Background

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 mission as NASA strives toward a new era of lunar exploration. Over the last decades, the successful Apollo program has provided us with a comprehensive understanding of the Moon’s geology and interior structure. The success of the Artemis program is therefore critically linked with our understanding of the starting lunar sample suite.

Along with impact cratering, volcanism is one of the two processes which have dominated the Moon’s geologic history. The Apollo missions collected two classes of basalt. Depleted means basalts are derived from a reservoir enriched in incompatible trace elements. Both of these reservoirs are identified by Figure 4. Until recently, the Moon’s youngest igneous deposits were thought to be the KREEP basalts, in their source region enriched in radioactive isotopes of K, Th, and U. However, the recent Chang’e 6 mission discovered that these young magmas come from a depleted mantle reservoir, opening our knowledge of the lunar interior (2).

Methods

We used the Rb/Sr and Sm/Nd isotope systems to study lunar magmatogenesis and to probe the Moon’s internal structure. Isotope ratios are 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. Lunar basalt samples were extracted from NASA’s Moonbase database.

Results

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, pre-normalized lunar Rb/Sr and Sm/Nd measurements compiled to date. The Rb/Sr system is described by Figure 3; which is a graph of the initial isotope compositions of lunar basalts plotted against their age. The composition of each sample can be connected to the initial isotope signature of the Moon’s interior. We find that the Moon’s interior is depleted in incompatible trace elements.

Discussion

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 150-km asteroid reshaped the entire lunar interior. Recent simulations suggest that the SPA impact triggered gravitational-driven mantle overturn (6). During this process, rocks KREEP-rich materials would have sunk to the Moon’s core instead (11).

Our Sm/Nd isotopic data provide experimental support for this hypothesis, which previously depended entirely upon computer simulations. Our research suggests that the KREEP basin source region differentiated 4.5 billion years ago (6). This is entirely similar to the age of the SPA impact itself. Two group of lunar scientists have used independent processes to estimate that the impact event took place around 4.3 billion years ago (6).

The Lunar Manoeuvre Ocean (LMO) hypothesis has been one of the central tenets of lunar science for over four decades (9). This model states that the lunar mantle was initially matter, and that a sequence of volatile-carbonate, plagioclase crust, and incompatible element-enriched material was subsequently crystallized out of this reservoir. A simplified description of this process is shown in Figure 1. The LMO model postulates that the Moon’s surface has been uplifted by 25 km due to the addition of new material.

The stratified model suggests an event(s) that would have had a significant effect on the Earth-Moon system. Our data demonstrate that the stratified lunar interior was significantly disrupted by the SPA impact event. The graph of a system region KREEP suggests that the Moon now possesses these 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 lateral scale, this study demonstrates that the processes which drive lunar differentiation and magnetization are still not completely understood. Future lunar exploration through the Artemis program is as important as we seek to improve our understanding of the formation and evolution of the terrestrial planets, including Earth.

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