COMPARING U-PB SIMS AGES OF CA-PHOSPHATES IN APOLLO 12, 14, AND 17 BRECCIAS.
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Introduction: In this study, we compare in situ U-Pb ages from Ca-phosphate grains obtained from breccias collected during the Apollo 12, 14, and 17 missions, and highlight the importance of high precision age determinations for dating impact events. Several previous studies have tried to link radiometric ages determined on Apollo samples to specific basin forming events. For example, based on Rb-Sr and ^{40}Ar-^{39}Ar studies of Apollo 12, 15 and 16 breccias, the Imbrium event was estimated to have occurred approximately 3850-3900 Ma ago (e.g., [1], [2]). On the other hand, ^{40}Ar-^{39}Ar ages of Apollo 14 breccias led to a suggestion of a considerably younger age of 3750 Ma [3], but this is not widely supported. More recent U-Pb studies on zircons in Apollo 12 [4] and the meteorite SaU 169 [5] yielded ages of 3914±7 Ma for the Apollo 12 breccias, and 3920±12 Ma and 3909±13 Ma for SaU 169, respectively. Liu et al. [4] and Gnos et al. [5] interpreted these older ages as dating the Imbrium impact. Similar controversy exists in the interpretation of ages determined from breccias sampled during the Apollo 17 mission. One of the main objectives of the Apollo 17 mission was to sample materials older than the Imbrium impact and to possibly determine the age of the Serenitatis impact basin. The widely accepted age for the Serenitatis impact ~3.9 Ga [e.g., 6] is based on several studies of Apollo 17 breccias. However, the range of ^{39}Ar/^{40}Ar ages (3.90 - 4.02 Ga) and differences in the petrology and chemistry of texturally different impact breccias [7] may imply that these breccias do not originate from one single impact event, e.g. Serenitatis. Spudis and Ryder [7] thus suggested that these breccias represent ejecta from local craters and/or larger distant craters.

In this study, we used in situ SIMS analyses on single phosphate grains in order to obtain precise U-Pb ages of host breccia samples. In comparison to zircon, the U-Pb system of phosphates is easily disturbed due to their low closure temperatures around 450-500 ºC [e.g., 8] and hence, the U-Pb system is likely to be reset during an impact event [9]. Therefore, their ages are expected to date the breccia formation.

Sample description: In total, ten samples were analysed from three Apollo landing sites.

Apollo 12: One thin section of sample 12013 described as a complex mixture of two polymict breccias was analyzed. One component present in the sample is black breccia, which has a general basaltic composition, and the other is a gray, silica and potassium rich breccia [10].

Apollo 14: A total of six thin sections from five different breccias were analyzed (14305, 14306, 14311, 14314 & 14321), which are all described as crystalline matrix breccias [e.g., 11].

Apollo 17: Nine thin sections from four different samples belonging to three distinctive types: (1) aphanitic (72255), (2) micropoikilitic (76015 & 76215) [12], and (3) subophitic (76055) impact melt breccias were investigated.

Method: The thin sections were polished in an ultrasonic bath using ethanol and distilled water before carbon coating. The identification of phosphate grains and the characterization of microstructures in the sections was performed using backscattered electron (BSE) images. U-Pb isotopic data was collected using CAMECA 1280 ion microprobe at the NordSIM facility, Swedish Museum of Natural History, Stockholm. The 2058 Ma apatite crystal BRA-1 was used as a reference for all analytical sessions. Data reduction was done using an in-house developed software and Isoplot [13]. All results are shown with 2σ errors.

Results: All data are concordant or nearly concordant as illustrated in Figure 1, suggesting closed system behavior of analyzed phosphate grains since the last thermal overprint significant enough to mobilize Pb in these grains.

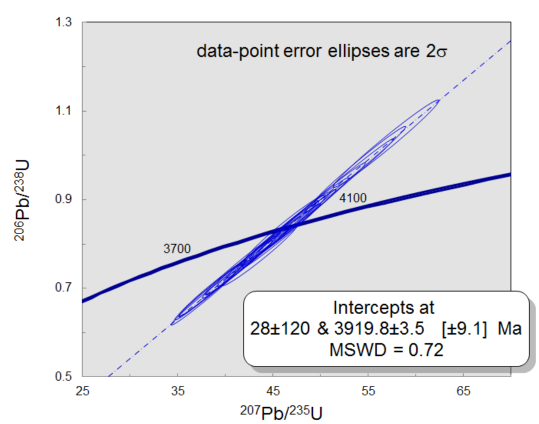

Figure 1. *Concordia diagram from sample 76055, Apollo 17 landing site.*

Determination of U-Pb ratios by SIMS includes correction for the matrix effects using independently characterized reference materials and inevitably incurs extra uncertainty associated with minor differences in both chemistry and instrumental conditions during the analysis of standards and unknown samples. Consequently, $^{207}Pb/^{206}Pb$ ratios are considered to give the best estimate of a sample age and are used in the following discussion of lunar phosphate data.

27 analyses of 23 phosphate grains in the Apollo 12 sample define a weighted average $^{207}Pb/^{206}Pb$ age of 3924.2±3.2 Ma (Fig. 2). This appears to be similar within the error to the ages obtained from three of five investigated Apollo 14 breccias (Fig. 2), showing $^{207}Pb/^{206}Pb$ ages of 3925.5±3.6 Ma (25 analyses in 17 grains), 3927.9±7.9 Ma (12 analyses in 5 grains), and 3928.6±3.7 Ma (28 analyses in 10 grains). The mean of these three is calculated as 3927.3±3.1 Ma. Two samples (14321 and 14311) yielded slightly older $^{207}Pb/^{206}Pb$ ages of 3942.8±4.5 (7 analyses in 3 grains) and 3938.0±4.0 Ma (27 analyses on 23 grains), respectively, with the mean of 3940.4±3.0 Ma. The $^{207}Pb/^{206}Pb$ ages obtained for four Apollo 17 samples also fall into two groups: the subophitic and aphanitic breccias have $^{207}Pb/^{206}Pb$ ages of 3919.6±3.3 Ma (22 analyses of 12 grains) and 3922.4±4.8 Ma (6 analyses of 6 grains) with the mean of 3921±2.9 Ma, whereas the micropoikilitic breccias show slightly older $^{207}Pb/^{206}Pb$ ages of 3930.2±6.2 Ma (17 analyses of 13 grains) and 3931.3±7 Ma (30 analyses of 13 grains) with a mean of 3930.8±4.7 Ma.

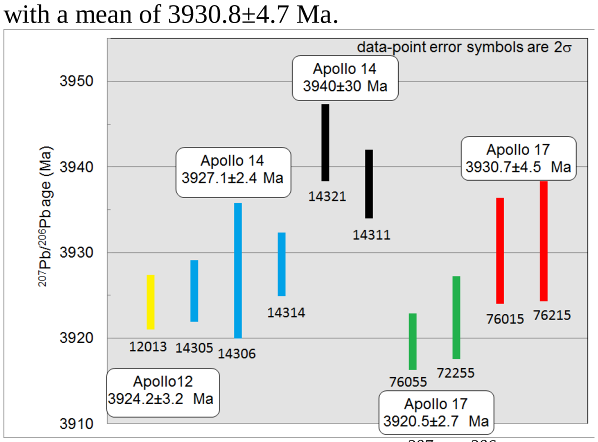

Figure 2. *Comparison of the mean $^{207}Pb/^{206}Pb$ ages from the different breccias collected at the Apollo 12, 14 and 17 landing sites.*

Discussion: The mean $^{207}Pb/^{206}Pb$ ages range over 20 Ma, which cannot be explained by the analytical errors at the level of precision achieved in this study. Therefore, the investigated breccia samples cannot originate from the same impact. While a complete separation of all age groups within the investigated set of samples is still impossible with the obtained uncertainty of about 3 Ma, some patterns become visible even at this precision. For example, the age of Apollo 12 sample 12013 is similar within the uncertainty to the ages of both, the younger group of Apollo 14 and the younger group of Apollo 17 breccias. However, the last two are distinctly different in age. Similarly, there are distinct groups of older and younger breccias at both, the Apollo 14 and Apollo 17 sites, but it is not possible to separate ages of older Apollo 14 from younger Apollo 17 breccias with the current level of uncertainty. Combining different pieces of chronological information together suggests at least three separate impacts recorded by the investigated breccia samples: (i) around 3920 Ma, (ii) between 3927 and 3930 Ma, and (iii) about 3940 Ma. While other impacts are conceivable, the current level of precision is not sufficient to resolve possible additional events. Nevertheless, the ability to identify different closely spaced impact events, as indicated above, has significant implications for understanding the origin of Apollo breccias, and models that describe the impact history of the Moon. Importantly it helps to discard suggestions that: (i) all Apollo landing sites are dominated by the ejecta from a single basin, (e.g. Imbrium; [14]), (ii) all Apollo 17 breccias were formed by the Serenitatis impact, (iii) all crystalline matrix breccia samples from the Apollo 14 landing site are part of the Fra Mauro formation, i.e. Imbrium ejecta.

Assigning specific ages to particular impacts on the Moon is less definitive and inhibited by the controversy in the interpretation of individual samples in relation to the specific stratigraphic units and absence of unambiguous links between these units and impact basins. All or some of these breccias may originate from any number of relatively small local impacts. On the other hand if conventional views that the majority of Apollo 14 breccias represent Imbrium ejecta, while poikilitic breccias from Apollo 17 site originate in the Serenitatis impact are accepted, 3927.3±3.1 Ma can be regarded as the best estimate of the timing of the Imbrium basin formation, while 3930.8±4.7 Ma would be the best estimate of the age of Serenitatis impact. It is worth noting that this implies that these two basins formed in the time span of a few million years and their ages are indistinguishable within error. The older Apollo 14 breccias with an age of 3940.4±3.0 Ma may be associated with an older basin such as Humorum, which is close enough to the Apollo 14 landing site to contribute a significant proportion of the overall material accumulated there, while the youngest 3921±2.9 Ma breccias at the Apollo 17 site could have been formed by one of a few younger basin forming impacts.

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