4.32 BILLION YEAR OLD IMPACT MELTS AT APOLLO 14: DATING THE PROCELLARUM BASIN?

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Introduction: Recent work has improved our understanding of lunar crustal structure and basin evolution on the Moon, but its early impact history and implications for solar system dynamics remain poorly established [1,2]. In particular, there is a derth of absolute ages, especially for the period >4.0 Ga, that could be related to basin-forming events. Here we present U-Pb isotopic data for Zr-rich minerals found in impact-melt fragments from Apollo 14 soil sample 14163 that, when combined with previously published data, dates an impact event at 4324±15 Ma. The compositions and ages of these impact-melt fragments provide unique information about the timing of early impact events and the composition of the lunar crust.

Results: Fourteen rocklets ranging in size from 1 to 3 mm were extracted from soil 14163. Most are impact-melt rocks with 10-30% clasts of mostly pyroxene and plagioclase (100 to 500 μm) in a crystalline matrix. Textures of the matrix vary from subophitic, formed by intergrowths of 10-20 μm plagioclase and pyroxene crystals, to poikilitic, with plagioclase and pyroxene reaching 20-50 μm size. Some fragments that contain no visible clasts have similar textures are also interpreted as impact-melt rocks.

All fragments contain notably large proportions of euhedral to subhedral ilmenite, zircon, apatite/merrillite and less abundant zirconolite and baddeleyite in the melt matrices. These grains often form intricate intergrowths with each other and rock-forming minerals, indicating their crystallization from the melt (Fig. 1). However, some slightly larger (~50 μm) zircon and phosphate grains can be interpreted as relict clasts based on their granular textures and relationships with the surrounding phases (Fig. 1). This implies that zircon and phosphate minerals were present in the target rocks. Some of these grains were profoundly remelted during the impact, which resulted in an oversaturation of the melt in Zr and P and crystallization of new grains of Zr-rich minerals and phosphates during melt solidification. The presence of zircon and phosphates indicates that the melts were significantly enriched in KREEP components and ties their provenance to the Procellarum-KREEP Terrane (PKT) [3].

Combined U-Pb zircon data obtained for all fragments form two main clusters on a concordia diagram (Fig. 2), between about 4.3 and 3.9 Ga. Phosphate data mostly concentrate on the younger end of this age range but some analyses are almost as old as the older zircon grains (Fig. 2).

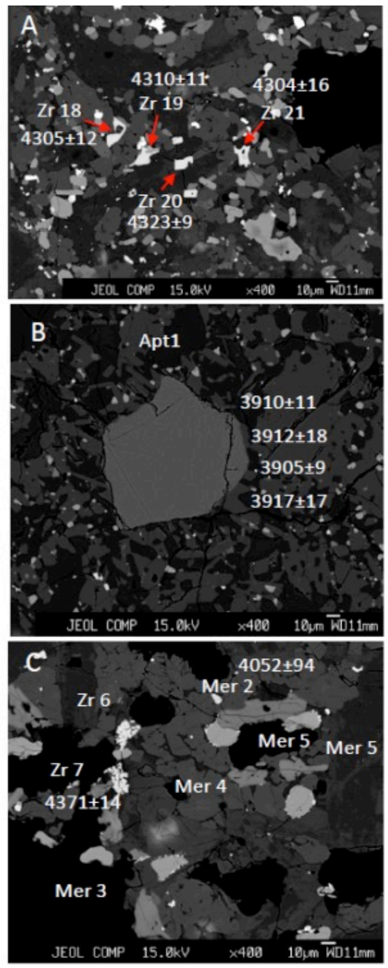

Figure 1: Zircon (Zr) and phosphate (Apt; Mer) grains in impact melt fragments from Apollo 14 soil 14161. A-zircon grains crystallized from impact melt; B-phosphate grain inherited from the target; C- granular zircon grains

Our interpretation of these data is that all U-rich minerals experienced variable resetting of the U-Pb system, with phosphate, where closure temperature is significantly lower than that in zircon, affected more profoundly by Pb loss than zircon. Our best estimate of the time of formation of zircon and phosphate is based on statistically valid analysis of grains interpreted texturally as grown from the impact melt (Fig. 2). Ten of these analyses define an age of 4324±15 Ma (MSWD=3.0, probability of fit P=0.002).

Our best estimate for the time of resetting is obtained by combining data from phosphates that are statistically indistinguishable from 3.9 Ga within the analytical uncertainties. This group is represented by 18 analyses of 15 phosphate grains from different fragments (Fig. 2) and defines an age of 3922±6 Ma (MSWD=1.2, P=0.23). Conversely, a minimum age of the target lithologies, remelted in the impact that produced the rocklets studied here (Fig. 2), can be determined from the five oldest analyses of zircon clasts at 4338±13 Ma (MSWD=1.5, P=0.2), which is indistinguishable from the age of the impact melt within the uncertainties. The obtained ages, combined with textural evidence, imply that the impact melt was formed at 4324±15 Ma, and that it occurred in a zircon-rich target with a minimum age of 4338±13 Ma. Further reworking occurred during a second impact event at 3922±6 Ma.

Discussion: The younger age of 3922±6 Ma can be interpreted as the time of the Imbrium impact. The older age of 4324±15 Ma would then be the time of formation of the impact melt, which was then caught in the Imbrium ejecta either at the Apollo 14 landing site or within the target rocks of the Imbrium impact.

The presence of abundant accessory phases such as zircons and phosphates is consistent with a substantial KREEP component in the analyzed particles. The current distribution of KREEP on the lunar surface appears to be strongly influenced by Imbrum ejecta [4] so interpretation of the 4.32 Ga age depends in part on assumed structure of the pre-impact crust and distribution of KREEP within the crust.

If KREEP was present only in the deep crust at 4.32 Ga, then a basin-scale impact possibly analogous to Imbrium or larger may be necessary to excavate a KREEPy impact melt at this time. However, if KREEPy materials were present closer to the surface perhaps due to redistribution related to Mg-suite magmatism, then smaller impacts might be able to rework KREEPy compositions at shallower depths. The coherence of the data on the particles analysed here suggests a large volume of melt that has been preserved since 4.32 Ga, consistent with a large impact event. Relict zircons and mineral clasts suggests that the igneous crust in the vicinity of this impact was well developed by at least 4.34 Ga, similar to the model age of KREEP and older than the isochron ages of many Mg-suite cumulates [5].

A problem that confronts all lunar sample studies using the current collection is that the pre-Imbrium geology of the PKT (the source of these 4.32 Ga impact melts) is not well constrained. The South Pole-Aitken basin contains regions that are moderately enriched in Th, but its ejecta is Th-poor [6]; therefore these A14 fragments are probably not SPA ejecta. Alternatively, these fragments may represent formation of a hypothesized Procellarum basin [7] although the lack of a clearly defined basin ejecta signature is a potential problem with that interpretation. In any case, they provide a younger limit on the age of lunar differentiation and formation of KREEP within the lunar crust.

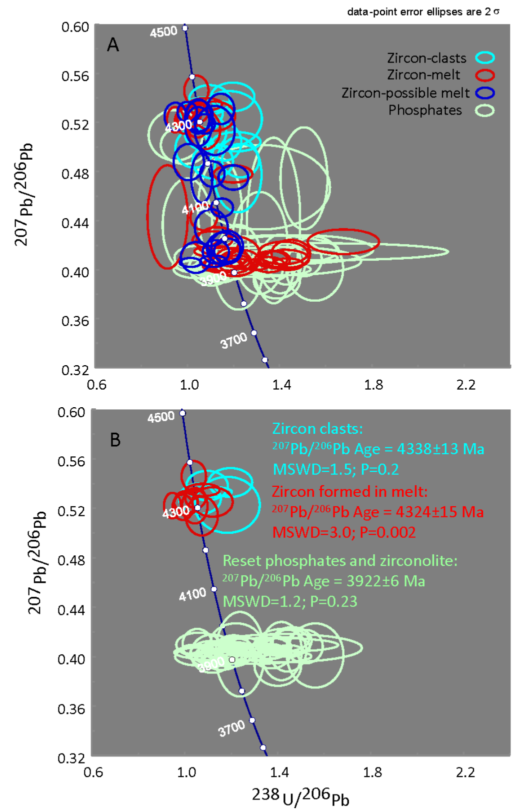

Figure 2: U-Pb data for zircon and phosphate grains from impact melt fragments. A-all data; B-data used for age calculations.

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