Isotopic Evidence for a Dynamic Lunar Mantle

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We compiled the most comprehensive set of radioisotope data on lunar basalts to date. Rb/Sr isotope data demonstrate that the structure of the lunar interior was disrupted by the catastrophic South Pole-Aitken Basin impact. Our results suggest that traditional model of a stratified lunar interior may require revision. Instead, the Moon's mantle may be similar to Earth's, with multiple distinct incompatible element-enriched reservoirs.

Background

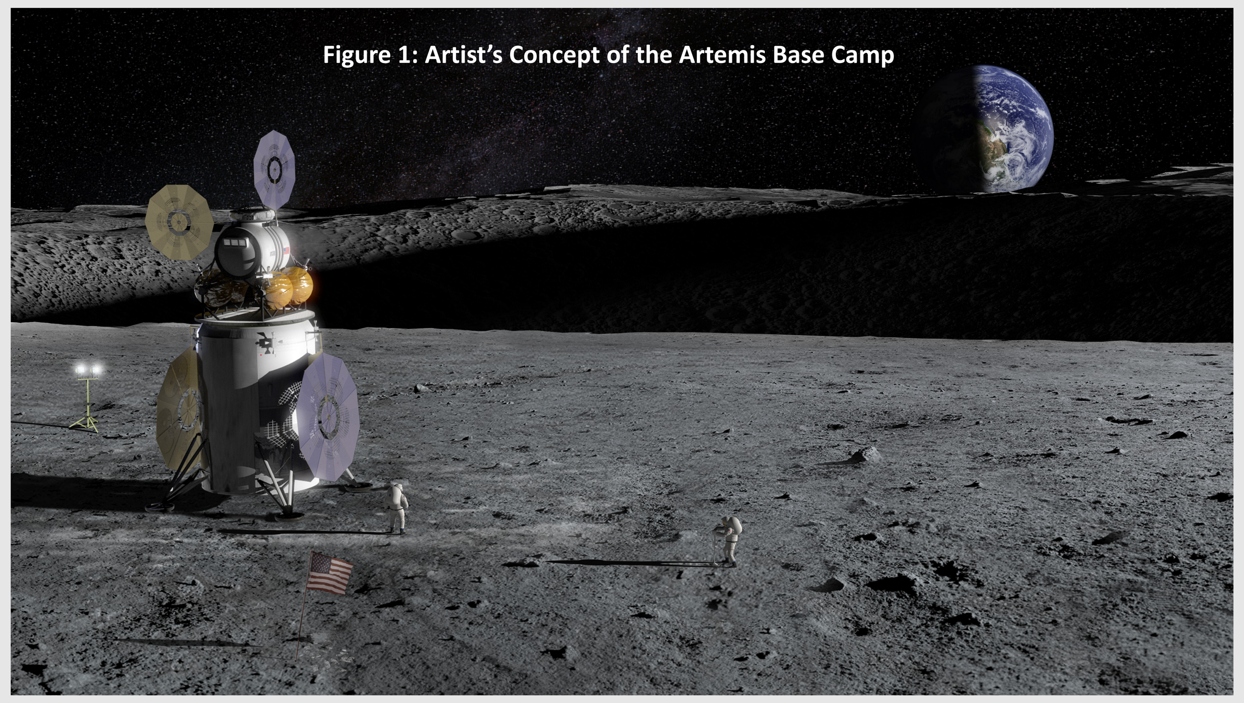

Figure 1: Artist's Concept of the Artemis Base Camp

50 years after the last Apollo lunar landing, NASA is preparing to return humans to the Moon through the Artemis program (**Figure 1**). Lunar science will be an integral component of the Artemis missions as NASA seeks to build upon the discoveries of the Apollo era. These voyages of exploration will rely upon a comprehensive understanding of the Moon's geology and internal structure. The success of the Artemis program is therefore intrinsically linked with our understanding of the existing lunar sample suite.

Along with impact cratering, volcanism is one of the two processes which have dominated the Moon's geologic history. The Apollo astronauts collected two classes of basalt. Depleted mare basalts are derived from mafic cumulates in the lunar mantle, while "KREEP" basalts are sourced from a reservoir enriched in incompatible trace elements [1]. Both of these reservoirs are identified by **Figure 6**. Until recently, the Moon's youngest igneous deposits were thought to be KREEP basalts, as their source region is enriched in radioactive isotope of K, U, and Th [2]. However, the recent Chang'e-5 mission discovered that these young magmas came from a depleted mantle reservoir, upending our knowledge of the lunar interior [3].

Methods

We used the Rb/Sr and Sm/Nd isotope systems to study lunar magmagenesis and to probe the Moon's internal structure. Radioisotopes were key tools for this investigation because they can be used to determine the elemental properties of a basalt's source region in addition to those of the rock itself. We utilized multiple calculations in this study; the equations for the Rb/Sr system are listed below. Analogous equations were used for the Sm/Nd system. Lanthanum data were extracted from NASA's MoonDB database.

Given Quantities:

$\left(\frac{^{87}Sr}{^{86}Sr}\right)_{now}$ and $\left(\frac{^{87}Rb}{^{86}Sr}\right)_{now}$: Determined analytically

$\left(\frac{^{87}Sr}{^{86}Sr}\right)_{Moon}$ = 0.69903 (Nyquist et al., 1973) [4]

$\lambda =$ Decay constant $= 1.393\times10^{-11}\ yr^{-1}$ (Nebel et al., 2011) [5]

Absolute ages of basalt samples given by U/Pb, Sm/Nd, or Rb/Sr isotope dating

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_{now} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_{initial} + \left(\frac{^{87}Rb}{^{86}Sr}\right)_{now} \times (e^{\lambda t} - 1)$$

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_{initial} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_{Moon} + \left(\frac{^{87}Rb}{^{86}Sr}\right)_{initial} \times (e^{\lambda t} - 1)$$

$$\left(\frac{^{87}Rb}{^{86}Sr}\right)_{source\ region} = \left(\frac{\left(\frac{^{87}Sr}{^{86}Sr}\right)_{initial} - \left(\frac{^{87}Sr}{^{86}Sr}\right)_{Moon}}{t_{Moon} - t}\right) \times \frac{1}{\lambda}$$

$$\left(\frac{Rb}{Sr}\right)_{source\ region} = \left(\frac{^{87}Rb}{^{86}Sr}\right)_{source\ region} \times \left(\frac{0.0986}{0.2783}\right)$$

Results

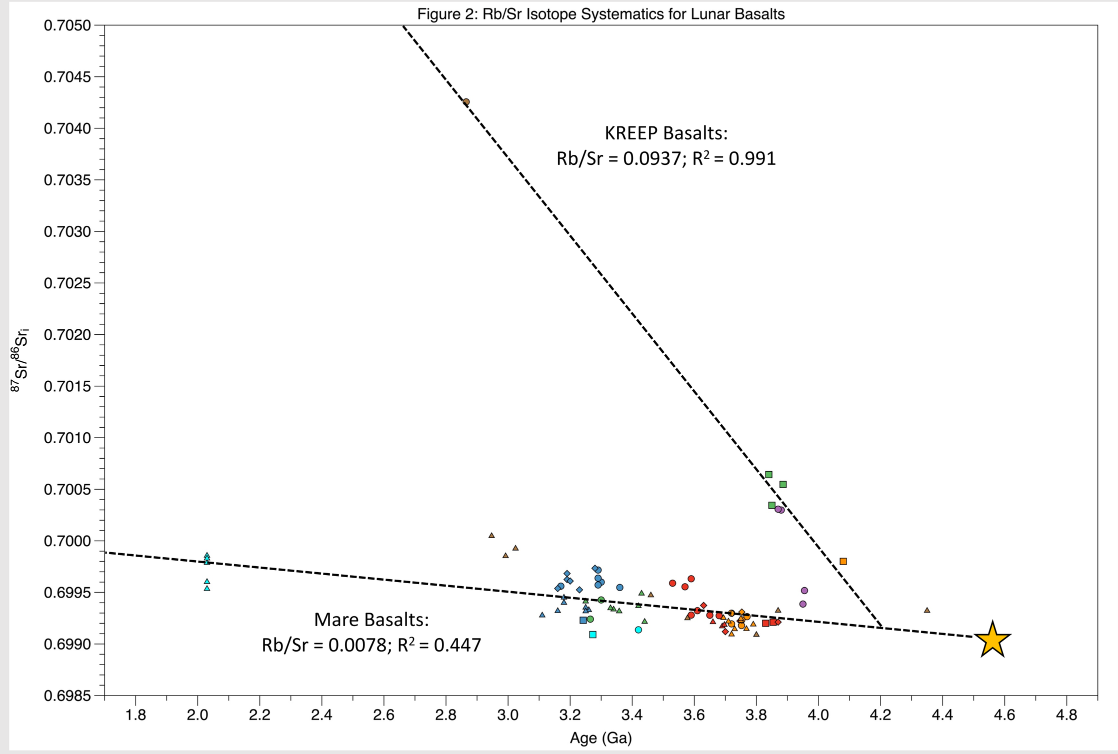

Figure 2: Rb/Sr Isotope Systematics for Lunar Basalts

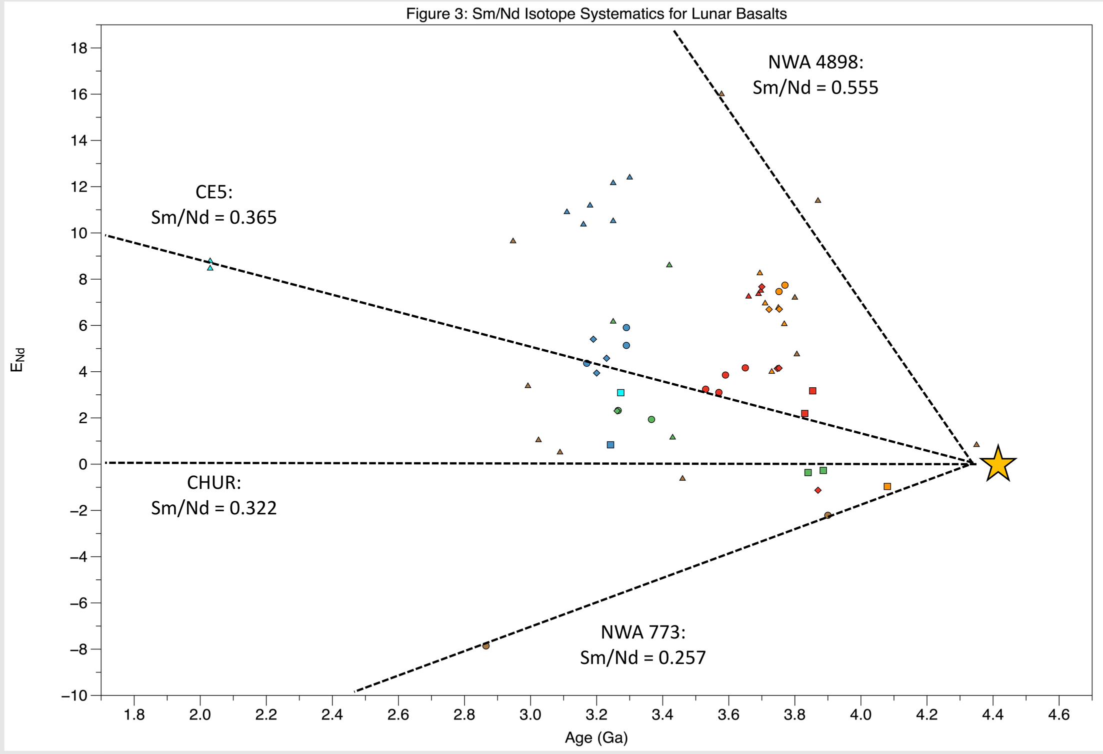

Figure 3: Sm/Nd Isotope Systematics for Lunar Basalts

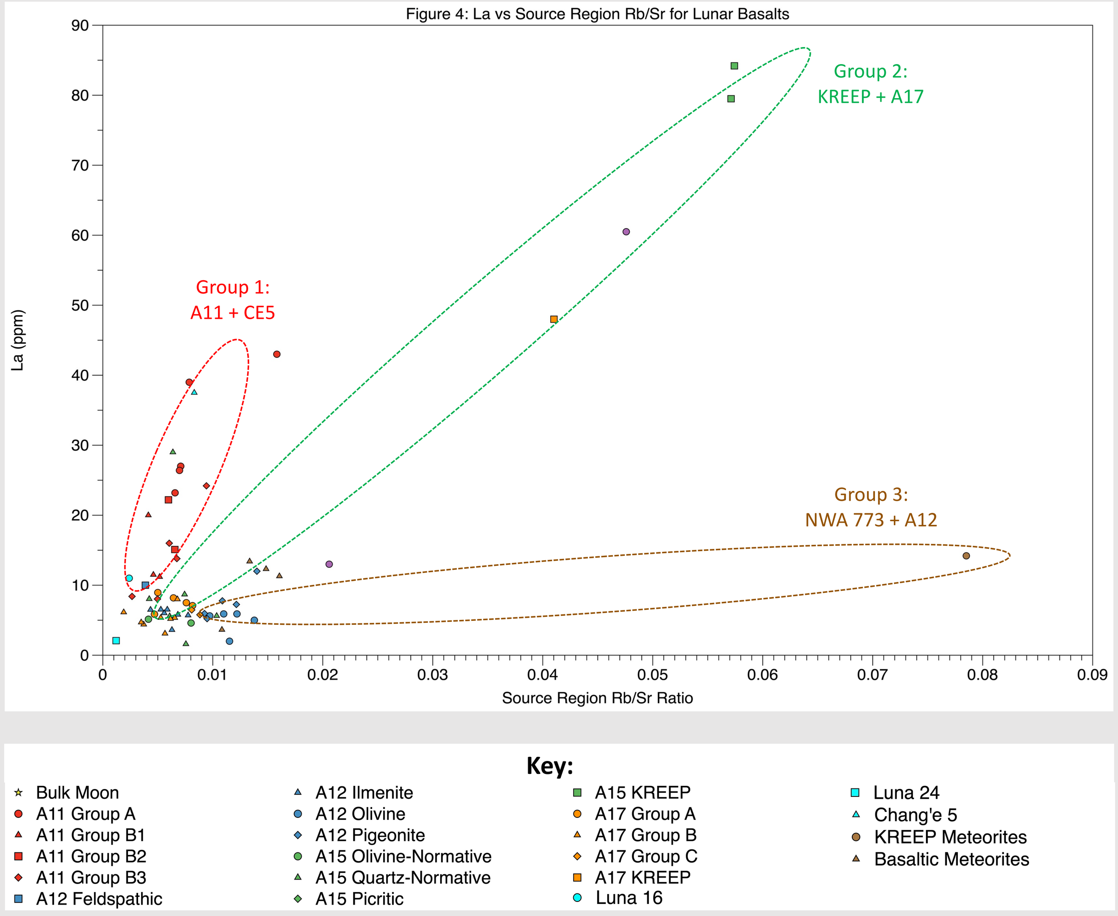

Figure 4: La vs Source Region Rb/Sr for Lunar Basalts

Our normalized and analyzed data can be visually represented by three figures. To the best of our knowledge, this dataset is the most comprehensive collection of publicly-available, peer-reviewed lunar Rb/Sr and Sm/Nd measurements compiled to date. The Rb/Sr system is described by **Figure 2**, which is a graph of the initial strontium isotope compositions of lunar basalts plotted against their ages. The composition of each sample can be connected to the initial strontium isotope ratio of the Moon (denoted by a gold star) by a line called an isochron. The slope of a basalt's isochron is directly proportional to the Rb/Sr ratio of its source region. Previous studies have assumed that the source regions for mare basalts and KREEP basalts both differentiated when the Moon formed [4]. We found that the KREEP basalt data are best modelled by a reservoir which diverged from the composition of the bulk Moon 4.2 billion years ago.

The Sm/Nd data can be represented by a similar diagram (**Figure 3**). ε_{Nd} is a parameter which describes a sample's $^{143}Nd/^{144}Nd$ ratio relative to that of a chondritic meteorite. The Sm/Nd data show much more scatter than the Rb/Sr data due to the similarities between the two elements' atomic radii and valence states. However, clusters of samples from several Apollo landing sites display significant variability in ε_{Nd}.

Rare earth elements and Rb are both thought to be enriched in a single KREEP reservoir. We tested this theory by plotting the lanthanum concentrations of lunar samples against the Rb/Sr ratios of their source regions in **Figure 4**. If occurrences of Rb and La are correlated, we would expect all lunar basalts to plot along a single linear trendline. Instead, they seem to fall into three different trends for incompatible element enrichment. This observation could be explained by fractional crystallization. However, this process struggles to account for several geochemical properties of the lunar samples, including the large negative europium anomalies of the Apollo 11 and Chang'e 5 samples in Group 1.

References

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Discussion

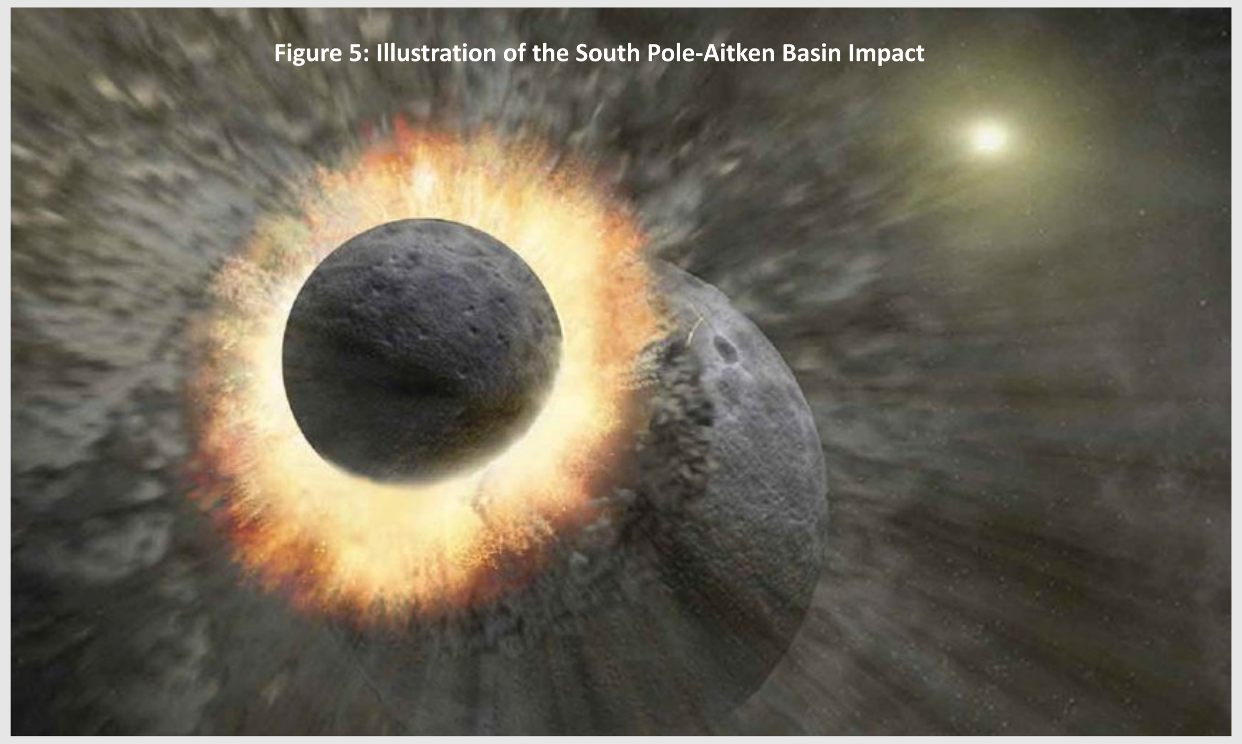
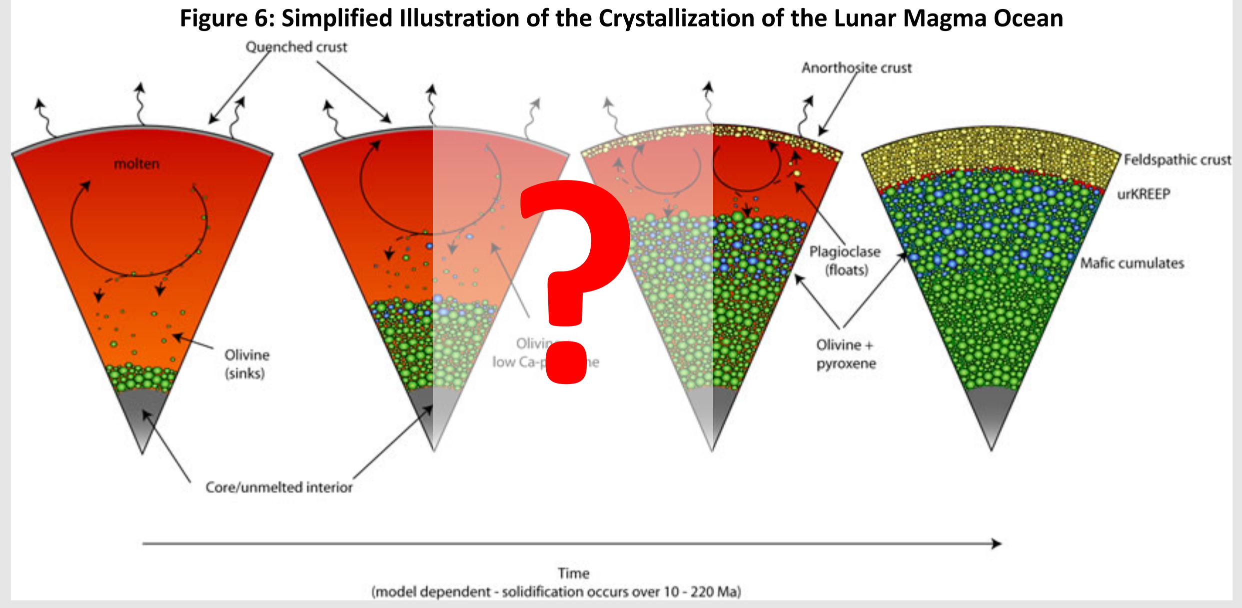


Figure 5: Illustration of the South Pole-Aitken Basin Impact

The South Pole-Aitken Basin (SPA) impact event was the largest impact in the history of the Moon. An illustration of the impact is seen in **Figure 5**. Our data imply that this catastrophic collision between the Moon and a 315-km asteroid restructured the contents of the lunar interior. Recent simulations suggest that the SPA impact triggered gravitationally-driven mantle overturn [6]. During this process, dense, KREEP-rich materials would have sunk to the Moon's core-mantle boundary.

Our Rb/Sr data provide experimental support for this hypothesis, which previously depended entirely upon computer simulations. Our research suggests that the KREEP basalt source region differentiated 4.2 billion years ago (Ga). This is strikingly similar to the age of the SPA impact itself. Two groups of lunar scientists have used independent proxies to estimate that the impact event took place around 4.25 Ga [7, 8]. Therefore, Rb/Sr isotopic data appear to support both the global mantle overturn hypothesis and the most recent age estimates for the SPA basin, which will be the site of NASA's Artemis Base Camp.

Figure 6: Simplified Illustration of the Crystallization of the Lunar Magma Ocean



The Lunar Magma Ocean (LMO) hypothesis has been one of the central tenants of lunar science for over four decades [9]. This model states that the lunar mantle was initially molten, and that a sequence of mafic cumulates, plagioclase crust, and incompatible element-enriched KREEP materials subsequently crystallized out of this reservoir. A simplified depiction of this process is shown in **Figure 6**. The LMO model predicts that the silicate Moon has a rigid interior with three concentric, monolithic layers.

Our data demonstrate that this stratified lunar interior was significantly disrupted by the SPA impact event. The graph of La vs source region Rb/Sr suggests that the Moon may possess three chemically-distinct, incompatible element-enriched reservoirs rather than a single KREEP layer. If this is true, the lunar mantle may resemble Earth's interior, which features at least five distinct basalt source regions.

On a broad scale, this study demonstrates that the processes which drove lunar differentiation and magmagenesis are still not completely understood. Future lunar exploration through the Artemis program is an imperative as we seek to improve our understanding of the formation and evolution of the terrestrial planets, including Earth.