**EARLY HISTORY OF THE MOON: ZIRCON PERSPECTIVE.** M.L. Grange[1], A.A. Nemchin[1], R.T. Pidgeon[1], C. Meyer[2]. [1]Department of Applied Geology, Curtin University of Technology, Bentley, Western Australia,



**Introduction:** The Moon is believed to have formed from debris produced by a giant impact of a Mars sized body with the Earth (at around 4.51 Ga), forming a primitive body with a thick global layer of melt referred to as the Lunar Magma Ocean (LMO) [1]. The crystallization of LMO created internal stratification of the Moon forming main geochemical reservoirs. The surface features on the Moon were shaped by the subsequent collision with several large impactors during a short period of time (3.9-4.0 Ga). This process known as the Late Heavy Bombardment [2] is supported by models of planetary motion, suggesting that rapid migration of giant planets could have triggered a massive delivery of planetesimals from the asteroid belt into the inner Solar System at about 3.9 Ga [3].

Although, general chronology of LMO and LHB is well established using both long lived (U-Pb, Rb-Sr, $^{147}$Sm-$^{143}$Nd and Ar-Ar) and extinct ($^{182}$Hf-$^{182}$W and $^{146}$Sm-$^{142}$Nd) isotope systems, some of these systems such as Ar-Ar [4-5] are known to reset easily during secondary thermal overprints. As a result important details in the timing of LMO and LHB remain unresolved. In addition, the relative weakness of these systems under high T conditions can potentially bias the chronological information towards later events in the history of the Moon.

On the contrary, the U-Pb system in zircon is known for its ability to survive extreme P-T conditions. Therefore, lunar zircon gives an additional angle to the studies of lunar chronology, providing additional insight into the LMO crystallization process and bombardment history of the Moon. The significance of zircon for the former is defined by the link between the appearance of zircon in the rocks and their enrichment in incompatible elements. Zircon crystallization is governed by the Zr saturation in the melt. Therefore, the abundance of zircon in lunar rocks is associated with the presence of KREEP. Consequently the oldest zircon should place a younger limit on the formation of KREEP reservoir on the Moon. This reservoir is believed to represent the very last melt fraction remaining after almost complete crystallization of the LMO.

The different response of zircon to the LHB, as compared to the other isotope systems, is highlighted by the almost complete absence of 3.9 Ga zircon grains in lunar samples [6]. However, some zircon grains contain texturally different parts with different ages, indicating a response to a bombardment history more complex than just late 3.9 impact flux.

This presentation aims to discuss a synthesis of zircon U-Pb work done in the last two years and implications of this work to the early history of the Moon.

**Constraints on the LMO crystallization:** The oldest zircon dated so far in a lunar sample is found in the impact melt breccia 72215. This large zircon (>500μm) is a relict fragment of a larger grain that was incorporated into the host breccia. It shows a complex pattern of isotopic resetting associated with the microstructural features visible in the grain. Four concordant analyses from undeformed part of the grain give a mean $^{207}$Pb/$^{206}$Pb age at 4417±6 Ma (2σ), interpreted as the crystallization age of the primary zircon. This age indicates therefore that the KREEP reservoir already existed at that time and constitutes a younger limit for KREEP formation. This also implies that the main part of the LMO (~90% at least) had already crystallized by around 4.42 Ga.

**Pre-3.9 Ga impact history:** Detailed textural studies and high resolution U-Pb ages of zircon grains show that some of these grains record impacts older than the LHB. These complex zircons are either included in the clasts of plutonic rocks found in the breccia samples or are fragments of very large original grains. Both these features indicate that zircons have crystallized at substantial depth and have been subsequently broken and/or deformed, and incorporated into breccia during impacts which bring them closer to the surface. Therefore, resetting and excavation of zircon from their original position within the lunar crust would require substantial energy of impacts, indicating a significant size of impactors.

*A ~4.33 Ga impact event.* The zircon from breccia 72215 that preserves oldest recorded age of 4417±6 Ma, also contains severely modified segments with an age of 4333±7 Ma, defined by the average of five concordant analyses. These analyses correspond to areas of significant lattice deformation, suggesting deformation-related Pb-loss. Therefore, this age reflects the mobility of both U and Pb in the grain during an impact capable to deform the zircon lattice and consequently dating this impact. Similar age of 4335±5 Ma (2σ) is calculated on the basis of 7 concordant analyses of acicular zircon formed within the impact glass pocket in the breccia sample 73217. Growth of this zircon in the impact melt unambiguously supports 4.33 Ga event at the Apollo 17 landing site.

*A ~4.2 Ga impact.* Clast-rich aphanitic melt breccia 73235 contains a large zircon aggregate of about 500µm in size [7]. It is constituted by irregularly shaped fragments varying in size preserving shocked features and surrounded by a matrix of zircon composition. This aggregate is interpreted to originate from a single primary zircon grain, broken, displaced and rotated during an impact event which also produced the matrix zircon. The latter gives the age of impact at 4187±11 Ma from an average of 8 measurements (95% conf.). This age of about 4.2 Ga is also supported by recently presented Ar-Ar ages of impact melts from both Apollo 16 and 17 landing sites [8] and a single plateau age of 4190±24 Ma on A16 impact melt rock [9].

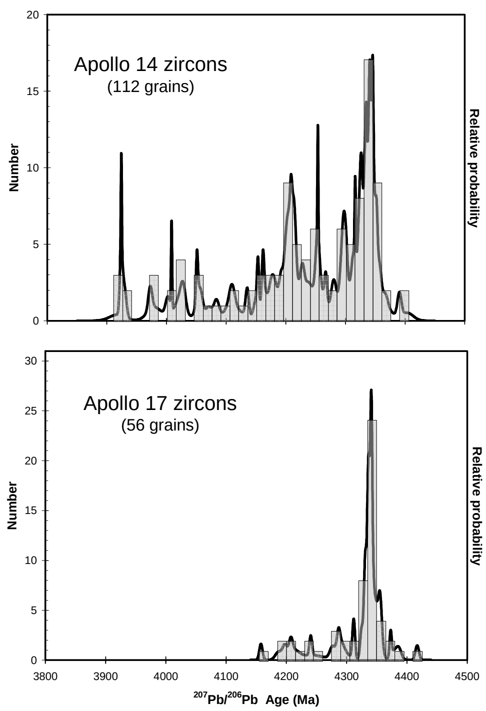


**Figure 1:** Overall distribution of zircons ages for Apollo 14 and 17, [after 10 and new unpublished data].

**Zircon age distribution patterns:** The 4.33 and 4.2 Ga ages of major impact events identified in some zircons are remarkably similar to major peaks visible in the overall age distribution patterns (Figure 1) constrained by the analysis of zircon grains found in the Apollo 14 and 17 breccia samples and separated from soil sample 14163. These patterns show major peak at around 4.35 at both landing sites. In addition, Apollo 14 samples display a second significant peak at about 4.20 Ga and a smaller one about 4.0 Ga, while Apollo 17 samples have a small number of 4.20 Ga grains [10]. The observed patterns indicate an uneven formation of zircon rich rocks through time, raising the intriguing possibility that post LMO magmatism was triggered by major impact events.

**Implications for the early history of the Moon:** The crystallization of the LMO can be bracketed by two main events: the giant impact with the age estimated based on the Hf-W data to be around 4.51 Ga and formation of the KREEP reservoir, representing the very last stage of LMO crystallization. High precision U-Pb measurement on zircon shows that this final stage of LMO crystallization took place no later than 4417±6 Ma. This implies that the main part of the LMO was solidified within about 100 m.y. after formation of the Moon.

While Rb-Sr and Ar-Ar data clearly highlight the importance of the LHB, this event in lunar history is completely absent from the zircon record. However the U-Pb zircon ages combined with some new Ar-Ar data for Apollo 16 and 17 impact melts indicate impacts at about 4.33 and 4.2 Ga. The relative intensity of the 4.33, 4.2, and 3.9 Ga events is not known. But the existence of pre-LHB impacts raises the possibility that the chronological record of the lunar impact history is more complex than that largely based on the Rb-Sr and Ar-Ar systems which are stongly biased towards the 3.9 Ga bombardment episode.

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