EVALUATING THE SIGNIFICANCE OF LUNAR CHRONOLOGY WITH NEW SAMPLES.

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Introduction: Most of what is known about the origin and evolution of the Moon is derived from laboratory analysis of samples returned by the six Apollo missions. These measurements have also proven to be critical for deciphering the history of the early Earth, which remains largely unpreserved in the terrestrial rock record. This is not to say that other types of investigations have not provided fundamental constraints on the origin of the Moon. Instead, a combination of remote sensing measurements and samples analysis have led to the current state of lunar knowledge.

One area where remote sensing has been particularly valuable is in extrapolating laboratory observation, completed on very small samples, to a significantly broader scale. In this way the results of detailed laboratory investigations have been used to constrain fundamental global-scale processes. For example, the observation that ferroan anorthosite suite (FAS) lithologies, characterized by the presence of anorthositic plagioclase, Fe-rich mafic phases, and ultra-low incompatible-element abundances, are widespread on the Moon led to the lunar magma ocean (LMO) hypothesis [1-2]. The global-scale nature of the LMO is further supported by the ubiquitous presence of high Th contents in the Procellarum-KREEP Terrane (PKT) which requires the widespread occurrence of rocks with incompatible element abundances similar to those observed from Apollo 14 and 15 samples interpreted to represent last products of LMO solidification [3-4].

However, many fundamental measurements completed on Apollo, and to a much lesser extent lunar meteorite, samples cannot be extrapolated using remote sensing techniques. The only way to evaluate whether these measurements represent global-scale processes, and constrain the origin of the Moon, is to evaluate whether the characteristics of the samples are common to all samples collected from geographically distant locations. For example, the absence of live short-lived nuclides, such as ^{26}Al, ^{53}Mn, and ^{182}Hf, in all lunar samples demonstrates the Moon is relatively young by solar system standards.

Other types measurements do not lead to such an unambiguous conclusion, because they can be interpreted in the light of regional, rather than global-scale geologic processes. Some of these data are discussed and potential sampling strategies near the South Pole that could yield relevant samples are highlighted.

The problem with chronologic interpretations: Recent chronologic investigations on lunar samples have demonstrated that there is a preponderance of 4.3-4.4 Ga ages. These ages have been obtained for: (1) the source regions of the mare basalts, (2) FAS samples, (3) the formation of urKREEP, and (4) many Mg-suite rocks [e.g., 5-7]. All of these measurements were completed on rocks obtained within the area sampled by the Apollo missions on the lunar nearside. The young ages determined for these samples have been interpreted in several ways. The simplest explanation is that they record the primordial differentiation of the LMO [5,7]. This is supported by evidence that suggests many are derived from the same geochemical reservoir characterized by Sm-Nd isotopic systematics that are similar to undifferentiated meteorites (Fig. 1).

If the Moon indeed solidified around 4.35 Ga, then older ages that have been determined for some lunar samples must be erroneous. This leads to the possibility that the 4.3 to 4.4 ages record a regional geologic event that occurred after LMO solidification. It has been suggested that widespread magmatic activity on the Moon could reflect a large impact [8], perhaps the one that produced the South Pole-Aitken (SPA) basin. Alternatively, the ubiquitous ~4.35 Ga age could reflect magmatism associated with density-driven overturn of the LMO following solidification [5].

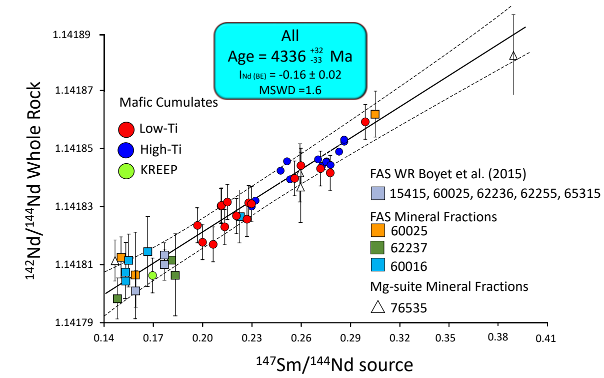

Figure 1. Sm-Nd isochron diagram of mare basalt sources, FAS, and Mg-suite samples indicating contemporaneous formation from a common undifferentiated reservoir.

Another problem associated with the interpretation of chronologic measurements concerns the temporal relationship between FAS and Mg-rich plutonic crustal rocks. The age concordance of these suites is illustrated in Figure 2. It has been interpreted to reflect production of the Mg-suite during, and immediately after, LMO formation as a result of overturn [9]. If Mg-rich magmatism results from overturn of the LMO, then

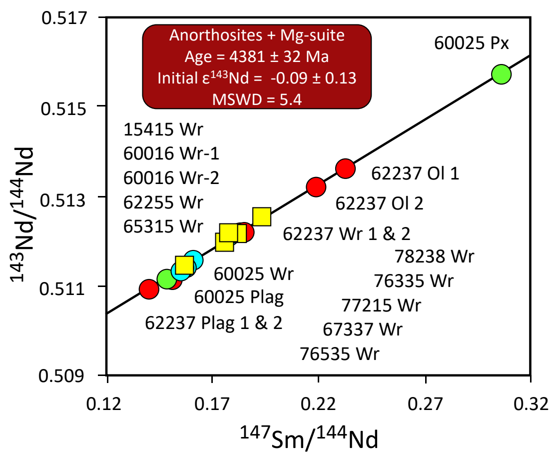

Figure 2. Whole rock isochron demonstrating contemporaneous formation of FAS and Mg-rich plutonic rocks.

Mg-rich plutonic rocks are expected to define a limited range of ages. Although the most recent chronology supports this contention, only samples collected by the Apollo missions have been analyzed.

Solution to chronologic interpretations: The only direct way to evaluate whether the measured ages record planet-wide events is to determine if they are preserved in lunar rocks on a global scale. For example, strong evidence for the formation of the Moon around 4.35 Ga would be provided if mare basalts and FAS samples collected from globally spaced locations on the Moon all fall on the Sm-Nd isochron represented on Figure 1. Conversely, a regional interpretation of the ~4.35 Ga age would be required if some mare basalt sources and FAS samples fell significantly off the Sm-Nd isochron. A similar conclusion might be drawn if the SPA impact was demonstrated to be contemporaneous with magmatism at 4.35 Ga.

Model ages determined for KREEP could also be gleaned from crustal rocks and lavas that contain a urKREEP component. A ~4.35 Ga urKREEP model age determined from samples collected outside the PKT would provide evidence for global solidification of the LMO at that time. Alternatively, KREEP model ages that are significantly different from 4.35 Ga would challenge the production of KREEP through solidification of a global LMO.

Finally, widespread ~4.35 Ga ages for Mg-rich plutonic rocks would provide strong evidence that they were produced on a global scale in likely association with overturn of the lunar mantle. However, given the short duration of overturn, if Mg-rich magmatism was found to occur over a measurable duration of time, then another heat source would likely be needed.

Desired samples: Key samples that could determine the significance of the 4.35 Ga age must be collected as far from the Apollo nearside landing sites as possible. The types of samples that are needed to evaluate the extent of Sm-Nd isotopic equilibrium on the Moon include Mg-rich plutonic rocks, anorthosite samples, and mare basalts. Samples from outside the PKT that are demonstrated to contain a KREEP component are also highly useful in this regard, because they will serve as the basis for KREEP model age determinations. Samples, that define the age of SPA, such as impact melt breccias, are needed as well because they illustrate whether magmatism associated with the 4.35 Ga age is affiliated with early large impacts on the Moon. Finally, Mg-rich plutonic rocks will also serve to demonstrate whether they are temporally associated with mare basalt source formation and FAS magmatism as suggested by the mantle overturn hypothesis.

The geologic formations around the South Pole have a high potential to yield samples that could constrain the significance of the chronologic investigations completed on the lunar nearside. Both the deep crust and volcanic rocks are exposed in this region and likely to be present in ejecta transported to the South Pole.

Surface capabilities needed to fulfill chronology goals: There are crew and mission architecture capabilities needed to fulfill these science goals. The astronauts need to be trained to recognize appropriate samples on the surface. Regardless of sampling location, most Apollo samples are inappropriate for chronologic investigations of any kind. Large breccias containing numerous clasts have proven to be indispensable in defining the geologic history of the Moon. By analogy to highland samples returned by the Apollo Program, breccias with masses on the order of 5 to 12 kg are ideal. This requires a capability of returning upwards of 100 kg of material per South Pole mission. Significant surface mobility, similar to Apollo 17, is also needed. This maximizes lithologic diversity, which is required to address any significant geologic question relevant to the origin and evolution of the Moon. This strategy facilitates identification of samples that share petrogenetic affinities with nearside samples, and yet are derived from different locations and geologic formations, allowing planetary scale processes to be identified and understood.

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