Origin and transportation history of lunar breccia 14311. R. E. Merle[1,2], A. A. Nemchin[1], M. J. Whitehouse[3], M. L. Grange[1,2], R. T. Pidgeon[1], J. F. Snape[3] and F. Thiessen[3], [1]Department of Applied Geology, Curtin University, Perth, Australia, [2]Research School of Earth Sciences, Australian National University, Canberra, Australia (renaud.merle@anu.edu.au), [3]Swedish Museum of Natural History, Stockholm Sweden.

Introduction: Apollo 14 landing site is believed to be widely covered by the ejecta of the Imbrium impact (Fra Mauro formation) with age estimates ranging from 3770 to 3920 Ma [1-5]. However, significant textural and petrological differences exist between breccia 14311 and the other breccias collected on this landing site. This sample also has an older exposure age (550-660 Ma) compared to ~30 Ma exposure age determined for the other breccia samples [2]. More importantly, Ca-phosphates from 14311 yield a $^{207}Pb/^{206}Pb$ age of 3938 ± 4 Ma (2σ) [6] which is significantly older than the $^{207}Pb/^{206}Pb$ age of 3927 ± 2 Ma (2σ) obtained from Ca-phosphate grains in three Apollo 14 impact breccias (14305, 14306 and 14314) and interpreted as the age of the Imbrium impact event [7]. Zircons from 14311 analysed by Raman spectroscopy give a radiation damage age of 3410 Ma ± 80 Ma (2σ) interpreted as the age of a mild thermal event [8]. This thermal event was hot enough to anneal the radiation damage in zircon (~ 230 °C) but still below the U-Pb system closing temperature of the Ca-phosphates (450–500 °C; e.g. [9]).

All these differences suggest that breccia 14311 was not formed during the Imbrium impact and thus question its origin and raise questions about its transport history from its formation location to the Apollo 14 site. Additional evidence related to the possible differences in the source of the breccia materials can be gained from the study of U-Pb zircon age patterns, as zircon can preserve information about magmatic and impact history of the target rocks [10-12]. The aim of this study is to compare newly obtained zircon U-Pb data for 14311 with previously published zircon ages for this sample and other breccia samples from the Apollo 14 landing site and investigate the origin of 14311 in the light of all available chronological information.

Sampling site and studied sample: The Apollo 14 landing site is located 600-800 km from the rim of the Imbrium basin. It was selected for its proximity to the ~ 30 Ma Cone Crater, thought to have excavated rocks of the Fra Mauro formation from below the surface regolith. Sample 14311 is a very coherent polymict impact melt breccia composed of 75 to 95% of crystalline matrix formed by a mosaic of pyroxene and plagioclase crystals or crystal fragments and Fe-Ti oxides and 5 to 25% of mineral and lithic clasts.

Results: U-Pb systems of zircons from five thin sections (14311,4; 14311,5; 14311,7; 14311,8 and 14311,90) have been investigated by SHRIMP at Curtin University and CAMECA 1280 at the Swedish Museum of Natural History.

The analysed zircons are separate crystals and fragments scattered in the breccia matrix, usually <100 µm in length and with sharp contacts with the matrix. Euhedral grains are very rare. None of the analysed grains show any textural evidence of crystallisation from the impact melt that consolidated the sample.

A total of 75 analyses were made on 51 grains. All data are concordant to slightly discordant forming two dense populations on the concordia diagram, one older than 4300 Ma and the other between 4300 Ma and 4200 Ma (Fig. 1). Smaller number of analyses are scattered between about 4150 and 3950 Ma. The youngest zircon analysed in 14311 has an age of 3932 ± 23 Ma (2σ), similar to the youngest zircon analysed in the previously published 14311 zircon ages dataset (3937 ± 18 Ma; [12]) and to the Ca-phosphate age of 3938 ± 4 Ma [6].

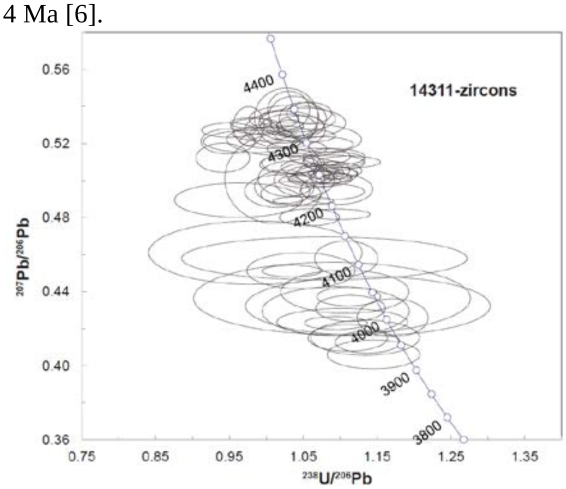

Fig. 1: Inverse concordia diagram showing ^{204}Pb-corrected zircon ages in sample 14311. Error ellipses are shown at 2 sigma level.

In order to compare the breccia datasets, we applied a statistical approach based on a Kolmogorov-Smirnov test (KS-test). This test is designed to compare distributions of two samples without making any assumption about the distribution of data. The KS-test shows that the age distribution pattern obtained from our new zircon analyses is statistically similar to that of

[12]. As a consequence, we have combined the two datasets and compared it with data from the other Apollo 14 breccias [10-11]. The KS-test indicates that 14311 is different from the other Apollo 14 breccias (14066, 14303, 14304, 14305, 14306 and 14083).

Both age distributions for sample 14311 and for other breccias show an age peak at approximately 4340 Ma. However, sample 14311 has an age peak at about 4240 Ma that is not present in the other breccias. Instead, the maximum of the age distribution for the other breccias is shifted to about 4200 Ma. In addition, younger ages in 14311 are distributed between three minor peaks at approximately 4110 Ma, 4030 Ma and 3960 Ma, whereas the distribution of ages for all other Apollo 14 breccias is centered at approximately 4020 Ma.

Discussion: The observed differences in zircon age distribution patterns imply that 14311 has incorporated material from target rocks different from that present in the majority of the other breccia samples collected at the Apollo 14 landing site. Nevertheless, the target rocks contain zircon and must originate from the Procellarum KREEP terrane. In addition, breccia 14311 was formed prior to approximately 3938 Ma (age of Ca-phosphates and youngest zircon), but had experience zircon radiation damage annealing at about 3400 Ma that could be related to either a residence in a hot ejecta blanket after a late impact, or long-lasting temperature perturbation due to the vicinity of hot basaltic flows [8]. Finally, 550-660 Ma exposure age reflects the time 14311 spent on the lunar surface and in the simplest scenario, it determines the time when the sample was finally delivered to the Apollo 14 landing site. In a more complex scenario, it represents the sum of different periods of time this sample spent at the surface of the Moon. However, the event at 3400 Ma that resulted in the heating of the sample and recovery of zircon lattice could also have outgassed the sample, resetting noble gas system and exposure age.

Combining all the chronological constrains obtained for the breccia 14311 allows three possible scenarios for its origin and delivery to the Apollo 14 landing site:

1) Breccia 14311 was formed somewhere in the Procellarum KREEP terrane by a 3938 Ma impact. It was deposited either at the Apollo 14 landing site or near the future site of the Imbrium basin by the ejecta of this impact. At 3927 Ma, it was integrated into the Fra Mauro Formation during the deposition of the Imbrium impact ejecta. The zircons were annealed by mare basalt flooding at 3400 Ma at the vicinity of Apollo 14 landing site. A small and local impact event excavated this sample at approximately 600 Ma and it has been at the surface of the Moon since that time.

2) Breccia 14311 was formed by the 3938 Ma impact event but was not transported by the Imbrium impact to the Apollo 14 landing site and never included into the Fra Mauro Formation. It was transported from its deposition location to the Apollo 14 landing site by an impact at approximately 600 Ma and remained at the surface of the Moon since this event. In this case the breccia was originally located near or buried by hot basaltic flows at 3400 Ma, before it was transported to the Apollo 14 landing site.

3) If an impact rather than mare basalt flooding is the cause of the 3400 Ma thermal event, breccia 14311 was formed by the 3938 Ma impact and deposited at the surface of the Moon for approximately 540 m.y. At 3400 Ma, the sample was transported to the Apollo 14 landing site by an impact ejecta which may or may not have mixed with Fra Mauro formation. Sample 14311 was then buried, hence stopping the cosmic-ray noble gas clocks. The sample was eventually excavated by the Cone Crater impact at 30 Ma leading to a final cumulative exposure age of approximately 600 Ma.

The simplest scenario (number 2) is the formation of this breccia during an impact at 3938 Ma followed by transportation to the Apollo 14 location by a ~600 Ma old impact. A possible candidate is the impact event that formed the Copernicus Crater since material associated with this impact is suggested to cover much of the Apollo 14 landing site area [13] and its accepted age is approximately 660-800 Ma [14-15] overlapping the estimated exposure age of sample 14311. Furthermore basalts in the area around the Copernicus Crater have an age around 3450 ± 50 Ma [16], which is in agreement with a 3400 Ma thermal event recorded by the zircon annealing age.

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