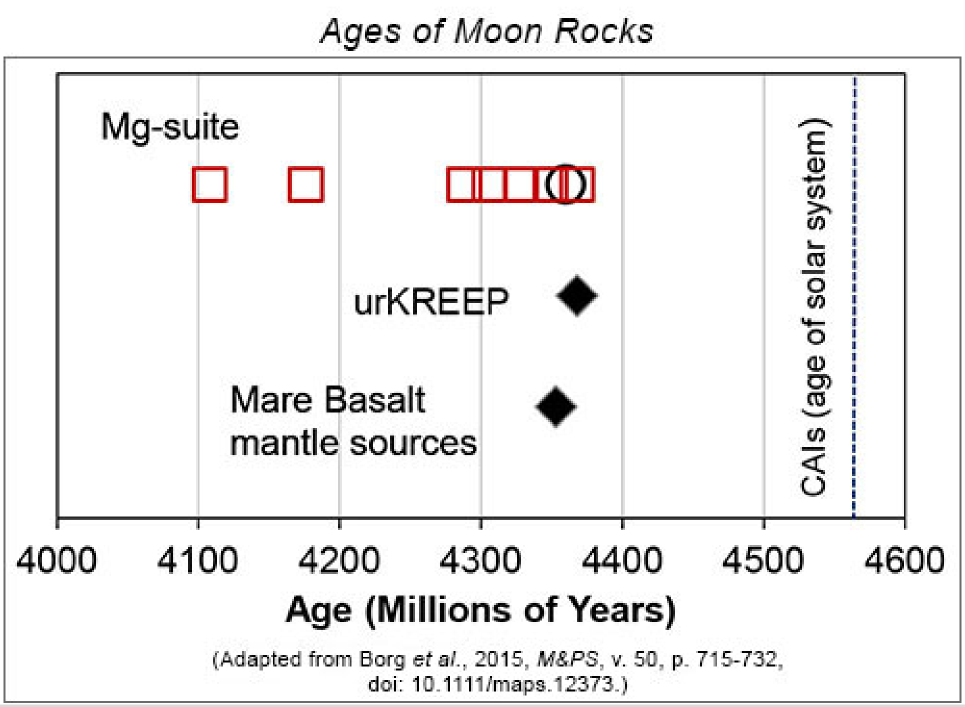


[Top] Ages of igneous rocks from the lunar highlands as a function of the reliability of their age determinations. The reliability index is simply the number of the five rules satisfied by a given age determination. The data plotted include duplicates of the same rock. [Below] The smaller diagram shows the data for rocks with reliability indices of 4 or 5 (i.e., the most reliable), removing duplicates for the same rock. The ages spread out, but appear to reach a maximum age around 4370 million years.



Having confidence in which rocks have not suffered the damaging effects of impact and metamorphism, they can be used to date solidification of the magma ocean. Lars Borg and colleagues did this, using rocks with reliability indices of 4 or 5. They determined Lu-Hf and Sm-Nd "model ages" of the magnesian-suite rocks. Such ages require some assumptions, the chief one in this case being that the initial Nd and Lu isotopic compositions started out with the ratio found in chondritic meteorites. By plotting the age versus measured initial Nd or Hf isotopic composition, they show that the data fall on well-defined lines that intercept the chondrite line at 4389 ± 45 million years (Nd) and 4353 ± 37 million years. The average of these two ages when weighted by the magnitudes of the uncertainty is 4368 ± 29 million years. Borg and coworkers argue that this age represents the formation age of the last dregs of the magma ocean, often called "urKREEP."

Similar model ages have been determined for groups of basalts from the lunar maria. This approach uses whole rock isotopic data instead of individual minerals and assumes that the isotopic compositions of the regions of the lunar interior where mare basalt magmas were produced reflect fractionation of Nd and Sm from a common primary magma (usually taken to be the magma ocean). The weighted averages of all such determinations is 4353 ± 25 million years. Notice that these model ages are similar to the upper range of ages determined from individual samples with high reliability indices.



Reliable ages for lunar highland igneous rocks compared with the model ages of urKREEP (representing the last stages of early lunar differentiation) and the places in the lunar interior that melted to make the mare basalts. The age of calcium-aluminum-rich inclusions (CAIs), thought to be the oldest materials to form in the Solar System, is shown for comparison. The lunar highland ages indicate a significant event in the 4340 to 4370 million year range.

Repercussions for Our Cherished Story of Lunar Differentiation

The Borg-certified ages indicate an upper limit at 4340 to 4370 million years. Borg and colleagues point out that reliable ages for the mineral zircon separated from lunar highland breccias also slam up against this chronological ceiling. Even more intriguing, John Valley (University of Wisconsin) and colleagues report that the oldest zircon found on Earth is 4374 ± 6 million years, in this same range. What does this narrow upper limit mean for the cherished idea of a magma ocean followed by magnesian-suite rocks? Does it imply that the magma ocean hypothesis needs to be tossed aside?

One explanation is that the ages record the time when magma ocean products cooled enough for the chronometers to begin counting. The products include the FANs, urKREEP, and the mare basalt mantle source regions. If correct, then the magma ocean finished crystallizing between 4340 and 4370 million years ago. The implications are either the Moon-forming giant impact occured later than we think or the Moon took one or two hundred million years to accrete after the impact or that once it formed the Moon stayed hot for a long period of time. Prolonged heating of the Moon could have been caused by gravitational interactions with the early Earth (tidal heating). This process was investigated in 2011 by Jennifer Meyer, Linda Elkins-Tanton, and Jack Wisdom (Massachusetts Institute of Technology). Dissipation of tidal forces can keep the anorthositic crust hot enough to continuously reset chronometers (in fact, even partially melt the crust) for up to 200 million years, perhaps explaining the lack of ages before 4370 million years.

Borg and co-authors discuss an alternative that derives in a straightforward way from the age data. The activity recorded in the 4340–4370 million year time frame (and even somewhat younger) may record a period of widespread and possibly voluminous magmatic activity in the Moon. In this hypothesis, both the ferroan anorthosites and the Mg-suite rocks formed at the same time. Thus, the ferroan anorthosites would have formed in intrusions. A complication is that the highlands crust is dominated by plagioclase feldspar, hence by anorthosite, so the anorthosite portions of the hypothetical intrusions would need to rise buoyantly and concentrate in the upper regions of the crust. This is not impossible. The rarity of rocks consisting of more than 95% plagioclase is consistent with the idea. Another complication is that it is not clear how the idea of widespread magmatic activity would lead to the mare basalt source regions and formation of urKREEP having the same age as the crustal rocks, except for coincidence, which is not particularly satisfying.

The cleaning up of age uncertainties will undoubtedly lead to improved understanding of the formation of the lunar crust and the nature of early melting inside the Moon. It seems certain that differentiation of the Moon was more complicated than the esteemed magma ocean model lets on.

Additional Resources

Links open in a new window.

- Borg, L. E., Gaffney, A. M., and Shearer, C. K. (2015) A Review of Lunar Chronology Revealing a Preponderance of 4.34–4.37 Ga Ages, *Meteoritics & Planetary Science,* v. 50, p. 715-732, doi: 10.1111/maps.12373. [**abstract**]

- Gaffney A. M. and Borg L. E. (2014) A Young Solidification Age for the Lunar Magma Ocean, *Geochimica et Cosmochimica Acta,* v. 140, p. 227-240, doi: 10.1016/j.gca.2014.05.028. [**abstract**]

- Gaffney A. M., Borg L. E., Asmerom Y., Shearer C. K., and Burger P. V. (2011) Disturbance of Isotope Systematics During Experimental Shock and Thermal Metamorphism of a Lunar Basalt with Implications for Martian Meteorite Chronology, *Meteoritics & Planetary Science,* v. 46, p. 35-52, doi: 10.1111/j.1945-5100.2010.01137.x [**abstract**]

- Meyer, J., Elkins-Tanton, L., and Wisdom, J. (2011) Coupled Thermal-Orbital Evolution of the Early Moon. *Icarus,* v. 208, p. 1-10, doi:10.1016/j.icarus.2010.01.029. [**abstract**]

- Valley, J. and 10 others (2014) Hadean Age for a Post-Magma-Ocean Zircon Confirmed by Atom-Probe Tomography, *Nature Geoscience,* v. 7, p. 219-223, doi: 10.1038/ngeo2075. [**abstract**]