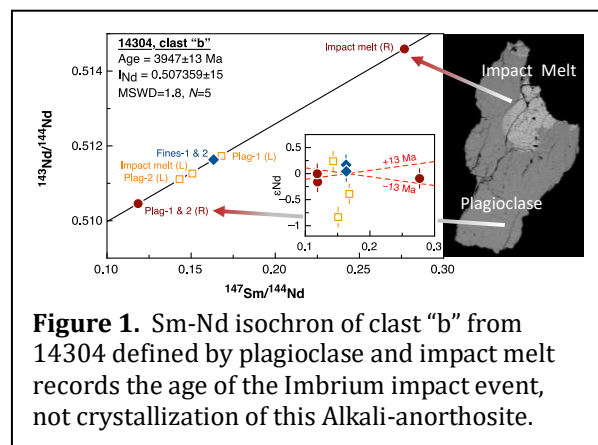**CHRONOLOGY OF SECONDARY LUNAR CRUST INFERRED FROM ROCKS OF THE TAURUS LITTROW VALLEY.**

L.E. Borg, T.K. Kruijer[1], C.K. Shearer[2], N.A. Marks[1], B. Jacobsen[1], S.B. Simon[2] and the ANGSA science team[3]. [1]Lawrence Livermore National Laboratory, Livermore, CA; [2] Dept. of Earth and Planetary Science, Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131 [3]the list of co-authors includes all members of the ANGSA Science Team (https://www.lpi.usra.edu/ ANGSA /teams/) (cshearer@unm.edu).

Introduction: The lunar highlands crust is composed to three major suites of rocks. The first is the ferroan anorthosite suite (FAS) characterized by high Ca-plagioclase and pyroxene and olivine with elevated Fe abundances, leading to the suggesting this suite represents a primary crystallization product of the lunar magma ocean (LMO). Although anorthosites are found in small quantities at most Apollo sites, most FAS samples come from the Apollo 16 site in the Descartes Highlands. The second major lunar crustal rock suite is the Mg-suite. It is characterized by mafic phases with elevated Mg abundances, Ca-rich plagioclase, and a K-REE-P (KREEP) enriched trace element composition. These rocks are abundant at the Apollo 17 landing site, but have also been identified as clasts in breccias from Apollo 14 and 15 sites. The final suite is the Alkali suite which is characterized by more Na and K-rich feldspars, Fe rich-mafic minerals, and very high abundances of KREEP. This lithology is represented by small clasts in breccias mainly from Apollo 14 and 15 landing sites, as well as by detrital zircons common to many regolith samples.

The chronology of the lunar crust is heavily biased by studies completed on samples from Apollo 16 and 17 landing sites. This stems from the fact, that of the 382 kg of samples returned from the Moon by Apollo, only ~15 crustal rocks have proven to be amenable for isotopic dating and 11 were collected at these two landing sites. By mass this represents less than about 0.2% of the entire Apollo collection. Nevertheless, a somewhat coherent, picture of lunar crustal chronology is starting to emerge.

Chronology techniques: It has taken decades to learn how to obtain reliable ages on lunar crustal rocks that can be interpreted in a geologic context with confidence. This stems from the fact that these ancient rocks have had complex post crystallization histories that have disturbed their isotope systems. As a consequence, of the 15 crustal samples collected from Apollo, less than half have yielded ages that can be deemed reliable [1]. An example is provided by clast "b" from Apollo 14 breccia 14304

collected from the Fra Mauro formation consisting of ejecta from the Imbrium impact basin. The first attempt to date this sample yielded Rb-Sr and Sm-Nd ages of 4108 ± 40 Ma and 4336 ± 81 Ma, respectively [2]. The 4.11 Ga age was interpreted to represent the crystallization age of the sample. A more recent detailed chronology/petrology investigation on this sample produced concordant Ar-Ar, Rb-Sr, and Sm-Nd ages that averaged 3944 ± 9 Ma (Fig. 1). If taken at face value these ages seem to indicate that igneous Alkali-suite crustal rocks crystallized at the same time the Imbrium impact is thought to have occurred [e.g., 3-5]. However, detailed examination of the mineral separates used to define the isochrons indicate that they are mixtures of plagioclase and impact melt, so that the 3 concordant ~3.94 Ga ages record the age of the impact, not crystallization.

Figure 1. Sm-Nd isochron of clast "b" from 14304 defined by plagioclase and impact melt records the age of the Imbrium impact event, not crystallization of this Alkali-anorthosite.

Ages of Mg-suite: The majority of Mg-suite samples (6 of 9) that have been dated were collected in the Taurus Littrow Valley because this is the source of all but one of the large Mg-suite samples. This is not to imply that Mg-suite rocks from other landing sites, found almost exclusively as small clasts in breccias, have not been dated - they have. However, these samples are very small, material allocated by curation is limited to even smaller masses, and the isotopic systematics of these clasts isoften partially disturbed, so that it has proven difficult to obtain concordant ages from multiple chronometers

on single samples [6]. This is critical because obtaining concordant ages from multiple chronometers is the only mechanism to ensure that the ages represent actual geologic events and are not a manifestation of contamination occurring on the surface of the Moon, or in the laboratory.

A compilation of ages determined on various lunar lithologies is presented in Figure 2. A whole rock isochron for Mg-suite samples from Apollo 14, 15, 16, and 17 landing sites is also plotted. The data points defined for individual samples and LMO cumulates are averages of multiple investigations completed on different aliquots of the samples [7]. The concordance of the ages provides confidence that they record crystallization of the rock. Note that the age of 76535 plotted on this diagram is adjusted following [8] for its slow cooling rate.

Figure 2. Compilation of ages determined on LMO cumulates, lunar crustal rocks, and detrital zircons. Figure modified from [7].
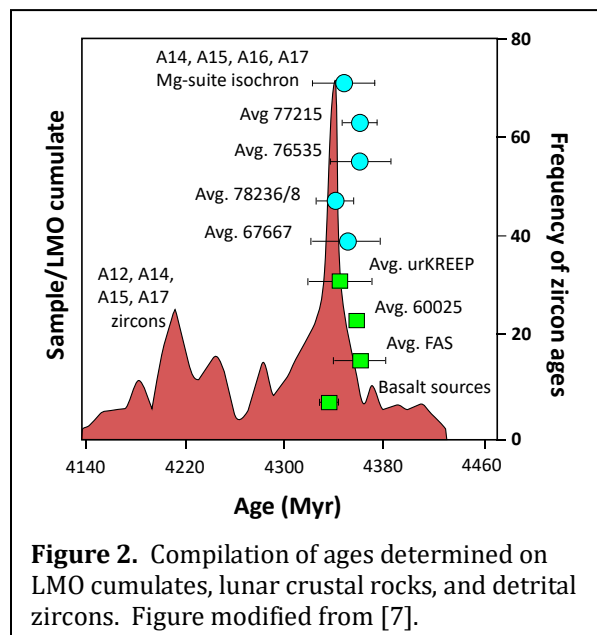
Note that the crystallization ages determined on the Mg-suites rocks (blue circles) is indistinguishable from ages determined on LMO cumulates (green squares). This is inconsistent with the geochemistry of the Mg-suite which suggest these rocks are derived from various mixtures of primordial crystallization products of the LMO. [e.g., 9] Specifically, derivation from Mg-rich mafic cumulates, plagioclase with affinities to that in ferroan anorthosite cumulates, and urKREEP. The close temporal affiliation of the Mg-suite with primary LMO cumulates suggest that the Mg-suite could be related to the primordial crystallization of the LMO. One of the more consistent interpretations is that the

Mg-suite was produced during overturn of the LMO that occurred shortly after, of perhaps contemporaneous with, the last stages of LMO crystallization [9].

Implications for future investigations of the lunar crust: Chronologic investigations of lunar samples provide a temporal framework needed to understand geologic processes. This is critical for the Moon where the original stratigraphy of samples has been disrupted by impacts. The best chronology that is currently available suggests that the LMO crystallized relatively quickly around 4.34 to 4.38 Ga [1,7], and that secondary crustal magmatism soon followed. Thus, global scale geologic events appear to be closely spaced in time. To better define their geologic relationships, age determinations using multiple isotope systems must be completed of significantly more crustal rocks, with markedly higher precision. These determinations must be accompanied by detailed petrographic investigations, otherwise little geologic significance can be placed on the ages.

Collection of samples for the Artemis program:

Understanding the early evolution of the Moon will require obtaining more ancient crustal samples by scouring the existing collections and collecting more samples in upcoming missions, notably Artemis and potentially Endurance A/R. The post-crystallization history of the samples is arguably most critical for chronologic investigations. Given the importance of these measurements, suites of lithologically diverse samples demonstrating minimal evidence for impact brecciation, addition of impact melt, and thermal metamorphism must be sought. Samples meeting these criteria are unlikely to be present in large quantities on the lunar surface so that a concentrated effort will be required to identify and collect them from the lunar surface.

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