**Imbrium Zircon Age for Apollo 73155 Serenitatis Impact Melt Breccia: Implications for the Lunar Bombardment History**

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**Introduction:** The Serenitatis basin is thought to be one of the oldest basins on the near side of the Moon [1]. The Apollo 17 landing site is located within the southeast area of Serenitatis basin. This area is of special interest as a site for ancient crustal rocks which were thought to have avoided the influence of Imbrium-basin-forming event [2]. Chemically and petrologically distinctive from Apollo 14 breccias (representative of Imbrium ejecta) [3], Apollo 17 samples are regarded as a single large impact source from Serenitatis basin [4]. Previous geochronological studies of Apollo 17 impact melt breccias (IMBs) by Ar-Ar chronometer place the age of Serenitatis basin formation at ~3.9 Ga [5]. This age for Serenitatis basin was interpreted as a spike in the impact flux during the so-called period of late heavy bombardment (LHB).

However, it has been argued that the predominant ~3.9 Ga ages of lunar near-side basins (including Serenitatis basin) may be due to Imbrium contamination [6]. Recent Ar-Ar studies of Apollo 16 [7] and Apollo 17 [8] highland IMBs suggested that they may actually contain considerable Imbrium components. Here, we present petrological, geochemical, and U-Pb geochronological results for Apollo 17 highland IMB 73155,69 thin polished section.

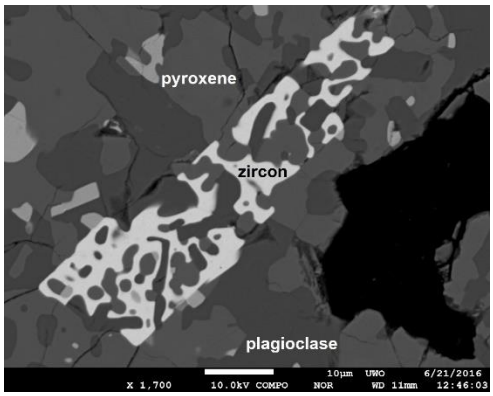


**Fig.1**. A representative ~50 μm zircon grain (backscattered electron image) in Apollo 73155 IMB.

**Petrology and Mineralogy:** Apollo 73155 is an impact melt breccia with fine-grained aphanitic matrix (>90 vol.%). It was sampled on the Light Mantle deposit at the foot of South Massif (Station 2A) in the Taurus-Littrow Valley, southeastern Serenitatis basin. The matrix consists of olivine, pyroxene and plagioclase. The Apollo 73155,69 has pigeonite to augite pyroxenes, Ca-rich plagioclase and Mg-rich olivine. The grain size of zircons ranges from a few microns to 50 μm. Most zircon grains are anhedral and have vermicular intergrowths with plagioclase and pyroxene grains (Fig. 1). This unusual texture of lunar zircons has been identified in the Imbrium-originated samples of lunar meteorite Sayh al Uhaymir (SaU) 169 and Apollo 12 high-Th IMBs [9].

**Results and Discussion:** Nanoscale secondary ionization spectrometry (NanoSIMS) analyses of the 73155 zircons have a weighted mean Pb-Pb age of 3928 ± 10 Ma (N=10, 2σ; Fig. 2). This age is consistent with the Ar-Ar age of 73155 matrix at 3937 ± 16 Ma [5]. The vermicular zircons of Apollo 12, Apollo 73155 and SaU 169 are thought to have crystallized in-situ and simultaneously within impact melts due to their small sizes (<20 μm) and enclosed inclusions (matrix minerals) [9-11]. This scenario is supported by the presence of high-Zr contents of the matrix inclusions within 73155 zircons. The vermicular intergrowths of these zircons with matrix minerals, and the overlapping ages of zircons and matrices, indicate that Apollo 73155 IMB and its zircons formed contemporaneously, and coeval with the Imbrium event.

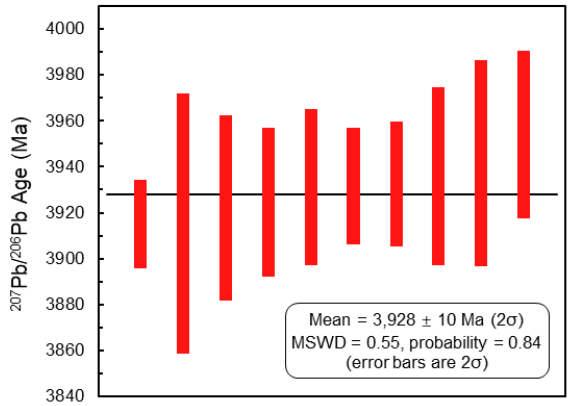


**Fig. 2**. Weighted mean and 2SD Pb-Pb age of 10 73155 zircon spots.

The zircon grains found in Apollo 73155 have comparable texture, ages and rare-earth-element (REE) concentrations to those found in Imbrium-originated SaU 169 and Apollo 12 high-Th IMBs. The 73155 zircon Pb-Pb average age is similar to Imbrium meteorite SaU 169 (3920 ± 13 Ma, 2σ) and Apollo 12 IMBs (3914 ± 7 Ma, 2σ) within errors. Besides, Apollo 73155 zircons have

extraordinarily high contents of U, Th and Y. The 73155 zircons (12 spots on 10 grains) have high contents of Y, ranging from 3279 to 6347 ppm; U and Th concentrations vary between 131−457 ppm and 254−302 ppm, respectively. These high Y, U and Th concentrations are similar to SaU 169 (U=161−294 ppm, Th=35−288 ppm, Y=1024−10318 ppm) and Apollo 12 (U=60−519 ppm, Th=51−425 ppm) samples [9, 11]. The Th contents and Th/U ratios of 73155 zircons drift distinctively from those of other Apollo 17 zircons (Fig. 3), which have a mean Th content of 49.9 ± 37.7 ppm (N=133, 1SD) and a mean Th/U ratio of 0.49 ± 0.13 [12-15]. In summary, Apollo 73155 zircons with high-U and -Th contents, ~3.92 Ga ages and Imbrium-like textures should have a similar source as SaU 169 and Apollo 12 high-Th samples. The lunar meteorite SaU 169 and Apollo 12 high-Th IMB were related to the Lalande impact crater within Imbrium basin [9, 16]. Therefore, the zircons in 73155 IMB may originate from the Lalande crater, and afterwards they were transported to its recovery site and recrystallized therein.

The aphanitic Apollo 73217,52 has impact ages of baddeleyite at 3929 ± 10 Ma, apatite at 3936 ± 17 Ma and polycrystalline zircon at 3934 ± 12 Ma [14], as well as the phosphate ages of Apollo 17 Station 2 and 6 at 3922 ± 5 Ma and 3930 ± 5 Ma [17], are indistinguishable from the Imbrium ages indicated by those of Apollo 73155, SaU 559, Apollo 12, Apollo 14 IMBs [18-20], These clustered U-Pb impact ages at 3.92−3.94 Ga might be the most precise estimate of the Imbrium event [21].

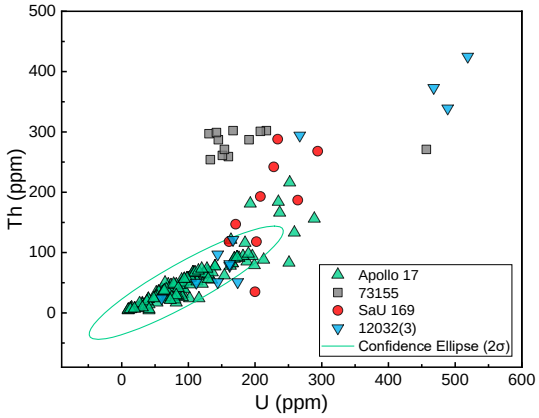


**Fig. 3**. Th and U concentration distribution of zircons in 73155, Imbrium IMBs (SaU 169 [9, 11] and Apollo 12 [9]) and other Apollo 17 samples [12-15].

Apollo 17 impact melts have been related to the production of Serenitatis ejecta because of mutual proximity [1]. Aforementioned in-situ U-Pb ages and Ar-Ar studies support that Imbrium-related materials can be identified in the Apollo 17 IMB suite. Moreover, topographical and crater-counting data from the Lunar Orbiter Laser Altimeter (LOLA) and the Lunar Reconnaissance Orbiter Camera (LROC) provide evidence that Serenitatis basin may be in fact older than Nectaris basin. From LOLA data, the crater density of Serenitatis basin (N(20) = 298 ± 60 $km^{-1}$), which is three times higher than that of Crisium (113 ± 11 $km^{-1}$), indicates that Taurus Mountains region predates Nectaris (135 ± 14 $km^{-1}$) [22]. From LROC images, the Sculptured Hills, a unit in the Taurus Mountains between Serenitatis and Cirsium, is not directly related to Serenitatis ejecta but instead to Imbrium ejecta [23].

**Conclusions:** The Apollo 73155 zircon grains have textural characteristics (vermicular intergrowths with matrix), U-Pb age (3928 ± 10 Ma) and trace-element contents comparable to those found in SaU 169 and Apollo 12 high-Th IMBs from Lalande crater area, Imbrium basin. Apollo 73155 zircons point thus towards an Imbrium component within Apollo 17 IMBs (Serenitatis samples). Together with updated topographical datasets from the LROC and LOLA, we suggest that Serenitatis basin was contaminated by Imbrium ejecta and is older than Nectaris basin. These results and observations support other evidences that a "Terminal Cataclysm" scenario for the lunar surface at ~3.9 Ga may have been overestimated because of the transportation of Imbrium-related impactites to other large basins.

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