REVIEW OF AGES OF LUNAR IMPACT ROCKS: IMPLICATION TO THE TIMING OF SERENITATIS AND IMBRIUM IMPACTS AND THE LHB MODEL.

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Introduction: Samples returned by the Apollo missions have given access to the materials with the preserved record of early history of the Solar System. A substantial analytical data base, which includes ages of a variety of rocks, has been accumulated during several decades following the Apollo missions. These data consistently indicate that the non-mare samples (highland rocks), collected at different landing sites, show a cluster of ages between 3.8 and 4.0 Ga [1-2]. This concentration of ages is interpreted to represent a global resetting of the various isotopic systems (Rb-Sr, Ar-Ar and U-Pb). As the Moon does not show any indication of metamorphic processes similar to those known on the Earth, this resetting has been attributed to meteoritic impacts. It has been proposed that the Moon experienced a period of time when massive amount of asteroids impacted its surface at a cataclysmic rate and reset the isotopic clocks on a global scale. This concept is known as the Late Heavy Bombardment or LHB hypothesis [2].

In addition to the absolute dating, attempts to establish relative chronology of the lunar events, based on craters counting and studies of relationships between different regional features visible in the images of lunar surface [e.g. 3], lead to the identification of main stratigraphic units exposed at each landing site. This work also resulted in the identification of about 45 major impact events, which produced structures (basins) several hundred kilometers in diameter. However, it is often difficult to relate the rock samples collected at the Apollo landing sites to a specific stratigraphic unit, mostly because the majority of samples were loose rocks collected on the regolith surface rather than from outcrops. In addition, linking the stratigraphic units to specific impact events is complicated by the difficulty in interpolating information obtained from the relatively small areas covered by the Apollo missions to the regional scale. Moreover, most of the samples are breccias that have recorded several events and often show complex chronological histories. Consequently it is often difficult to relate observed ages to the specific impact events. Nevertheless, the Fra Mauro formation sampled at Apollo 14 site is commonly interpreted as Imbrium ejecta. A number of samples from Apollo 15 site located at the rim of Imbrium basin are also interpreted as formed during this impact, while some of the impact melt breccias from Apollo 17 landing site are linked to the Serenitatis impact and some samples from Apollo 16 site may have been influenced by Nectaris event.

Regardless of interpretation of different samples and sites, the LHB model implies that the majority, if not all, of identified 45 major impact basins were formed during a short period of time of about 200 Ma. Consequently the ability to resolve individual impact events places strict limits on the precision of absolute ages and requires consistency between the results obtained using different isotopic systems. However, available data have been obtained using slightly different approaches, at different stages of development of analytical protocols and show different level of precision and accuracy. In addition, various data sets indicate variable degree of resetting of different isotopic systems. As a result, the lunar age database has to be filtered to identify the most reliable ages that reflect different impact events. The aim of this study was to determine a consistent approach to this filtering and to isolate reliable data that can be used to constrain precise timing of major impact events in the lunar history.

Methodology: We have reviewed published Ar-Ar and Rb-Sr ages determined on impact melt samples as well as U-Pb ages of phosphates, which are known to reset easily during a thermal overprint. In addition several U-Pb ages of zircons have been used, where textural features indicate that zircon is formed from the impact melt. The following filtering criteria were applied to identify the most reliable data sets:

Ar-Ar ages. Only ages obtained by the step-heating method were considered, as they provide a way to check the internal homogeneity of the analyzed material. Ages with errors in excess of ±20 Ma were not included. Further selection of the Ar-Ar ages was based on statistical criteria, such as the number of steps and the % of ^{39}Ar release used to define the age, to avoid ages that could represent a mixing between different components present in the sample. When necessary, the ages have also been updated for the new age of the standard.

Rb-Sr ages. Mineral isochrons constrained for the impact melts have been considered and filtered on the statistical basis, where all analyzed fractions (>3) define a unique isochron, which is evaluated using MSWD and/or probability of the fit. The ages have also been updated for the decay constant proposed by [4].

U-Pb ages. Ambiguity of initial Pb correction is the main factor reducing accuracy of U-Pb ages of lunar samples. Consequently only data sets with the ^{206}Pb/^{204}Pb higher than 1000 have been considered to minimize the effect of this correction.

Results: Filtering of ages published in about 60 original articles results in a relatively smaller number of accepted ages. However, it also substantially reduces the observed scatter of ages, leading to a more coherent and internally consistent dataset (Figure 1).

The data set for the Apollo 14 landing site remaining after filtering consist of U-Pb ages of apatite and is interpreted to represent the best age estimate for the Fra Mauro Formation, sampled at that site. A very consistent Ar-Ar mean age is obtained from 5 aphanitic impact melt rocks from Apollo 15; however, linking them to a specific unit is a hard as there is no consensus regarding the origin of these rocks. The more abundant Ar-Ar results for Apollo 16 rocks show a wider spread of ages. Nonetheless, 9 of these ages give a very consistent mean at 3897±12 Ma that probably defines timing of both Cayley and Descartes Formations sampled at that site. Finally, most of the Ar-Ar results obtained for Apollo 17 impact melts are consistent with the U-Pb ages of apatite and zircon and are slightly older than the samples collected at the other landing sites (Figure 1). Three apparent outliers (Figure 1) represent either older events that could have been preserved by some breccias [7,14] or younger local impact event [7].

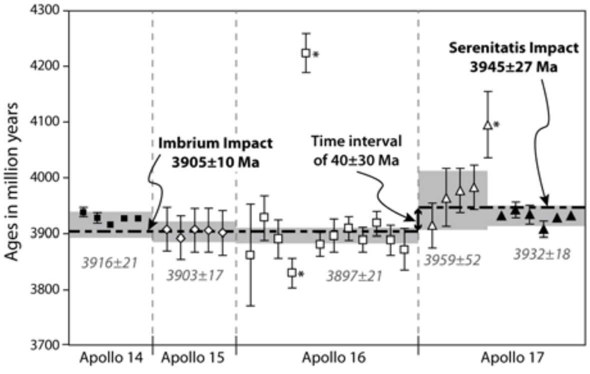

Figure 1: Filled symbols=U-Pb ages. Open symbols=Ar-Ar ages. The grey bands represent the mean ages and their errors for each landing sites and correspond to the italicized numeric values given in the figure. The symbols marked with an asterisk are excluded from the average calculation.

Discussion: The similarity of ages of Apollo 14, 15 and 16 samples suggests that they formed at the same time and could be related to the Imbrium impact. If this is the case, the average age of this group of samples gives the age of the Imbrium event at 3905±10 Ma. The Apollo 17 samples remaining after filtering have been collected along the slopes of the South Massif, in the so-called Light Mantle, interpreted to be part of the Serenitatis ejecta blanket [17]. Therefore, the mean age of 3945±27 Ma determined by these samples is likely to date the Serenitatis impact. The average ages constrain a time interval of 40±30 Ma between two impacts. The stratigraphic relationships between major impact basins indicate that 3 (out of the 45) basin-forming impacts probably occurred between Serenitatis and Imbrium events. This implies that 5 major impacts occurred during the time interval of 40±30 Ma, which is equivalent to a rate of 0.125 impacts/Ma. Several interpretations of this rate are possible, considering the first 500 Ma lunar history between the crystallisation of the lunar magma ocean and the Imbrium impact:

(1) A constant rate of 0.125 impacts/Ma during 500 Ma would create 63 basins. As only about 45 have been identified, this scenario is unlikely, although it is possible that older impacts have been erased by younger events.

(2) A rate higher than 0.125 impact/Ma is even less likely as it would create an even larger number of basins. This also excludes an exponentially decreasing flux of meteoritic bodies, such as proposed by the “accretion tail” hypothesis.

(3) The alternative and viable explanation is a lower impact rate prior to the Serenitatis impact event. Even if this rate cannot be determined precisely, it implies that the meteoritic flux was not constant but punctuated by spike(s) when the impact rate increased dramatically. One of these spikes can be represented by the Serenitatis-Imbrium interval (LHB?). It is also possible that the Moon history was marked by more than one spike of higher impact rate during the first 500 Ma of its history.

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