Apollo 12 breccia 12013: Comparison and interpretation of U-Pb SIMS ages of Ca-phosphates and zircon.

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Introduction: The U-Pb system of zircon is characterised by a high Pb diffusion closure temperature of 900-1000 ˚C [e.g. 1] and is traditionally viewed as extremely resilient and able to withstand high P-T overprints. Consequently most of the studies of lunar zircon conclude that the analysed grains record the magmatic history of the Moon [e.g. 2], although rare cases of secondary zircon formation linked to impact events have been recognised [e.g. 3]. The possibility of partial Pb loss from the zircon grains remains poorly investigated in lunar zircon research, with the exception of two studies. One presents the case of Apollo 15 zircon, where partial Pb loss is easy to recognise since the time of impact (1.4-1.5 Ga) is significantly younger than the age of zircon crystallisation (at about 4.3 Ga) causing visible discordance of affected analyses [4]. The observed Pb loss is also easy to explain as there is sufficient time between zircon crystallisation and impact to accumulate radiation damage of zircon lattice and enable Pb diffusion. The second case was presented by Zhang et al. [5] and was based on a study of Apollo 12 thin section 12013,6 where the impact that formed the breccia sample is likely to be close to 3.9 Ga and possible zircon Pb loss is more difficult to recognise. However, observed textural relationships between zircon and other phases suggesting a common origin of several zircon grains combined with highly variable ages of these grains led to the conclusion that only the oldest recorded age at about 4.3 Ga is close to the crystallisation age of the zircon, while younger ages are secondary and impact related [5].

Taking into account the significance of this observation for lunar zircon chronology, we have investigated zircon from two other sections of 12013. U-Pb data for Ca-phosphate grains found in this sample were also obtained to establish the precise time of the sample formation, i.e. the impact that consolidated breccia 12013.

Sample description: Breccia 12013 consists of a mixture of two distinctive breccias: one is black, the other grey [6]. Both lithologies exhibit plastic deformation [7] indicative of a formation at high temperatures around 990-1110 ˚C, and both parts are interpreted as having formed during one single impact event [7]. The black portion is composed of noritic fragments with a groundmass that is chemically similar to KREEP basalts. The grey portion is dominated by granitic components and skeletal intergrowth of silica and K-feldspar [7]. Furthermore, Valencia et al. [8] divided the breccia into three compositional lithologies: granite, REE-rich impact melt and a mafic component. Ca-phosphates occur as apatites and merrillites but composite merrillite-apatite grains are also observed. Both, the Ca-phosphates and zircon grains exist in the black and grey part of the breccia. The grains have a subhedral to anhedral shape and the majority occur as fragments within the matrix. Some of the grains occurring in the grey lithology are enclosed by an intergrowth of silica and K-feldspar indicating initial formation of Ca-phosphates and zircon at the same time during crystallisation of the felsic melt.

Analytical methods: The analytical protocol followed a similar procedure as published elsewhere [e.g. 9]. The U-Pb ratios in Ca-phosphates were calibrated against the 2058 Ma apatite crystal BRA-1 in all analytical sessions, whereas zircon analyses were corrected against the 1065 Ma zircon crystal 91500. The mass filtered $^{16}O_2^-$ primary ion beam was projected through Köhler apertures of 50 or 100 µm to obtain a spot size of 5 or 10 µm, respectively. Before each analysis of Ca-phosphates, an area of 12 µm was pre-sputtered for 70 seconds, whereas an area of 20-25 µm was pre-sputtered for 80 seconds for zircon analyses. All individual results are shown with internal 2σ uncertainty, while any weighted averages are given as external 2σ uncertainty.

U-Pb results: The analysed Ca-phosphates (29 analyses in 23 grains) have an average $^{207}Pb/^{206}Pb$ age of 3924±3 Ma (MSWD = 1.20, P = 0.22). The results do not indicate any age variation between the black and grey portion of the breccia. A total of 33 analyses were performed on 25 zircon grains. Nine zircon grains occur within the black part of the breccia and 16 grains belong to the grey part of the breccia. Thirteen out of those 16 grains are enclosed by the intergrowth of silica and K-feldspar. The individual $^{207}Pb/^{206}Pb$ ages determined for zircon grains within the black lithology of the breccia spread from 4037±16 Ma to 4328±14 Ma. Zircon occurring within the grey part of the breccia have a similar range of individual $^{207}Pb/^{206}Pb$ ages varying from 3982±6 Ma to 4315±10Ma. Six zircon grains (three within each lithology of the breccia) show CL features composed of darker and lighter CL zones. SIMS spots were only placed in the darker zones because of the relatively small size of the grains (10-20 μm) which did not allow placing more than one spot without overlapping the pre-sputter areas.

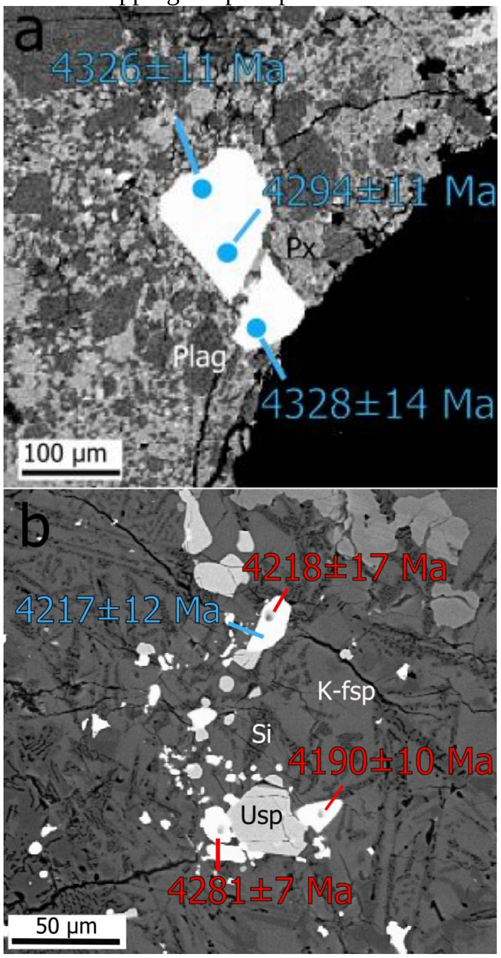

Figure 1. *(a) The oldest zircon grain consists of two fragments and is located within the black part of the breccia. (b) Example of zircon grains situated within the grey portion of the breccia and in direct contact with ulvöspinel. Data are from Zhang et al. ([7], red; multiple analyses of each grain) and this study (blue, one analysis). Abbreviations: K-fsp=K-feldspar, Si=silica, Usp=Ulvöspinel, Px=Pyroxene and Plag=Plagioclase.*

Discussion: Zhang et al. [5] recognised that only the oldest ages at about 4.3 Ga in the obtained dataset for sample 12013 may reflect the zircon crystallisation time, while the younger ages can be a result of Pb loss. However, based on the apparent intra grain homogeneity of ages (statistically similar ages have been obtained from multiple analyses of most of individual grains and different CL zones in some grains), they interpreted these younger ages as dating several impact events that post-dated zircon crystallisation. However, one of their grains (Zrn3), located in the black part of the breccia, exhibits alternation of dark and bright CL zones and shows at least four age groups with one age close to the proposed zircon formation age [5]. Assigning the other three ages to three separate impacts would imply that different parts of a 30 micrometer grain behaved differently with each one losing Pb completely in three separate impact events. A more tolerable interpretation is that the observed age distribution is a result of differential Pb loss in a single impact event. If that is the case the other grains in the sample showing younger ages are likely to have also experienced partial Pb loss and their ages do not date any real event in the history of the Moon. Nevertheless, taking into account that zircon in the black part of the breccia is located as fragments in the matrix and has therefore lost its petrologic context, some of these grains can still preserve primary ages that are different from the oldest ~4.3 Ga age (Fig. 1a) recorded in the sample. Clasts in the grey part of the breccia appear to be dominated by felsic (silica K-fsp) rock. Some of the clasts contain zircon grains, which most likely represent a single felsic melt crystallisation event and must have the same age. Observed variability of ages of at least thirteen zircon grains (example in Fig. 1b) from granite clasts between 4315±9 and 3982±6 Ma is a clear indication of Pb loss and the simplest explanation is that this was a variable (incomplete) Pb loss in response to a single impact event. The timing of this event is defined by Ca-phosphate data as 3924±3 Ma, while the time of granite formation is defined by the oldest zircon grains as 4310±5 Ma (three grains, MSWD = 0.95, P = 0.39). It is highly likely that 12013 zircon grains outside the granite clasts experienced similar variable Pb loss during the 3924±3 Ma impact.

The observed partial Pb loss clearly has implications for previous studies of lunar zircon, though these studies mostly analysed zircon grains larger than about 50 micrometers in size, which are potentially more resistant to the effects of resetting of the U-Pb system. Nevertheless, currently available zircon age distribution patterns can be distorted by the partial Pb loss and carful investigation of conditions favouring Pb diffusion in lunar zircon of different sizes is necessary to define an unbiased array of primary zircon ages.

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