TIMING AND DURATION OF MARE BASALT MAGMATISM: CONSTRAINTS FROM LUNAR SAMPLES. M. Anand[1,2] and K. Terada[3], [1]Department of Earth and Environmental Sciences, The Open University, Milton Keynes, MK7 6AA, UK (M.Anand@open.ac.uk), [2]Department of Mineralogy, The Natural History Museum, Cromwell Road, London, SW7 5BD, UK, [3]Department of Earth and Planetary Systems Science, Hiroshima University, Higashi-Hiroshima 739-8526, Japan.

Introduction: One of the important issues in lunar science relates to the understanding of the timing and duration of mare magmatism which has significant implications for the thermal evolution of the lunar interior through time. Remote sensing studies of the Moon have indicated existence of mare regions as old as 4 Ga and as young as 1 Ga [1,2]. In contrast, most lab-based studies involving direct age dating of "returned" basaltic lunar samples (from Apollo and Luna missions, and lunar meteorites) by radiometric techniques have yielded much narrower age ranges for mare magmatism, typically in the time interval of 3.9 to 3.1 Ga [3]. However, less attention have been given to some notable examples of ancient mare magmatism, samples of which exist in terms of 4.2 – 4.3 Ga basalts [4,5]. Recently, a number of chronological investigations of basaltic lunar samples have revealed crystallization ages which are older, as well as, younger, than previously known range for mare basalt ages [6-10]. These new findings have necessitated revisiting the topic of ages and duration of basalt volcanism on the Moon and the causes and consequences of it for the lunar evolution with implications for post-accretion planetary differentiation processes.

Mare basalt ages from Apollo and Luna samples: Earlier studies indicated that the high-Ti basalts from the Apollo 11 and Apollo 17 sites are relatively older (3.5 to 3.9 Ga) compared to low-Ti mare basalt samples from Apollo 12 and 15 sites (3.1 to 3.4 Ga). In addition, the very-low-Ti (VLT) mare basalts from Luna 24 have crystallization ages (e.g., 3.2 to 3.3 Ga [3]) similar to the low-Ti basalts. However, Ar-Ar age dating of some basalt fragments from Luna 24 regolith has yielded younger crystallization ages [7,8], and in one case, the youngest crystallization age for any directly dated lunar basalt so far (ca. 2.5 Ga; [7]). However, since a large correction, for trapped Ar, was required in these studies, an independent age constraint using a different isotopic method is desirable to confirm such young mare basalt ages. The least abundant, KREEP-rich mare basalt samples from Apollo collections have yielded ancient crystallization ages (~ 3.8 Ga or older [11-13]).

Mare basalt ages from lunar meteorites: In the last decade, over 50 distinct lunar meteorites have been discovered from various locations on the Earth. Out of these 50+ stones, ~ 15 are crystalline basalts or dominantly a mare basaltic breccia. These new type of "returned" lunar samples have provided a new impetus for lunar research and in many cases, they appear to be significantly different than the lunar samples that were collected by the Apollo and Luna missions. Some of the additional findings from lunar meteorite studies in the context of the timing and duration of mare basalt volcanism are as follows: (1) almost all low-Ti mare-basaltic meteorites have crystallization ages similar to those collected by Apollo and Luna missions; the exception is NWA 032, which has a crystallization age of ~ 2.8 Ga [9,14] (2) all VLT basaltic lunar meteorites have crystallization ages older than 3.5 Ga, and in one case extending up to 4.35 Ga [6,15-17]. (3) a KREEP-rich basaltic lunar meteorite, NWA 773 has much younger crystallization age (2.8 - 2.9 Ga [9,10]). Thus, our previous knowledge of the timing and duration of mare magmatism appears to have been sample limited, and in contrast to earlier observations, there is no systematic relationship between the ages of mare basalts and the compositional type.

Pre- and post- basin filling mare volcanism: Cryptomaria are mare basalt deposits whose low-albedo signature has been hidden or obscured by superposed high albedo material [18]. These deposits are assumed to represent an earlier phase of mare volcanism predating the main phase of basin-filling mare deposits that formed between 3.9 to 3.1 Ga. Direct samples of cryptomare have been lacking or were difficult to identify in the lunar sample collections. Until recently, two previous studies have reported ~ 4.2 Gyr ages for basalt clasts in Apollo 14 breccias [4,5] fitting into the definition of cryptomaria, suggesting that mare volcanism occurred early during the lunar crust formation. This earlier observation of pre-Imbrian mare volcanism has received further support from recent age dating of a VLT mare-basaltic meteorite, Kalahari 009, which has a U-Pb crystallization age of 4.35 Ga [6]. This ancient crystallization age for Kalahari 009 magma has also been confirmed by Lu-Hf dating (4.286 ± 0.095 Ga; [19]). Thus, there is increasing evidence that mare basalt magmatism started as early as 4.35 Ga; only ~ 150 Ma after the accretion and differentiation of the Moon. At the other extreme, a 2.8 - 2.9 Ga crystallization age for KREEP-rich lunar meteorite NWA 773 suggests that KREEP magmatism on the Moon occurred over a protracted period of time covering at least an interval > 1 Ga [10].

Initiation and eruption of mare magma: Based on the impressive body of research conducted on returned lunar samples by Apollo astronauts and Luna automated missions, a common consensus appeared which suggested that mare volcanism occurred mainly after the late heavy bombardment around 3.8 – 3.9 Ga, in the form of large basin (maria) filling basalts comprising the distinctly visible dark regions on the near-side of the present day Moon.

Numerous models have been proposed for the initiation of lunar mantle melting leading into mare basalt eruption on to the lunar surface. These models strongly rely on the data available for the timing and duration of mare basalt volcanism, either from radiometric dating of lunar samples or model ages derived from remote sensing studies. One end member model involves "passive" mechanism for lunar magmatism, which invokes partial melting through internal heating by radioactive elements associated with KREEP [20]. Another "passive" mechanism model appeals to large-scale overturn of stratified cumulate lunar interior, after the Lunar Magma Ocean crystallization, causing mare magmatism over a protracted period [21]. At the other end, an "active" mechanism model proposes two-stages in lunar magma generation triggered by impacts [22]. In the first stage, a basin-forming impact event causes large degrees of instantaneous mantle melting, followed by a second stage involving adiabatic decompression melting and extrusion of mare basalts into the newly created impact basin [22]. The ancient age of Kalahari 009 and its geochemical features appear compatible with the "active" mechanism model, and may be a manifestation of a pre-Imbrium basin-forming event on the Moon. On the other hand, basaltic samples such as NWA 773 which are inherently KREEP-rich may have had mantle melting initiated by the over abundance of heat producing elements in the source region. In all likelihood, distinctly different or a combination of a number of petrogenetic processes operating in the lunar lithosphere might have been involved in the generation and eruption of mare magmas, potentially overlapping in space and time.

Future prospects: Lunar exploration is at a very exciting stage, with a number of countries currently involved in lunar exploration programme via orbiter and lander missions with a plan for permanent settlement on the Moon in not too distant future. After Earth, Moon is the only planetary body for which we have the most comprehensive geological dataset and undoubtedly the wealth of lunar knowledge gained since Apollo days, through remote sensing and lab-based studies of lunar samples, will guide future lunar missions. In the context of mare basalt petrogenesis, we must use our current knowledge to identify potential landing sites for returning lunar samples that will help fill in the gaps in our current lunar sample collection. Since the first 500 Ma of Earth's geological history is completely erased by the plate-tectonic processes, Moon is our best hope to retrieve rocks formed during the earliest phases of solar system evolution. This will improve our understanding of the origin and evolution of the Earth-Moon system with implications for other terrestrial planets. At the same time, targeting younger mare regions for future sample return missions will be equally rewarding in extending our knowledge of the lunar magmatic history, and help refine the lunar cratering curve, which has ramifications for dating other planetary surfaces in the inner solar system.

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